Spatial Data on different scales in GEM

Allows for Quatification of Geomorphological changes following Extreme Events

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Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2017

GEM

Greenland Ecosystem Monitoring

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2017

GEM
Greenland Ecosystem Monitoring

Greenland Ecosystem Monitoring

STRATEGY 2017-2021

AARHUS UNIVERSITY
DCE - DANISH CENTRE FOR ENVIRONMENT AND ENERGY

GEM
Greenland Ecosystem Monitoring

GEM
ANNUAL REPORT

About GEM

Greenland Ecosystem Monitoring (GEM) is a long term monitoring program operated by greenlandic and danish research institutions. GEM was initiated in 1996 and has over the past two decades established itself firmly as an internationally leading climate change related environmental barometer measuring climate impacts and ecosystem changes in the Arctic.

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

GEM covers marine, terrestrial, limnic and glaciological compartments of the ecosystem (Fig. 1) across a climatic gradient from High- to Low-Arctic regions of Greenland. The GEM strategy 2017-2021 has expanded the geographical coverage of the programme to address key scientific questions and enable upscaling of results to a Greenlandic scale (Fig. 2).

This provides a unique foundation for mapping and analysing ecosystem responses to temporary and more permanent climate changes within specific and different climatic regimes. This approach also improves the understanding of feedbacks between arctic ecosystems and the global climate system.

GEM data are submitted to more than 10 international thematic data repositories and GEM researchers participate in over 35 international scientific networks, programmes and projects.

GEM data are freely available through http://data.g-e-m.dk/.

The GEM Strategy 2017-20121 is available here http://g-e-m.dk/gem-publications/gem-reports/.

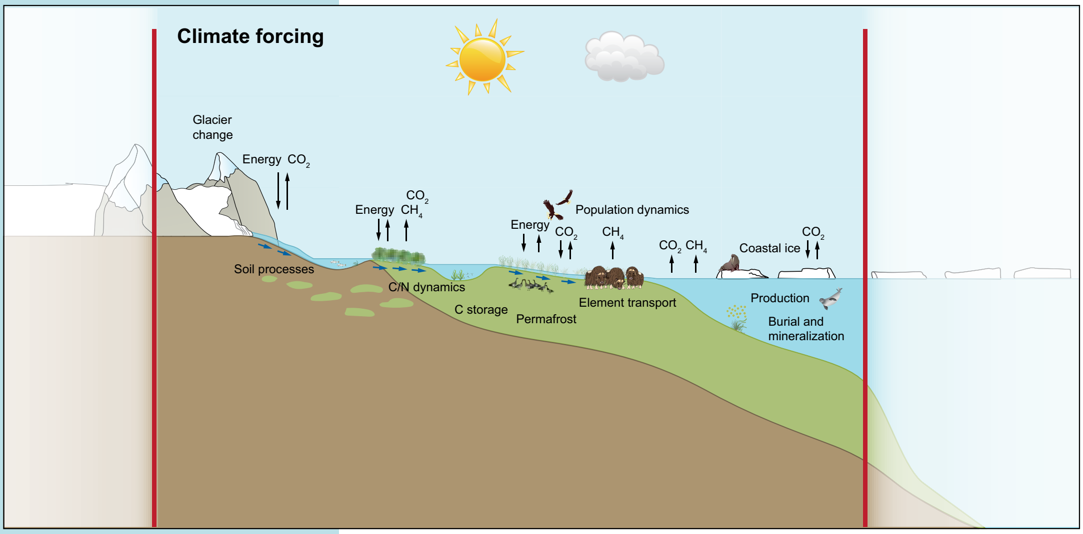
GEM in an international context

In April 2017, GEM held a session at the Arctic Monitoring and Assessment Programme (AMAP) conference 'From knowledge to action' in Washington DC, US. The session 'Linking national monitoring programmes with arctic and global initiatives' used GEM as a case for how local monitoring programmes can contribute to international projects, programmes and assessments. Participants included AMAP, CAFF/CBMP, INTAROS, INTERACT, IPCC, IPBES, IASC and Danish decision makers. An important outcome of the session was that Greenland/Denmark now contributes to the IPBES biodiversity assessment of South and North America (including Greenland).

GEM in a greenlandic context

A number of Greenlandic and Danish research institutions operate long term monitoring programmes in Greenland. GEM arranged a synergy workshop

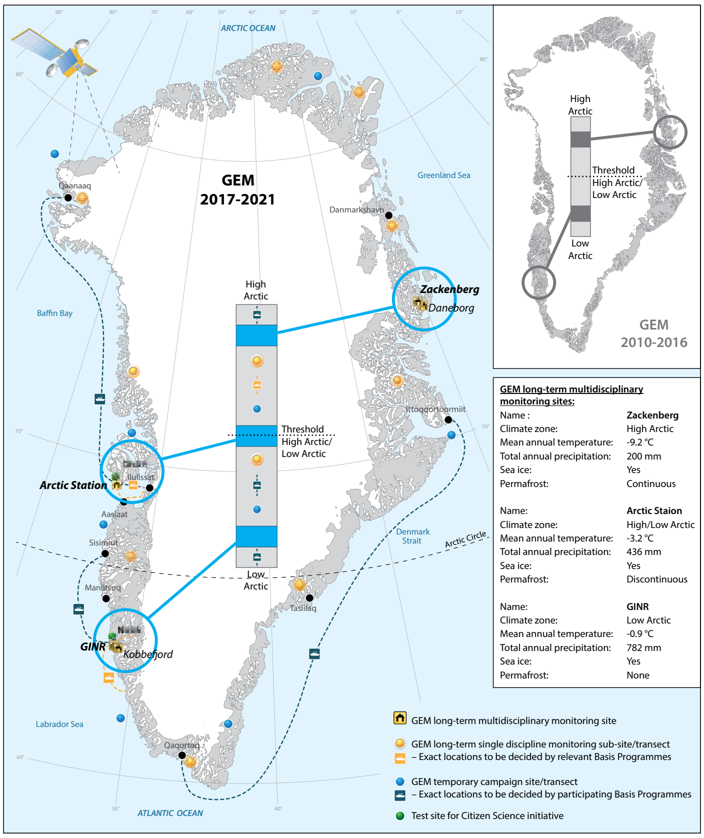
Figure 1. The GEM domain.



CARDS 2017

GEM at a glance 2017

- Basis Programmes active in 2017: 14 + GEM Remote Sensing
- GEM scientists in the field: 75
- Scientific publications: 101
- Conference posters: 10
- Courses using GEM data: 7
- Conferences with GEM representation: 8
- GEM conference presentations: 19



GEM long-term multidisciplinary monitoring sites:

Name :	**Zackenberg**
Climate zone:	High Arctic
Mean annual temperature:	-9.2 °C
Total annual precipitation:	200 mm
Sea ice:	Yes
Permafrost:	Continuous
Name:	**Arctic Staion**
Climate zone:	High/Low Arctic
Mean annual temperature:	-3.2 °C
Total annual precipitation:	436 mm
Sea ice:	Yes
Permafrost:	Discontinuous
Name:	**GINR**
Climate zone:	Low Arctic
Mean annual temperature:	-0.9 °C
Total annual precipitation:	782 mm
Sea ice:	Yes
Permafrost:	None

- GEM long-term multidisciplinary monitoring site
- GEM long-term single discipline monitoring sub-site/transect – Exact locations to be decided by relevant Basis Programmes
- GEM temporary campaign site/transect – Exact locations to be decided by participating Basis Programmes
- Test site for Citizen Science initiative

Figure 2. Sampling strategy for the GEM 2017-2021 strategy period.

(Photo: Jonas Koefoed Rømer).

early 2018 to provide an overview of existing long-term research and monitoring initiatives in Greenland related to climate and ecosystems and explore opportunities for cooperation with other programmes and government agencies. The workshop had participants from eight research institutions and five ministries, and resulted in 15 potential collaborative synergies that are explored in detail by the participating institutions.

Expanding geographical coverage

Following aims set out in the GEM Strategy 2017-2021, the programme geographically expanded its monitoring efforts in 2017 with the introduction of the remote sensing initiative and further building monitoring capacity by adding a GlacioBasis component at GEM main sites at Nuuk and Disko in West Greenland. 2018 will see further expansion of monitoring efforts at the Disko main site with the implementation of a MarineBasis component.

GEM Remote Sensing

In 2017, GEM launched a remote sensing initiative for improved process understanding and upscaling/ downscaling elements of the GEM Strategy 2017-2021. In 2017, the programme included cloud cover, land surface temperature, topographic wetness, NDVI, albedo and snow line. An internal workshop was held to facilitate to further development of the initiative by:

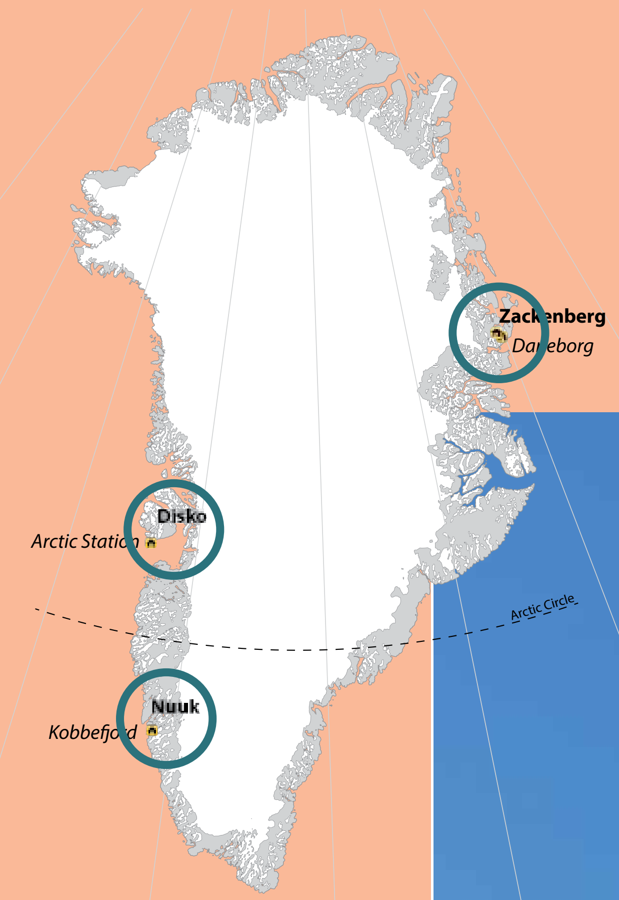
- Showing preliminary results.
- Discussing validation efforts and options across BasisProgrammes.
- Discussing opportunities across programmes for upscaling of local observations or processes in time and space.

The GEM database is at the time of writing being updated with all data from 2017 and this annual report card presents example of findings from and issues relating to the 2017 field season. It also shows the cooperation between GEM and other initiatives including rock glacier southern limit expansion in western Greenland, return of the lemming peak at Zackenberg, extreme rain events resulting in geomorphological changes and example of an educational initiative for high schools using GEM data.

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

New feature!

In the first section, GEM Basis Programmes present themselves along with monitored parameter groups and selected data time series.



GEM
CLIMATEBASIS PROGRAMME

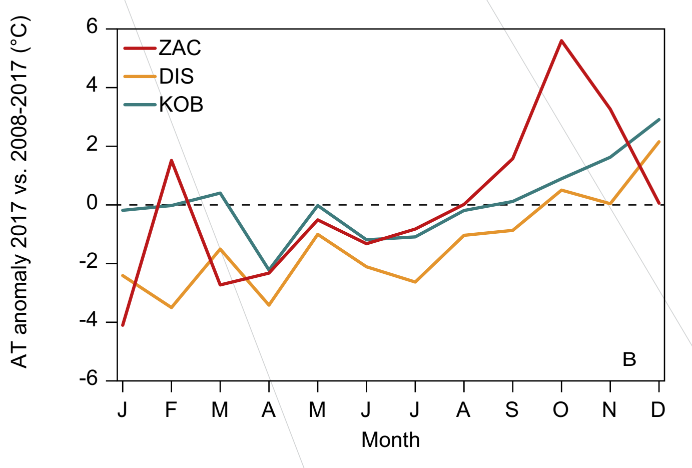
The GEM ClimateBasis programme monitors climate and hydrology in Zackenberg, Disko and Kobbefjord. The collected data builds base-line information on climate variability and trends used by all the other programmes within GEM and serve as a trustworthy foundation for climate change adaptation strategies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

Monitored parameter groups

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

Run-off data is delivered to the World Hydrological Cycle Observing System (WHYCOS) and the Global Runoff Data Centre (GRDC) networks under the auspices of the World Meteorological Organisation (WMO). 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. Effort 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 GEM GeoBasis programme.

Figure 1. Monthly air temperature anomaly 2017 compared to the common reference period 2008-2017 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). The year started colder than usual and ended warmer than usual. Annual temperature at Disko significantly lower than usual (-1.31 oC), while Zackenberg and Kobbefjord was slightly warmer (+0.02 and +0.03 respectively). All numbers refer to the period 2008-2017 where we have overlapping data at all stations.



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DESCRIPTION

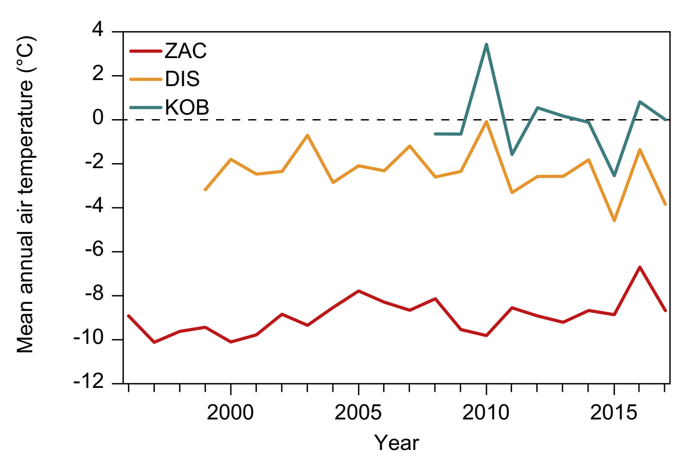


Figure 2. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). Very different temperature regimes can be pointed out with mean annual temperatuers way below zero at Zackenberg, a few degrees below zero at Disko and around zero in Kobbefjord. Despite the month-to-month variability not being very high in Kobbefjord (Fig. 1), the interannual variability is particularly strong. The overall trend is significantly positive for Zackenberg.

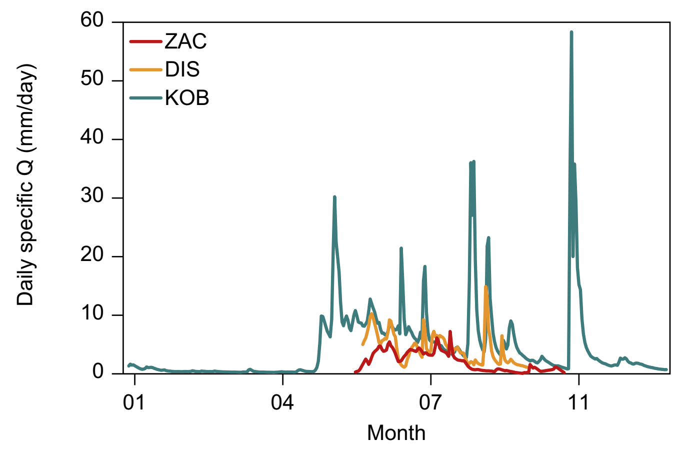


Figure 3. Specific daily discharge (run-off per unit area) at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB) during 2017. While Zackenberg and Disko have no runoff during winter (and thus no permanently installed measurement setup), Kobbefjord shows year-round discharge. The different climatic conditions are mirrored in the discharge time-lines. Zackenberg shows the least specific discharge and Kobbefjord the highest. Autumn storms bring strong discharge pulses in Kobbefjord with up to almost 60 mm/day.

