Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2018

GEM

Greenland Ecosystem Monitoring

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2018

GEM

Greenland Ecosystem Monitoring

GEM ANNUAL REPORT

About GEM

Greenland Ecosystem Monitoring (GEM) is a long term monitoring programme operated by Greenlandic and Danish research institutions. GEM was initiated in 1996, and remained in its 23rd year (2018) of operation committed to be an integrated monitoring and long-term research programme on ecosystems and climate change effects and feedbacks in the Arctic.

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

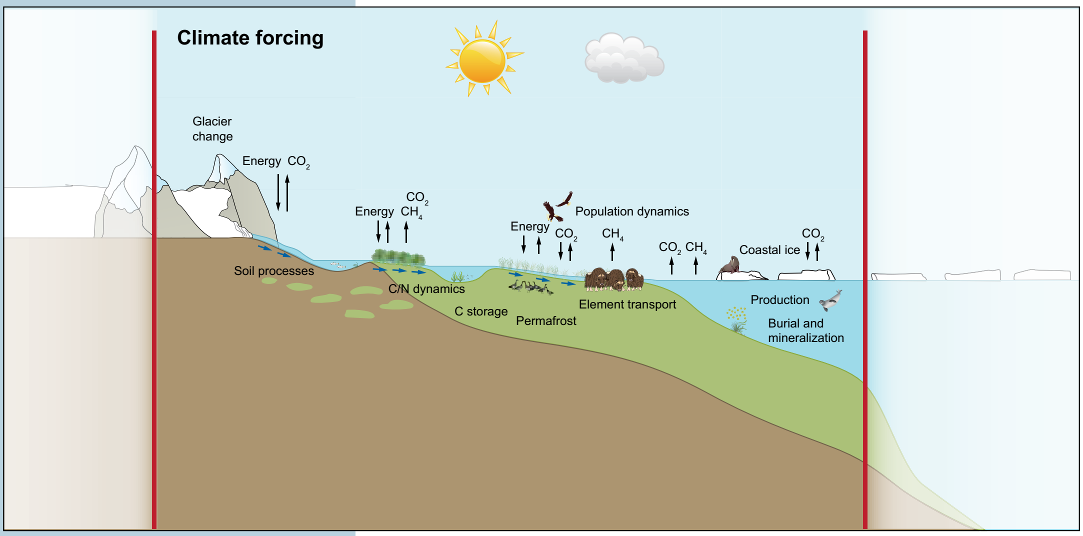
The year 2018 was characterized by deep and prolonged snow cover and a cold, wet summer in many areas of Greenland, and notable so at the Zackenberg site. This resulted in ecosystem wide reproductive failure across all taxonomic groups. Ongoing climate change and extreme weather events may lead to changes in community structure, biomass and productivity affecting entire ecosystems. Indications of such changes are seen in Disko Bay, which were included in the MarineBasis programme in 2018, and act as a baseline for documenting changes and potential ecosystem shifts, potentially with impacts on the economy of Greenland.

Probably somewhat independent of the special weather conditions in 2018, some unprecedented and rapidly developing geomorphological features were observed. A so called galloping thermokarst formation (permafrost thaw and subsequent erosion) appeared close to Zackenberg research station, where almost 300 m^3 substrate were eroded from one thermokarst feature alone over a few months. This rapid development in undisturbed terrain may send a clear warning message to construction work in permafrost areas elsewhere in Greenland, as these respond to gradual warming.

The long term monitoring is fundamental for detecting, analysing and understanding such changes and in this edition of the GEM Annual Report Cards we present aspects of change of the rather special year of 2018, along with stories of methodological developments that will improve our understanding of ecosystem processes and change.

In 2018, new thematic study areas within GEM were initiated, as an open forum for GEM researchers to meet and exchange information and ideas along certain topics. These topics include initially, the use of molecular techniques (RNA/DNA) in monitoring, the use of UAV technologies (drones, boats, and submarines), the remote sensing area at large scale and finally the 'back to the future' (BTF) concept, which is detailed later in two report cards in the current issue. More reports from these thematic areas are envisioned to be included in future annual report cards.

The GEM domain.



GEM

Greenland Ecosystem Monitoring

CARDS 2018

GEM at a glance 2018

- Basis Programmes active in 2018: 14 + GEM Remote Sensing
- GEM scientists in the field: 88
- Scientific publications: 78
- Conference posters: 10
- Courses using GEM data: 17
- Conferences with GEM representation: 27
- GEM conference presentations: 33

International cooperation and outreach

The GEM Secretariat presented the programme at a number of international conferences and held a session at the Arctic Biodiversity Congress 2018 focusing on how to design long term monitoring programmes to feed arctic and international assessments.

In 2018, GEM also got involved with the programme T-MOSAiC, Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections. This research and synthesis project provide an integrated, cross-disciplinary evaluation of how the changing Arctic Ocean affects terrestrial environments, from the coastal zone to the continental interior – the environmental domain covered by GEM.

In autumn 2018, GEM launched three new social media accounts on LinkedIn, Facebook and Twitter. This allows a more dynamic update on GEM publications, interviews, news from field work and general information about the GEM programme and participants. The tweets and posts are intended to reach a broad audience, and more than 80% of our approximately 100 followers on twitter are external to GEM. GEM is also present at ResearchGate, so please join us on the social media platform you prefer.

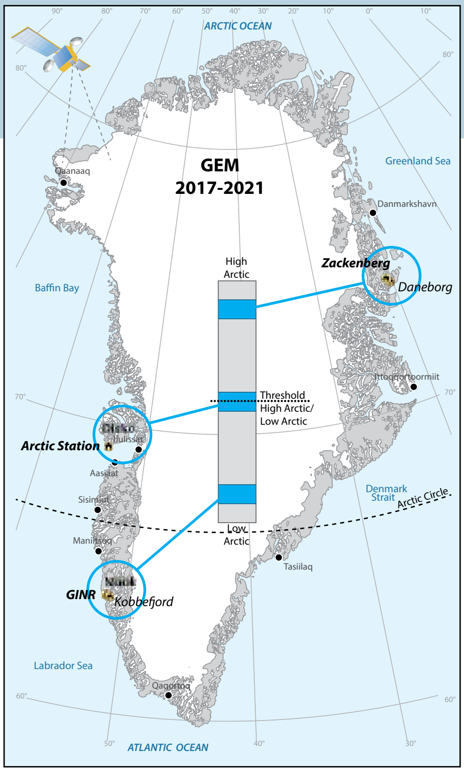
Links to GEM papers in peer reviewed journals and other publications and reports can be found on the GEM website www.g-e-m.dk.

GEM database

The GEM database (http://data.g-e-m.dk/) contains data from the first monitoring started in Zackenberg in 1996 and now also includes data from Nuuk and Disko. The database includes data on more than 2500 parameters and the data are shared in 21 international thematic data repositories. In 2018, several new developments were added to the database, including; a search function, data availability period (first and last date), web-GIS, and download purpose. In 2018, the GEM database was used by 300 active users of which 200 were new to the system. The majority of users come from Denmark and Greenland, but users from more than 70 different countries across the world are registered.

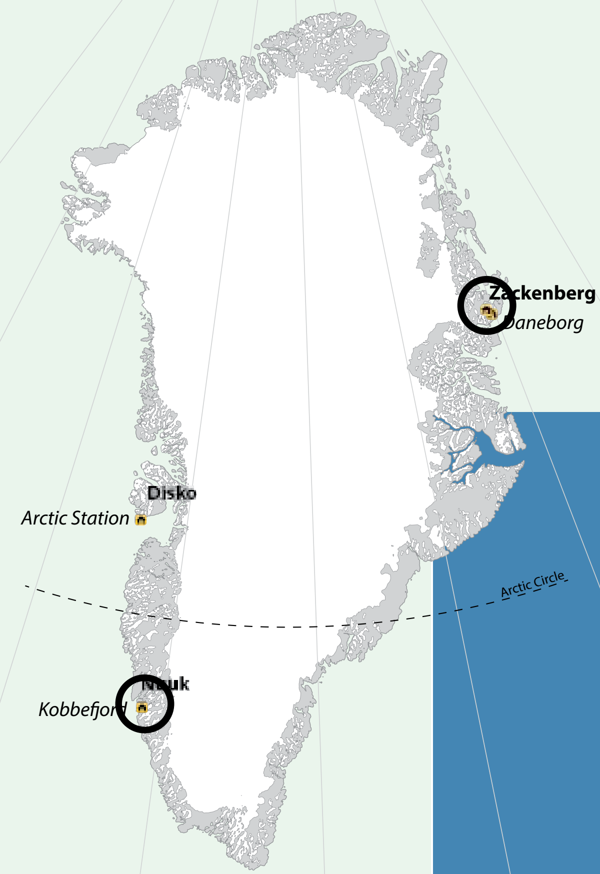
GEM mid-term status evaluation 2019

In 2018, the GEM steering group committee requested a 'Mid-term status evaluation' to make sure the programme is on track with the 2017-2021 strategy, and to identify focus areas for the remaining part of the strategy period. Two years into the strategy, the evaluation was finalized in 2019. It provides a status of what has been achieved so far, in relation to general GEM objectives and initiatives, as well as Basic Programme specific milestones and deliverables. The steering group received a draft 'Mid-term status evaluation' in beginning of 2019. The evaluation received positive and constructive feedback from the steering group, and suggestions to incorporate information about use of the GEM database and logistics were then included in the final evaluation document, which is now available for download on the GEM homepage www.g-e-m.dk.



GEM sampling strategy.

Photo: Lars H. Hansen



Annual Report Card 2018

ECOSYSTEM-WIDE

Extreme events, such as the 2018 extreme amounts of snow, are hard to predict from past knowledge, and predicting the ecological consequences of such events is even harder. However, based on the unique long-term monitoring data from the Greenland Ecosystem Monitoring programme, we can now not only document a rare climatic event, but also quantify the ecological consequences.

The plants and animals currently living in the Arctic are highly adapted to life under environmentally extreme conditions that may vary dramatically between years but also during the course of the year. Long-term monitoring programmes, such as GEM, document intra- and inter-annual variability in plant and animal abundance, phenology, distribution and reproduction in detail. When trying to predict future changes, we usually rely on trends in such data. However, changes in environmental conditions may be so extreme or happen so fast that arctic organisms may struggle to keep up. Extreme events may inflict consequences onto the arctic ecosystems that are impossible to predict from current knowledge and may even bring the ecosystem to a completely new state.

In 2018, the large amount of snow at both Zackenberg, Kobbefjord and Disko resulted in delayed snow-melt at the three sites (see pp 40-41), and the onset of the snow-free season was far later than observed during the past two decades of monitoring. The biological monitoring at Zackenberg and Kobbefjord offer a unique opportunity to quantify the ecological impacts of such extreme events, and these ecological impacts turned out to be substantial and evident across all taxa monitored.

The most pronounced effect observed was an almost complete reproductive failure across plants and animals. Though the number of flowers produced by most monitored plant species were within the ranges observed in previous years, flowering was so delayed that seeds were unlikely to develop before the end the snow-free season. This was particularly the case at Zackenberg and to a lesser extent so in Kobbefjord even though flowering phenology there was also late compared to previous years (Fig. 1). Arthropods numbers were lower than in previous years and their emergence also very delayed. This is likely to have repercussions for the plant-pollinator interactions (Schmidt *et al*. 2016). The delayed snow-melt and reduced number of arthropods resulted in a collapse in the breeding populations of shorebirds at Zackenberg, with both record low numbers and so delayed onset of nest initiation that fledglings were

Photo: Lars Holst Hansen.

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Source:

GEM BioBasis

REPRODUCTIVE FAILURE

unlikely to have sufficient time and resources to prepare for the migration south. In Kobbefjord, the late snowmelt also resulted in record low numbers of passerine birds observed. Moreover, the majority of birds were observed during spring arrival where almost no snow-free ground was available, or during autumn migration when smaller flocks passed through the monitoring area. The mammalian species at Zackenberg also showed no or very low reproduction, with no arctic fox cubs and almost no muskox calves observed.

Breeding failures of individual taxa has been observed before (Schmidt *et al*. 2012; Schmidt *et al*. 2015), but during the past decades of monitoring, we have not witnessed such an ecosystem-wide reproductive failure. A single year with breeding failure is not likely to pose a serious threat to the taxa reported here. However, future arctic climates are expected to include more snow (Liu *et al*. 2012), and we might be facing more years with extreme snow conditions – this will be a game-changer for the organisms living in the arctic ecosystems today.

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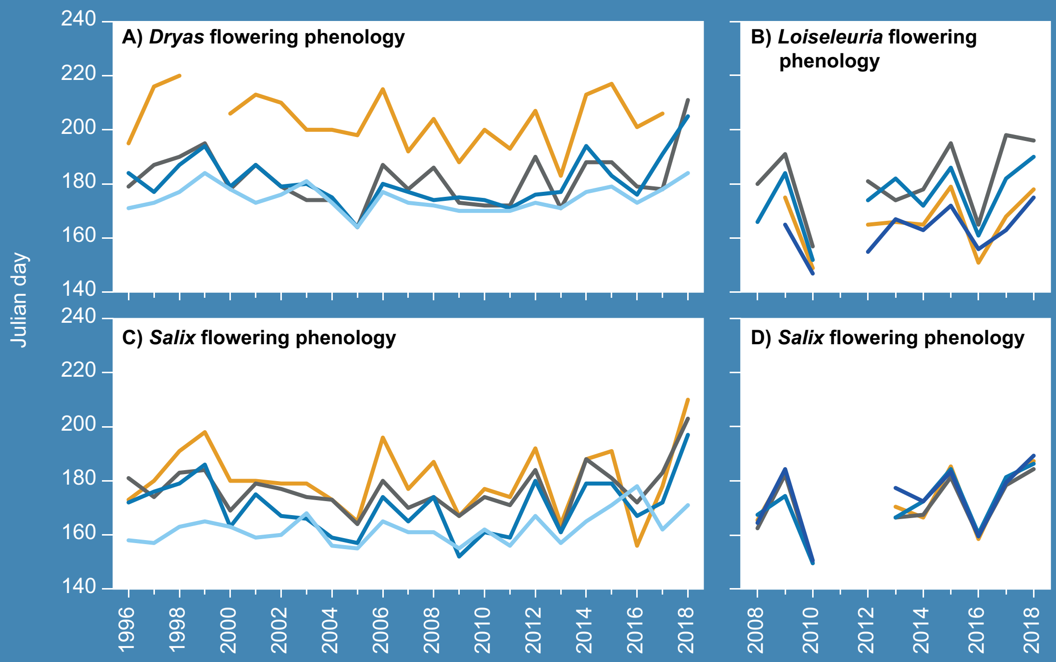

Figure 1. Ecological impacts of delayed snow melt. Plant flowering phenology (Julian day of 50% flowering) for important plant species in Zackenberg (A and C) and Kobbefjord (B and D) during the period 1996 to 2018. Note that missing data in Zackenberg (A) indicates that 50% flowering was never achieved. In Kobbefjord, an insect outbreak in 2011 (Lund et al. 2017) resulted in all flowers and catkins (B and D) were eaten by larvae. This likely also resulted in the lack of flowering in Salix in 2012 (D). Colors show individual plots.

Photo: Lars Holst Hansen.

THE IMPLICATION
ON THE CHAMBERLIN GLACIER

On Disko Island, Western Greenland, there are several hundred glaciers, of which a majority have shown recession, as a consequence of increased air temperatures. Glaciers at 800 m or more above sea level, with coverage of more than 5 km^2 and an ablation area facing south to northwest are the most sensitive to climatic changes. Such glaciers will respond rapidly to ongoing climatic change with altered patterns in glacial runoff which in turn will affect fluvial regime and thus have implications for the freshwater biota of glacial influenced streams and lakes.

Solar radiation is the largest source in the surface energy balance of Greenland's glaciers and the amount of energy absorbed is controlled by surface albedo. The seasonal snow cover, having a higher albedo than glacier ice, reduces the amount of radiation absorbed during the first part of the melt season. Abiotic (dust, soil, glacial flour, etc.) and biotic particles (bacteria, algae) situated on top of the snowpack, and later on the ice once the snow cover has melted, reduce albedo and increase surface melt rates.

The biotic organisms often form a strong red colour that originates from the pigmentation of living algal cells. However, green and orange colours are also common and colour changes over the season occur as environmental changes take place and affect the physiological status of the cells. Light and moisture (wetness) are crucial for the development, but the controlling mechanisms are not fully understood. The organisms involved in forming these coloured patches belongs to bacteria, cyanobacteria and various groups of photosynthetic algae of which chlorophycae (green algae) is most often reported.

The red algal blooms at the Chamberlin glacier on Disko Island

During the last 3 years (2016-2018) large red patches on top of the snowpack at the Chamberlin have been observed and the phenomenon has been analysed more closely during 2017 and 2018 (Fig. 1).

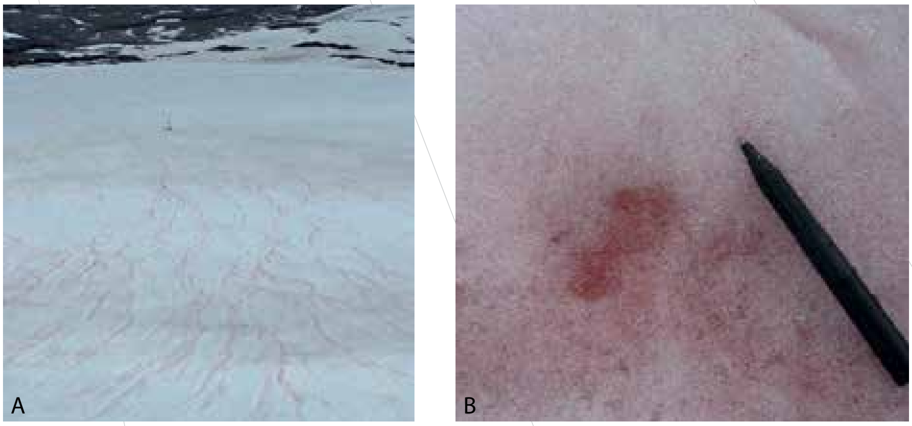

Figure 1. A) a snow-slope with channel-like red features. Photo is taken from Stake 3 looking downglacier on 3 July 2016 at Chamberlin glacier. B) close-up of the red-colored snow. Photos: Michele Citterio.

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OF SNOW ALGAE

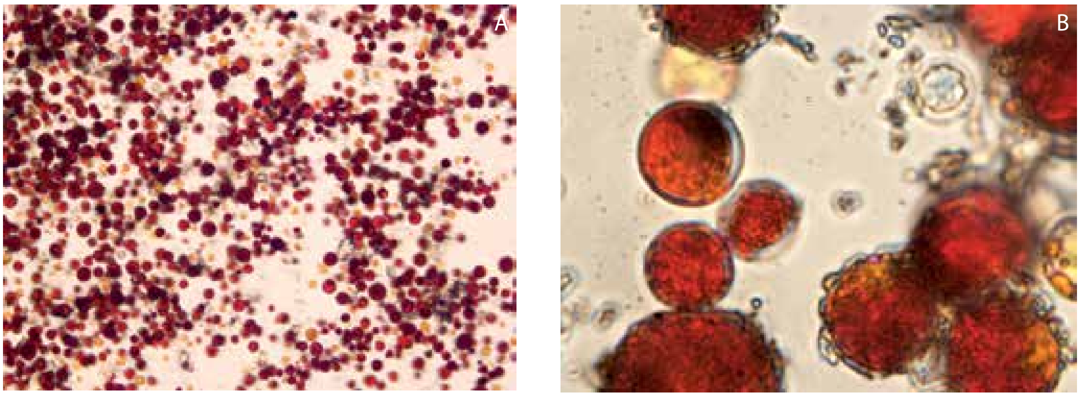

Figure 2. A) a dense sample with the cyst stage of Chlamydomonas nivalis *from the Chamberlin glacier during July 2017. B) a close-up of the cells (the size of individual cells are 8-10 µm in diameter). Photos: Trine Perlt.*

The red patches are created by living and growing assemblages of the snow alga *Chlamydomonas nivalis* (Fig. 2) which is one of the most common photosynthetic species living in and on snow packs.

It is reasonable to assume that the algae found on the Chamberlin glacier can be responsible for a "bio-albedo" effect leading to accelerated retreat of the snow line, earlier exposure of the underlying darker glacier ice, and consequent enhanced glacier mass loss. Darkening from algae blooming in the snow pack and its glaciological impact is starting to be investigated through predictive modelling, but field observations are still lacking.

To further expand the spatial coverage of the field observations, in 2018 measurements were also started on Qasigiannguit glacier (Nuuk) and further are planned for 2019 at both GEM sites.

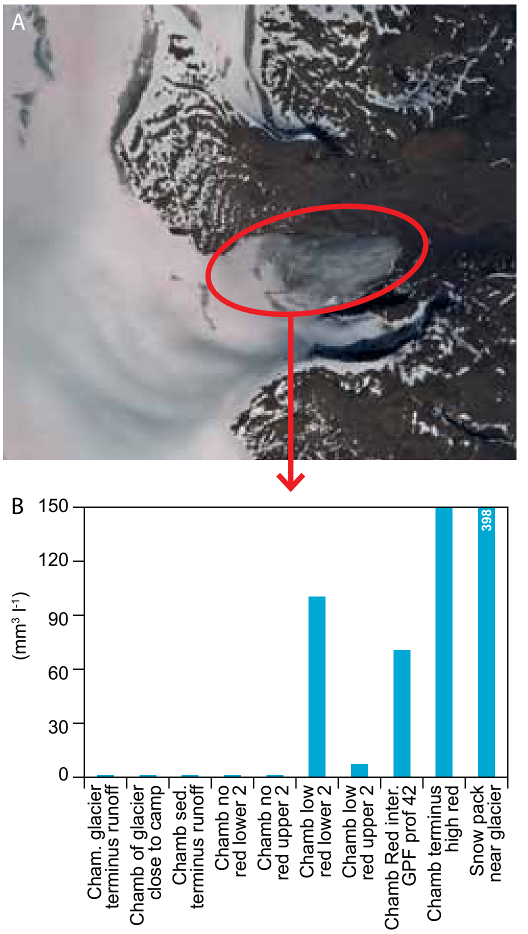

Figure 3. A) The algal bloom on Chamberlin glacier seen from space as red-coloured snow patches on a Sentinel-2A acquisition from 26 July 2017 (produced from ESA remote sensing data, image processed by GEUS). The part of the glacier where samples were collected is also marked. B) The biovolume of Chlamydomonas nivalis *from the Chamberlin glacier during July 2017 (Data: Kirsten S. Christoffersen).*

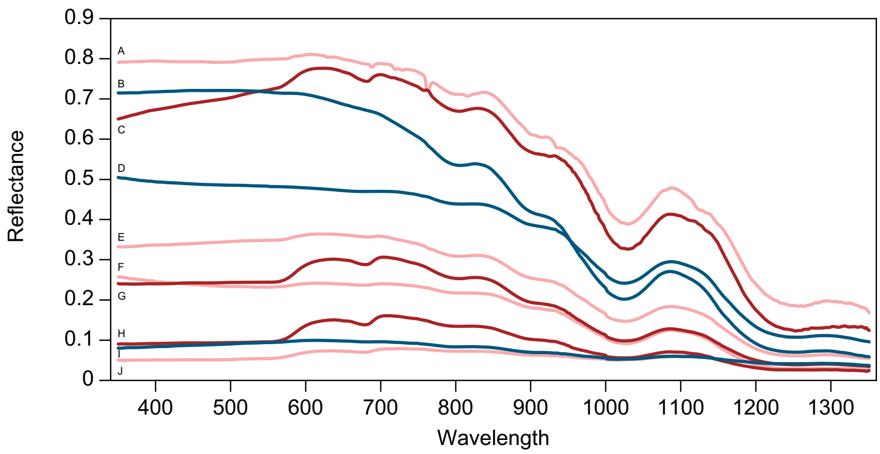

Figure 4. Spectra of snow (A B, C), ice (D, E, F, G), and cryoconite material (H, I, J) from the surface of Chamberlin glacier in August 2018 classified based on the visual perception of the abundant presence of snow algae (dark red lines), low abundance of snow algae (light red lines) and absence of snow algae (blue lines).

REWINDING THE TUNDRA
– THE REMARKABLE DEVELOPMENT

Thermokarst erosion is a well-known feature of permafrost landscapes. Early in the Greenland Ecosystem Monitoring programme such geomorphic features have been documented as active on the centennial (hundreds of years) timescale in the Zackenberg valley (Christiansen, 1998) – some of them old and stable, others acting dynamic in response to snowmelt and spring water movement. However, during the years of monitoring at Zackenberg there has never been such a fast and "galloping" type thermokarst erosion feature as one that developed quickly after snowmelt 2018 in close vicinity to the Zackenberg station.

The first signs of the thermokarst (Fig. 1) developing between the small fen area Gadekæret and the Zackenberg River, emerged out of the snow in late June 2018 and developed fast in the subsequent weeks (Fig. 2). The thermokarst emerged after a consistent soil warming trend has been observed during the first three decades of monitoring at Zackenberg, and marked increase during early winter in recent years. This trend is also clear for the soil layers between 30 cm and 1.3 meters depth (data from Zackenberg Climate station) where the collapse of segregated ice has happened and most likely triggering the thermokarst (Fig. 3 and 4).

The time sequence of the thermokarst development in 2018 is captured by drone imagery obtained between 28 June and 9 September (Fig. 2). It is also clear from a 2014 drone image (Fig. 2), that the thermokarst had been in a relatively stable shape for at least four years preceding its rapid development during July 2018. A subsequent preliminary analysis of the soil volume lost downstream during these few weeks adds up to 290 m^3. The total area of the scar opening in the landscape during July-August reached 173 m^2 in the last image obtained in 2018 (9 Sept).

The top 30 cm soil was analysed for ^{14}C and the organic components of the soil dated to a maximum age of 400 years (analysis made at the Lund University ^{14}C lab). This means, that the formation of the segregated ice (30 cm depth and below) and development of soil layers above it appears to have been formed during the Little Ice Age cold period (1300–1700). The rapid washing away and oxidation of the soil material following the collapse of the permafrost may, hence, be considered a rewinding of the clock of landscape development that has taken place over a centennial timescale within just a few months.

Preliminary measurements of greenhouse gas exchanges within and around the thermokarst show clear signs of dramatic increased releases of methane, and through the massive volume loss of soil an obvious change in the long-term atmospheric uptake of CO_2, that the landscape otherwise have been documented to have (Lund

Figure 1. Drone photograph taken in south-westerly direction of the thermokarst area with Zackenberg research station in the background. The area within the white dotted line is the thermokarst study area analyzed in the images pictured in figure 2. Photo: Lars Holst Hansen.

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Source:
GEM GeoBasis/soil temperature
Data can be accessed on: www.data.g-e-m.dk

LANDSCAPE CLOCK 400 YEARS IN TWO MONTHS

OF A GALLOPING THERMOKARST

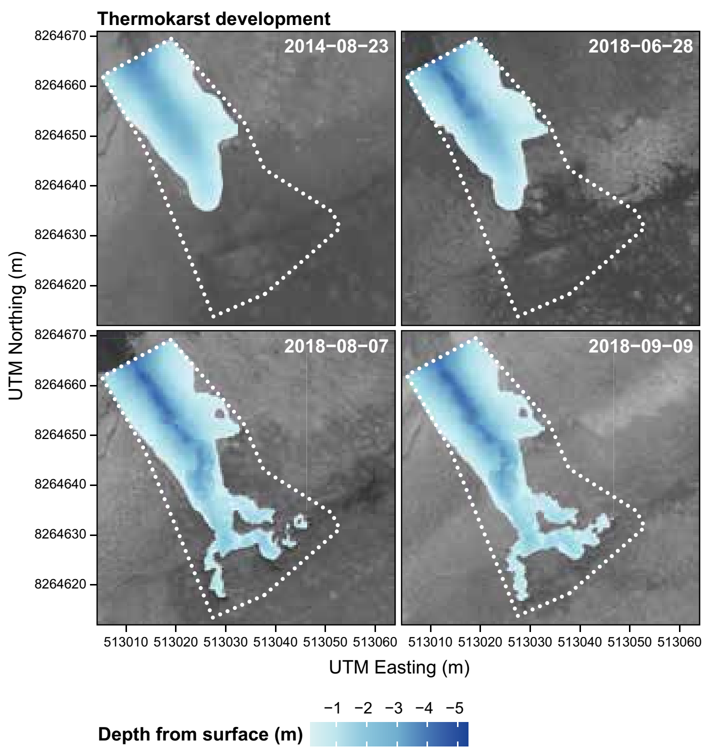

Figure 2. Drone images analysed for spatial and volumetric development of the thermokarst between 23 August 2014 and on three occasions during the summer of 2018. The white dotted line corresponds roughly to the one super-imposed on the photograph in Figure 1.

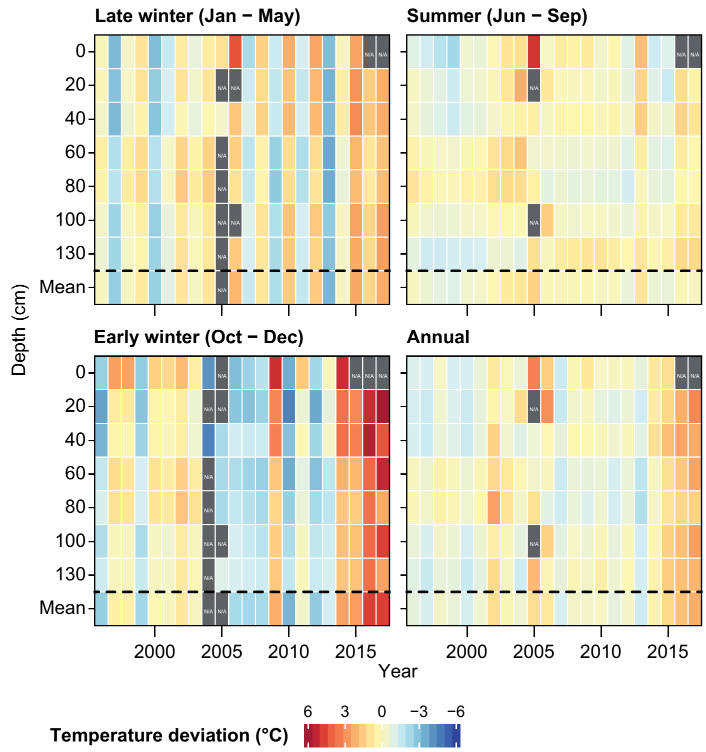

Figure 3. Annual soil temperature anomalies in a depth profile from 1996 to 2017 relative to the mean of the whole period at the Zackenberg main climate station close to the thermokarst site. Dark grey means missing data and the mean is not calculated where data is missing from three or more depths.

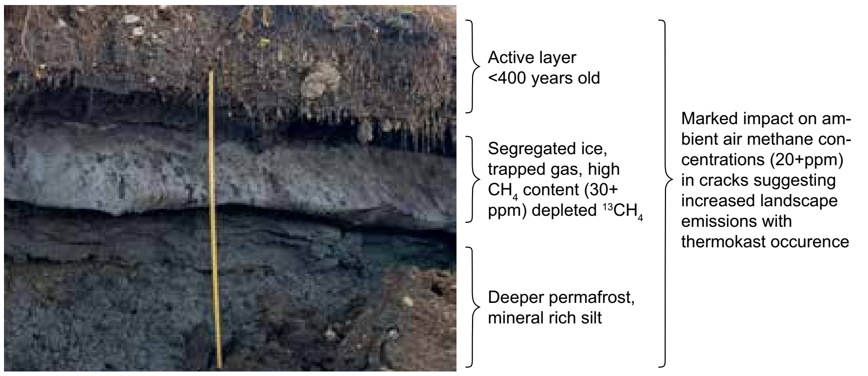

Figure 4. The exposed thermokarst profile with some of the preliminary data from analysis made both in situ and through subsequent analysis of soil samples. Note the one meter stick for scale. Photo: Lars Holst Hansen.

et al., 2012). The heath/grassland ecosystem type, that the area represented before the thermokarst collapse, are well known to have very low methane exchange or even acting as net atmospheric consumer (Christensen *et al.*, 2000). This same system now see high concentrations of methane in the cracks as an indicator of substantial emissions (Fig. 4).

Overall an example of dramatic landscape change happening in the heart of one of the GEM main monitoring areas where we have the unique possibilities for documenting consequences for ecosystem functioning in a rapidly changing Arctic.

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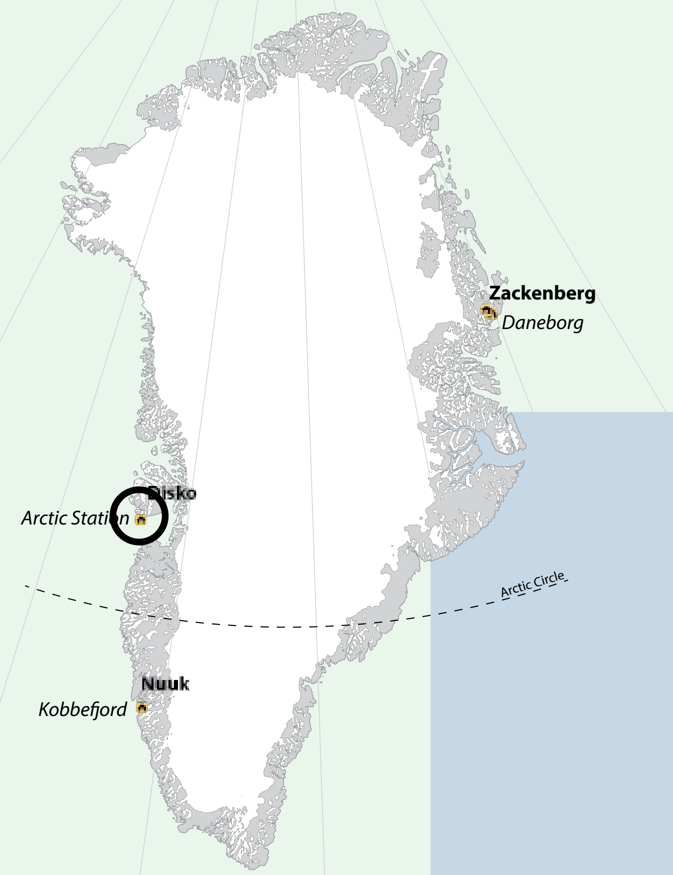

SEASONAL AND VERTICAL VARIA- PARAMETERS IN THE PELAGIC

The pelagic food web forms the base of the marine food web. Thus, changes in the community structure, biomass and productivity due to climate change will affect entire ecosystem composition and production, and potentially the economy of Greenland.

Disko Bay was included as a new main site in the marine component of the Greenland Ecosystem Monitoring programme in 2018. Disko bay is located on the west coast of Greenland and represent a location in the transition from low Artic to high Arctic waters. The monitoring site is located outside the town of Qeqertarsuaq in the Disko Bay at >300 m depth.

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[3]Natural History Museum

Source:

GEM MarineBasis, Disko.

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

TION IN PHYSICAL/CHEMICAL AND BIOLOGICAL
FOOD WEB, DISKO BAY, GREENLAND

A spring bloom of diatoms and the haptophyte *Phaeocystis* developed in mid-April 2018 in the surface waters, when the temperature was still <0 °C (Fig. 1). The phytoplankton bloom depleted the major nutrients (N, P, Si) in the surface waters during late May. After the spring bloom sedimentation, a subsurface bloom of phytoplankton developed at the pycnocline, which lasted the entire summer. In late autumn, after mixing of the water column had brought nutrients back up to the surface, a smaller secondary bloom developed. As the day length and the incoming irradiance decreased during late autumn the phytoplankton biomass dropped to low winter levels.

The establishment of a baseline study site in Disko Bay will allow us to, together with the two other GEM MarineBasis programmes from Nuuk and Zackenberg, to detect climate-associated future changes, in e.g. increased surface temperatures, reduction of sea ice cover in winter, ocean acidification and freshening. Such changes will most certainly impact fishes and thereby the Greenlandic economy.

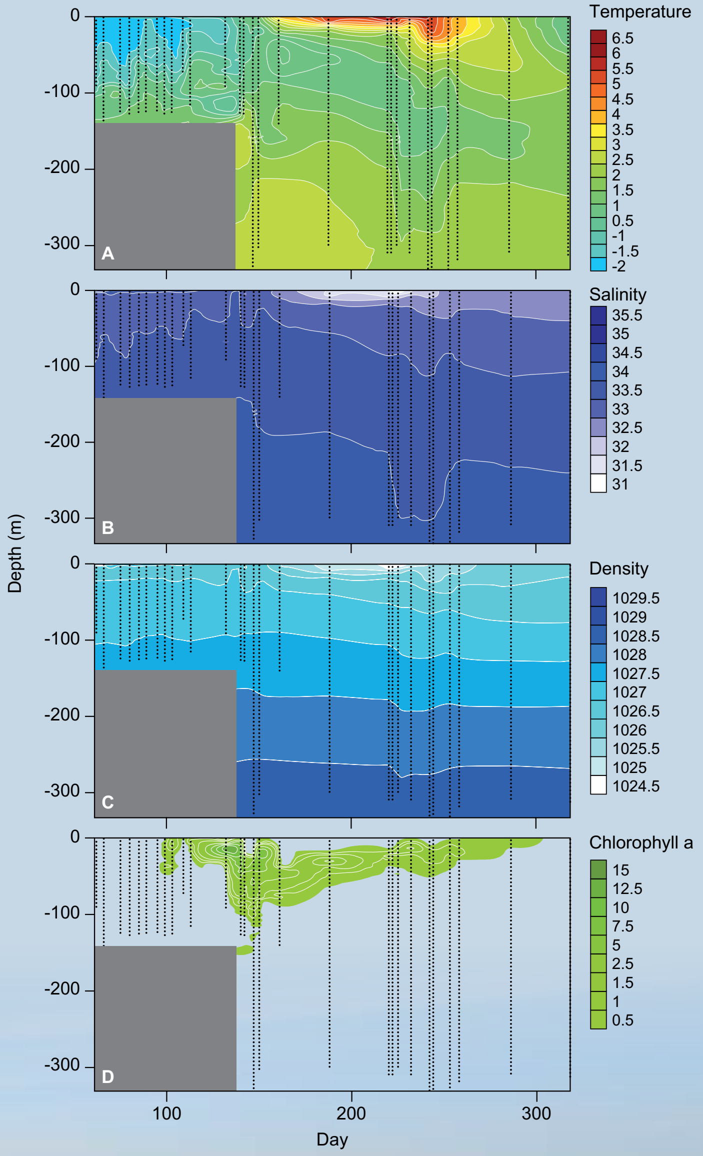
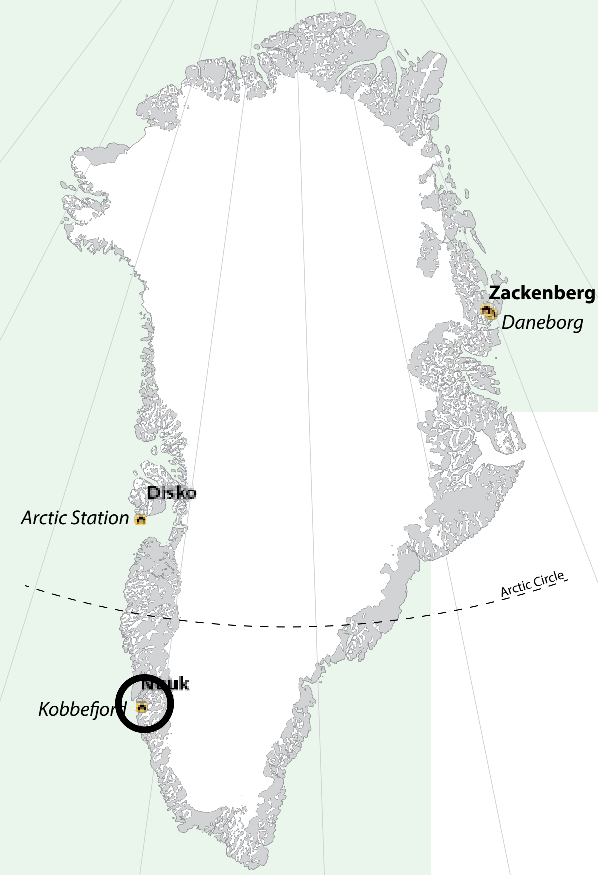


Figure 1. The vertical distribution of (A) temperature, (B) salinity, (C) water density, (D) Chlorophyll a fluorescence at the monitoring station outside Qeqertarsuaq, Disko during 2018.



TOWARDS
THE STATE AND FATE

The snow we look forward to every winter has important consequences for the atmosphere above and the ground below. A detailed snow survey carried out in Kobbefjord every year now includes a drone survey with the aim to better understand the spatial variability of the snow cover. This upscaling of the data will allow us to link this highly variable interface to changes in the other ecosystem variables measured at the site.