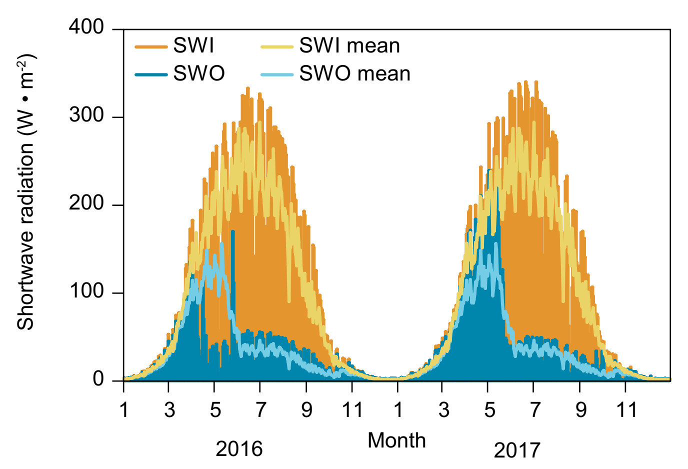
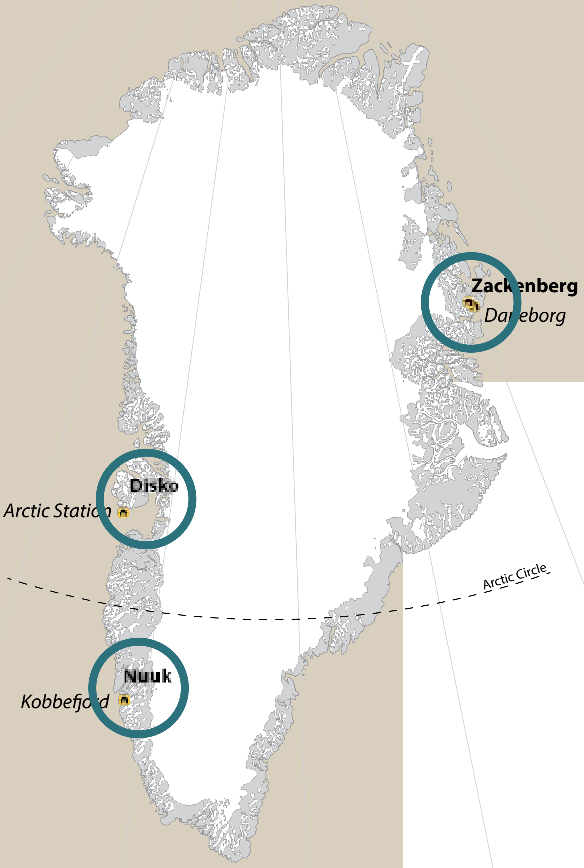


Figure 4. Shortwave incoming radiation (yellow) and shortwave outgoing radiation (blue) for 2016-2017 from Kobbefjord with their respective means since 2008 in grey tones. 2016 had one of shortest snow cover periods since 2008. This had a strong effect on the surface energy balance in winter and spring. While the incoming shortwave radiation (SWI) was similar for two consecutive years, the outgoing shortwave radiation (SWO) was quite different in sping, even when compared to the mean SWO from a ten year time series data (SWO mean).

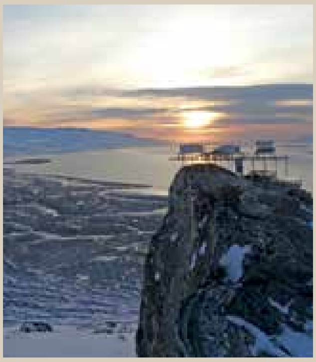
(Photo: Jakob Abermann).



Annual Report Card 2017

GEM
GEOBASIS PROGRAMME

The GEM GeoBasis monitoring programme focuses on selected abiotic characteristics describing the state of greenlandic terrestrial environments and their potential feedback effects in a changing climate (e.g. effects of permafrost thaw, energy fluxes and greenhouse gases). Monitored plot data 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 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.


(Photo: Kirstine Skov).

A view of Zackenberg valley and Young Sound 19-10-2017. Cameras are mounted on the rock as part of the automatic photo monitoring. Snow depletion curves for the area are based on these photos. Photo: Kirstine Skov.


Snow covered fen in Kobbefjord (Nuuk) 10-04-2018 (Photo: Kerstin Krøier Rasmussen).


Looking upstream in Røde Elv where a person is about to start a discharge measurement 27-06-2017. Skarvefjeld in the background is a 800 m high plateau mountain (Photo: Charlotte Sigsgaard).

Lead institutions

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University of Copenhagen, Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

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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

DESCRIPTION

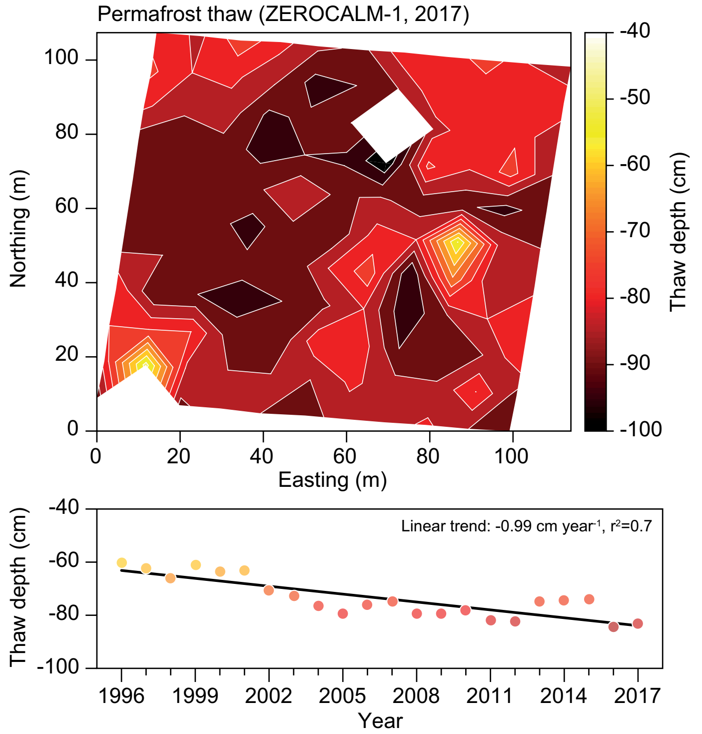


Figure 1. Spatial variability in maximum thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid (ZEROCALM-1; upper panel). During 2017, maximum thaw depth (mean 83 cm) was observed 18 August. Lower panel shows the long-term trend in annual maximum thaw depth since monitoring began in 1996. Data are fed into the CALM (Circumpolar Active Layer Monitoring) database.

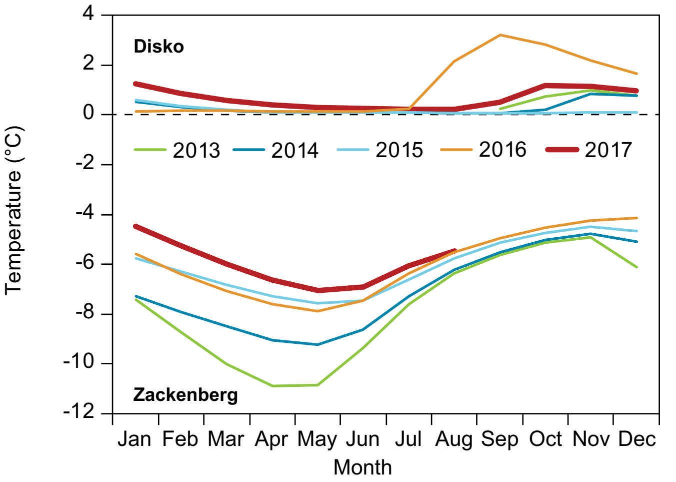


Figure 2. Monthly average ground temperatures measured in boreholes in Zackenberg (300 cm depth) and Disko (350 cm depth). Only seasonal freezing, no permafrost, observed at Disko, while Zackenberg has permafrost, but large year to year fluctuation depending on snow depth, cover period and timing.

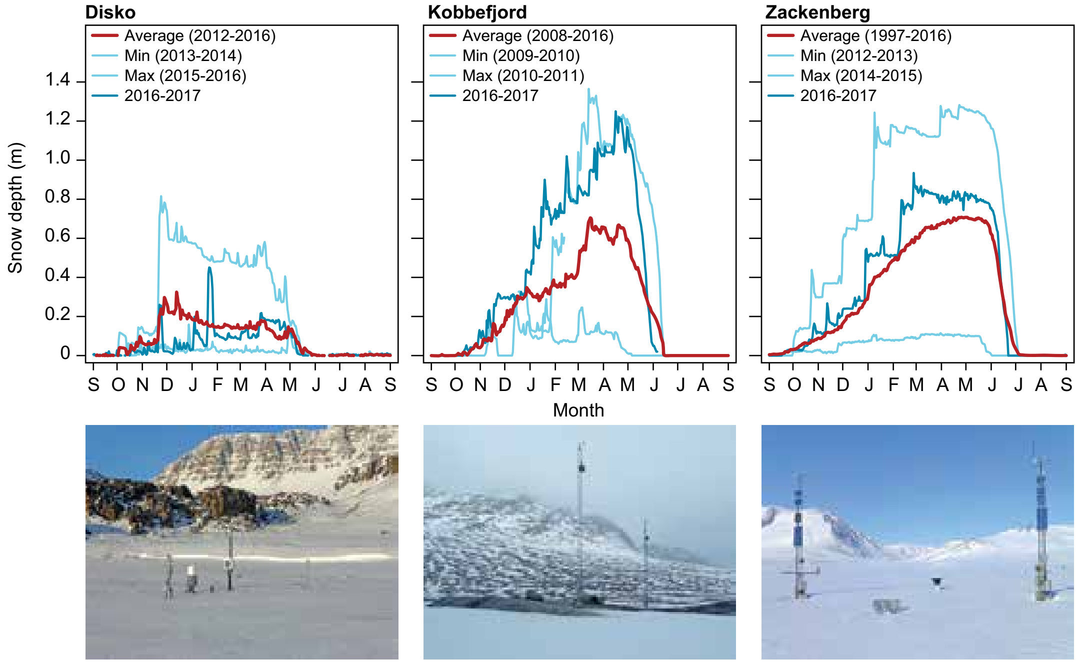
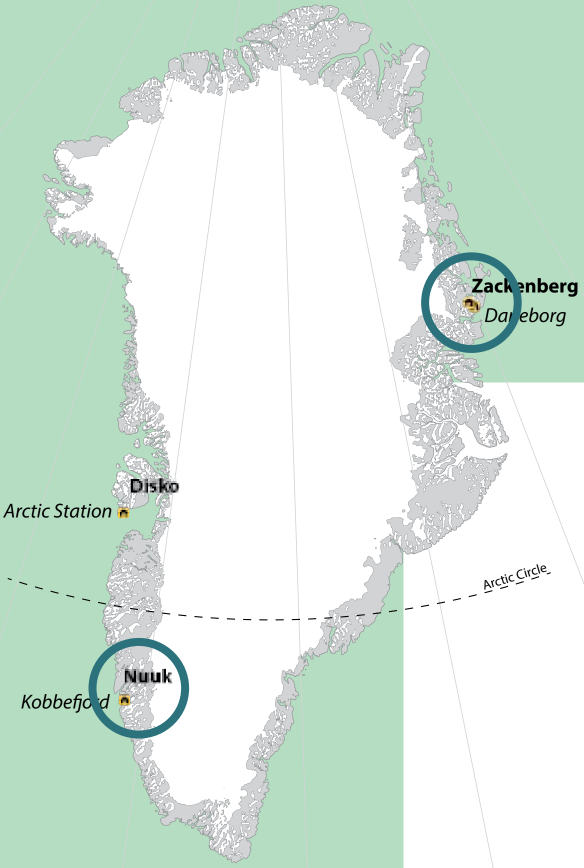


Figure 3. Snow depth measurements in Disko (top left panel), Kobbefjord (top middle panel) and Zackenberg (top right panel) with photos from each site below (from left to right: Charlotte Sigsgaard, Jakob Abermann and Kirstine Skov). Blue lines are daily averages of snow depth during 2016-2017. Snow is a key property in arctic ecosystem functioning and information on spatial distribution and temporal patterns in snow cover is essential to study climate and ecosystem change.



Annual Report Card 2017

GEM
BIOBASIS PROGRAMME

The GEM BioBasis programme is the biodiversity component of the GEM programme. The programme studies key species and 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 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 parameters, their resilience towards biotic and abiotic perturbations, as well as their long-term trends. BioBasis has strong linkages to Arctic Council's Circumpolar Biodiversity Monitoring Program (CBMP). 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.

(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

Lead institutions:

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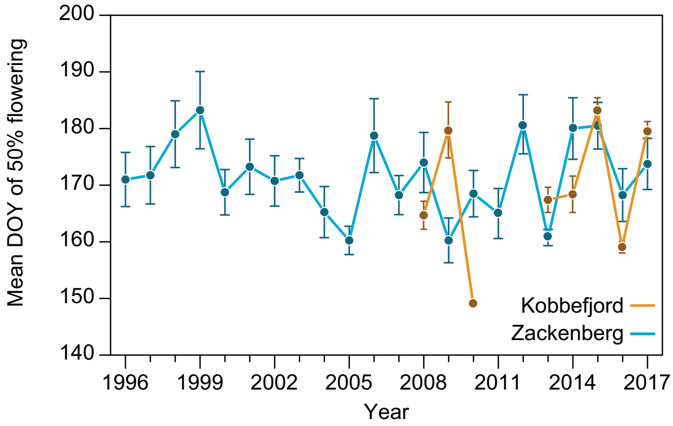


Figure 1. Day of 50 % flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix flowering phenology in selected permanent plots in Kobbefjord and Zackenberg 1996-2017. No flowering was observed in Kobbefjord in 2011 and 2012 due to insect outbreak.

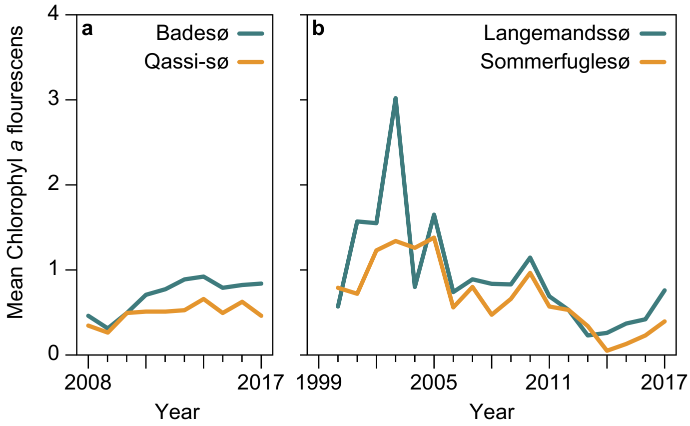


Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord 2008-2017 (a) and Zackenberg 1996-2017 (b). Green lines indicate lakes with fish, orange lines lakes without fish.

(Photo: Stine Kjær Petersen).

Moss campion in Kobbefjord (Photo: Katrine Raundrup).

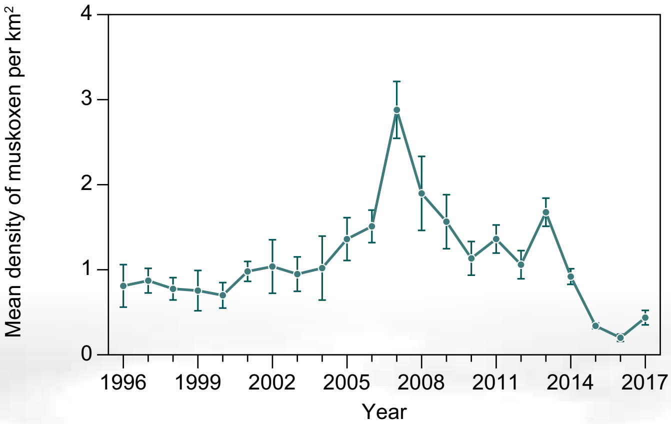
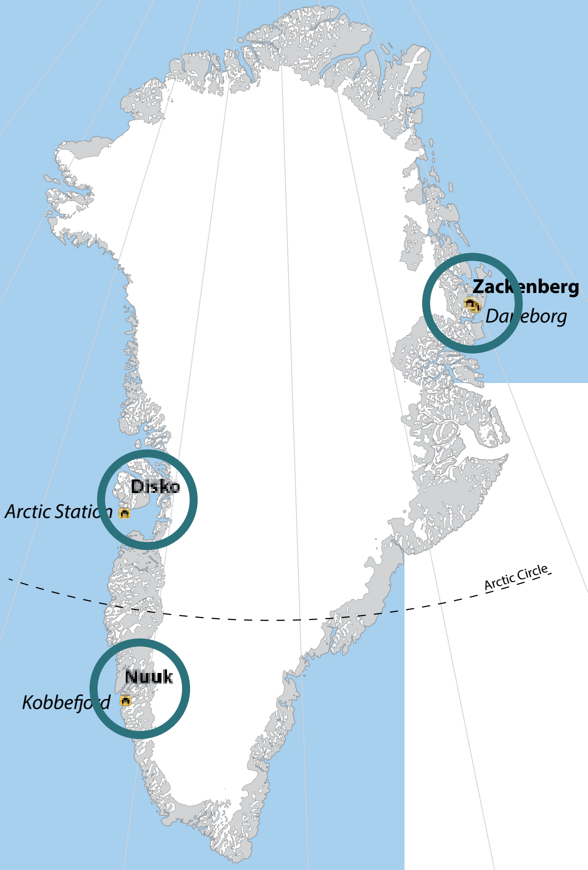


Figure 3. Muskox is the largest terrestrial herbivore in Greenland. The graph shows inter-annual variation in muskox population densities at Zackenberg 1996-2017.

(Photo: KatrineRaundrup).



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GEM

MARINEBASIS PROGRAMME

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
- pCO2
- DIC
- TA
- Nutrients
- Chlorophyll a Concentration
- Phaeopigments Concentration
- Pelagic Primary Production
- Particulate Sinking Flux
- Plankton
- Fish Larvae
- Benthic Vegetation
- Marine Mammals
- Sea Birds

(Photo: Thomas Juul-Pedersen).

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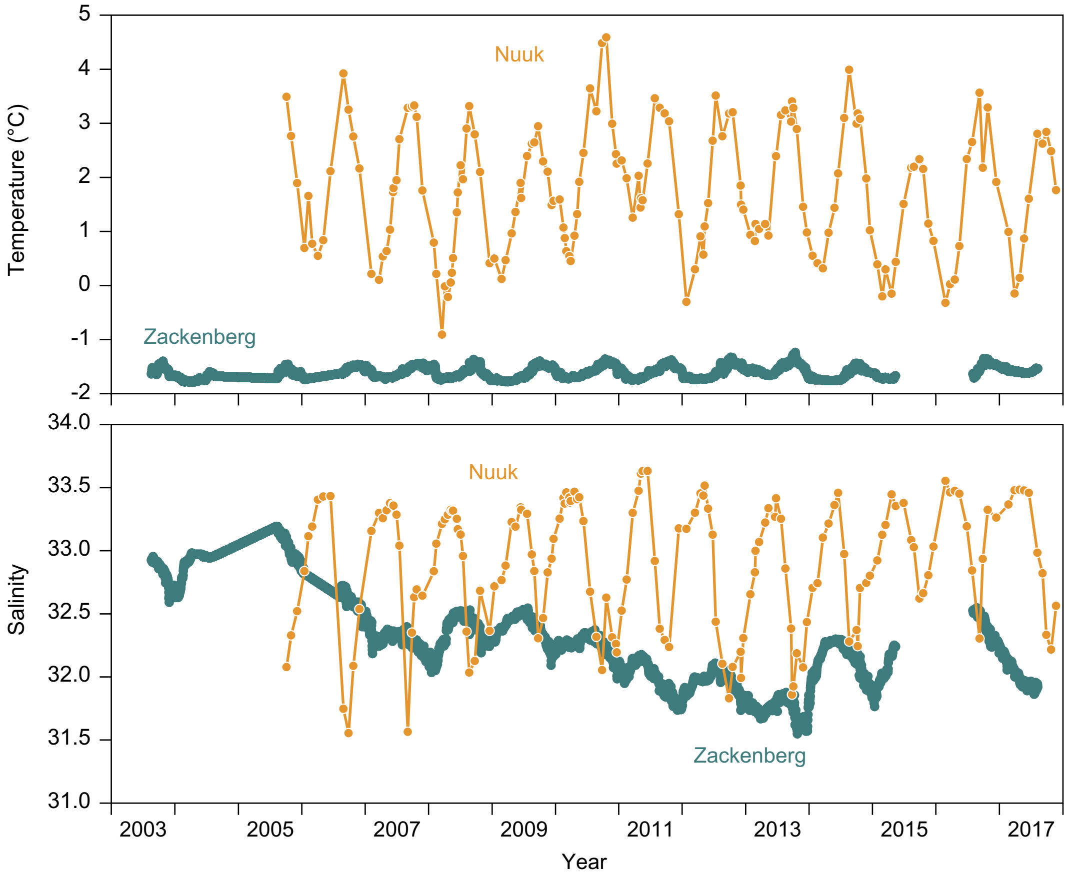


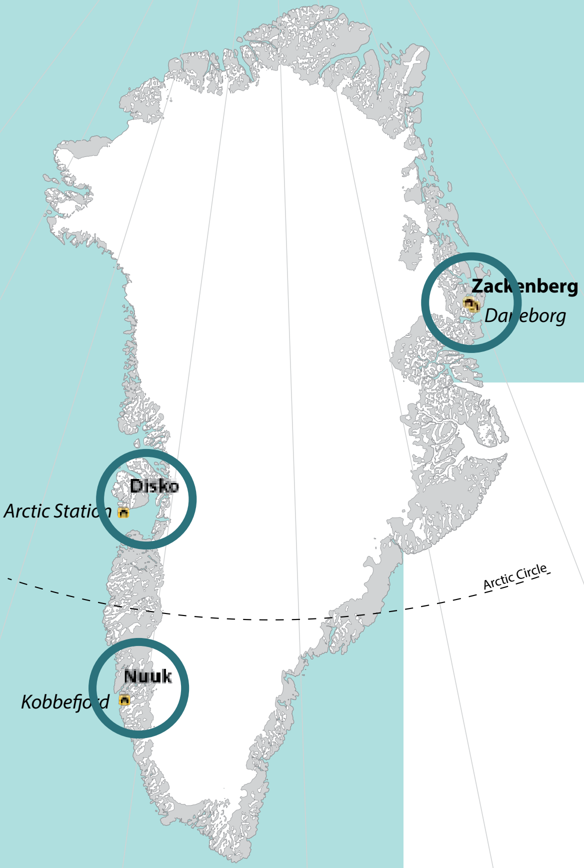
Water temperature and salinity at the permanent monitoring stations in Nuuk and Zackenberg. The time series from Nuuk represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring deployed at an average depth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

Automatic sea ice camera (Photo: Mie H. S. Winding).

(Photo: Mie H. S. Winding).

(Photo: Thomas Juul-Pedersen).

GEM
GLACIOBASIS PROGRAMME



The GEM GlacioBasis programme monitors the surface mass balance and the surface energy budget of glaciers at the Zackenberg, Kobbefjord/Nuuk and Disko to quantitatively understand the drivers of glacier change. 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/Nuuk (since 2012/2013) and Chamberlin glacier, a sector of Lyngmarksbræen ice cap on Disko Island (since 2015/2016). The GlacioBasis programme provides in situ calibration and validation data for the GEM Remote Sensing Initiative and work closely with other GEM Basis programmes, PROMICE (the Programme for the Monitoring of the Greenland Ice Sheet), DMI and ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Austria). The GEM GlacioBasis apply internationally standardized protocols and best practices from WMO GCW (World Meteorological Organization's Global Cryosphere Watch) and WGMS (World Glacier Monitoring Service). The programme is represented in the Steering Group of WMO GCW and function as support platform for external projects like EU-H2020 INTAROS.

(Photo: Daniel Binder).

(Photo: Michele Citterio).

Monitored parameters:

- Glacier surface mass balance
- Glacier weather and surface energy budget
- Glacier surface elevation
- Glacier surface velocity
- Snow depth and density

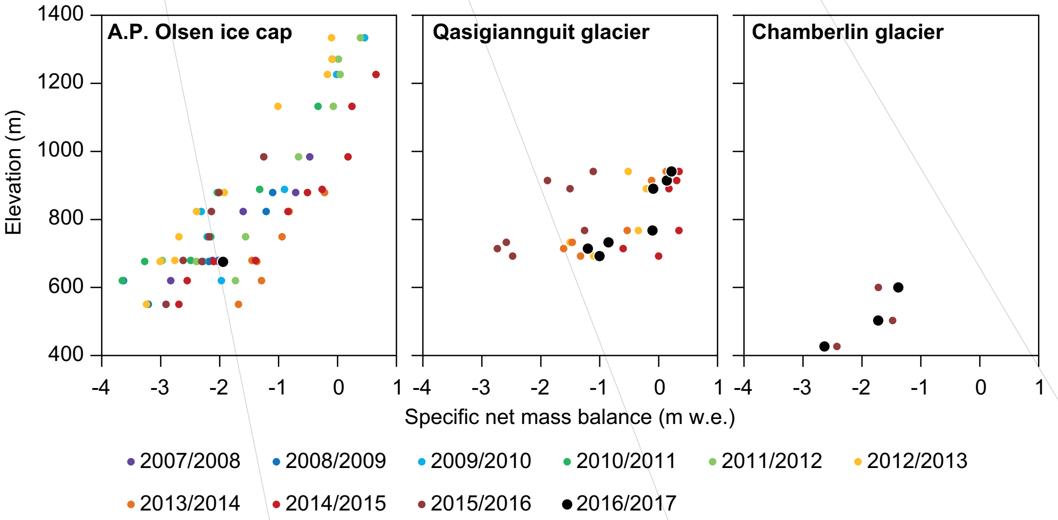


Figure 1. Specific surface net mass balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 3 stakes with more added in 2017 and planned for 2018).

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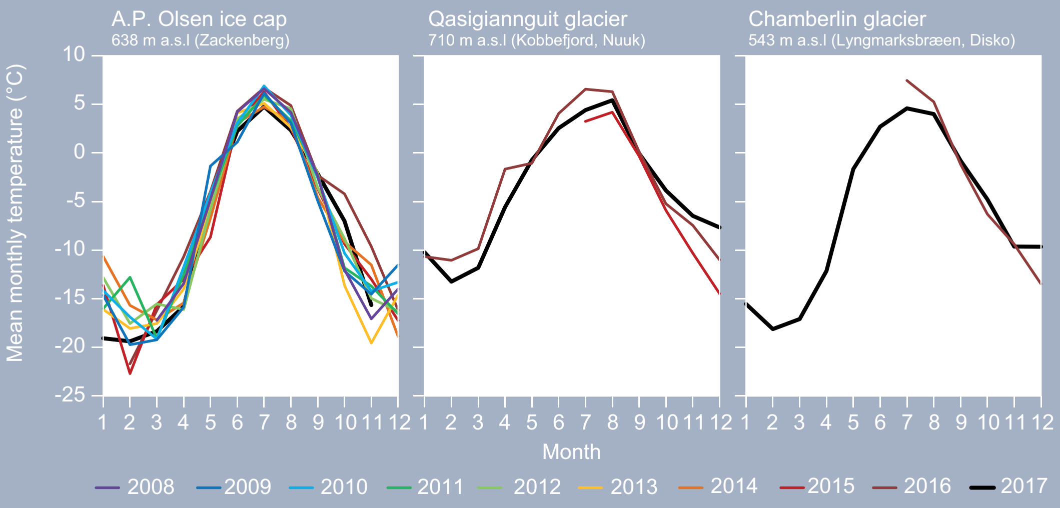


Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites.

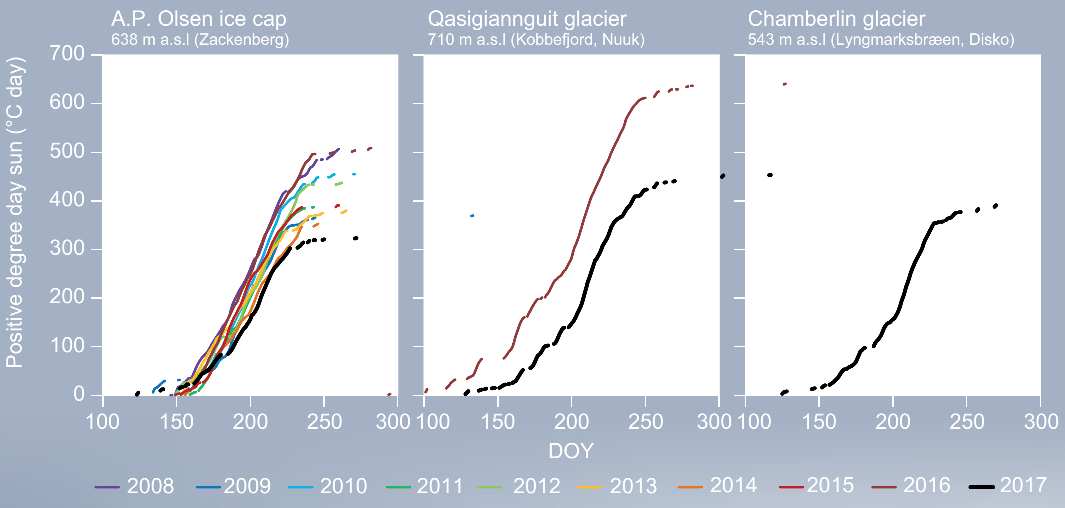
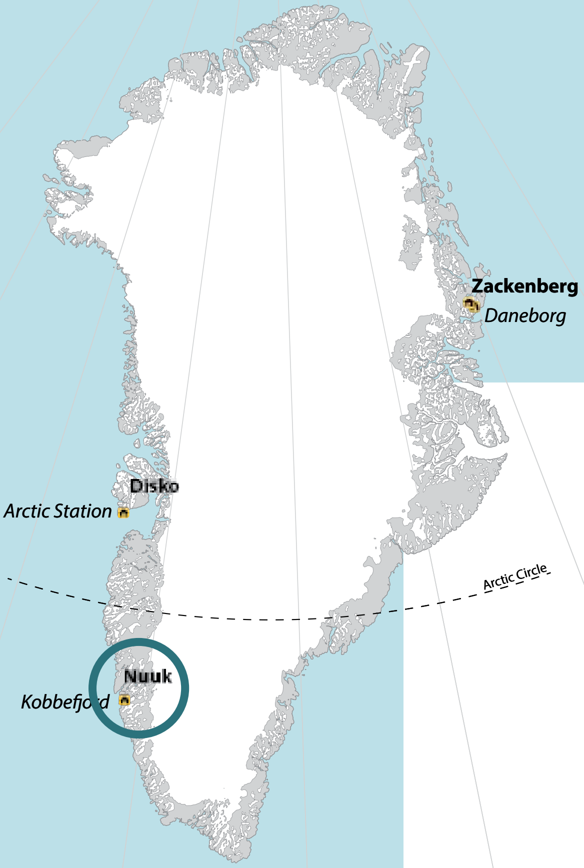


Figure 3. Positive degree day (PDD) sums from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites. Only seasons with complete data coverage are shown, gaps visible in the plots indicate sub-freezing daily mean temperatures.

(Photo: Sille Marie Myreng).