Snow cover is a normal, and for many a highly anticipated, part of winter. While we may enjoy the increased levels of light during the long winter days due to the higher reflectance of snow, or the freedom of clipping into a pair of skis; snow also plays an integral role in the annual cycle of ecosystems and contributes to the freshwater component of the hydrological cycle. Both flora and fauna are affected by the depth, structure and timing of the snow cover. For example, a layer of ice at the base of the snow pack caused by surface melting during a warm period in the winter, can mean that reindeer will starve as their food source is locked below the icy barrier. On the other hand, a thick layer of snow will protect and insulate the ground, and any vegetation, seeds or animals hibernating there, from the freezing winter air temperatures.

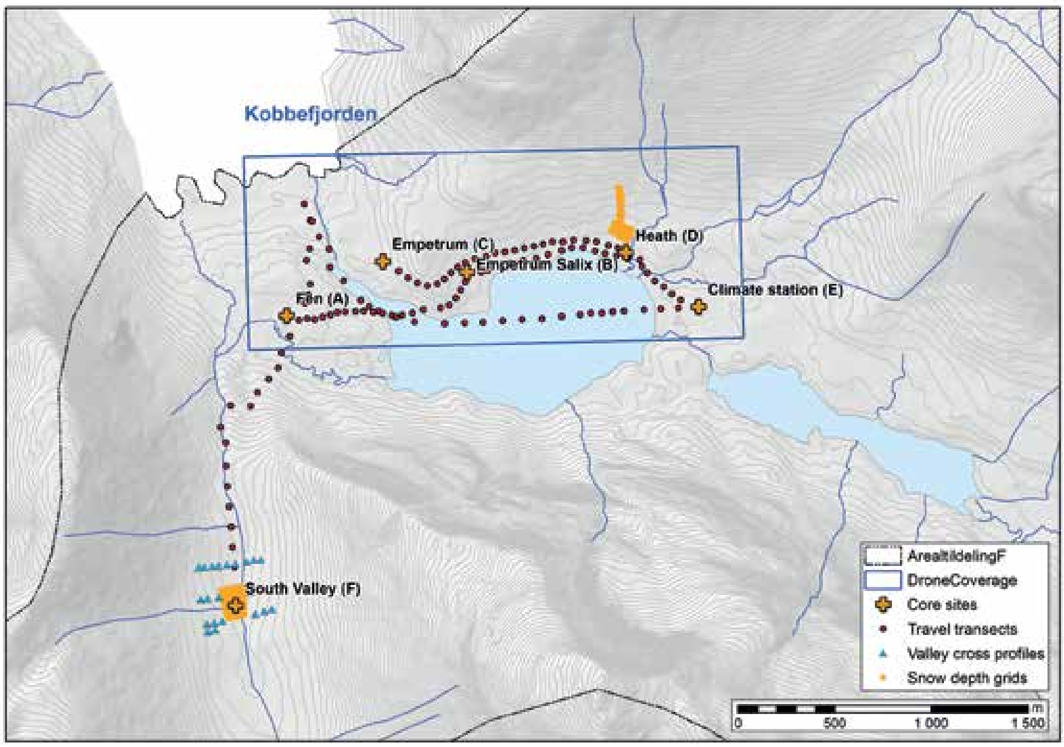


Figure 1. Point measurements and transects to measure snow depth and properties each year in Kobbefjord. The Blue box shows the area covered by the drone flight (Fig. 3)

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[3]University of Graz, Austria

Source:

GEM ClimateBasis, Kobbefjord

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

UNDERSTANDING
OF SNOW IN KOBBEFJORD

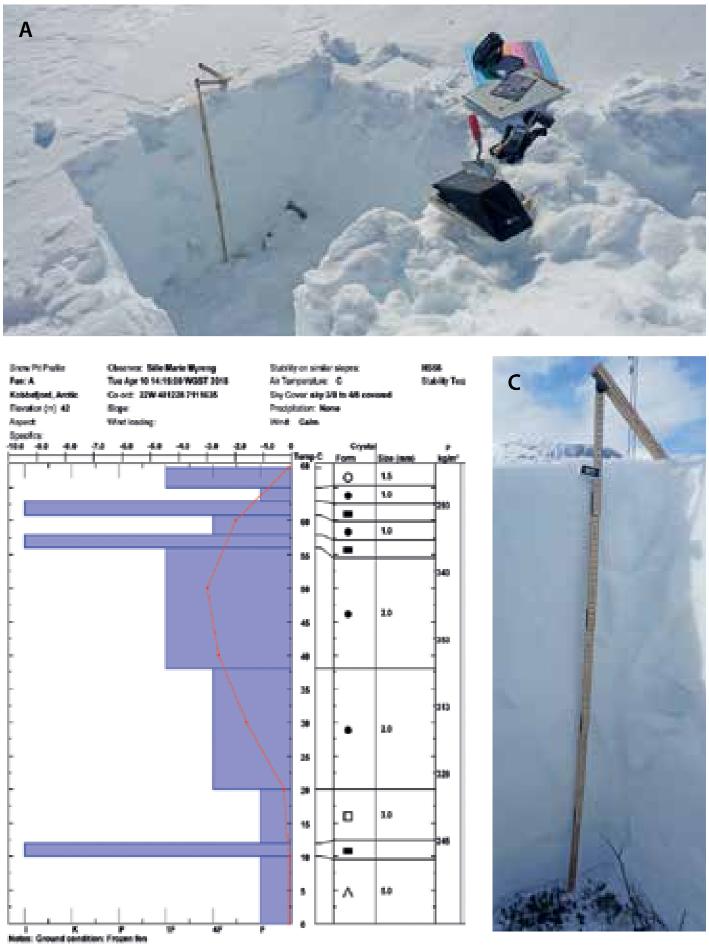


Figure 2. A) Typical snow pit after all the measurements have been made (see where snow has been removed for density measurements). B) Graph showing how the temperature in the snow pack varies with depth. The top of the snow pack is highly influenced by the air temperature. If the snow is deep enough, it will act as a blanket insulating the ground from the freezing air temperatures above. C) Snow pit and thermometer used to measure snow temperature with depth. These measurements are made at several locations during the annual spring snow survey in Kobbefjord.

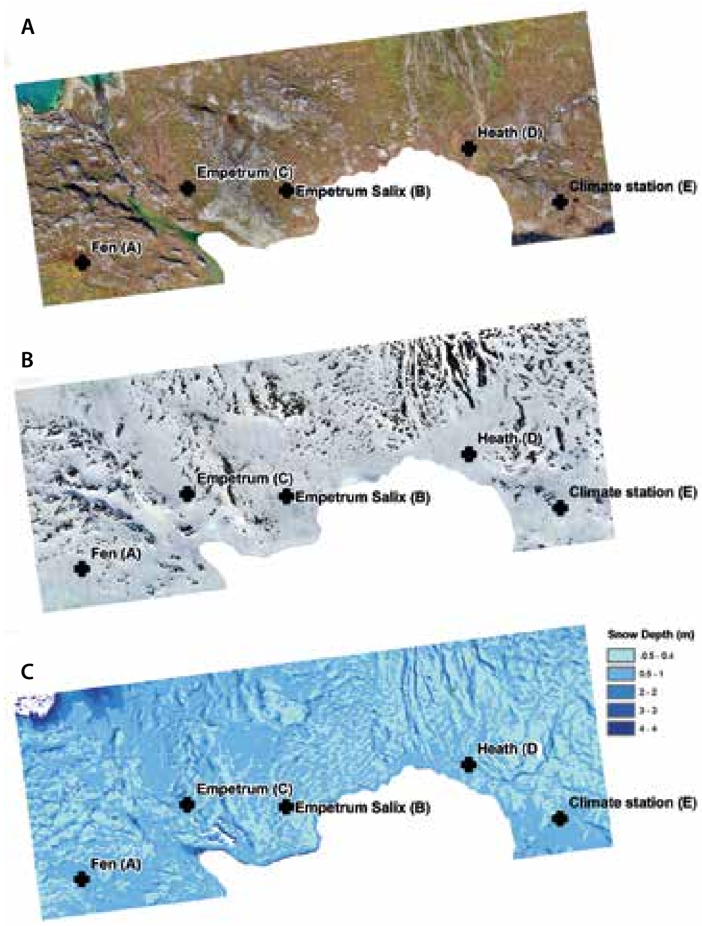
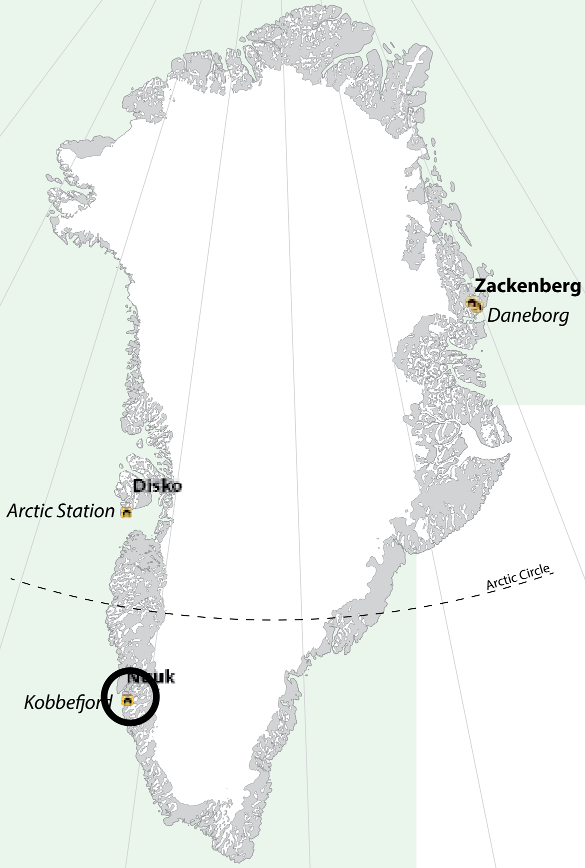


Figure 3. Images collected by the drone in the autumn (A) and spring (B) are used to derive snow depth over the entire area (C).

A snow survey has been performed every year since 2008 in Kobbefjord. The aim of the survey is to systematically characterize the snow pack. Snow depths are measured in transects and grids throughout the valley to map the spatial distribution of snow in the monitoring area (Fig. 1). To investigate how the snowpack interacts with other ecosystem parameters, the snow temperature, layering and crystal structures are measured close to the GeoBasis, ClimateBasis and BioBasis sites (Fig. 2). This makes it possible to study the influences of the snowpack on e.g. radiation, soil temperatures, vegetation and gas fluxes; and to monitor how the snowpack is influenced by the different topography and vegetation of the sites.

In 2018, a drone was included in the snow survey work to upscale the long term ground based measurements, and help to increase our understanding of the spatial variability of the snow cover. The methodology is simple: the drone is flown in the autumn, when leaves and vegetation are at a minimum, and again during the spring snow survey. A digital surface model (DSM; a map of surface elevations) is constructed from the drone photos. The difference in the surface elevation between the autumn and the spring DSM gives the snow depth (Fig. 3).

The spatial coverage of the snow survey encompasses established Greenland Ecosystem Monitoring sites; thus the detailed ground survey, together with the larger spatial coverage of the drone data, allows us to better quantify this dynamic interface between the highly variable atmospheric boundary layer and the ground below.



WARMING WATERS

PRIMARY PRODUCTION IN

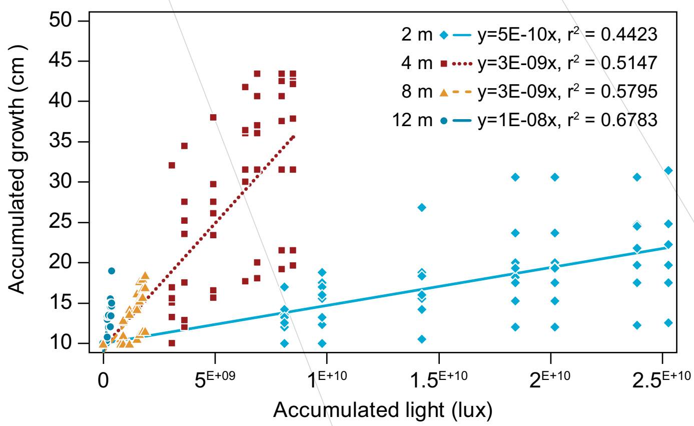
In temperate and warm water lakes, macrophyte depth distribution is light dependent. In nutrient poor, clear watered Kobbefjord lakes, macrophyte depth distribution is strongly affected by temperature and thus the length of the ice-free season, more than the light conditions. Therefore, in an increasing temperature scenario, we may expect macrophyte expansion, increased primary production, and thus an increasing carbon and nutrient cycling in arctic limnic systems.

Submerged macrophytes are key primary producers in freshwater ecosystems. The productivity of submerged freshwater macrophytes is strongly influenced by irradiance and climate conditions such as length of the growing season and temperature, and is therefore likely to change with latitude.

By combining Greenland Ecosystem Monitoring data with experimental *in situ* and laboratory data, we studied the potential for increased macrophyte production and coverage in arctic lakes in a future warmer climate. *In situ* growth experiments with *Callitriche hamulata* were performed at 2 to 12 m depth in combination with nutrient assay experiments at 2 m depth, and growth experiments performed in the laboratory at four temperatures from 5 to 20 °C under saturated and light-limited conditions.

The laboratory experiments show that phosphorus can be a limiting factor for macrophyte growth, but *in situ* results also indicate that nutrients are not the limiting factor for the macrophyte growth or depth distribution, as macrophytes can grow at both 8 and 12 m depth (Fig. 1), which is deeper than the observed depth distribution of 5.5 m. Rather the short growing season combined with low summer temperatures may limit the expansion of *C. hamulata*. The study demonstrates that *C. hamulata* is a very temperature-sensitive plant, particularly around 10 °C (Fig. 2), and in a future warmer climate the thermocline is expected to expand deeper into the water column and thus cause an increasing temperature near the *C. hamulata*'s maximum depth distribution.

Figure 1. Experimental accumulated growth vs accumulated light during a 2-month period at 2, 4, 8 and 12 meter depth in Badesø. Symbols indicate replicates.



Authors:

Torben L. Lauridsen[1], Tina Mønster[2], Katrine Raundrup[3], Josephine Nymand[3] & Birgit Olesen[1]

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Source:

GEM BioBasis – Lakes submerged vegetation monitoring in the limnic programme.

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

MAY INCREASE MACROPHYTE

GREENLANDIC LAKES

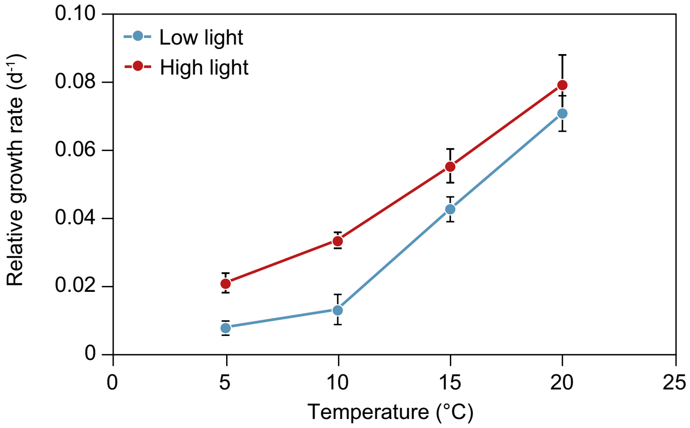


Figure 2. Growth response of Callitriche hamulata *collected from Badesø, measured as relative growth rate, to temperatures at low (25 µmol photons m^{-2} s^{-1}) and high irradiance (150 µmol photons m^{-2} s^{-1}). Averages ± SE, n = 3.*

Therefore, at the present light conditions we can expect an expansion of both depth distribution and coverage, which may affect the overall primary production in arctic lakes and the carbon cycling in these lake ecosystems. Our findings strongly support and confirm predictions of increased growth and a more northerly distribution range of cold-temperature submerged macrophytes in a warming climate. Increasing temperatures may, however, also allow more southerly species to migrate northwards into low arctic areas and consequently compete with native species affecting depth distribution and species ranges.

Figure 3. Experimental setup for In-situ growth experiments at 2, 4, 8 and 12 m depth. Photo: Tina Mønster.

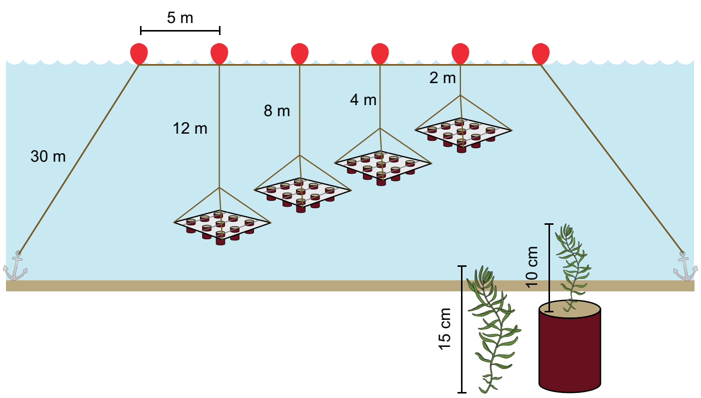
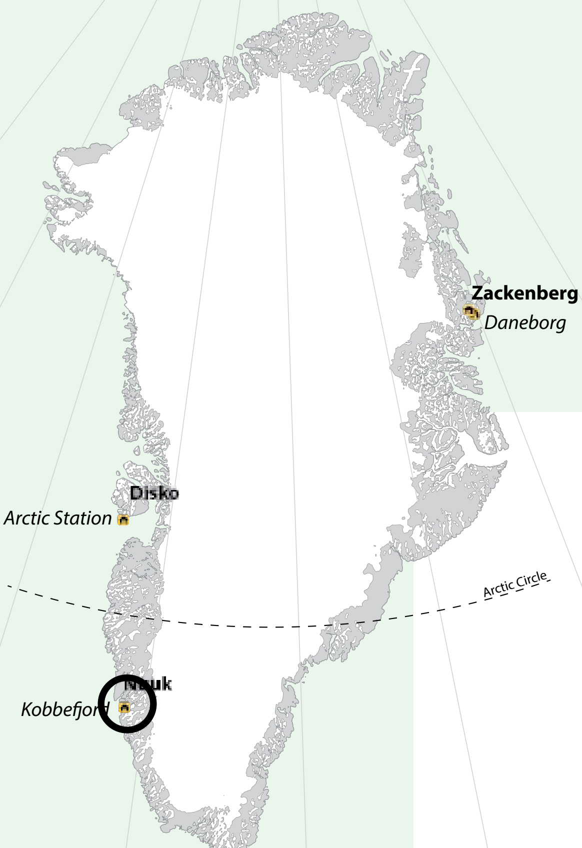


*Figure 4. In 2018 a new species, alternate water-milfoil (*Myriophyllum alterniflorum*) was confirmed in Badesø, Kobbefjord. Only continuous monitoring will determine if its presence is transitory or if it persists or even spread in the lake due to changing climatic conditions. Photo: Katrine Raundrup.*



MOUNTAIN GLACIERS
IN GREENLAND ARE DIFFERENT

The large Greenland Ice Sheet is surrounded by more than 20,000 local mountain glaciers and ice caps (Rastner et al. 2010). They generally lie at lower altitudes and hence are vulnerable to recent climate change. The surface area of the ice sheet is about 20 times larger than that of all the local mountain glaciers and ice caps combined, while its volume is 170 times greater (Huss and Farinotti, 2012; Morlighem et al. 2017).

Both the Greenland Ice sheet and the local glaciers and ice caps have seen changes in recent years (see GEM Report Cards 2017). The absolute mass loss from the Greenland Ice sheet is larger, while the specific mass loss per unit area is smaller compared to the local glaciers and ice caps.

Comparing recent studies covering a similar time period (van den Broeke *et al.* (2016); Noël *et al.* (2017)) shows that specific mass loss from local mountain glaciers and ice caps is about four times higher than that from Greenland Ice sheet, underlining the higher sensitivity of local mountain glaciers and ice caps mass balance to ongoing climate change. These studies also show that the uncertainties of mass change estimates of local mountain glaciers and ice caps are about two times as large as the one for the Greenland Ice sheet. The small glaciers typically also lie in complex terrain and are therefore difficult to resolve in models.

Currently only 5 out of the 20,000 local mountain glaciers and ice caps are regularly monitored, and Greenland Ecosystem Monitoring (GEM) contributes to this with three time series. A.P. Olsen Ice Cap has a continuous mass balance time series since 2008, a small mountain glacier near Nuuk was added to the programme in 2012 and in 2017 GEM initiated the Disko GlacioBasis programme. Here, we show some results recently published by Abermann *et al.* (2019), that use data from the GEM GlacioBasis Nuuk programme of Qasigiannguit glacier (Fig. 1), which may help answer the question: how different is the mass and energy balance of a local mountain glacier near the coast compared to a similar latitude on the Greenland ice sheet?