THREE-DIMENSIONAL OF BADESØ LAKE SUPPLEMENTING

Just above the NuukBasic field station is a large lake, Badesø. The lake is central to the hydrological system and drainage basin of the area. Freshwater from the terrain, glaciers, streams and lakes of three nearby valleys run into the lake and further towards the fjord Kangerluarsunnguaq, in Danish Kobbefjord.

The Badesø lake is a part of the freshwater monitoring programmes of both BioBasis, ClimateBasis and GeoBasis (Topp-Jørgensen *et al.*, 2017). In 2006, ClimateBasis established the hydrometric station H1, which measures the water discharge at the outlet of the lake. The GeoBasis programme monitors the annual ice cover of the Badesø lake and the connected lakes using cameras on nearby mountains. The BioBasis programme includes monitoring of nitrogen (N), phosphorus (P), Chlorophyll *a* (Chl *a*), zooplankton, phytoplankton and vegetation as well as measurements of Secchi depth in the lake.

The maximum depth of the lake was previously estimated to be 35 m (Lauridsen *et al.*, 2011), but a general bathymetric model of the lake did not exist prior to this mapping effort. The objective of the fieldwork on Badesø in 2017 was to survey the contours of the lake bottom remotely, from a series of echo sounding measurements, to produce a 3D bathymetric model and depth contours to support the scientific investigations and analyses of the lake and the hydrological system.

Bathymetri measuring team at Badesø lake. Inflatable boat mounted with a board and a pole for the echo sounder (Photo: Maia Olsen).

Story by:

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UNDERWATER TERRAIN MODEL

THE TERRESTRIAL TERRAIN MODEL AT GEM MAIN SITE NEAR NUUK

With a consumer-grade Garmin Echomap Chirp 42dv echo sounder mounted on an inflatable boat, the team surveyed the lake over three days; first during vegetation sampling along the shores, and later in a series of transects across the lake. In total, the survey team recorded 9139 depth measures and discovered a section of the lake deeper than 35 m, detected by 40 soundings in the interval of 35 and 38 m depth.

The data from the echo sounder was transferred to GIS software, and an assisting coastline of the lake was manually digitized using imagery from the Sentinel-2a optical satellite. The measurements and the coastline data were interpolated to a digital terrain model for the lake bottom using a Triangulated Irregular Network (TIN) algorithm. The resulting digital three-dimensional model has been utilized to produce a contour map of the lake and calculate the total volume - c. 9,385,000 m^3 and the water surface area - 0.74 km^2.

Further fieldwork is planned in 2018 on the Badesø lake for filling the spatial gaps in the model. In addition, the team plans to expand the survey to cover the nearby Qassi-sø and Langesø lakes using a small remote controlled boat with a mounted echo sounder.

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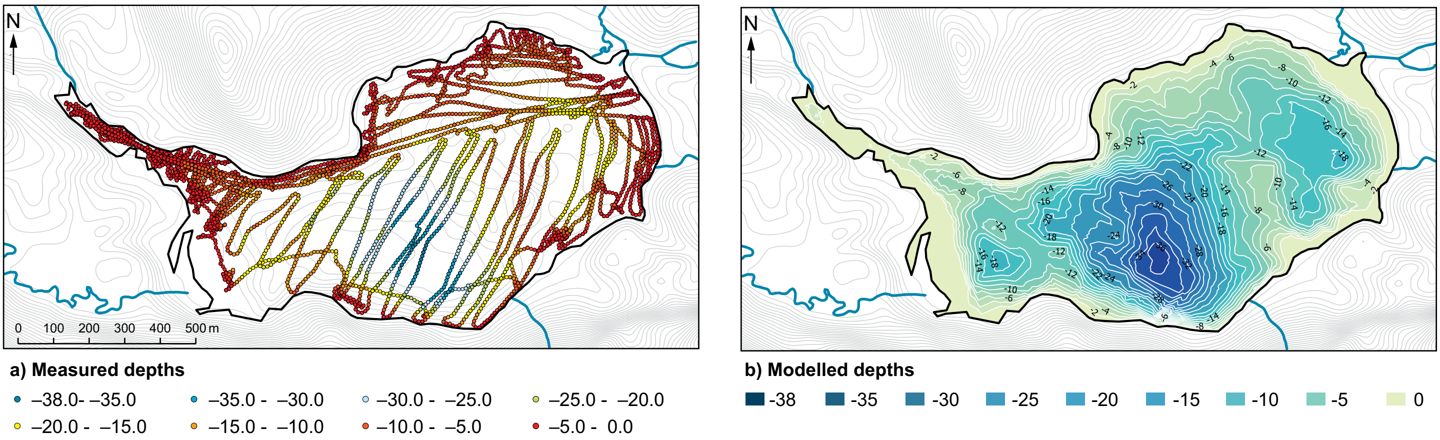
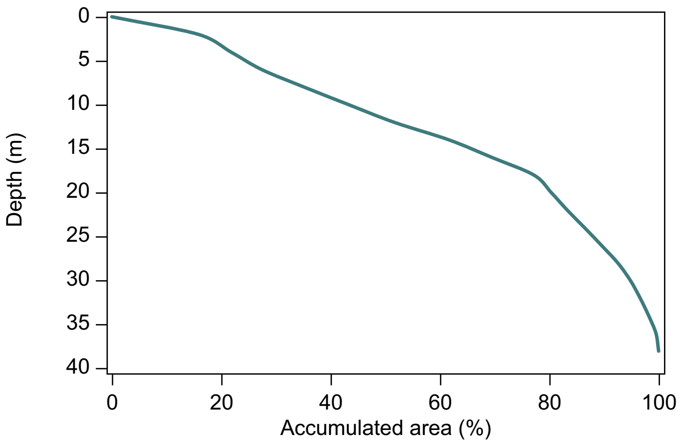


Figure 1. a) Map of the bathymetry model and contours derived from the measured depths. Units are meters below the lake surface. b) Map of Badesø lake displaying the depths recorded with the echo sounder from -0.1 m to -37.9 m.

Figure 2. Hypsograph of Badesø lake derived from the bathymetry model displaying accumulated area (%) at increasing depth (m). The graph shows changes in accumulation ratio at 2 and 18 m depths.



UNIQUE APPLICATION OF THE NEW GEM REMOTE

The recently initiated GEM Remote Sensing initiative has made it possible to develop satellite-based products specifically parameterized for Greenland. One of the products, calibrated land surface temperatures for the entire ice-free Greenland, is just released. Surprisingly, a trend analysis of the dataset performed within CENPERM shows that surface temperatures have been stable or showed a cooling trend during the last 15 years. However, a summer-warming has occurred in the south-western part of Greenland where most people live, and at a time of year where the impact of higher temperatures can affect the vegetation and permafrost degradation directly since there is no insulating snow.

Surface temperature measurements from satellites are a unique data source of temperatures which are independent of other measured datasets, unlike other spatially gridded climate datasets such as ERA Interim and CRU. The MODIS satellites offer land surface temperature data across the entire globe at an accuracy of less than 1 °C. In the Arctic, the data have a cold bias due to clouds contaminating the measurements. In GEM, we have produced a validated (against *in-situ* air temperature stations in the ice-free Greenland) version of the surface temperatures which have also been gap-filled in cloudy periods using algorithms based on the long-term observations of surface temperature and radiation at the GEM sites. Furthermore the surface temperatures can be superior to a few point-based air temperature measurements in the sense that they are spatially distributed and closer linked to biophysical processes in the land surface or vegetation canopy than the standard 2 m temperature.

We have analyzed the trends of monthly averages of the surface temperatures, and found that Greenland has experienced a slight cooling across the mid-latitudes during the last 15 years. However, the summer period (June, July, August) has experienced a warming, which could affect growing season processes such as snow melt, plant growth, and permafrost thaw. The warming has occurred in south-western Greenland where most people live today.

We show that the temperatures in the last decades are correlated with anomalies in the general surface air pressure over Greenland (Greenland Blocking Index), and this pattern show that we are likely to enter a new period of warming.

The satellite-based temperature dataset is currently being made available via the GEM database, by request of period and location – http://data.g-e-m.dk


(Photo: Andreas Westergård-Nielsen).

Story by:

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Data source:

GEM ClimateBasis – Meteorology and GEM GeoBasis – Meteorology

References

Westergaard-Nielsen, A. *et al.*, 2018. Contrasting temperature trends across the ice-free part of Greenland. Scientific reports, 8(1), 1586. doi:10.1038/s41598-018-19992-w

SENSING TEMPERATURE PRODUCT

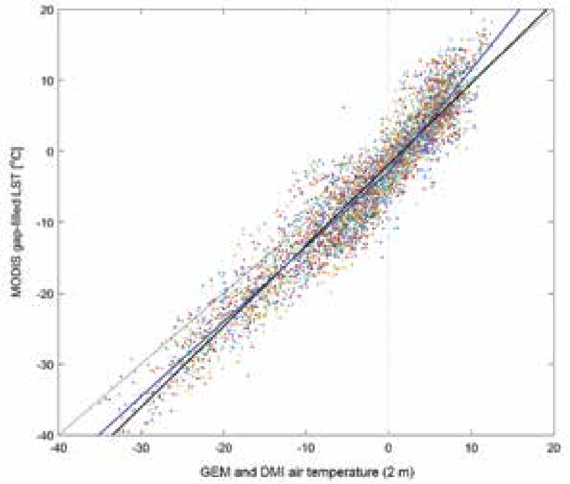


Figure 1. Validation of the cloud gap-filled skin temperature dataset (Land Surface Temperature, LST) against GEM and DMI air temperature stations.

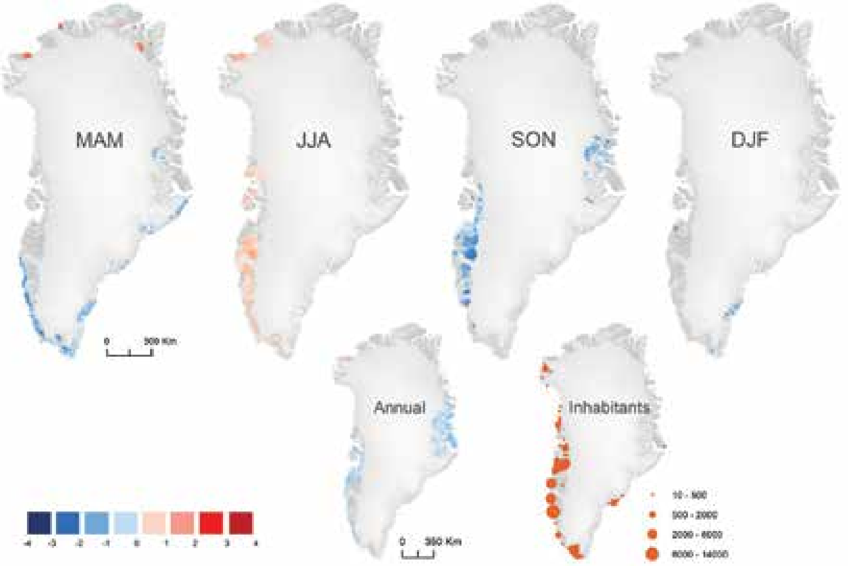


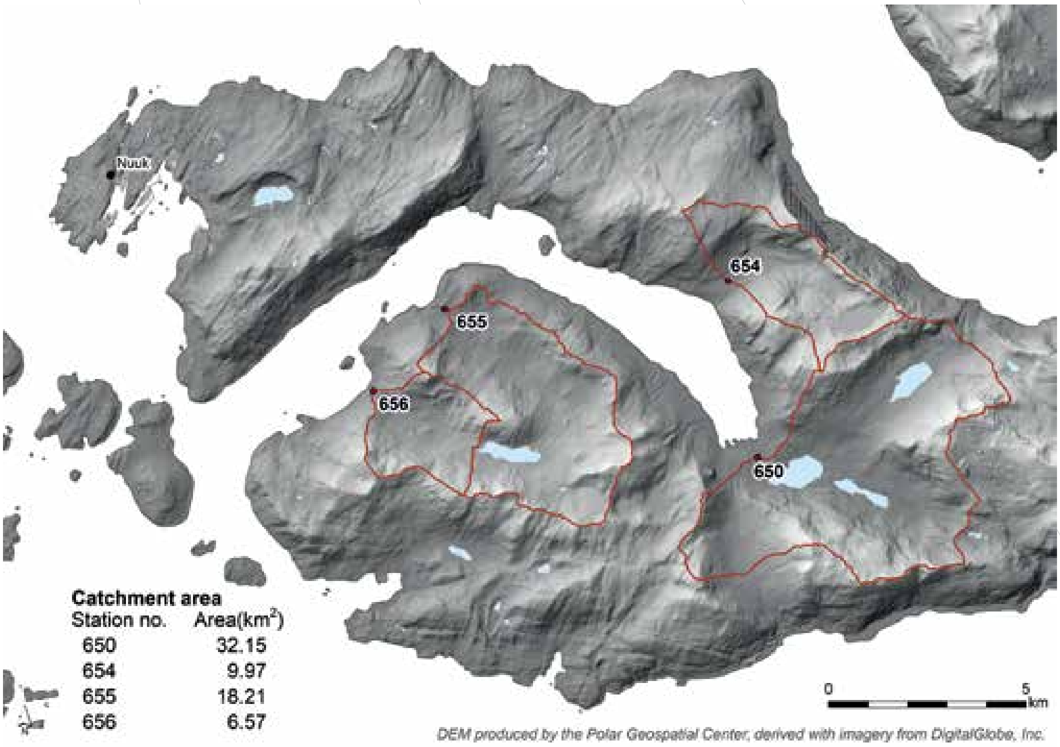
Figure 2. Trends in seasonal and annual gap-filled skin temperatures (MODIS) from 2001-2015, analyzed with seasonal Mann Kendall test and Sen slope. A cooling has occurred in spring and autumn in the mid- and southern latitudes, while there has been a summer warming in South-west Greenland. Letters indicates month names March (M), April (A), May (M), etc.

Figure 3. The active layer depths have increased during the last decades at the southern part of Disko where probing is conducted as part of the GEM program. This is likely caused by warmer summer temperatures despite a slight cooling on annual mean temperatures from 2001-2015 (Photo: Andreas Westergaard-Nielsen).

SMALL RIVERS
IN THE BIG PICTURE

The GEM ClimateBasis program provides time series of climate and hydrology in Greenland. The most prominent time series is the Zackenberg discharge curve, which has been monitored since 1996. However, small rivers and rivulets in Greenland are abundant and often overlooked. We now release three quality-controlled time series of rivers in Kobbefjord, Nuuk, not more than 15 km apart, and show some reoccurring patterns descriptive of the local climate.

There is very little information available on discharge-regimes in Greenland. The few longer-term data series that exist are generally focused on discharge from the ice sheet. However, there are also many catchments in non- or little glaciated environments. Many settlements in Greenland get their water from such sources away from the ice sheet. There is indeed a societal need to better understand those rivers' responses to climate change and Kobbefjord serves as an ideal test site for this (Fig. 1).



DEM produced by the Polar Geospatial Center, derived with imagery from DigitalGlobe, Inc.

Figure 1. The sub-catchments of Kobbefjord presented in this contribution.

Story by:

Jakob Abermann[1,*], Sille Marie Myreng[1], Jordi Cristóbal Rosselló[1,2], Dorthe Petersen[1] & Martin Olsen[1]

[1]Asiaq – Greenland Survey, Greenland

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Data source:

GEM ClimateBasis – Hydrology

In order to get reliable information on discharge, a relation between water level and discharge measurements has to be established for individual streams. Once that is done, autonomous water level measurements can be used in order to calculate the discharge indirectly. This allows for the establishment of base-line data serving many scientific questions such as the analysis of the current hydrological cycle and its influence on downstream ecosystems or the development of future hydrological scenarios.

Currently, there are discharge time series for four catchments in the Kobbefjord area, based on 123 manual discharge measurements over nine years. Results show how local variation in climate affects the hydrological cycle of the four catchments (Fig. 2). Although the shapes of the curves resemble each other (the peaks seem to almost occur simultaneously), the sites show interesting differences. For instance, catchment area 650 seems to respond later to major precipitation events and the lakes hamper the magnitude of the signal.

Catchment specific discharge (discharge per unit area) allows for direct comparison of catchments with different sizes. There is generally higher specific discharge in catchments 656 and 655, which can be explained by the local precipitation pattern, where heavy rain often arrives from the Southwest and, thus, more orographically induced precipitation occurs, while 650 and 654 are more shaded.

A specifically designed setup also allows for a view on discharge during winter, which makes the presented time series rather unique. These hydrological time series from the GEM programme are the only greenlandic contribution to the Global Runoff Data Centre under the World Meteorological Organisation (WMO).

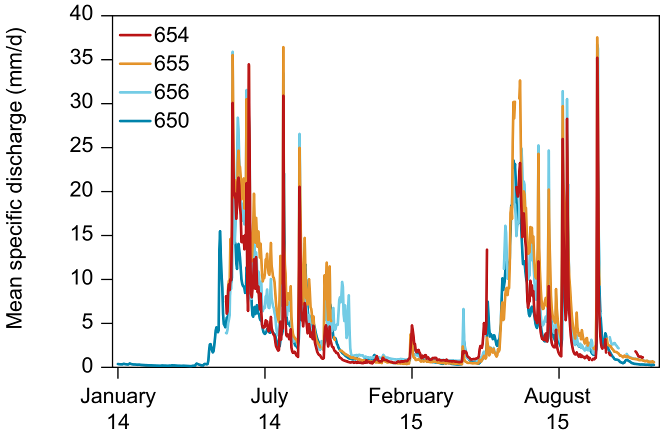

Figure 2. Specific daily discharge (per unit area) from stations 650, 654, 655 and 656 for two selected years (2014-2015). Differences in the shape of the curves reflect local variations in precipitation, glacier cover and snow depth.

Discharge measurements in 656 (Photo: Lucas Davaze).

The water level station at 655 (Photo: Sille Marie Myreng).

Winter conditions at 656 (Photo: Sille Marie Myreng).

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CHASING CLOUDS
OR HOW CLOUD DYNAMICS

Surface air temperatures in the Arctic have shown a significant increase especially in the past few decades. Temperature changes are strongly linked to changes in the radiative fluxes caused by changes in clouds, water vapor and greenhouse gas concentrations. Therefore, clouds play a key role in the Arctic by modulating the radiation balance.

Clouds are essential to understand the net surface energy balance influencing surface warming as well as ice and snow melt, as the difference between the radiation budget components for average cloud conditions and cloud-free conditions (also known as cloud radiative forcing) is positive over most of the year (Vihma *et al.,* 2016). While clouds reduce the shortwave incoming radiation to the surface through their high albedo, clouds also augment the downward longwave flux to the surface increasing surface warming (Serreze and Barry, 2011).

The role of clouds to enhance snow and glacier melt is still poorly known. While some authors claim clouds enhance meltwater runoff (Van Tricht *et al.,* 2016) others claim that decreasing cloud cover drives the recent mass loss on the Greenland ice sheet (Hofer *et al.,* 2017). Despite their crucial importance for understanding Arctic climate change, present numerical models struggle to represent Arctic surface energy balance (Tjernström *et al.,* 2008), which is partly due to poor representation of cloud properties (de Boer *et al.,* 2014). Thus, improving the current knowledge of cloud type and cover is paramount to understand their influence on Arctic systems.

Disko Bay, a highly relevant region for the Greenlandic society, has been identified as a hotspot of recent climate change in Greenland (Abermann *et al.,* 2017) showing changes in surface temperature trends (Westergaard-Nielsen *et al.,* 2018). More than 20% of the Greenlandic population that lives in the Disko Bay area relies on fishing and hunting for income (Goldhar and Ford, 2010). Changes in surface warming patterns due to changes in cloud dynamics may influence species composition and abundance, as well as sea ice and snow melt thus affecting Disko Bay's population economy and traditional way of life.

To improve the current knowledge on cloud dynamics Asiaq – Greenland Survey in collaboration CENPERM at University of Copenhagen and supported by the GEM ClimateBasis program installed a state-of-the-art profiler and a sky camera in 2016 (Fig. 1) at Qeqertarsuaq (Disko Island). While the sky camera data provides crucial data to derive cloud type and cover (Fig. 2), the atmospheric profiler provides vertical humidity and temperature data needed to characterize clouds and their radiation properties (Fig. 1). In addition, a high precision pyrgeometer was installed to understand cloud dynamics and its effects on the surface warming.

Furthermore, these datasets also support GEM Remote Sensing initiatives by providing essential ground truth data for remotely assessing cloud cover. Preliminary data (Figure 1 and 2) also show that high-resolution temperature profiles are useful to quantify the duration and frequency of inversion layers, characterized by warmer air masses with increasing altitude which has important implication for upscaling soil-plant interactions in mountainous areas of Greenland.

Story by:

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Data source:

GEM ClimateBasis - Profiler and sky camera

GEM ClimateBasis - Meteorology

GEM RemoteBasis - Clouds

MIGHT INFLUENCE THE CLIMATE IN THE ARCTIC

(Photo:Jakob Abermann).

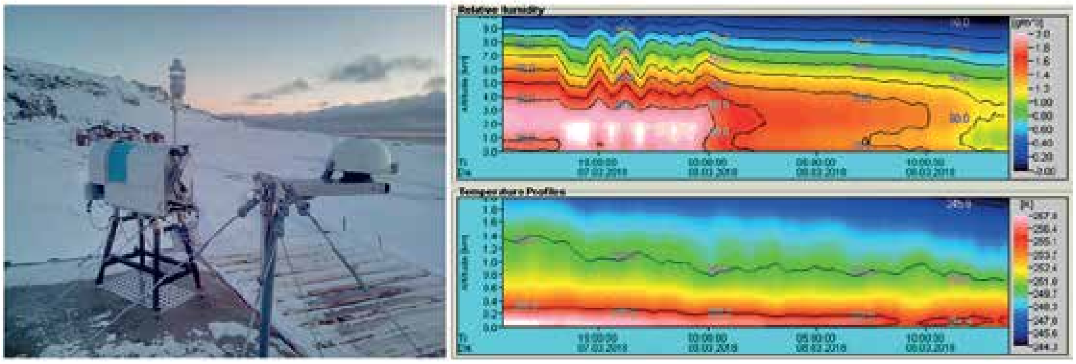

Figure 1. Left panel: RPG-HATPRO atmospheric profiler (left) and hemispherical sky camera (right) instruments at Arctic Station (photo taken by Jordi Cristóbal Rosselló). Right panel: Hourly humidity and temperature vs. altitude data acquired by the RPG-HATPRO atmospheric profiler for 07-03-2018.

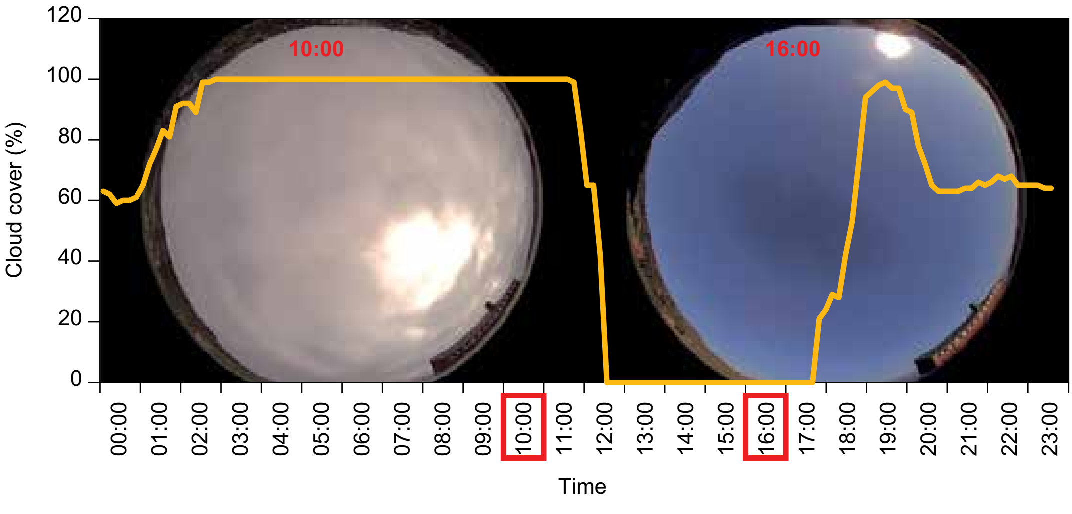

Figure 2. Hourly fractional cloud cover (in %) for 10/08/2016 at Disko using hemispherical sky camera imagery (Wacker et al., (2015)). Image acquisition times of the background image are marked in red.

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CHALLENGING
THE SOUTHERN BOUNDARY

Rock glaciers are permafrost features, abundant in mountainous environments, and are extremely interesting as indicators of past and present climate. Evidence of an active rock glacier was observed near Nuuk, around 250 km further south than the previously suggested southern limit for active rock glaciers in western Greenland. While passive rock glaciers are known at this latitude in West Greenland, this study aimed to determine if there are indeed active rock glaciers this far south.

(Photos: Kirsty Langley).

Rock glaciers are characterized by a 'steadily creeping perennially frozen and ice-rich debris on non-glacierised mountain slopes' (Fig. 1.) They hold information on past and present climate as they i) maintain permafrost in a given climate, and ii) may contain much older ice than glacier ice (Krainer *et al.,* 2015). Their runoff may contribute to local water supply in inhabited areas and thereby impact water chemistry significantly (Thies *et al.,* 2007). It is therefore crucial to know about rock glaciers' occurrence and their dynamic regime.

Permafrost dynamics are key for understanding instabilities. Significant fluctuations in rock glacier movement have been shown, and are partly triggered by climate, partly by local conditions (Delaloye, Lambiel and Gärtner-roer, 2010; Nickus *et al.,* 2015). An increased dynamic variability is expected under changing climatic conditions (Delaloye *et al.,* 2013). While the area around Nuuk is acknowledged to contain sporadic permafrost (Humlum, 1982; Christiansen & Humlum, 1993), there are, to our knowledge, no studies investigating rock glaciers.

We have investigated a conspicuous rock glacier on Bjørneø. It has a clearly defined snout, distinct foliations in the central region, and notably, a lack of pioneer vegetation, all suggesting that it may be active.

A number of field methods were employed to determine the thermal regime, dynamic activity and climatic conditions. The thermal regime was obtained by measuring the 'Bottom Temperature of Snow' (BTS) during the winter (Haeberli and Patzelt, 1982). The dynamic activity was assessed based on orthophoto and derived Digital Elevation Model from repeated drone flights with a 1 year interval. The climatic conditions were recorded continually for the study period with a simple and robust temperature/air pressure sensor, installed near the snout of the potential rock glacier in order to give a first-order idea of temperature gradients between Nuuk and the rock glacier.

The BTS measurements show a clear drop in temperatures, on the order of 10 °C, over the rock glacier compared to the surrounding areas suggesting an active permafrost landform with a well demarcated thermal regime. It is noteworthy that the lowest temperatures are found in areas with the highest concentration of surface undulations, while the flatter front lobe is relatively warmer. This may support the morphological indication that a younger rock glacier is flowing over an older one. We were unable to detect any dynamic activity, but suggest that a longer time interval may give positive results.

The project is funded by the Greenland Research Council and was supported by GEM ClimateBasis Nuuk.

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Data source:

GEM ClimateBasis Kobbefjord

OF ACTIVE ROCK GLACIERS IN WEST GREENLAND

Figure 1. The rock glacier on Bjørneø, and the island's location in the Godthåbsfjord (Photo: Dorthe Petersen).

Figure 2. 'Bottom Temperature of Snow' data collection (left) and temperature/air pressure sensor near the snout of the rock glacier (Photos: Jakob Abermann).

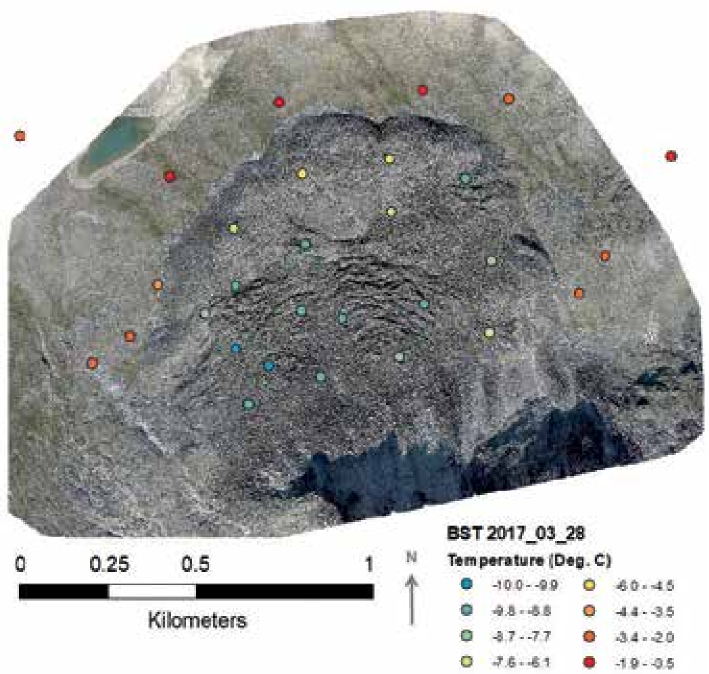

Figure 3. 'Bottom Temperature of Snow' results over and around the rock glacier.

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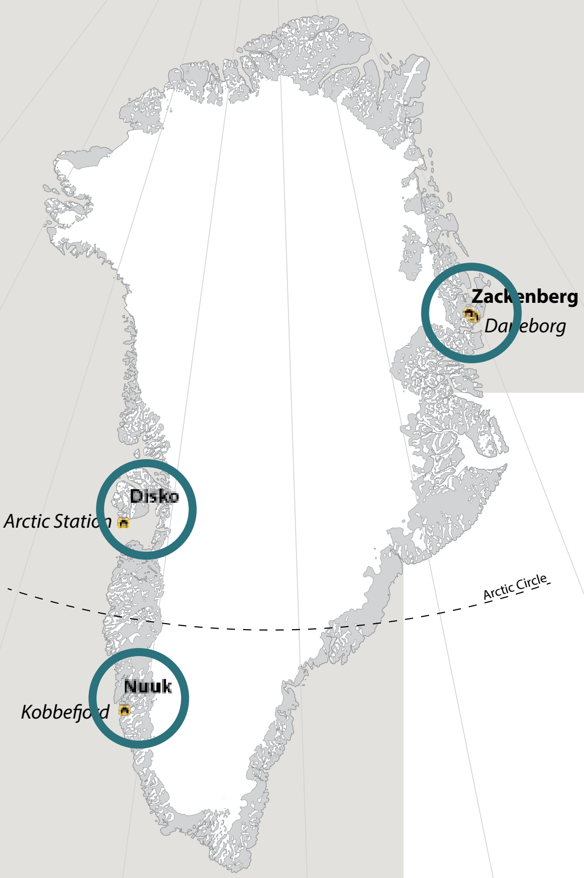

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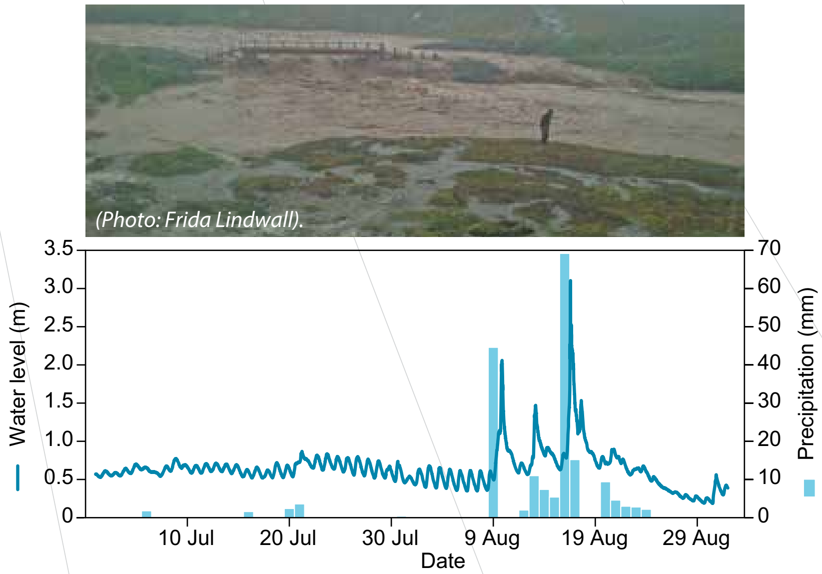
EXTREME RAIN

– WHAT ARE THE CONSEQUENCES

Essentially all climate models predict a strong increase in Arctic precipitation during the 21st century. An intensified hydrological cycle will have a number of implications for the Arctic cryosphere, affecting both terrestrial and marine ecosystem functioning, and the Greenlandic society. Integrated long-term observational programmes are crucial for documenting and understanding environmental effects of increasing precipitation, both in terms of means and extremes. In this report card, we demonstrate effects of extreme rain events across the main GEM sites.