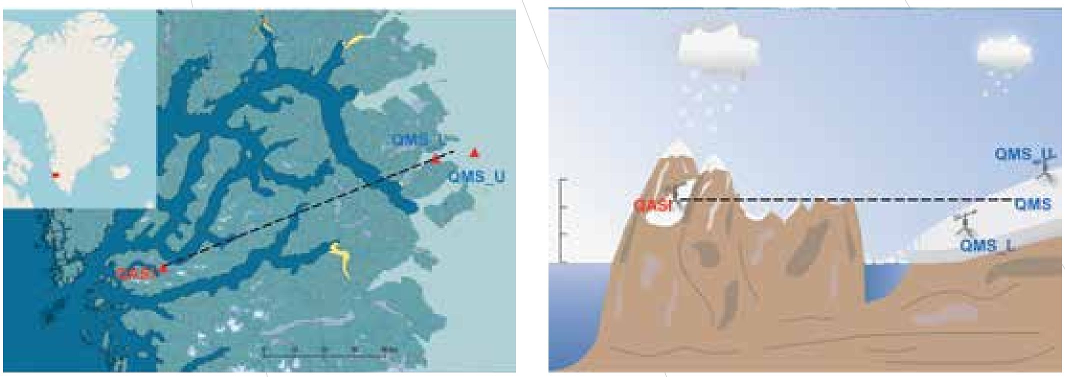


Figure 1. The study area in southwest Greenland (left panel) and a schematic sketch of the location of QASI vs. QMS (QMS_L and QMS_U). The distance between QASI and QMS is 103 km while the distance between QMS_L and QMS_U is 13 km. GlacioBasis Nuuk cooperates with PROMICE on the QASI station, while the QMS stations are PROMICE stations. The data can be seen real-time on the PROMICE website (https://www.promice.dk/WeatherArchive.html?stationid=209).

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Source:

GEM GlacioBasis, Nuuk

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

THAN THE ICE SHEET

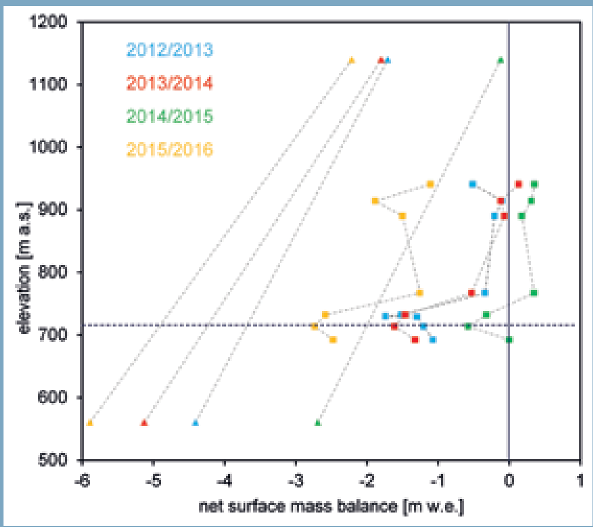

Figure 2. Net mass balance at QMS_L and QMS_U on QMS (triangles) and at all available stakes at QASI (squares). Same colours mean the same year. The horizontal line shows the elevation of the AWS on QASI (710 m a.s.l.) and for which we perform the comparison.

The results show that the differences are very strong: Net surface mass balance is on average 2.2 m water equivalents (w.e.) less negative at the coast, compared to on the ice-sheet at the same elevation and a similar latitude (Fig. 2). We find a larger energy turnover at the ice sheet margin on Qamanarssup Sermia than measured on the coastal mountain glacier Qassigiannguit, with both energy input and output being of larger absolute value on the ice sheet margin. More cloudiness and a thicker snow cover at the relatively humid coastal glacier result in a less negative mass balance. Lower wind speeds at the coastal glacier result in weaker turbulent heat exchange between atmosphere and ice surface. On annual average, 17 W/m^2 more energy is available for melt at the ice sheet margin compared to the coastal glacier at the same elevation. Despite the mass loss of lower areas of the ice sheet being much stronger, than on the local glacier we investigated, the large area at high altitudes of the ice sheet causes the total specific surface mass balance to be of a smaller absolute value.

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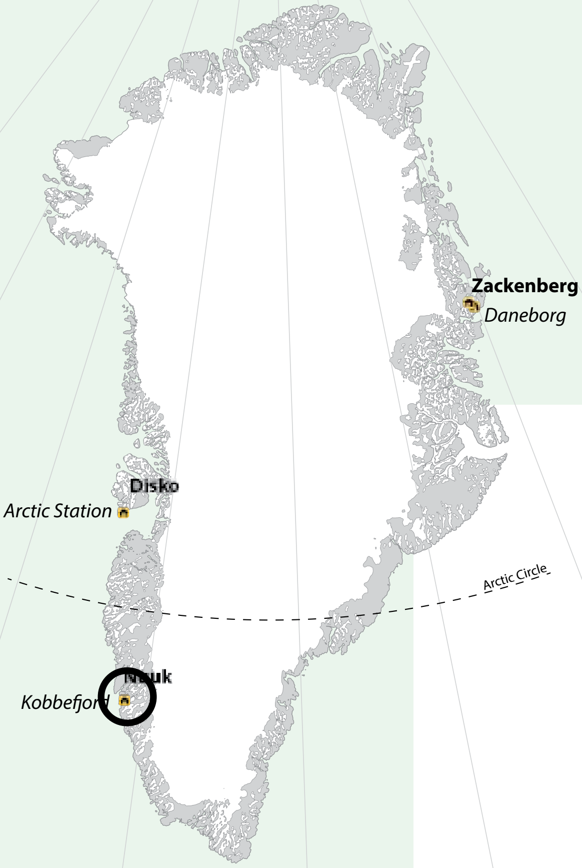
Qasigiannguit Glacier, where GEM GlacioBasis Nuuk has been running a monitoring programme since 2012.



Annual Report Card 2018

THE POTENTIAL OF
TO IMPROVE THE DESCRIPTION

Arctic fjords, linking land and ocean, are amidst some of the most climate-sensitive regions on the planet. Although they are highly vulnerable to climate warming, there is currently a gap in meteorological data needed to capture climate gradients in these complex areas in Greenland.

Mobile meteorological measurements in Greenland are essential to study complex gradients in fjord systems and enhance process understanding for upscaling and modelling purposes. In order to study larger spatial gradients, increasing the spatial resolution required to explain complex fjord system climate variability, mobile measurements are valuable.

In 2016, Greenland Ecosystem Monitoring (GEM) programme installed an automatic weather station on a commuter ferry (Marie Martek) to collect meteorological data. The ferry, which travels weekly between Nuuk and Kapisillit samples the fjord system (Fig. 1, left). These data are useful for testing small-scale performance of climate models in complex fjord systems and complement several land-based meteorological stations. Additionally, meteorological stations (operated by Asiaq – Greenland Survey) are used for comparison purposes.

Figure 1. Left panel: the weather station mounted on the vessel Marie Martek. Right panel: Data display in the passenger cabin. Photos: Jakob Abermann.

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Source:

GEM ClimateBasis, Nuuk

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

MOBILE WEATHER STATIONS

OF COMPLEX FJORD CLIMATOLOGY

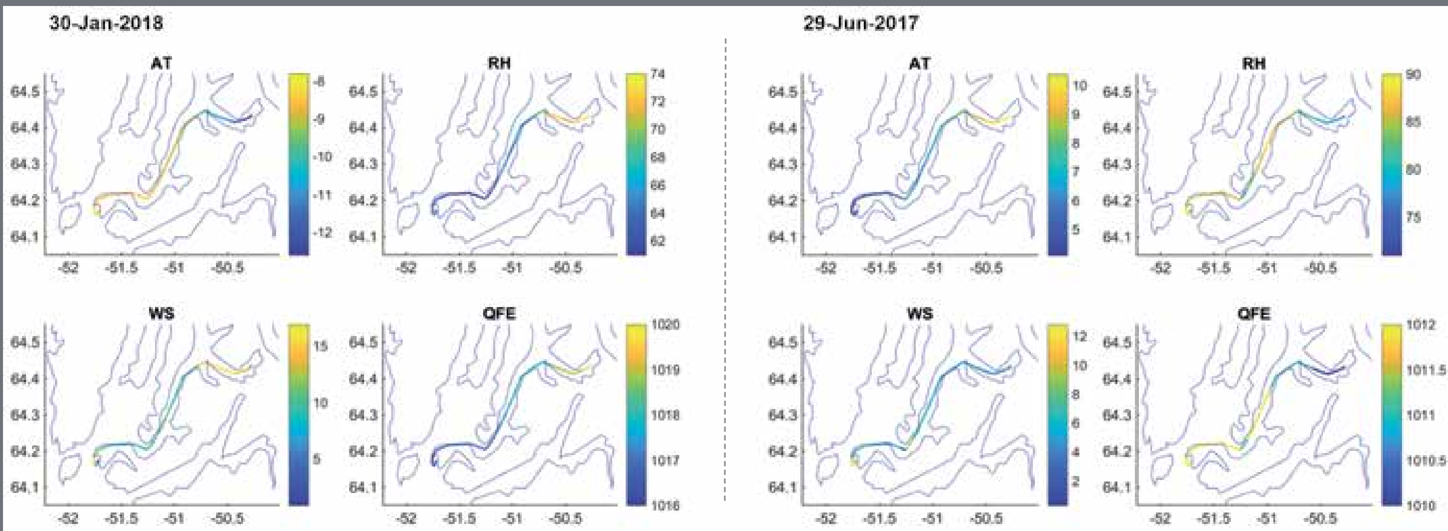

Figure 2. Two examples of the recorded transects for air temperature (AT), relative humidity (RH), wind speed (WS) and pressure (QFE) for a classical winter example (left, 30 January 2018) and a summer example (29 June 2017).

The ferry based automatic weather station provides data on air temperature, air pressure and wind speed. Additionally, the data is visualised in the common areas of the ship, allowing for increased visibility of the GEM programme among local communities (Fig. 1, right).

Preliminary results show interesting patterns of climate variability in the fjord system (Fig. 2). In the winter, it is about 5 °C colder in Kapisillit than in Nuuk, with higher humidity, higher wind speeds and a higher pressure, while in the summer air temperature is higher in Kapisillit, relative humidity lower, wind speed more variable and pressure lower. Summarizing all transects, we can see a clear seasonal dependence following continentality gradients with colder temperatures in winter and higher in summer in the inland parts of the fjord (Fig. 3).

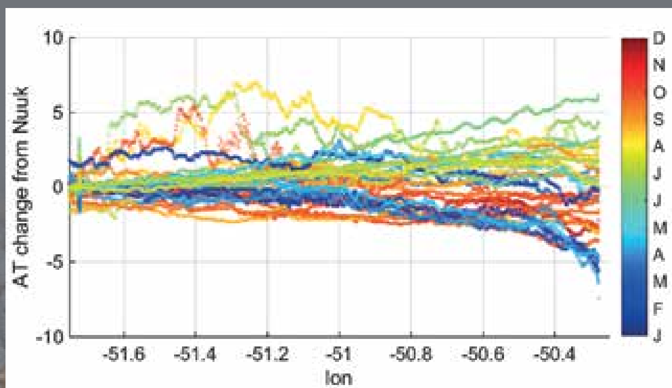

Figure 3. All recorded air temperature transects as a function of longitude relative to Nuuk. The color code shows the time of the year (red and blue: winter months, green and yellow: summer months).

Photo: Kirsty Langley.

Annual Report Card 2018

MIND THE (DATA)

In the harsh Greenlandic winters it is difficult and sometimes impossible to obtain reliable measurements of the fluxes of energy or gasses, that we put much faith in, in our interpretation of the climate response of the Arctic. At a recently added study site on Disko, line power and a permanently staffed station enables flux measurements through winter, and we are therefore able to quantify the importance of off-season CO_2 fluxes. In 2017, there was an annual net carbon uptake of 17 g carbon (C) and one third of respiration occurred in the off season, showing the importance of year-round measurements.

The Geobasis measurements at Disko is located next to the more than 100 years old research station, Arctic Station, just outside the town Qeqertarsuaq. The flux monitoring site was established a few years ago, and has been part of the Greenland Ecosystem Monitoring (GEM) programme since 2017. One of the reasons for adding Disko as a GEM main station was, that measurements could be maintained through winter, which is not possible at the sites in Nuuk and Zackenberg, due to the lack of power and staff to maintain the programme during winter. Now after the first initial years, we are able to evaluate the scale of fluxes measured during the cold and dark season relative to the annual exchange of CO_2.

In many types of measurements, there will be longer or shorter periods where the data quality is less than perfect or data are missing entirely due to measurement conditions or instrument failure. This is certainly true also for eddy covariance measurements of fluxes, where it is perfectly normal that 20 to 40 % of the measurement period are missing, and needs to be gap-filled in order to obtain credible annual values of the relevant fluxes. The fact that these gaps are not evenly distributed, but more frequent during nights and winter, of course constitute an additional obstacle.

Eddy covariance mast (EC1) and snow cover in Østerlien, January 2018. Photo: Kjeld Mølgaard.

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

[2]Asiaq – Greenland Survey

Source:

GeoBasisDisko/Flux monitoring/Gas flux (EC1)

GeoBasisDisko/Meteorology/AWS2-Meteorology

GeoBasisDisko/Meteorology/AWS2-SnowGroundTemp

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

GEM
Greenland Ecosystem Monitoring

GAP!

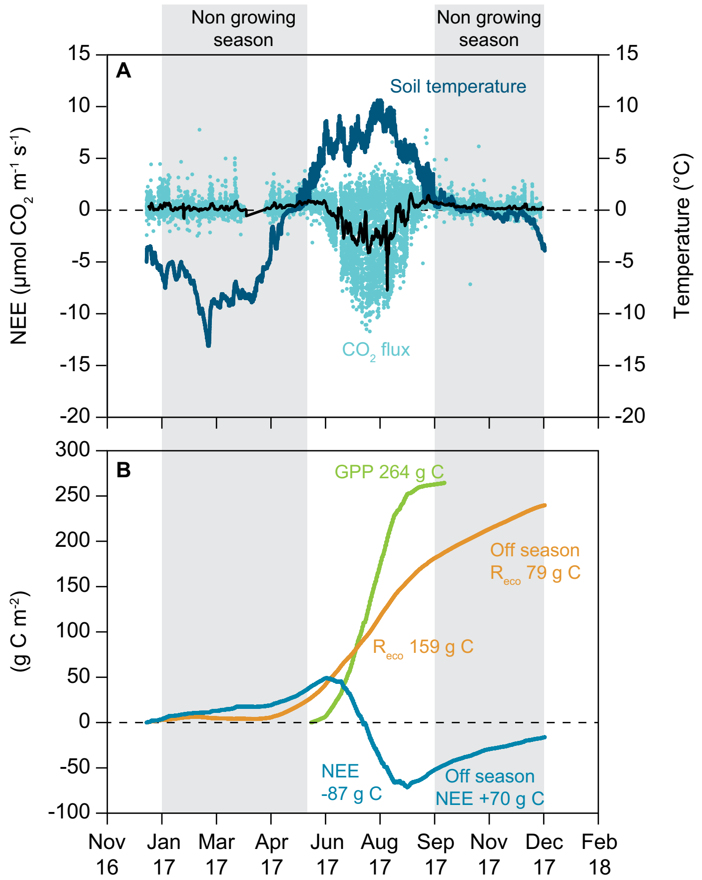
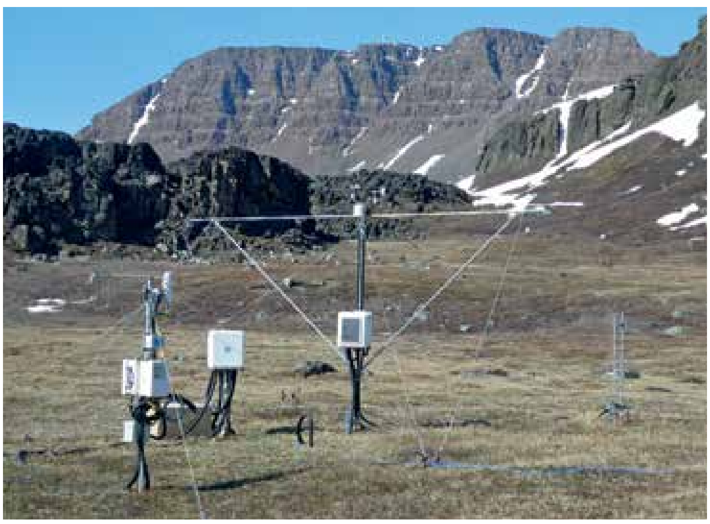


Figure 1. Eddy covariance flux measurement during 2017 at Disko A) Measured NEE and Soil temperature B) modelled values of GPP, R_{eco} and measued gap filled NEE values.



In Figure 1, measured CO_2 flux (NEE) is displayed together with soil temperature from the GeoBasis site in Disko for 2017. Overall the measured data covers 79 % of the year with the largest gap in data in late March to mid-April, due to an instrument failure, but with minor gaps (0.5 to 2 h) in the data all weeks of the year. In the lower part of the figure, we have partitioned the measured net CO_2 flux into ecosystem respiration (R_{eco}) and gross photosynthesis (GPP) in order to increase our understanding of dependency of environmental controls and to be able to fill the gaps in the measured data. The grey areas of the graph represent non-growing season determined by no photosynthetic activity (GPP=0), which allows us to compare growing season data with non-growing season data, thus tell us the importance of having winter time measurements at the site. By comparing the graphs in the lower part (b) of the figure, it is possible to tell how much of the CO_2 was exchanged during the growing season, and also how well the gap-filling procedure is able to replicate the measured data. It can be noticed that the net ecosystem exchange (NEE) during the growing season accounts for an uptake of 87 g C pr m^2, which is marginally more than what is lost during the off season period (70 g C), indicating that growing and non-growing seasons are nearly equally important and the two large opposite numbers combined account for the delicate net annual balance.

The graph also gives an indication of how well a fitted model is able to fill-in the gaps, long or short. In this case we have used NEE values from the growing season during night time, as representatives for ecosystem respiration (R_{eco}), and let the commonly used dependency to soil temperature (panel a) drive R_{eco} through the entire year, as you would also do if e.g. winter season measurements were missing. It can be noticed that there is a difference of 9 g C (79-70 g C) during off season, which is also the difference between the annual values of NEE (17 g C) and the sum of annual values of GPP and R_{eco} (26 g C). These values compare well with a newly published modeling study by Zhang *et al.* (2019). In absolute values, these differences are not large and actually smaller than the difference during growing season, but may be important when used for interpretations of effects of a change in climate or expanded to a larger area.

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Automatic weather station (AWS2) and Eddy covariance mast (EC1) in Østerlien near Arctic Station, Qeqertarsuaq. Photo: Charlotte Sigsgaard.

MACROALGAE:
INDICATORS AND BUFFERS

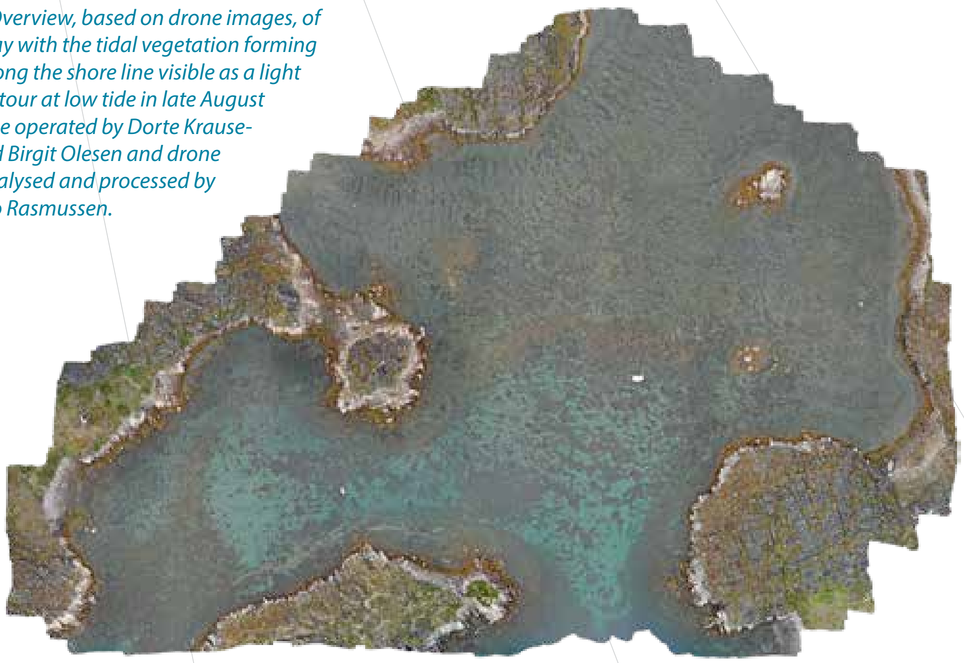
Macroalgae are important components of the Greenland Ecosystem Monitoring (GEM) programme because they are sensitive indicators of climate change and have many ecosystem functions. This includes climate change adaptation, by e.g. creating oases of high pH during the Arctic summer, climate change mitigation through carbon sequestration and new habitat through their expansion. They are part of the GEM programme in Nuuk and Young Sound and since 2018 also in the Disko Bay. Macroalgae are expected to grow faster and expand their distribution and associated ecosystem functions in a warmer future with longer open water periods.

Macroalgae form a productive fringe along the shores of Greenland from vegetation in the tidal zone (Fig. 1) to subtidal kelp forests down to maximum depths of 40-60 m (Fig. 2). The GEM MarineBasis programme includes monitoring of tidal macroalgae in Nuuk, subtidal kelp forests in Young Sound and both tidal and subtidal macroalgae in Disko Bay. Studies along latitudinal gradients in combination with studies at each of the three GEM monitoring sites show the following highlights on macroalgae:

Macroalgae as climate change indicators

- Tidal vegetation of the species knotted wrack (*Ascophyllum nodosum*) has its northernmost documented distribution limit at Qeqertarsuaq and Kronprinsens Ejland, and these sites also hold the longest known record of growth rate of this species. The growth rate of this tidal vegetation increases with warming and the distribution is also expected to expand with warming (Marbà *et al*. 2017 and 2018).
- Kelp forests grow faster and deeper in response to longer open water periods (Fig. 3)
- Kelp forests grow particularly deep at offshore sites in the Disko Bay where depth limits extend deeper than 61 m.

Figure. 1. Overview, based on drone images, of Fortuna Bay with the tidal vegetation forming a fringe along the shore line visible as a light brown contour at low tide in late August 2018. Drone operated by Dorte Krause-Jensen and Birgit Olesen and drone images analysed and processed by Michael Bo Rasmussen.



Authors:

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[1]Arctic Research Centre, Department of Bioscience, Aarhus University

[2]King Abdullah University of Science and Technology (KAUST), Red Sea Research Center (RSRC) and Computational Bioscience Research Center (CBRC), Thuwal, Saudi Arabia

[3]Department of Bioscience, Aarhus University

Data source:

GEM MarineBasis, Disko Macroalgae

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

OF CLIMATE CHANGE

*Figure. 2. Dense kelp forest at Kronprinsens Ejland dominated by sugar tangle (*Saccharina longicruris*). Photo from underwater video early September 2018, Dorte Krause-Jensen.*

While Greenland terrestrial forests are absent or localised in few protected areas, the marine kelp forests are abundant along the coasts of Greenland. The marine forests can be several meters tall and may represent the major forests of Greenland although few know of them. To local communities these marine forests are important as they are habitat and nursery area for e.g. fish species such as lumpfish and could, through sustainable harvest or farming, provide resources ranging from food and feed to building material, high-value products and fuel. The monitoring of these forests provide input to their sustainable management and increase attention on their importance.

Macroalgae as buffers of climate change

- Intense photosynthesis of tidal macroalgae and kelp forests create oases of high pH, documented in particular for the Disko Bay area (Fig. 4), thereby supporting calcification of shell-forming organisms such as mussels also in a future potentially more acidified ocean.
- Part of the vast production of macroalgae is exported to oceanic carbon sinks where it is sequestered. This phenomenon is now receiving focus along the Greenland coast through the newly initiated 3-year project "CARbon sequestration by Greenland's MArine forests in a warming Arctic (CARMA)" funded by the Independent Research Fund Denmark.

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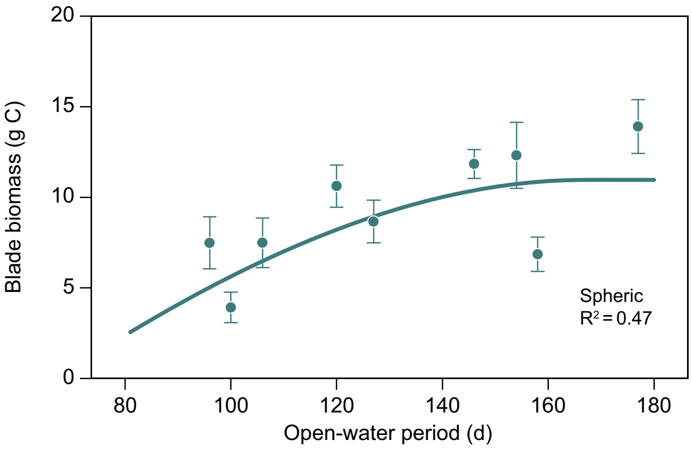


*Figure. 3. Size of the annual blade, representing the annual production of sugar tangle (*S. latissima*) in Young Sound, northeastern Greenland, as a function of the duration of the open-water period (of the preceding year and the current year until the day of sampling). Data represent means (± standard error) for the years 2003-2011. The coefficient of determination (R^2) for a spheric model fit is shown. From Krause-Jensen et al. 2012.*

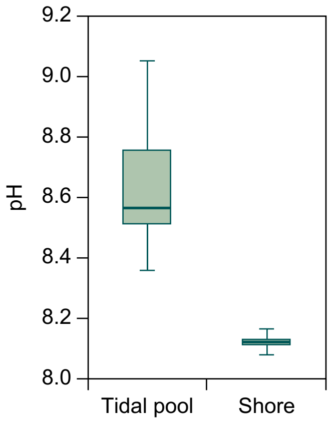
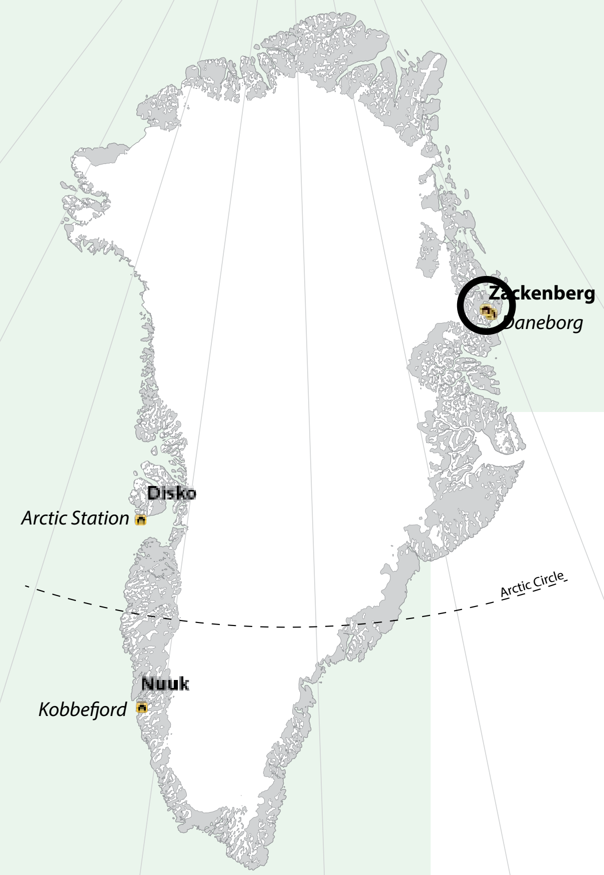


Figure. 4. Levels of pH, in tidal pools as compared to adjacent open waters in Disko Bay. Central line shows median levels, boxes 25-75 % percentiles and whiskers minimum and maximum values. From Duarte & Krause-Jensen 2018.



HIGH RESOLUTION
IN 1 HA. SNOW PLOT

A central feature of the Arctic landscape is snow, which persists for 8 to 10 months of the year. Snow affects pivotal Arctic ecological processes such as vegetation phenology, soil organisms, permafrost and carbon fluxes (Bokhorst et al., 2016; Callaghan et al., 2011). Important characteristics are snow cover extent, duration, temporal change, thermal insulation and snow depth (AMAP, 2012). Satellites can be used to measure both the snow cover extent, duration and temporal changes, it is, however, not suitable to measure the snow depth. Information about snow depth requires more surface-based measurements and such observations mainly come from monitoring stations throughout the Arctic (AMAP, 2012).

Snow depths can be measured using different methods with diverse temporal and spatial resolution. Point observations are usually conducted using ultrasonic pulses with a high temporal resolution. Non-stationary snow depth measurement methods can range from simple avalanche probes to ground penetrating radars (GPR). Such methods increase the spatial resolution, however, due to logistical issues the temporal resolution is limited, moreover they are invasive as the equipment has to be physically moved to the location where measurements are desired. To further increase the spatial resolution, unmanned aerial vehicles (UAV) combined with photogrammetry have shown promising results.

During the 2018 season, GeoBasis Zackenberg performed two UAV surveys over the Zackenberg Circumpolar Active Layer Monitoring (ZEROCALM 1) site. The first UAV survey was conducted on the 25th of May at the end of winter. In addition to the drone survey, routine GPR measurements was also performed for comparison, along with few manual snow depth


Figure 1. Member of GeoBasis team, Marcin Jackowicz-Korczynski, performing UAV survey on over ZEROCALM 1plot at Zackenberg. Photo: Lars Holst Hansen, 25th of May 2018.

Authors:

Daniel Alexander Rudd, Kirstine Skov & Marcin Jackowicz-Korczyński

Department of Bioscience, Aarhus University

Source:

GEM GeoBasis Zackenberg

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

GEM

Greenland Ecosystem Monitoring

SNOW DEPTH MONITORING

IN LESS THAN 10 MIN!

measurements. The second UAV survey was performed on the 8th of August when the area was snow free, to define the site typography. In both cases, the commercial UAV platform DJI Phantom 4pro was used, flying 100 m above the ground level. During each of both surveys 42 images were captured (with 80 % overlap). The flight time for a single UAV mission was less than 10 minutes. Based on collected images, two digital elevation models were constructed (Fig. 2 & 3). By simply subtracting them from each other, it was possible to obtain an output which directly corresponds to the snow depth (Fig. 4). Comparison between both methods shows very promising results (Tab. 1 & 2) clearly indicating obvious advantage of the performing UAV based snow depth surveys: fast, relatively cheap, non–invasive and with high spatial resolution.

Table 1. Comparison between manually measured snow depth, performed next to ground control point (GCP), and results from the difference between snow covered and snow free digital surface models (DSM). The difference could be explained by the fact that the UAV survey provides a DSM, which includes vegetation, while the GPR provides the distance to the ground surface.

GCP#	Location	Manual measured (cm)	Modeled (cm)	Difference (cm)
1	South west	128	116.6	11.4
2	South east	117	116.4	0.6
3	Noth east	122.5	118.1	4.4
4	North west	119	117.3	1.7
5	Middle	124	118.1	5.9
Average				4.8

Table 2. Calculations of the total volume of the snow within the study area based on both methods. After correcting the UAV model with average vegetation height, the difference between the methods is less than 2 %.

Method	Total snow volume within ZC1 (m^3)
TIN model based on GPR measurements	12815.7
UAV model (+4.8 cm to account for vegetation)	12589.6

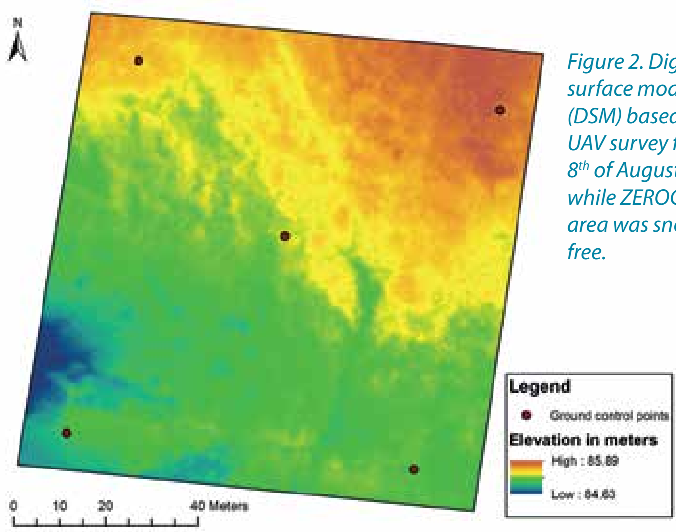


Figure 2. Digital surface model (DSM) based on UAV survey from 8th of August 2018 while ZEROCALM1 area was snow free.

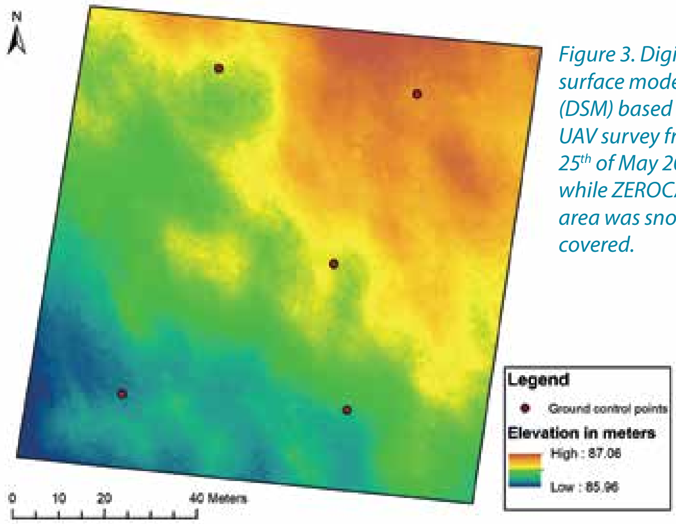


Figure 3. Digital surface model (DSM) based on UAV survey from 25th of May 2018 while ZEROCALM1 area was snow covered.

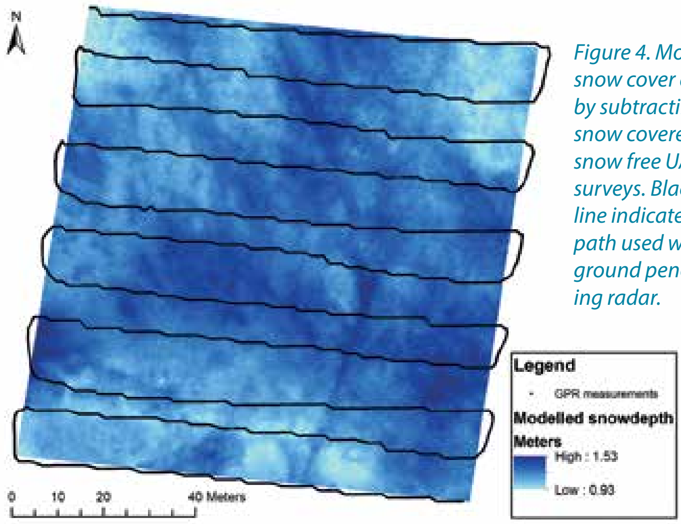


Figure 4. Modelled snow cover derived by subtracting snow covered and snow free UAV surveys. Black line indicates the path used with the ground penetrating radar.

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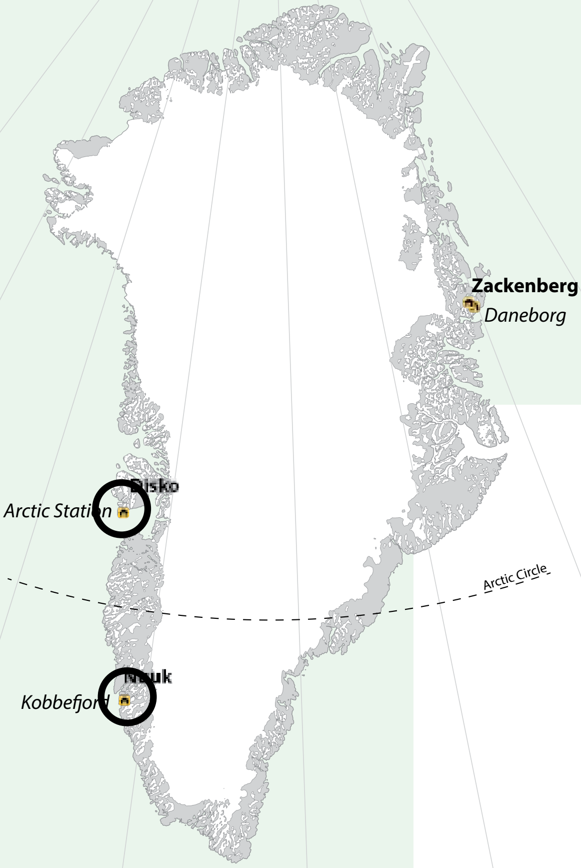

SCALING UP

IMPROVING A KNOWLEDGE

Arctic amplification, referring to more rapid increases in air temperatures in the Arctic compared to other parts of the globe, is causing widespread melting of snow and ice, sea-ice retreat, rise in the global sea level and changes in the surface energy budget leading to an acceleration of the hydrological cycle. Quantifying the surface energy balance at regional scales is key for better understanding Arctic ecosystem response and vulnerability to these changes.

Surface air temperatures in the Arctic have shown a significant increase, especially in the past few decades (Serreze and Barry, 2011). Increases in precipitation and local evaporation in the Arctic are leading to an acceleration of the hydrologic cycle, transforming the Arctic into a warmer place. Arctic regions, largely dominated by tundra, are witnessing unprecedented changes in response to climate warming. These include increases in river discharge (Bintanja and Selten, 2014) and significant changes in vegetation such as Arctic greening (Bhatt *et al.*, 2010), among others.

The hydrologic response of the Arctic ecosystems is dynamically coupled to the region's surface energy balance. A wide range of ecosystem dynamics depend on the combined changes in energy partitioning and hydrology. For a better understanding, this requires improved techniques for spatiotemporal characterization of land-atmosphere exchanges of water and energy at regional scales (Cristóbal *et al.*, 2017). Due to remoteness, harsh winter conditions, and the high costs of maintaining ground-based measurement networks in the Arctic, remote sensing represents the only economically feasible and reliable source of information to infer surface energy fluxes at regional scales.

In 2018, the Greenland Ecosystem Monitoring (GEM) ClimateBasis programme with joint support from the Greenland Research Council and in collaboration with GEM GeoBasis programme, United States Agricultural Department, NASA, started an initiative to improve the current knowledge on the surface energy balance and how to scale-up surface energy fluxes from the plot to the regional scale using

Figure 1. Collecting data by the Arctic Station flux station (Disko Island) using a LiCor LAI-2200 Plant Canopy Analyzer. Photo: Jordi Cristóbal in 1st September 2018.