Arctic precipitation will increase in the future, with an associated increase in precipitation extremes (Toreti *et al* 2013). Recent modelling efforts indicate that the Arctic will receive the majority of its precipitation as rain, rather than snow, towards the end of this century (Bintanja and Andry 2017). This will have important impacts on glacier mass balance, river discharge, geomorphology, vegetation, ecosystem-atmosphere interactions and ocean circulation. Extreme rain events and associated flooding/erosion may also have implications for the Greenlandic society in terms of landscape changes, damage to local infrastructure (e.g. roads, houses and supply systems) and ice crust formation on snow affecting ungulate foraging. During recent years, we have observed extreme rain events in Disko (August 2014), Zackenberg (August 2015) and Nuuk-Kobbefjord (April 2016).

In Disko, extreme rainfall in August 2014 (monthly total 177 mm) caused flooding in the area and erosion along the riverbanks of Røde Elv (Fig. 1). During the day with peak rainfall (70 mm on 16 August), the river water level rose by more than two meters, with associated high amounts of sediments being transported through the system to the ocean. Furthermore, the water supply for the town Qeqertarsuaq was disabled for several days due to mudflows damaging water pipelines.



(Photo: Frida Lindwall).

Figure 1. Flooding of Røde Elv (Disko Island) in August 2014 and associated precipitation and river water level measurements.

Story by:

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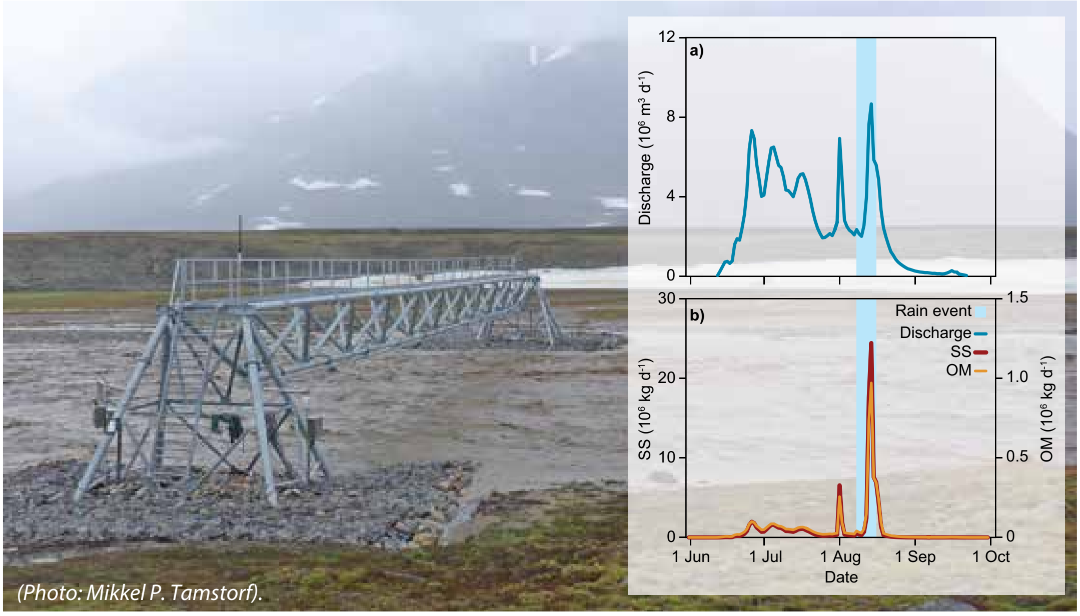
Data source:

GEM GeoBasis and ClimateBasis monitoring components in Zackenberg, Kobbefjord and Disko

EVENT

FOR ARCTIC ECOSYSTEMS?



(Photo: Mikkel P. Tamstorf).

Figure 2. Flooding of river Zackenbergelven in August 2015 and daily time series of river discharge and transport of suspended sediment (SS) and organic matter (OM).

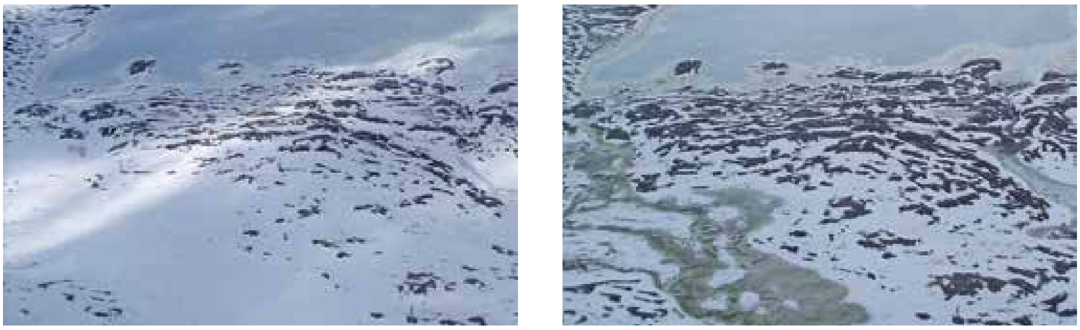


Figure 3. The rapid hydrological response of the April 2016 rain event in Kobbefjord caused the river to break up quickly and peak in very high discharge (Photos: GEM GeoBasis Nuuk).

A similar extreme summer rain event occurred in Zackenberg in August 2015. Record rain amounts were recorded 8-16 August (totaling 91 mm). Although the impact on Zackenbergelven river discharge was moderate (contributing 8 % to annual total), the effect on river transport of matter was large. The rain event increased the annual transport of suspended sediment and organic matter by ca. 58 and 51 %, respectively (Fig. 2). In addition, the prolonged period with cloudy conditions limited plant CO_2 uptake and reduced the annual CO_2 sink in a wetland ecosystem by approximately 60-70 % (data not shown).

Rainfall during winter can also have major consequences for Arctic ecosystems. Rain-on-snow events can result in permafrost warming and frost damage to plants due to loss of insulating properties of snow, as well as causing ice layers limiting foraging areas for Arctic mammals (Putkonen and Roe 2003). Moreover, heavy rain events during winter, as observed in Kobbefjord in April 2016, can lead to slush flow avalanches resulting in surface erosion and vegetation damage, as well as constituting a potential hazard for infrastructure. Winter rain events result in rapid hydrological response as the water cannot infiltrate the frozen ground and quickly reaches streams and rivers. Furthermore, it may also cause melting of snow which may add to the flooding (Fig. 3). This caused the April 2016 event to be the second highest river discharge ever measured (maximum: 23 m^3 s^{-1}), caused by the heavy but not record breaking precipitation (25 mm between 9 and 11 April 2016).

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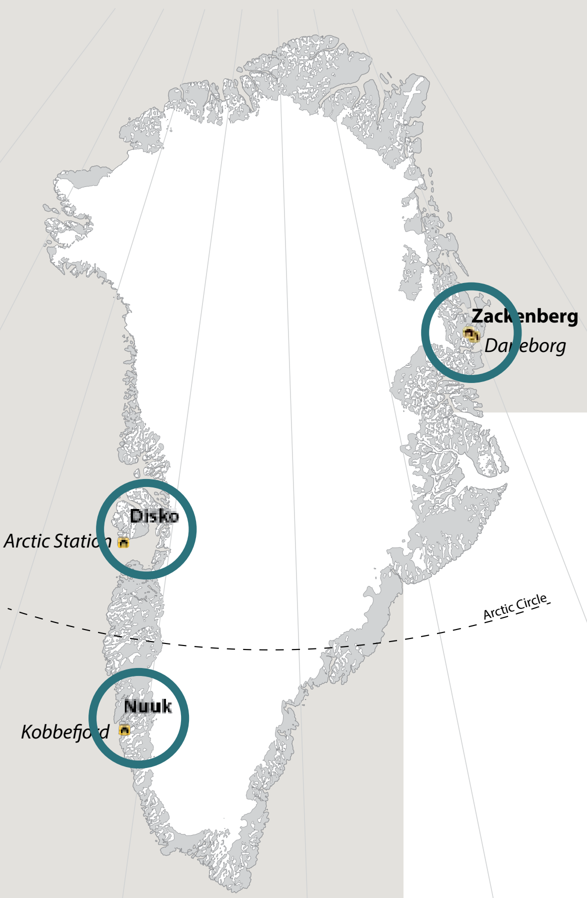

USING DATA-MODEL APPROACHES TO BETTER

The terrestrial CO_2 exchange in Arctic tundra plays an important role in the global carbon (C) cycle and is particularly sensitive to the ongoing warming experienced in recent years. To improve our understanding of the atmosphere-biosphere interplay, GEM monitors ecosystem CO_2 exchange and links it to biogeochemical processes. Combining ecosystem models and GEM's field observations allows us to study the underlying processes of Arctic ecosystem CO_2 exchange. This is also crucial when it comes to making predictions about the future state of the C cycle.

The eddy covariance (EC) measurements of net ecosystem exchange (NEE) of CO_2 – Carbon budget accounting for both CO_2 uptake (photosynthesis) and CO_2 release (respiration) – are conducted for various ecosystems in Zackenberg (Lund *et al.,* 2012), Nuuk-Kobbefjord (López-Blanco *et al.,* 2017) and Disko (Zhang *et al.,* in prep). The GEM CO_2 exchange monitoring aims to estimate and predict greenhouse gas fluxes, including if the ecosystem is a sink or a source of carbon, and how much it contributes to local and global climate change regimes. The GEM stations are included in the European research infrastructure ICOS (Integrated Carbon Observations System) as well as the global data network FLUXNET.

While the EC technique is a widely used flux monitoring approach, its temporal and spatial coverage is restricted in the Arctic due to remoteness and harsh conditions. Furthermore, knowing only the NEE doesn't explain the underlying ecosystem processes resulting in carbon exchange between the atmosphere and terrestrial environment. Combining NEE measurements with mathematical models describing ecological processes gives us a better understanding of ecosystem carbon dynamics, to extrapolate plot measurements in space and time, and to assess the impacts of climate change on the CO_2 budget.

The Soil-Plant-Atmosphere (SPA) model and the CoupModel are two examples of process-based models that simulate the coupled transfer of heat and mass (i.e. carbon, water, and nitrogen) in soil-plant-atmosphere systems. Both models consist of several modules that represent the processes essential to ecosystem hydrology, plant physiology, vegetation dynamics, and soil biogeochemistry. These two models use extensive datasets available in GEM to calibrate and validate CO_2 fluxes, improving the overall performance in describing the ecosystem C dynamics.

For example, SPA uses time lapse photography to determine growing season plant phenology and snow cover data to regulate soil temperatures below the snow pack, not only increasing the

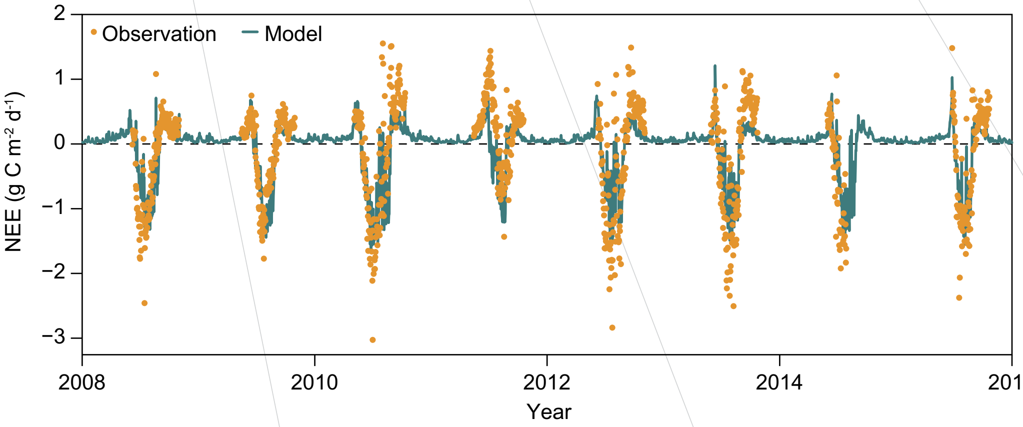

Figure 1. Time-series of observed and modelled NEE calculated by the SPA model in the Kobbefjord – fen site. Negative values indicate ecosystem C uptake, and positive values indicate ecosystem C release.

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Data source:

GEM GeoBasis – CO_2 monitoring (NEE)

GEM GeoBasis – Automatic Photo Monitoring (% of greenness and snow coverage)

GEM GeoBasis – Meteorology (Soil temperature)

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

UNDERSTAND CO$_2$ EXCHANGE IN ARCTIC ECOSYSTEMS

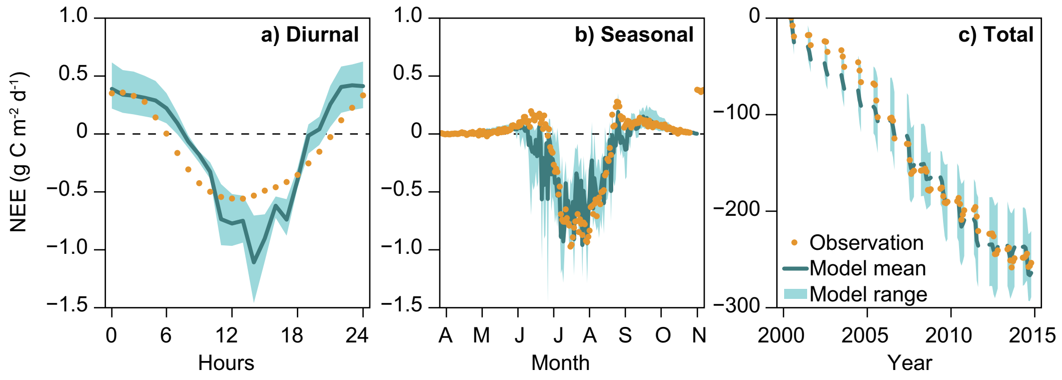

Figure 2. Diurnal (a), seasonal (b) and total cumulative (c) patterns of NEE for 2000-2014 in the Zackenberg heath site. The line and uncertainty band denote the estimates of the CoupModel. The uncertainty band stands for one standard deviation of the accepted model runs, which were quantified using the general likelihood uncertainty evaluation (GLUE) approach.

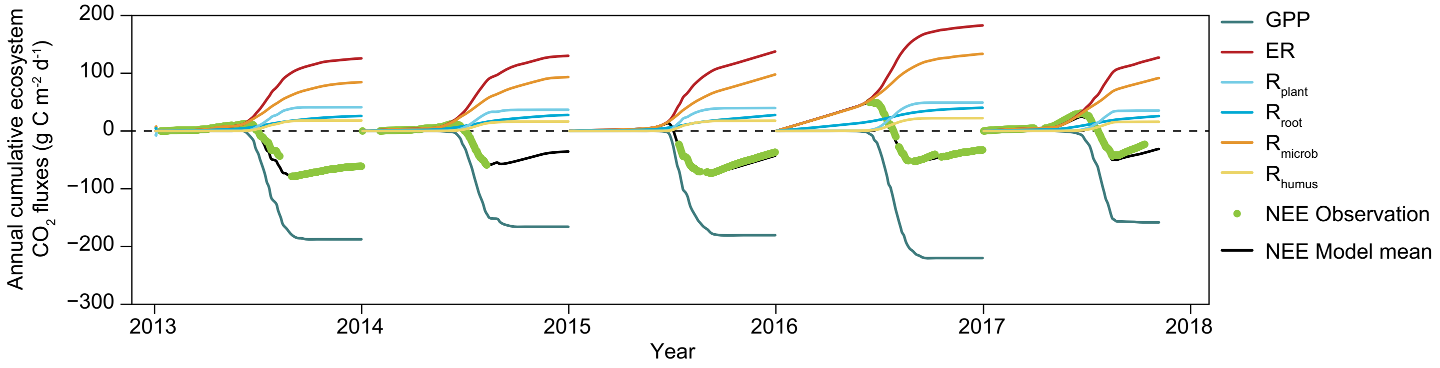

Figure 3. Annually-integrated major ecosystem CO$_2$ fluxes simulated by CoupModel for the Disko heath site. NEE: net ecosystem CO$_2$ exchange, GPP: gross primary productivity, ER: ecosystem respiration, R_{microb}: Microbial respiration, R_{plant}: total plant respiration, R_{root}: root respiration, R_{humus}: humus respiration.

degree of agreement between model and observations, but also the confidence to predict wintertime periods (Fig. 1). The CoupModel has been applied to capture different temporal patterns (i.e. diurnal, seasonal and long-term) of NEE by using a general likelihood uncertainty evaluation (GLUE) framework (Fig. 2), and it quantified different ecosystem compartment CO$_2$ fluxes (Figure 3). The GLUE approach also helps to identify the processes and parameters that critically determine the terrestrial ecosystem C cycle response to climatic variabilities.

The data-model approach generates novel outputs, allowing us to explore mechanisms and controls that otherwise would not have been possible to address individually. The snow season and the delayed effects of wintertime variables such as the snow cover are usually not taken into account, despite their importance for the C budget. The data-model approach also identifies the needs for additional measurements. For instance, more wintertime flux measurements are needed to produce a comprehensive full picture of the terrestrial C cycling; and more measurements on plant phenology, plant photosynthetic parameters, plant and soil structure and C and N stocks are suggested to improve our process understanding of C cycling in changing environments.

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CLIMATE CHANGE
– NEW HIGH SCHOOL

20 years of monitoring data from the GEM programme has been synthesized into a new set of high school teaching material. The aim is to increase the awareness of Arctic climate change through the unique knowledge provided by the integrated ecosystem monitoring. Selected data series from GEM are used to illustrate Arctic climate change and feedback mechanisms.

Scientists across many disciplines agree that climate change is amplified in the Arctic. But how does this amplification manifest itself? When temperatures increase, what will happen to terrestrial snow cover? What implications will changes in snow cover and temperature have in relation to permafrost degradation, greenhouse gas fluxes and energy balance? Which feedback mechanisms are particularly important in relation to local and global climate change?

These questions may be very abstract and difficult to grasp for non-scientists. In an effort to make Arctic climate change and its implications more tangible, we have developed a set of teaching material targeting high school students. The material equip students with tools to critically assess information about climate change from various sources and put single studies into a broader context. By bringing in real world data to demonstrate climate change mechanisms with both local and global implications, we combine scientific methods and societal relevance, which we hope will also invoke interest for environmental science in general and inspire young people to choose a scientific career.

(Photo: Kirstine Skov).

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Data source:

GEM GeoBasis and ClimateBasis monitoring components from Zackenberg

IN THE ARCTIC
TEACHING MATERIAL

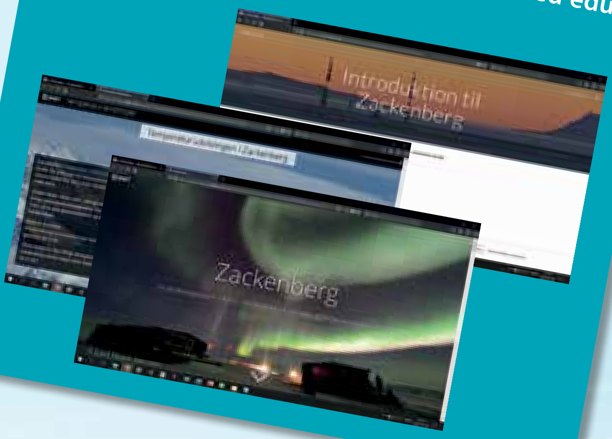
The teaching material has been developed in close collaboration between the GeoBasis programme and Egedal Gymnasium (high school) to ensure easy use for teachers and that it adheres to the Danish curriculum. Through text, data and exercises the students are guided through recent changes in the High Arctic environment at Zackenberg in Northeast Greenland, using the unique time series from ClimateBasis and GeoBasis programmes. The material consists of a short introduction to the Arctic and the Zackenberg area, followed by six themes, each with sufficient material for approximately one teaching module. The themes include:

- Temperature
- Snow
- Permafrost
- Carbon dioxide fluxes (CO_2)
- Radiation balance
- Energy balance

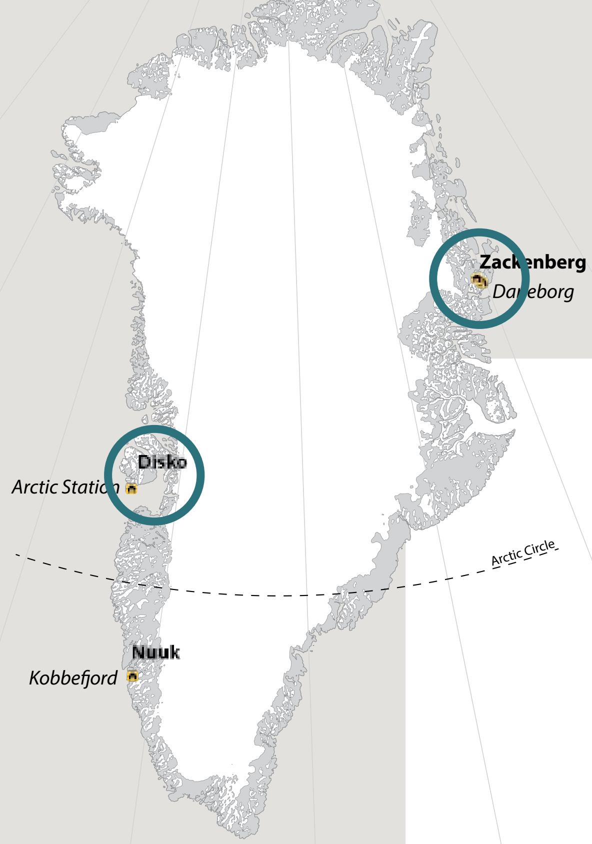
Each theme is set up as an individual 'Story Map' in ArcGis Online (made freely available for Danish high schools through the SkoleGis programme, supported by GeoInfo A/S). In the story maps, the text and exercises unfold through cascades with background figures and photos. This new lay out is used with the aim of making the material more comprehensible, as the students scroll their way through many years of data.

The material is made available for all high schools through *Danmarks Undervisningsportal*: https://www.emu.dk/modul/zackenberg-og-klimaet. Links to each story map can be accessed here: https://sites.google.com/view/zackenberg/startside. The material is in Danish and has been developed with financial support from the Ministry of Education.

Example of a bottom-up initiative using GEM data for educational purposes. GEM will in this strategy period (2017-2021) facilitate the use of additional GEM data for other climate change related educational initiatives.



(Photo: Kirstine Skov).



SPATIAL DATA ON
ALLOWS FOR QUANTIFICATION OF

The recent advances in both the usability and sensors in drone technology allow for an increasing integration of such data in the GEM programme. The ability to combine spatially distributed snapshots in time from drones with existing long time series of timelapse images from fixed cameras constitutes a highly flexible source of spatial monitoring data. The general character of this data can support research activities across the GEM sub-programmes, and allows for capturing the timing and magnitude of e.g. extreme events. Here we demonstrate the use of drones to quantify riverbed erosion resulting from an extreme glacial lake outburst and rain events.

Drones are increasingly becoming integrated parts of research projects and monitoring in biogeosciences. The strengths are numerous with options to obtain both systematic surveys as well as additional pin-pointed surveys in the case of local extreme events. Long-term monitoring of ecosystem variables allows for detecting and describing sudden events and ecological surprises (Lindenmayer *et al*., 2010), while the use of drones can support the quantification and spatial dynamics of such events. As a consequence of climate change, the frequency and impact of extreme events is expected to increase in the future (Post *et al*., 2009).

Precipitation anomalies were recorded on Disko Island, West Greenland, on the 9th and 16th of August, 2014, when approx. 50 and 80 mm of rain, respectively, fell over the course of a week. The long-term average summer precipitation is 135 mm (June through August). These events resulted in substantial river runoff and erosion of the riverbed at Røde Elv. A drone survey conducted shortly after revealed several landslides, of which the single largest could be estimated from a drone-based DSM (Digital Surface Model) to approx. 1700 m^3 or 2210 tons of moraine soil flushed into the delta (given a standard soil bulk density of 1.3 g/cm^3).

A substantial glacial lake outburst flood occurred in the Zackenberg River on the 6th of August, and a significant collapse of the concave river banks followed between the 28-29 of August 2017. The collapse was most likely due to the outburst event, and the eroded sediment was flushed into the Zackenberg delta. The average transport of suspended sediment in the river is ~58000 tons/yr (1996-2015). In comparison, an estimated 11600 m^3 or 15000 tons of sediment eroded from the mapped stretch (given a standard soil bulk density of 1.3 g/cm^3).

The timing of both heavy rain events and glacial lake outbursts is important for the volume of eroded sediment that is transported from land to sea. Moreover, a rain event will also erode from the soil surface in the entire catchment whereas outbursts will mainly impact the river banks. Events during summer and early autumn are more likely to have high impact as both river banks and the landscape is thawed and thus more unstable than during winter. A future expectation of increased rain fall, especially in the fall (Bintanja & Andry, 2017) underlines the importance of quantifying the impact of these events, and ultimately to include them in e.g. carbon budget estimates.

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[#]These authors contributed equally

Data source:

GEM GeoBasis – Drone surveying

GEM GeoBasis – River discharge monitoring

GEM DiskoBasis – Precipitation measurements

DIFFERENT SCALES IN GEM

GEOMORPHOLOGICAL CHANGES FOLLOWING EXTREME EVENTS

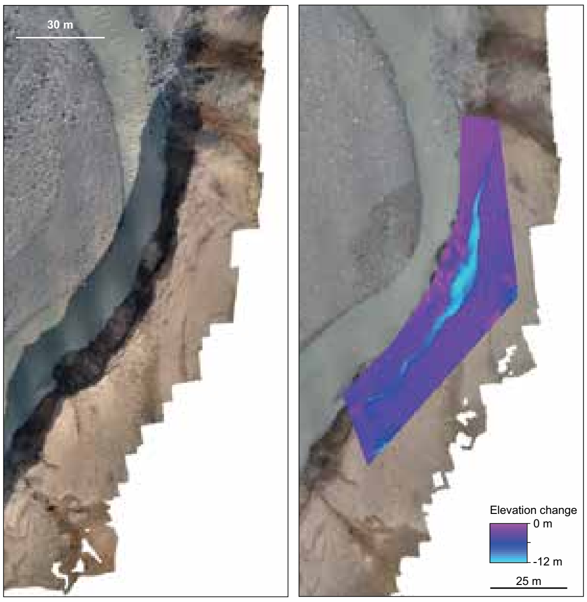

Figure 1. Drone maps (orthophotos and DSMs) derived from before (Left) and after (Right) a substantial land slide in the Zackenberg river bank, most likely caused by a glacial lake outburst flood. Change-detection based on the DSMs allows for quantification of eroded sections in the river bank (Left: 25th of August 2017. Right: 29th of August 2017).

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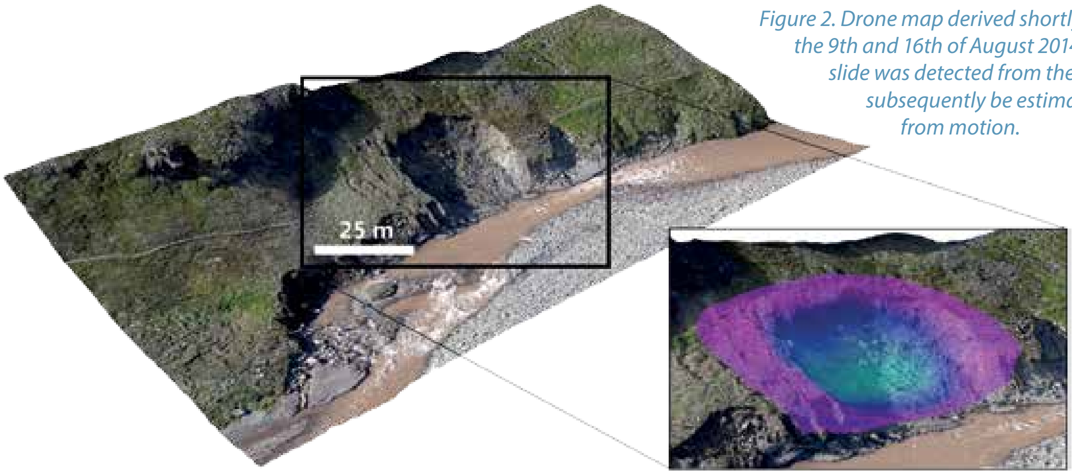
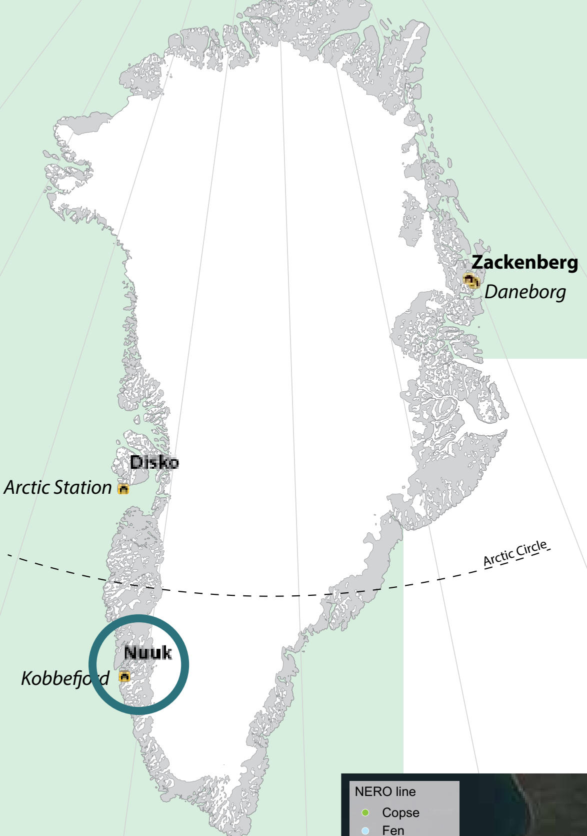


Figure 2. Drone map derived shortly after two extreme rainfall events on the 9th and 16th of August 2014, near Arctic Station, Disko. A clear landslide was detected from the drone images, and the volume could subsequently be estimated using a DSM based on structure from motion.