Authors:

Jordi Cristóbal[1,2], Jakob Abermann[3,1], Kirsty Langley[1], Martha C. Anderson[4], William P. Kustas[4], Christopher Hain[5], Thomas Friborg[6] & Birger Hansen[6]

[1] Asiaq – Greenland Survey

[2] Geophysical Institute, University of Alaska Fairbanks, USA

[3] University of Graz, Austria

[4] United States Department of Agriculture, USA

[5] National Aeronautics and Space Administration, USA

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Source:

GEM ClimateBasis – Radiation

GEM ClimateBasis – Surface energy balance

GEM GeoBasis – Flux measurements

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

SURFACE ENERGY FLUXES:
GAP IN THE ARTIC HYDROLOGICAL CYCLE

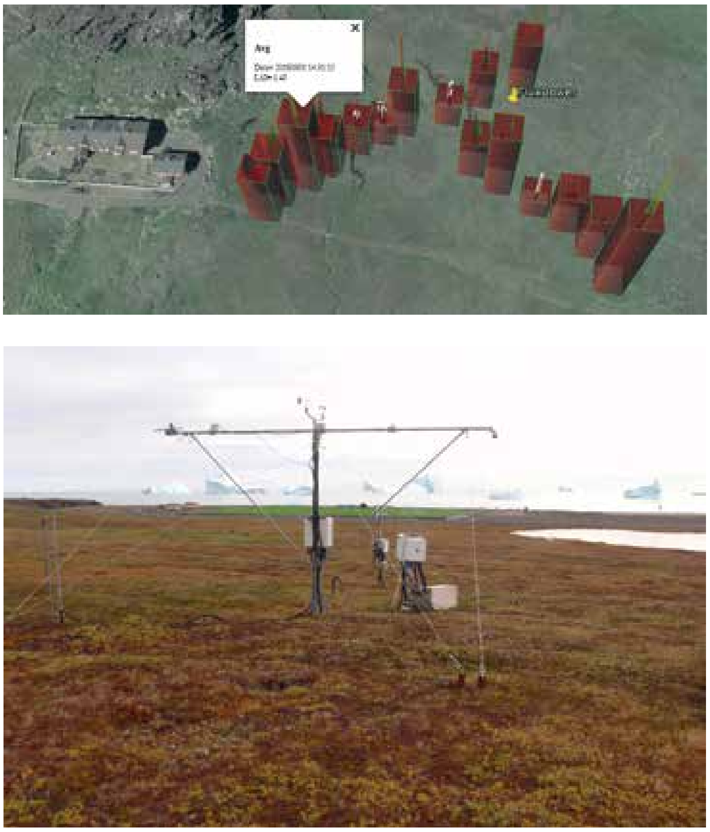

Figure 2. Upper panel: LAI data at the Arctic Station flux tower (Disko Island) in 1st September 2018 (background image courtesy of Google Earth). To show plot spatial variability, LAI field measurements are displayed in red columns. Lower panel: Arctic Station flux tower. Photo: Jordi Cristóbal.

remote sensing data. Two main activities are being carried out: a) calibration and evaluation of thermal remote sensing data based on a two source energy balance model (TSEB) for tundra at local scales with leaf area index (LAI) remote sensing inputs (Cristóbal *et al*. 2017) and; b) field data collection of LAI at Disko and Kobbefjord for model upscaling (Fig. 1, 2 and 3, respectively). Preliminary results show mean turbulent flux errors at local scales (Fig. 4) of around 50 W•m^{-2} at half-hourly timesteps, similar to errors typically reported in surface energy balance modelling studies conducted in Arctic regions. Thanks to these findings, we are currently building toward a regional implementation of this model for Greenland Arctic tundra. This model will utilise multiplatform and multitemporal thermal satellite remote sensing to assess the response of surface fluxes to the acceleration of the hydrological cycle in the Arctic.

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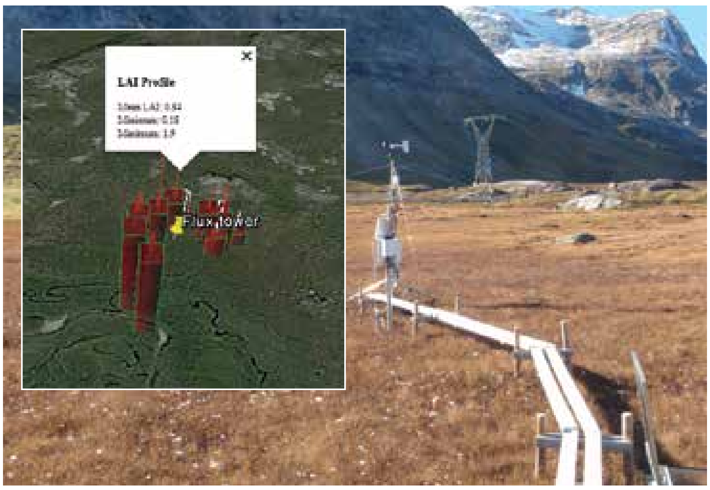


Figure 3. Insert panel: LAI data collected at Kobbefjord's fen flux tower (Nuuk) in 18th September 2018 (background image courtesy of Google Earth). To show plot spatial variability, LAI field measurements are displayed in red columns. Background photo: Fen station flux tower. Photo: Jordi Cristóbal.

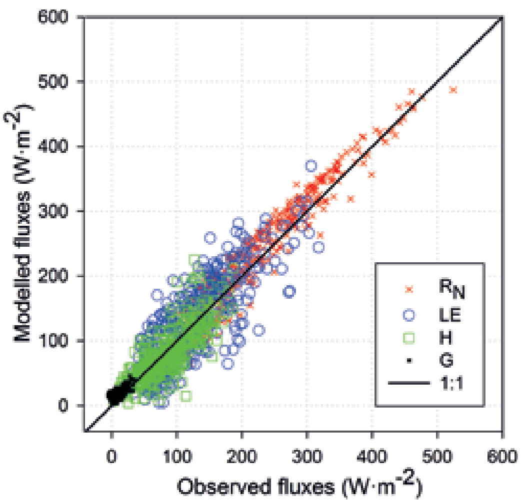
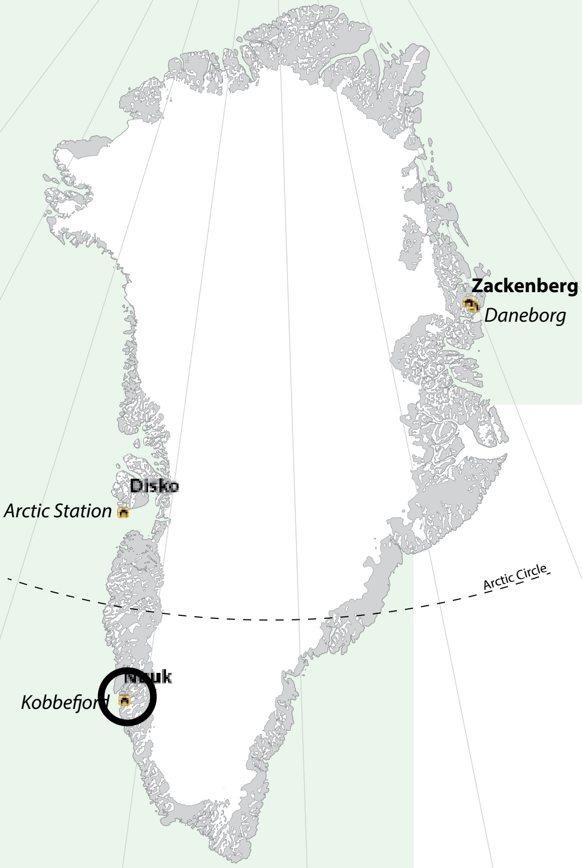


Figure 4. Preliminary comparison of modelled vs. measured half-hourly fluxes with residual closure at the fen flux tower at Kobbefjord (see Figure 3.) from June to September 2012. The 1:1 line represents perfect agreement with observations.



A SYMBIOSIS
MARINE MONITORING

The Greenland Ecosystem Monitoring programme (GEM) MarineBasis-Nuuk has since 2015 collaborated closely with the Arctic Science Study Programme (ASSP) on teaching marine ecology for graduate students. The students learn about the ecology of the Godthåbsfjord system in an Arctic context working with monitoring data, while student projects provide new data to the monitoring programme.

The ecology of the Godthåbsfjord system has been studied and monitored monthly since 2005 making it a model system for teaching high latitude coastal ecology. A semester of natural science courses has been offered in Nuuk since spring 2015 as a collaboration between Greenlandic and Danish institutions. These courses focus on the interaction between climate and environment in Arctic ecosystems. The students are engaged in collecting samples in the field, analyzing them onsite and comparing the obtained results to existing monitoring and research data as well as published findings from Greenland and the Arctic.

One course, in particular, focusing on Arctic marine/aquatic ecosystems was designed to link directly with the ongoing marine monitoring and research in Godthåbsfjord. During this course, students are either partaking in the annual monitoring length transect onboard the research vessel 'Sanna', as part of the

Photo: Mie Winding.

Authors:
Thomas Juul-Pedersen &
Mie Sichlau Winding
Greenland Institute of Natural Resources

Source:
MarineBasis Nuuk

BETWEEN
AND EDUCATION

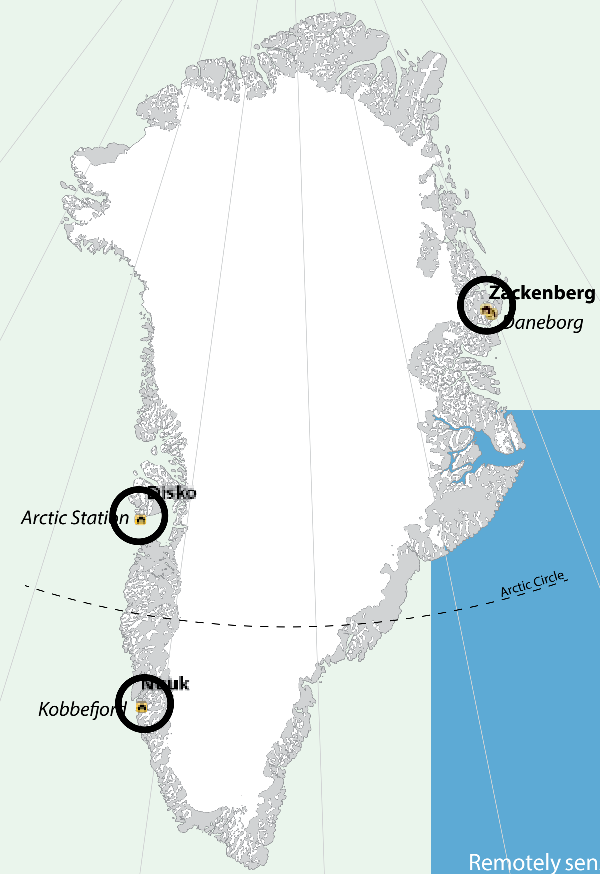
MarineBasis-Nuuk programme, or sampling at monitoring stations using smaller research boats. The data collected by the students supplement the ongoing monitoring, providing additional information on physical, chemical and biological parameters and processes.

Student projects have produced comparative results on the pelagic carbon budgets of the monitored Godthåbsfjord and the neighbouring fjord system Ameralik, depicting the biomass and production of phytoplankton in relation to the abundance and grazing pressure of zooplankton. These findings are subsequently put into a seasonal, interannual and decadal perspective in student exercises and reports, by the time series on key physical and chemical environmental conditions and plankton parameters collected within the monitoring programme. The production of relevant and usable data further act as a motivational factor for the students attending the course, as stated by one student "It is motivating and good to know that our data collected during the course contributes to the monitoring".

This ongoing collaboration between monitoring and education has proven mutually beneficial, as well as promoting knowledge about the monitoring programme and expanding the use of monitoring data beyond the courses (e.g. master thesis projects).

Photo: Thomas Juul-Pedersen.

Photo: Thomas Juul-Pedersen.



THE REMOTE SENSING
EVOLVED WITH NEW

The recent remote sensing initiative within the Greenland Ecosystem Monitoring programme has focused on producing operational methods to deliver calibrated and up-to-date datasets, based on satellite imagery. The recent advances include land surface temperatures at 100 m spatial resolution from 2016 and onward for GEM main sites. Normalized vegetation index data is likewise becoming available for GEM main sites at 10m spatial resolution, and at 250 m resolution for the entire ice-free part of Greenland.

Remotely sensed satellite imagery is becoming increasingly available to a broader scientific and public audience. Readily available up-to-date products such as derived surface temperature, vegetation indices, biomass estimates etc. are being produced by experts, and made readily available for applied use cases. GEM has embraced this development with their remote sensing initiative, where a selection of satellite-based data products is being offered.

One of the most recent outputs from GEM in this space is 100 m resolution land surface temperatures (LST) based on the Landsat 8 thermal infrared sensor (TIRS). The TIRS data is converted to land surface temperatures using a single-channel method proposed in Christóbal *et al*. (2018). The method builds upon local GEM measurements of temperature and atmospheric water vapour, and is consequently calibrated for the specific areas in which it is applied. Due to the high northern latitudes, the overpass frequency of Landsat 8 is bi-weekly for the GEM sites, thus setting the upper limit for the temporal resolution of the LST.

Another output is calibrated Normalized Difference Vegetation Index (NDVI), based on the MODIS sensors (daily coverage of the ice-free part of Greenland) at 250 m spatial resolution. NDVI is also being processed from the Sentinel-2 satellites, with a maximum bi-weekly temporal resolution, and a spatial resolution of 10 m. These NDVI data will be available from GEM main sites only, calibrated against in-situ measurements.

The data are becoming available through the GEM database, or by request to the author.

Authors:

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Department of Geosciences and Natural Resource Management, Center for Permafrost, University of Copenhagen

Source:

The data are becoming available through the GEM database, or by request to the author.

BASED INITIATIVE IN GEM HAS
CALIBRATED PRODUCTS BEING OFFERED

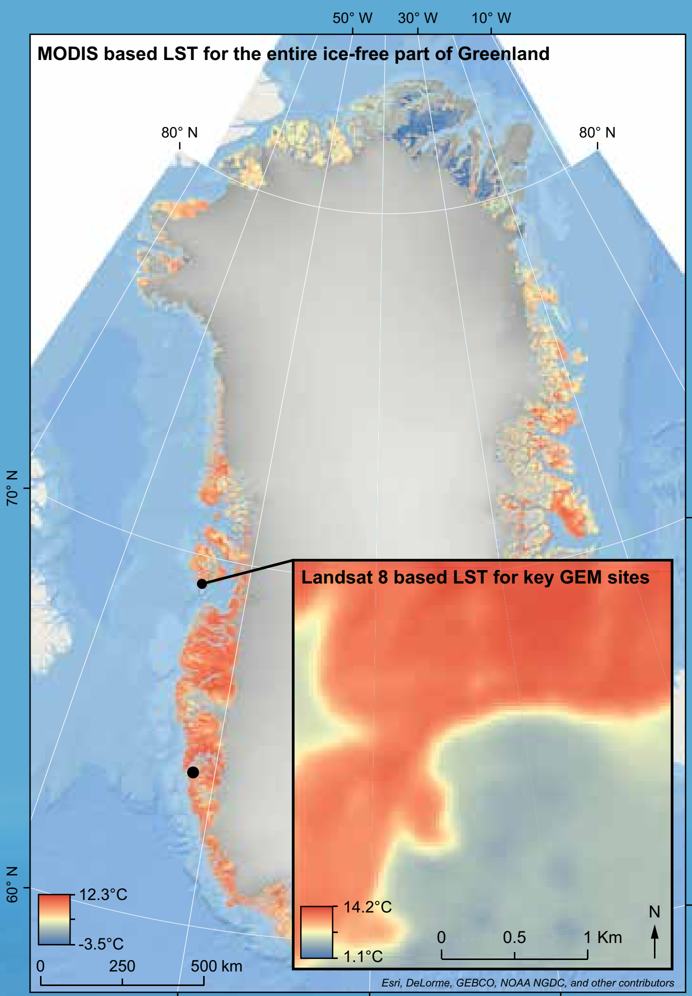

Figure 1. MODIS and Landsat based land surface temperatures, exemplified by 100 m resolution surface temperatures at Disko Island.

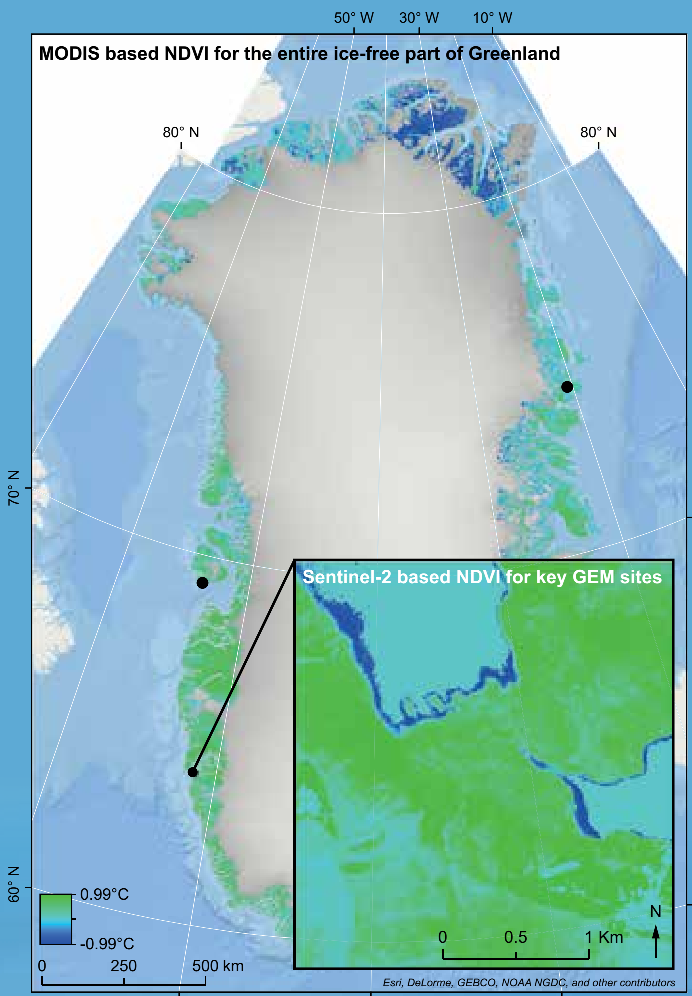

Figure 2. MODIS and Sentinel based Normalized Difference Vegetation Index, exemplified by 10 m resolution data from Kobbefjord, and 250 m covering the ice-free part of Greenland

The GEM sites are located close to fjords or the coast, and represent heterogeneous landscapes and ecosystems. Here it is exemplified by a view over the coastline near Arctic Station, Disko Island. Having a combination of high spatial resolution data from the GEM sites allows for better separation between surface classes such as land, water, ice, vegetation etc., while the larger scale data covering the entire ice-free Greenland allows for studying continuous gradients between GEM sites as well as regional dynamics. Photo: Andreas Westergaard-Nielsen.

References:

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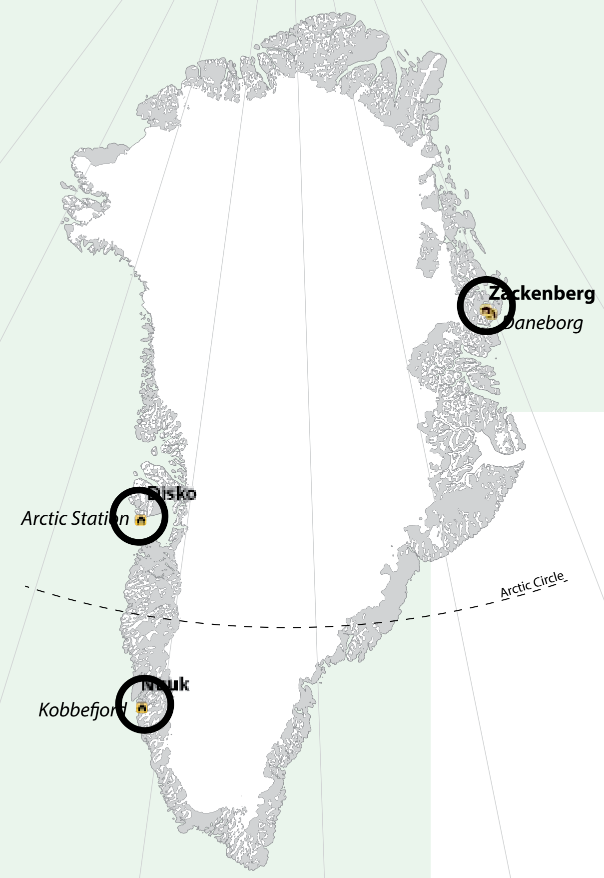

BACK TO THE FUTURE

USING HISTORICAL RECORDS AND

The monitoring efforts that is forming the core of the Greenland Ecosystem Monitoring (GEM) programme started in the mid-1990s as the Zackenberg Ecological Research Operations, ZERO, concept. The acronym "ZERO" meant to refer to year-zero of studying a subsequent and progressively warming climate trajectory and its impact on arctic ecosystems. While the warming trend since then has been shown to take effect, the concept does somewhat constrain the starting point of the investigations.

Historical records, however, form an anchor back in time for the current efforts to document and understand ecosystem change. Hence, a new thematic focus area of the GEM programme has been initiated in order to locate and compare archival records with the monitoring sites today to "extend" the time series back in time with information of the ecosystems before the monitoring started.

In Greenland, the amount of photos and other historical records are substantial. Known historical archives include e.g. records from scientific and military expeditions across the country. Several studies have used those to describe the dynamics and changes of different highly visual parameters such as e.g. vegetation (1) and glacial extent (2). At a circumarctic scale the BTF concept saw special focus during the International Polar Year 2008-2009 and among other communications, a whole special issue of the journal AMBIO was published (3).

We will in the GEM-BTF context take the concept and focus on the monitoring areas that was established some 25 years ago in Zackenberg and a decade ago in Nuuk and later at Disko. While focus will be on the directly visible changes, we will also search for evidence of change (or no change – resilience) in other documentations of the landscape. Further to the most evident visual changes in glacial extend, we will search for evidence of geomorphological changes, thermokarst appearance and other types of climate related responsive parameters in the landscape, which will hold information on the longer term aspects of changes we have observed in our recent detailed GEM records.

The challenge for GEM-BTF is to look in the detail and in previously ignored material to locate our current GEM main monitoring sites (or even the precise measurement locations) in the historical material. Subsequently then map them with current available images and other types of processing techniques to form a platform for research into environmental change over decadal/centennial scale and also ensure that the legacy of these historical records is protected for the future.

This set of annual report cards include the following example from Nuuk as a teaser to see deeper analysis and to be followed by a range of other studies at the GEM main sites in the years to come.

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(BTF) IN GEM

PHOTOS TO EXTEND ECOSYSTEM MONITORING BACK IN TIME

Composite picture showing several aspects of the the BTF concept. It is repeat photography of Østerlien on Disko Island pictured from a 8-mm cine film taken in 1969 by Terry V. Callaghan and a picture of the same area taken 25 July 2009 by Torben R. Christensen. The persons pictured are the supervisor of Terry V. Callaghan's PhD Dr. Martin Lewis in 1969 in the centre and to the right Terry V. Callaghan with student Elin Jantze in 2009. There are, hence, knowledge transfer on site through three generations of researchers distributed over 40 years as well as the digitized photographic comparison (and vegetation analyses) stored along with the solid modern geo-referencing, that ensures the legacy for future generations. Illustration from Callaghan et al. 2011 (4).

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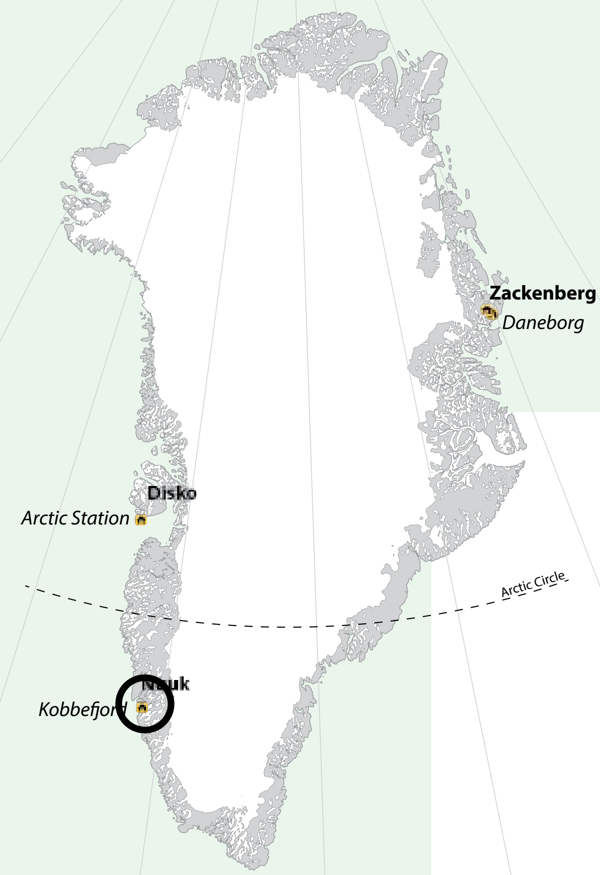

KOBBEFJORD
– THE HINRICH JOHANNES

The rediscovery of the geographer and geologist Hinrich Johannes Rink's (1819-1893) photos captured in Kobbefjord in the late 1860s triggered a new focus on the use of different historical records in a Greenland Ecosystem Monitoring (GEM) context.

In Kobbefjord, automatic cameras and manually captured photos of glaciers and snow patches secure that changes of the geomorphology, snow cover and vegetation have been monitored systematically for the last ten years. In August 2018, the photographic monitoring of the valley was extended with re-photographing and rectifying some of Rink's photos (Fig. 1 and 2).

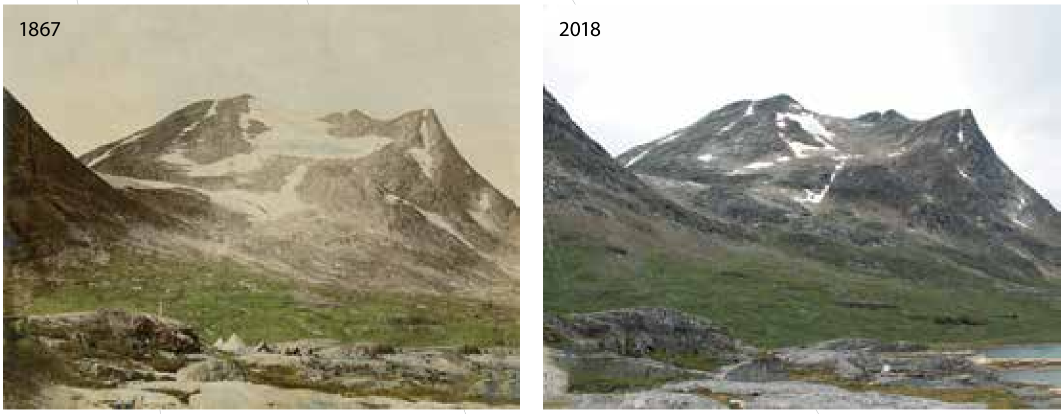

Figure 1.Left: H. J. Rink's hand coloured photo from August 1867. Looking from within 100 meter of the current Kobbefjord research station location towards the west. Right: Repeat of H. J. Rink's photo, captured in August 2018. Note Kobbefjord just visible to the right and the retreat of the glacier. Photo and rectification: Sebastian Marker Westh.

Figure 2. Left: H. J. Rink's hand coloured photo from August ca. 1867. It is taken from the northern site of the river towards the south and Qaqarssuaq. Right: Repeat of H. J. Rink's photo, captured in August 2018. Notice the retreat of the Qaqarssuaq-glacier. Photo and rectification: Sebastian Marker Westh.

Authors:

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RINK HERITAGE

Many of Rink's photos from the bottom of Kobbefjord are taken within the GEM monitoring area and include pictures of the glaciers and snow patches, of the river outlet and images where it is possible to identify different types of vegetation. The comparison of old and new photos hereby contributes to a broader knowledge of how glacial extent, vegetation and the general geomorphology have developed with time. This can help interpreting the dynamics of the ecosystem monitored today.

To increase the temporal resolution from before the monitoring started in 2008, a search after relevant historical records from the Kobbefjord area has now begun. There is a large potential in the unknown amount of private photos captured by locals through the many years of use for recreational and fishing purposes. A campaign to locate such local historical records has now started using brochures, posters, social media and newspapers (Fig. 3). The aim is to involve locals in the program and to draw more attention from the public in Nuuk to the monitoring site in Kobbefjord. A similar effort will be included in further BTF studies in inhabited areas with GEM sites like Disko.

Figure 3. Front of public "wanted" announcement folder asking for input to historical information about the monitoring area in Kobbefjord, February 2019.

Annual Report Card 2018

GEM CLIMATEBASIS

The ClimateBasis programme monitors climate and hydrology in Zackenberg, Kobbefjord and Disko and is run by Asiaq – Greenland Survey. The collected data build base-line information on climate variability and trends for all the other sub-programmes within GEM and serve as a trustworthy foundation for adaptation strategies for the Greenlandic society. The stations are embedded in Asiaq's extensive climate and hydrology monitoring network.

Monitored parameter groups

- Air Temperature
- Air Humidity
- Air Pressure
- Precipitation
- Radiation
- Wind
- River hydrology
- Snow properties
- Fractional cloud cover

The run-off data from GEM-ClimateBasis 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 supply in order to be able to treat data gaps and sensor biases consistently. Hydrometric parameters are monitored on various automated stations. A challenging focus is put on the establishment of reliable stage-discharge relations, whose temporal stability depends on the river bed. At the river Zackenberg for instance, repeated glacier outburst floods require an updated stage-discharge relation every year, where the related field work is performed together with the GeoBasis programme.

In 2018 we observed temperatures close to average in Zackenberg (ZAC) (0.03°C warmer than the 2008-2018 average), however the year was significantly colder in Kobbefjord and Disko (-1.1°C and -1.3°C respectively, cooler than the average for 2008-2018). Month-to-month variability is a function of latitude and thus highest in ZAC. The winter was exceptional, ZAC experienced the warmest February in the last decade (this has been exceeded in the historical records). In comparison, Kobbefjord had the coldest February. Disko was also far colder than average, but not a record for the last 10 years. All 3 stations experienced the coldest summer of the past decade.

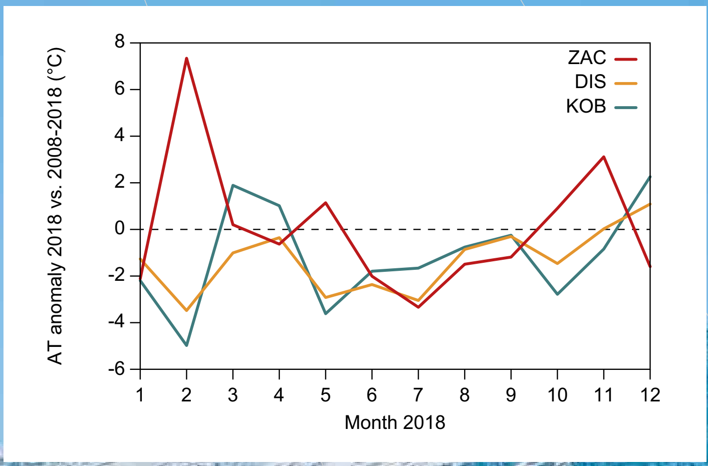

Figure 1. Monthly air temperature anomaly 2018 compared to the common reference period 2008-2018 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

Lead institutions:

Zackenberg and Nuuk:

Asiaq – Greenland Survey, manager: Kirsty Langley, kal@asiaq.gl

Disko:

Asiaq, Greenland Survey, manager: Jordi Cristóbal Rosselló

Contributing authors:

Jordi Cristóbal Rosselló, Kirsty Langley, Stefan Jansen, Sille Marie Myreng, Martin Olsen, Dorthe Petersen, Kerstin Krøier Rasmussen, Magnus Lund, Kirstine Skov, Thomas Friborg, Jakob Abermann, Charlotte Sigsgaard

GEM
Greenland Ecosystem Monitoring

PROGRAMME DESCRIPTION

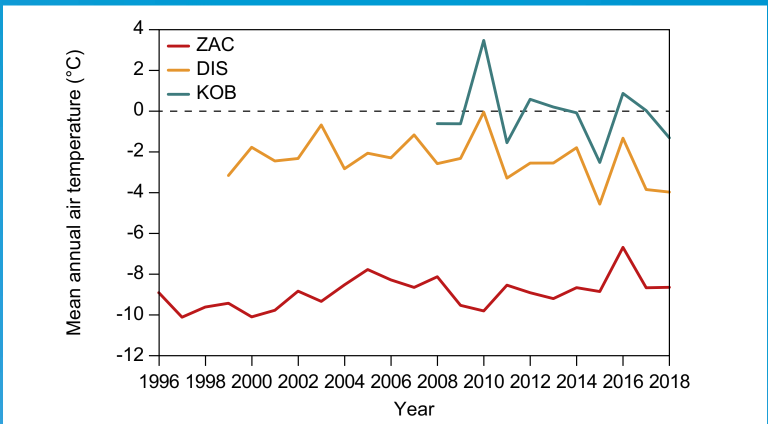

Figure 2. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

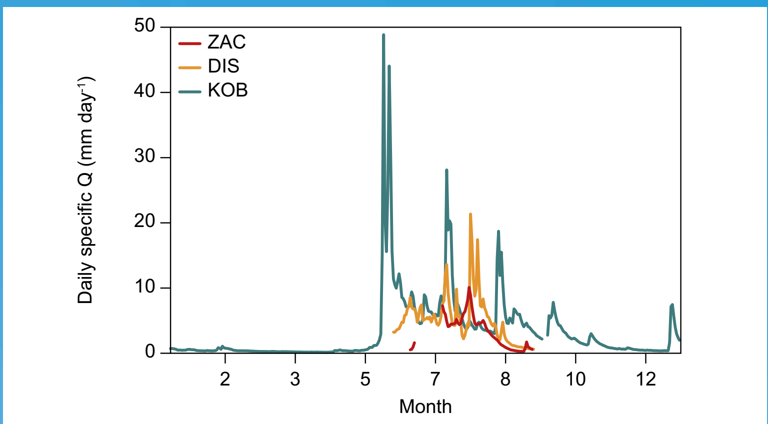

Figure 3. Specific daily discharge (runoff per unit area) at the three GEM sites: Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB) for 2018. In winter, ZAC has no flow and DIS no winter instrumentation, while KOB shows year-round discharge. The different climatic conditions are mirrored in the discharge time-lines clearly showing the drier regime in ZAC compared to KOB and DIS and the N-S gradient from DIS to KOB.

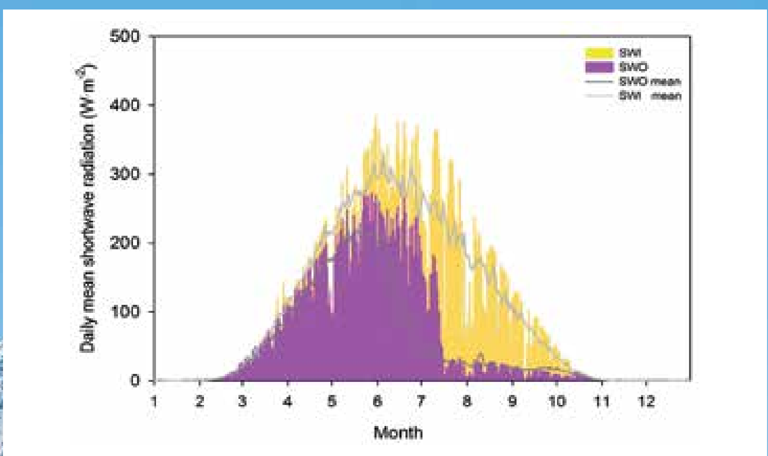

Figure 4. Daily mean shortwave incoming radiation (yellow) and shortwave outgoing radiation (purple) for 2017-2018 (SWI and SWO, respectively) with their respective daily means from 1995 to 2018 (SWI mean and SWO mean, respectively) in grey tones for Zackenberg.

In comparison to 2017, we observed a colder year in 2018 in KOB, while ZAC and DIS had a similar mean annual air temperture. Very different temperature regimes can be pointed out with mean annual temperatures way below zero at Zackenberg, a few degrees below zero at Disko and around zero in Kobbefjord. The interannual variability in Kobbefjord is particularly strong.

This year has been the record late start for ZAC flow (19th of June) due to low temperatures. Notably, in 2018 there was no glacier lake outburst flood from A.P.Olsen glacier. DIS experienced the largest summer discharge on record due to a heavy rain event in August, although the record is still short (from 2015) and photos indicate a larger event in 2014. In KOB, the 2nd highest spring discharge on record occurred in May, and an unusual peak occurred in late December due to a warm spell coinciding with a large rain event. Field work for discharge in Zackenberg and Disko is done in tight collaboration with GeoBasis.

In 2018, one of the longest snow cover periods for the last 20 years was recorded at Zackenberg (see pp 40-41), due to a cold spring and summer. This had a strong effect on the surface energy balance during the summer, and is visible in the shortwave radiation data. While daily mean outgoing shortwave radiation from 1995 to 2018 (SWO mean) usually decreases by June due to snow melt, in 2018, much more energy was reflected to the atmosphere due to the extended snow period. This impacted the vegetation and the soil by decreasing the amount of energy absorbed and had a strong influence on the active layer by decreasing its depth.

(Photo: Jakob Abermann).

Annual Report Card 2018

GEM
GEOBASIS

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

Monitored parameters

Snow properties
- Snow cover
- Snow depth
- Snow density

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

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

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

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

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

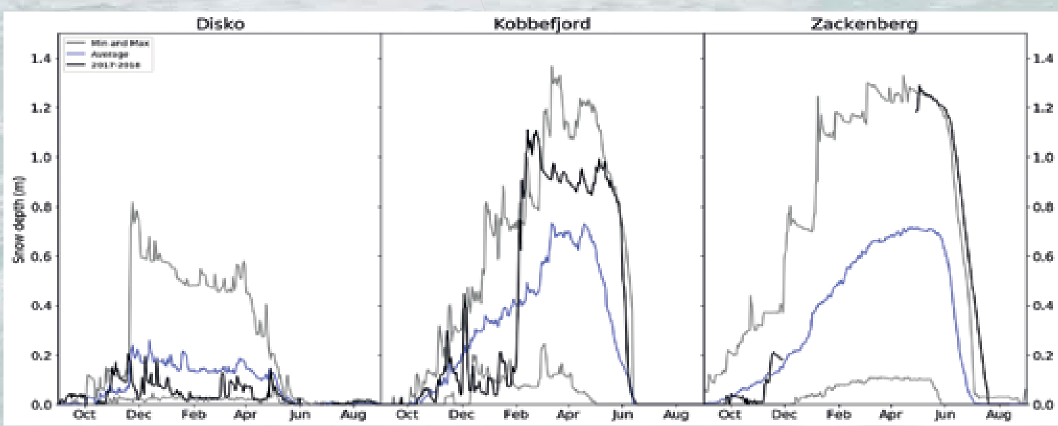

Figure 1. Daily snow depth measurements in Disko (left), Kobbefjord (middle) and Zackenberg (right). Black lines are snow depth in 2018, blue lines are average and grey lines are min and max for the historic record. Snow is a key parameter in arctic ecosystem functioning. Thus, several different monitoring methods are put in place to get information on spatial distribution and temporal patterns in snow cover, across the three GEM sites. Methods include time-lapse photography, transect surveys, snow density measurements and, as shown here, long term point-based monitoring of snow depth. Data used in the figure: Disko: 2012-2018, Kobbefjord: 2008-2018 and Zackenberg: 1996-2018.

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Contributing authors:

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PROGRAMME DESCRIPTION

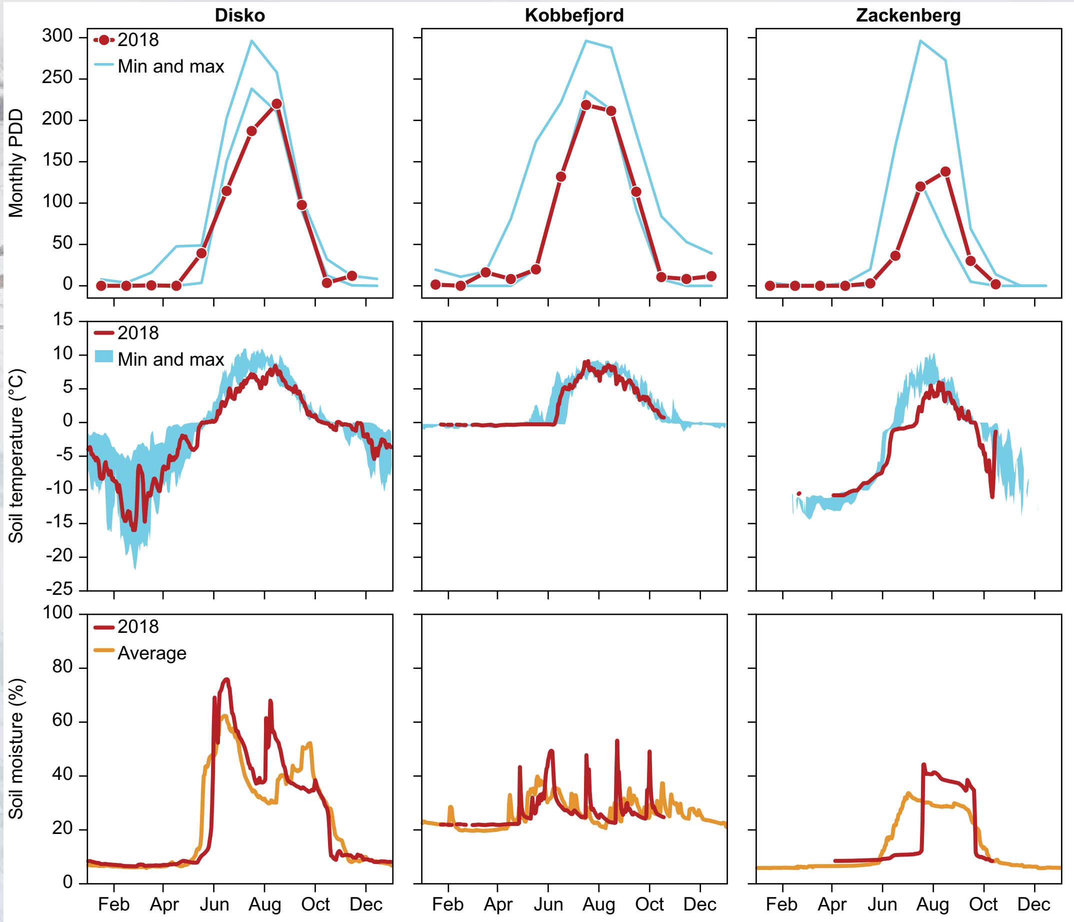

Figure 2. Accumulated monthly positive degree days (PDD) across sites (top panel) in 2018 compared to minimum and maximum PDD in historic data. Heath soil temperatures in 10 cm (middle panel) in 2018 compared with minimum and maximum and soil moisture within the top 10 cm, shown together with average. Soil temperature and soil moisture content are important parameters for plant growth, phenology, permafrost, energy fluxes and carbon exchange. Soil temperature and soil moisture are measured under several different vegetation communities and in a wide range of depths, as part of the GeoBasis program. Data used in the figure: Top panel: Disko: 2012-2018, Kobbefjord: 2008-2018 and Zackenberg: 1996-2018. Middle panel: Disko: 2012-2018, Kobbefjord: 2012-2018 and Zackenberg: 2014-2018. Bottom panel: Disko: 2012-2018, Kobbefjord: 2013-2018 and Zackenberg: 2005-2018.

The 2018 growing season marked itself by being generally cold, wet and late starting across the three main GEM sites. In Kobbefjord and Zackenberg large amounts of snow were recorded, whereas in Disko it was below average (Fig. 1). The insulating effect of the snow is clearly illustrated in the winter soil temperatures from Kobbefjord and Zackenberg, which are generally less fluctuating compared to Disko (Fig. 2).

The number of positive degree-days was among the lowest or lower than previously recorded temperatures. The cold and wet summer at all sites, was mirrored in low soil temperatures during summer and soil moisture around or above average throughout the summer season (Fig. 2).

In Zackenberg, the large amounts of winter snow and relatively low summer temperatures resulted in a record shallow active layer, breaking an ongoing trend towards increasingly deep active layer (Fig. 3).

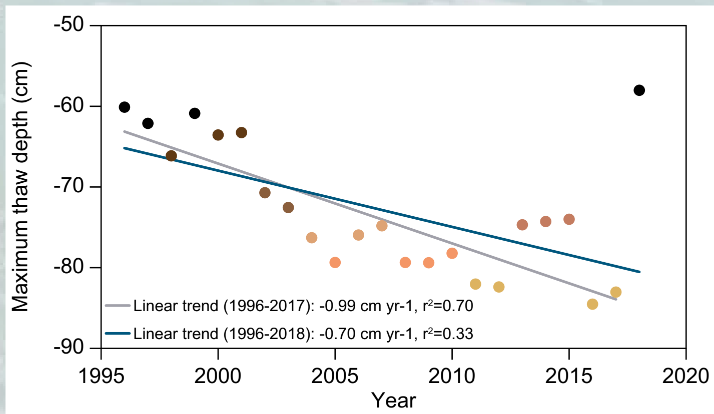

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid #1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing and temperature recordings from boreholes.

Photo: Lars Holst Hansen

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GEM BIOBASIS

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

Moss campion in Kobbefjord. Photo: Katrine Raundrup.

Photos: Lars Holst Hansen.

Monitored parameter groups

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

Arthropods and microarthropods
- Abundance
- Emergence phenology
- Herbivory rates

Birds
- Abundance
- Reproductive phenology
- Reproduction and predation rates

Mammals
- Abundance
- Spatial distribution
- Reproduction and predation rates

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

General
- Tissue sampling
- Plot-scale abiotic parameters

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Nuuk:

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GEM
Greenland Ecosystem Monitoring

PROGRAMME DESCRIPTION

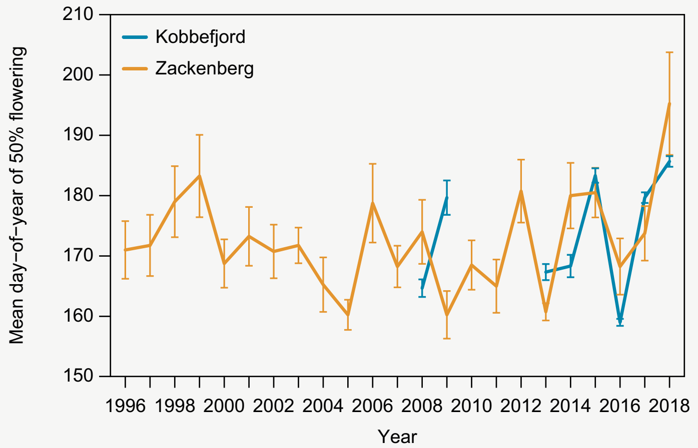

Figure 1. Day of 50% flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix *flowering phenology in selected permanent plots in Kobbefjord and Zackenberg 1996-2018. Note that no flowering was observed in Kobbefjord in the years 2010 to 2012 due to insect outbreak.*

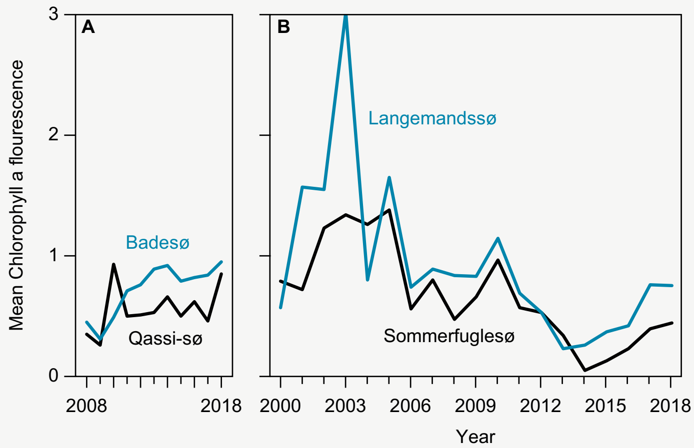

Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at A) Kobbefjord 2006-2018 and B) Zackenberg 2000-2018. Blue lines indicate lakes with fish, black lines lakes without fish.

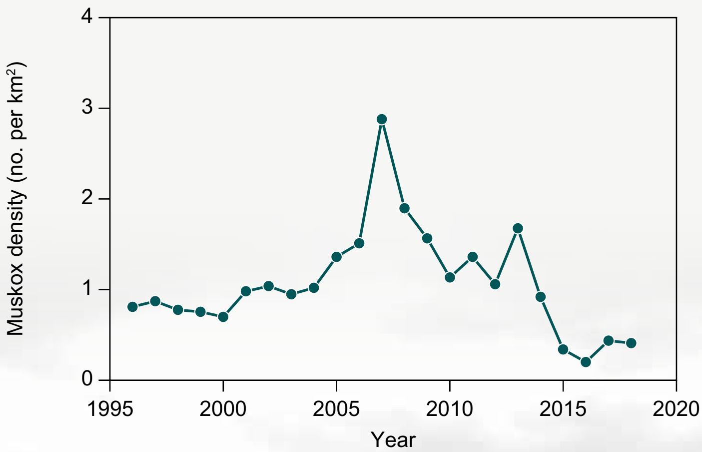

Figure 3. Inter-annual variation in muskox population dynamics at Zackenberg 1996-2018.

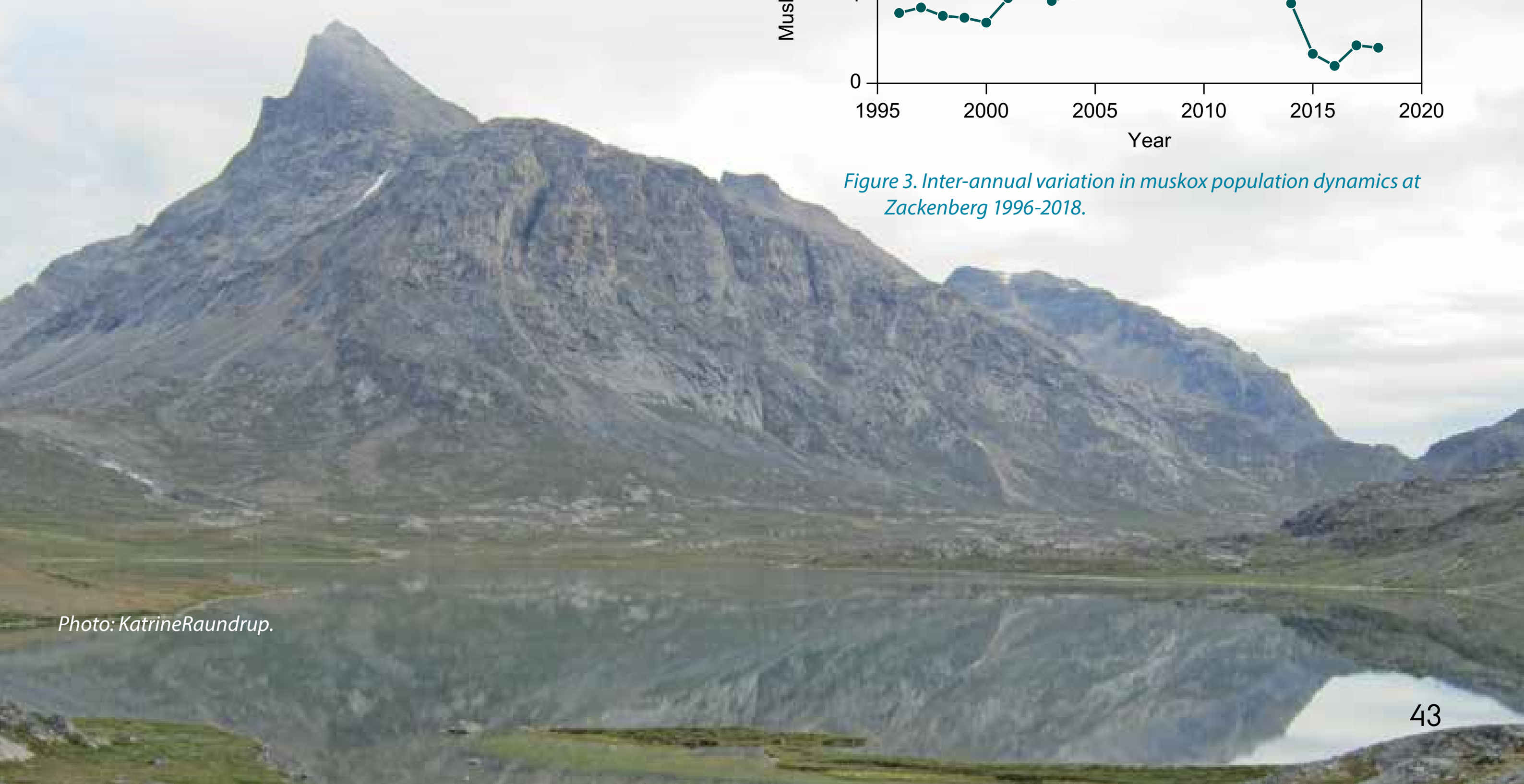

Photo: KatrineRaundrup.

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GEM MARINEBASIS

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

Monitored parameters:

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

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Photo: Let It Snow APS.

PROGRAMME DESCRIPTION

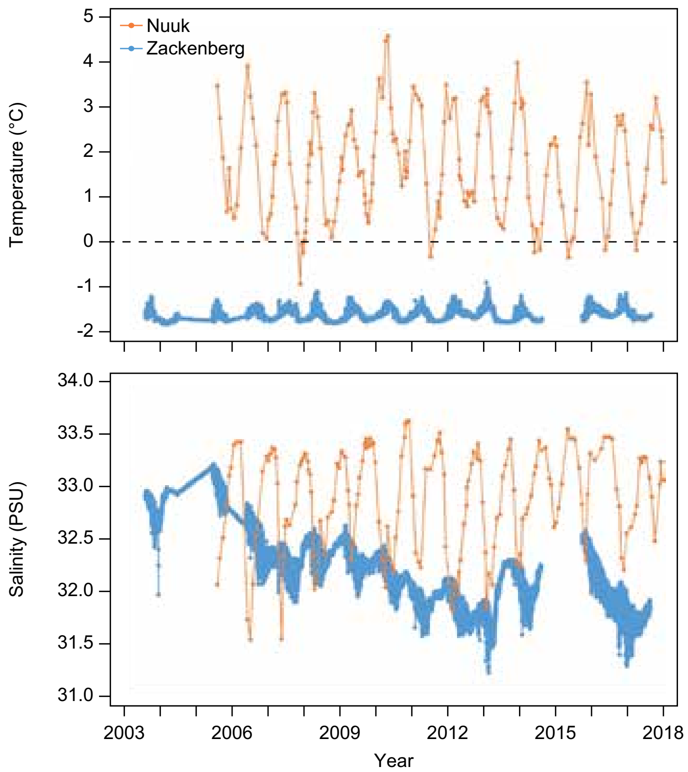

Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk and Zackenberg. The time series from Nuuk represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring deployed at an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

Photo: Mie Winding.

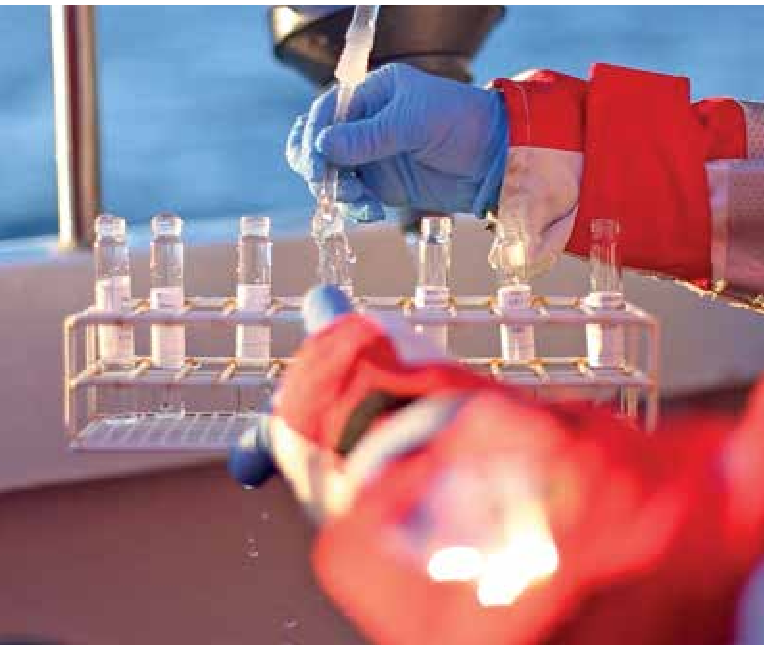

Photo: Let It Snow APS.

Photo: Let It Snow APS.

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GEM
GLACIOBASIS

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

The LYN-1 automatic weather station during maintenance, on the tongue of Chamberlin glacier. Photo: Laura H. Rasmussen, KU.

Photo: Daniel Binder, GEUS.

Monitored parameters:

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

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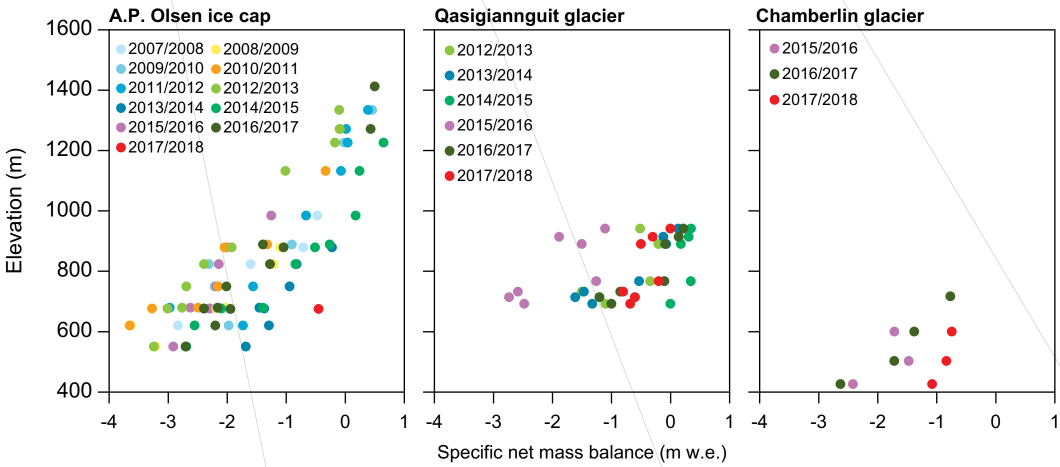


Figure 1. Specific surface net balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 5 stakes with 2 more added in 2018 and first remeasured in 2019). For A.P. Olsen the stake readings will become available after the 2019 spring field campaign; the black dot shown for 2018 is from an automatic sensor.

PROGRAMME DESCRIPTION

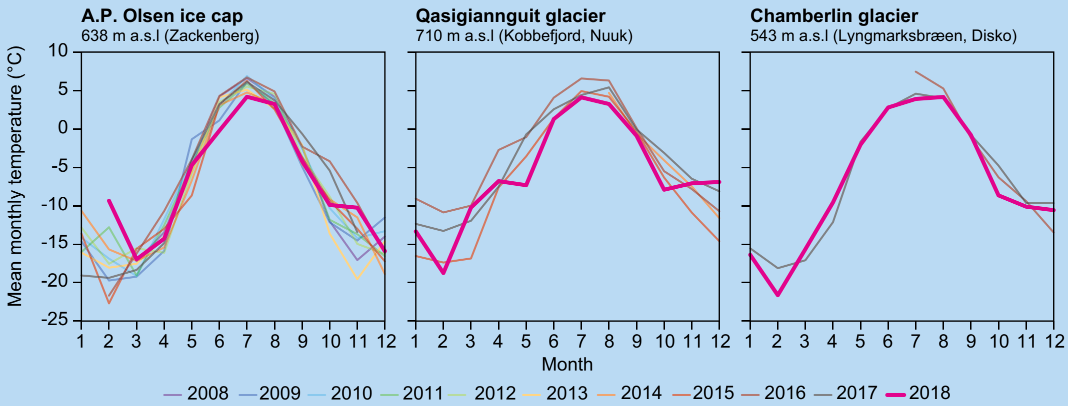


Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites.

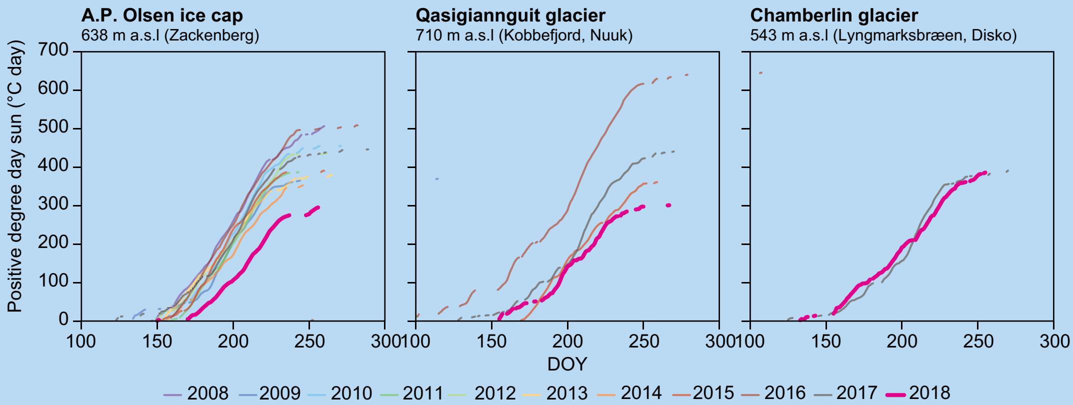


Figure 3. Positive degree day (PDD) sums from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites. Only seasons with complete data coverage are shown, gaps visible in the plots indicate sub-freezing daily mean temperatures.

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

The LYN-2 automatic weather station newly installed in May 2018 at the summit of Lyngmarksbræen ice cap, of which Chamberlin glacier is part. Photo: Michele Citterio, GEUS.

Greenland Ecosystem Monitoring

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

ClimateBasis Programme

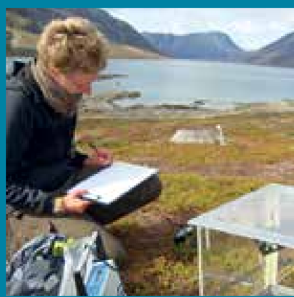
The GEM ClimateBasis Programme studies climate and hydrology providing fundamental background data for the other GEM programmes.

GeoBasis Programme

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

BioBasis Programme

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

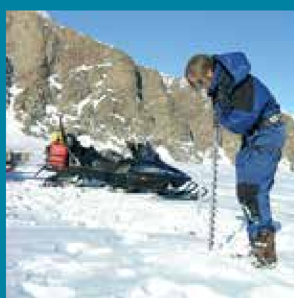


MarineBasis Programme

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

GlacioBasis Programme

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



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