Figure 3. Continuous monitoring, here with time lapse cameras, is essential to capture the exact timing of ecological events. Here it is the emptying of the A.P. Olsen glacial lake over the course of a day (Left: 11th of August 2009. Right: 12th of August 2009). The temporal resolution of this dataset is not achievable with drones due to weather conditions and limited man power.



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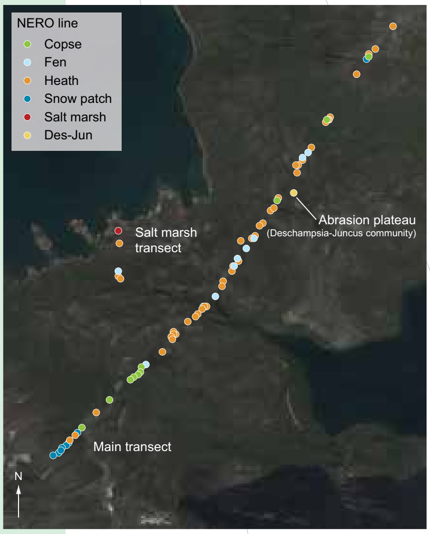
MONITORING
VEGETATION CHANGE IN

The permanent vegetation transect, the NERO line, in low arctic Kobbefjord, was established in 2007 and surveyed for the third time in 2017 (Bay et al., 2008, 2013). The three survey datasets do not indicate any major changes in the vegetation composition or in the distribution of the vegetation types.



The NERO line is located in the Kobbefjord study area, southwest Greenland (See map) and is the low arctic counterpart to the ZERO line in high arctic Zackenberg, Northeast Greenland. The vegetation transect was established in order to detect climate induced long-term temporal and spatial changes in the species composition and distribution of the vegetation types. The NERO line covers major vegetation types in the study area and consists of three transects: one long main transect (valley bottom to highest located vegetation on mountain slopes on both sides of the valley, in total 2.5 km) and two shorter in vegetation types with limited distributions (Bay *et al.,* 2008). The main transect is divided into 67 vegetation zones based on four main vegetation types of the study area (copse, dwarf shrub heath, fen or snow patch vegetation). The two shorter transects were established in salt marsh (consisting of six vegetation zones) and on an abrasion plateau with a *Deschampsia flexuosa-Juncus trifidus* community (consisting of one vegetation zone). Up to ten plots (marked by metal tubes) were placed within each vegetation zone two meters a part.

When the transects were established in 2007, 653 plots (Bay *et al.,* 2008) were analyzed within the 74 vegetation zones using the Böcher-modified Raunkjær analysis (Böcher 1935). Due to natural causes (e.g. wildlife, erosion) and human activity, a large number of plots have been lost between the surveys and only 516 of the original 653 plots were re-analysed in 2017.

Table 1. Number of plots, species and species:plots ratio 2007, 2012 and 2017. Note that the number of plots decreases from 2007–2017. The loss of plots are both within each vegetation type (except abrasion plateau) and in total.

	2007			2012			2017		
	No. species	No. plots	Species plots ratio	No. species	No. plots	Species: plots ratio	No. species	No. plots	Species: plots ratio
Copse	37	89	0.42	42	82	0.51	37	79	0.47
Heath	57	395	0.14	53	344	0.15	44	299	0.15
Fen	29	77	0.38	30	64	0.47	27	58	0.47
Snow patch	37	65	0.57	41	59	0.69	32	54	0.59
Salt marsh	5	7	0.71	8	6	1.33	7	6	1.17
Abrasion plateau	6	20	0.30	7	20	0.35	7	20	0.35
Total	83	653	0.13	82	575	0.14	68	516	0.13

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Data source:

GEM BioBasis Nuuk - Vegetation

LOW ARCTIC GREENLAND

(Photo: Ida Bomholt Dyrholm Jacobsen).

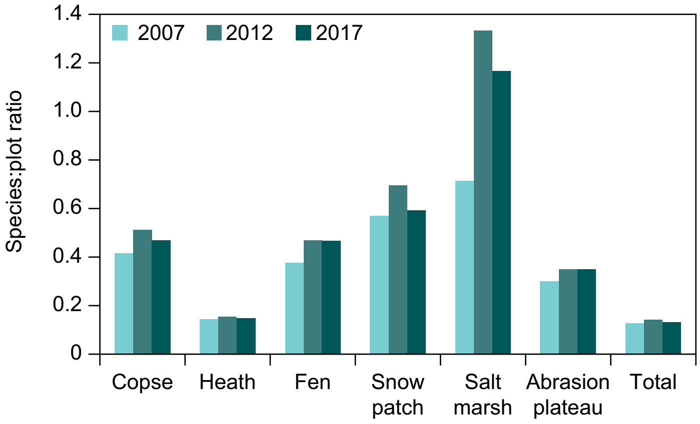

Figure 1. Ratio of number of species:plots. The absolute number of species in each vegetation type and in total decreased from 2007 to 2017. However, so did the number of plots. The ratio of number of species:plots remains relatively stable (with in vegetation type year to year) and indicate that the decrease in numbers of species is related to the decrease in number of plots. This ratio of numbers of species:plots cannot be considered an indicator for diversity or adequate for comparison between vegetation types (since the number of plots varies between vegetation types , see Table 1).

No new species have been recorded along the transects, and the number of vascular species has in fact declined over the years (83 species in 2007, 82 in 2012 and 68 in 2017, see table 1). This is possibly explained by the loss of plots, since the number of species pr. plot is generally unchanged except for the salt marsh (Figure 1). The variation for salt marsh is pronounced due to a small number of plots and a small number of species.

Generally, there has been little changes in the distribution of the vegetation types along the NERO line. Contrary to arctic areas in North America (Myers-Smith *et al.*, 2011, Tape *et al.*, 2006), there are no signs of expanding dwarf shrub species along the transects. Abundance of the shrub dwarf birch (*Betula nana*) remains at the same level across the three surveys, but with a tendency of increased abundance in the fen vegetation zones (Figure 2) despite a larvae outbreak severely impacting the dwarf shrubs in general in 2011 (Lund *et al.*, 2017). Vegetation response to climate change is slow and continued monitoring is important to follow the expected changes over time.

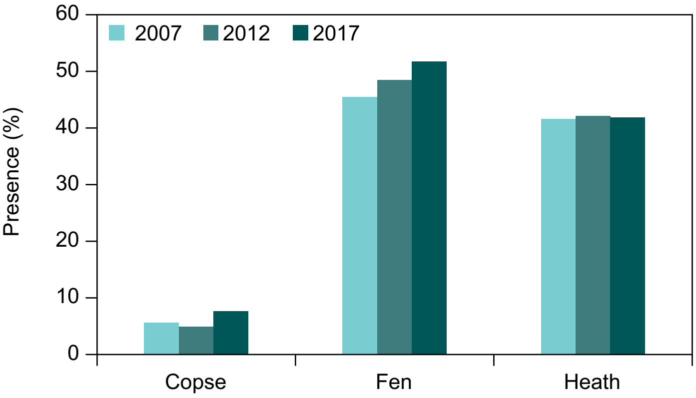

Figure 2. Presence (%) of Betula nana in plots (see Table 1) in 2007, 2012 and 2017. Betula nana is only found in the copse, fen, and heath vegetation types. In copse and heath the precense of Betula nana varies little. There is with a tendency of increased abundance in the fen vegetation zones. Further analysis are needed to determine if these results are significant.

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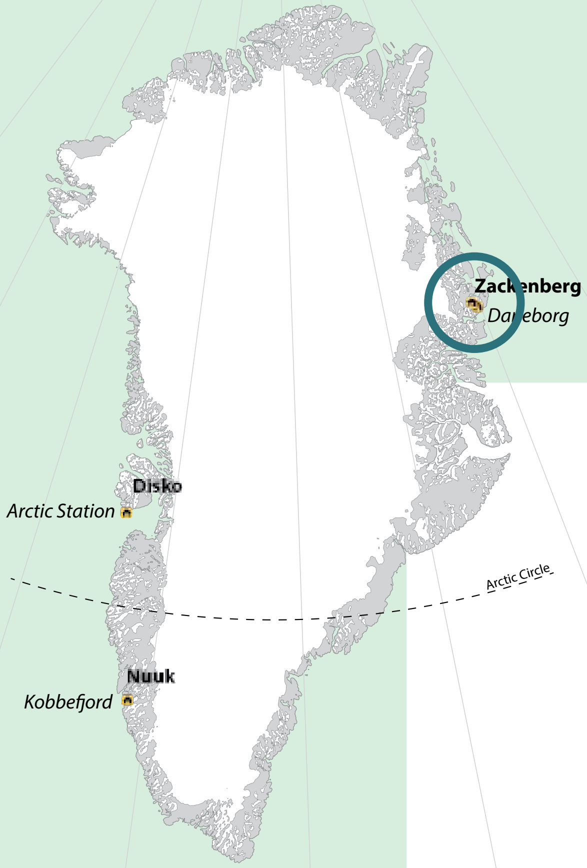

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THE RETURN
OF THE LEMMING


(Photo: Lars Holst Hansen).

After two decades of low-density fluctuations, Zackenberg saw the largest lemming peak in 2017 since the establishment of the station in 1996, and all vertebrate predators responded positively to the excess of lemmings. Whether the peak marks the return of the regular lemming cycles or it indicates a shift towards more erratic population dynamics is currently unknown.

Lemmings play a key role in the Arctic tundra biome as both consumer of plants and as prey for most vertebrate predators there. In many areas across the circumarctic region, lemmings exhibit regular multi-annual density fluctuations, often referred to as population cycles. Until around year 2000, population dynamics of collared lemmings in Northeast Greenland were also considered cyclic with a four-year periodicity (Schmidt *et al.*, 2012). However, since the peak in 1998, the lemming winter nest density has fluctuated with relative low numbers at Zackenberg. A similar pattern was observed at the more southerly site on Traill Island, where lemmings are also monitored (Schmidt *et al.*, 2012). It was therefore unexpected, but long awaited, that the lemming population at Zackenberg suddenly peaked in 2017, and did so at a remarkably high level (Fig. 1).

Lemming predators rely heavily on lemming peak years for reproduction (Schmidt *et al.*, 2012; Barraquand *et al.*, 2014). In years with few lemmings, long-tailed skuas cease to breed. Being long-lived, they simply wait for better lemming years. In lemming lows at Zackenberg, the Arctic fox relies on alternative food sources, such as muskox carcasses. The unprecedented lemming peak in 2017 triggered an instant response


(Photo: Lars Holst Hansen).

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Data source:

GEM BioBasis – Mammal monitoring, Bird monitoring in all predators: Long-tailed skuas were breeding at very high numbers and Arctic foxes were breeding in most breeding dens. Even a pair of snowy owls, a rare visitor at Zackenberg, stayed in the area the entire summer, though breeding was not confirmed. The response of the stoat, another lemming specialist, is expected to be delayed one year, and thus primarily manifested the following year. Nonetheless, even stoats were observed more often in 2017 than in previous years.

The trophic system on the tundra is highly inter-connected, and species therefore most often share resources and predators (Schmidt *et al*., 2017). The high lemming abundance may therefore have repercussions for other species not directly trophically linked to the lemmings. Hence, for instance ground-nesting birds often experience lower predation rates when lemmings are numerous as the predators focus on these and thus less on finding bird nests and young. However, in 2017, predation rates were very high on all ground nesting bird nests monitored. Even the long-tailed skua, having great success in producing clutches, suffered very high predation on both eggs and chicks. None of their young made it to fledging. Hence, ground-nesting birds did not experience a predatory release, which stresses the complexity of trophic interactions, even in the relatively simple Arctic food webs.

Whether the long awaited lemming peak at Zackenberg indicates the return of the lemming cycles to the area, or whether the sudden peak indicates that lemming population dynamics is becoming less regular and more erratic, is to be determined over the next years. Either way, due to the central position of lemmings in the trophic interactions, the status and trends of lemming populations is a strong indicator of the state of the tundra vertebrate community in the Arctic region.

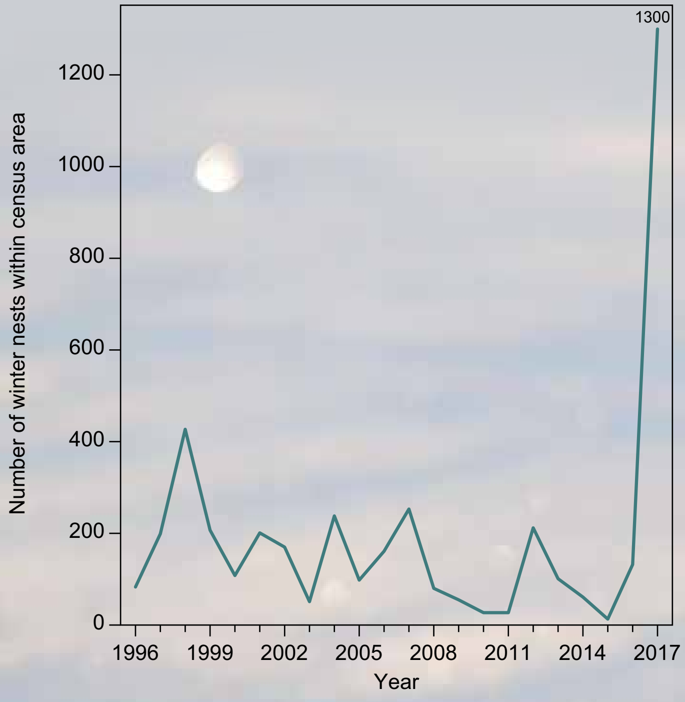

Figure 1. The abundance of lemmings as indicated by the number of lemming winter nests within the lemming census area from 1996 to 2017. Updated from Schmidt et al., (2012).

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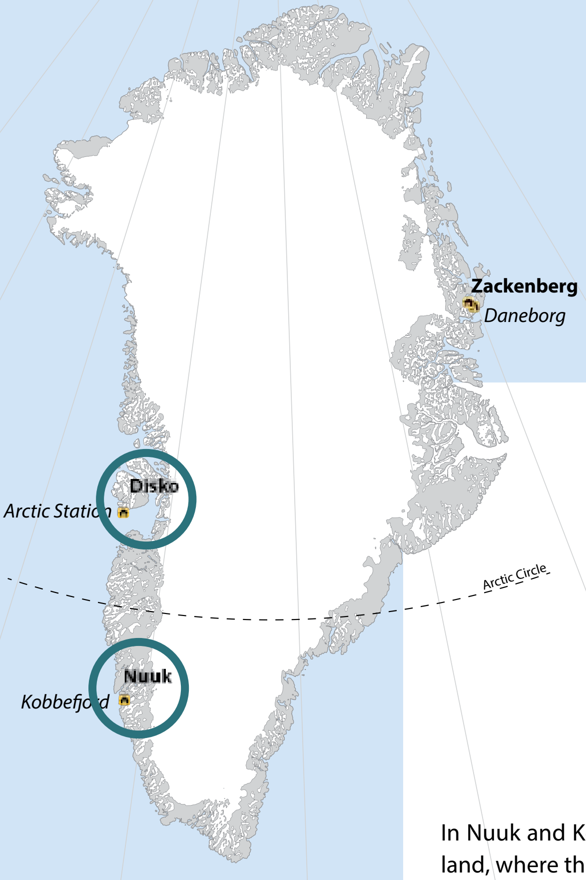
(Photo: Lars Holst Hansen).



ARCTIC MARINE WARMING STIMULATES THE

Knotted wrack (Ascophyllum nodosum) is a habitat-forming macroalga, widely distributed in the intertidal zone throughout the North Atlantic Ocean from Portugal to Greenland. Our study demonstrates that warming and longer ice-free periods enhance growth of this species near its northernmost occurrence in Greenland and in northern Norway. Projected global warming suggests increased importance and pole ward expansion of A. nodosum and other species of the North Atlantic Ocean marine biota.

In Nuuk and Kobbefjord, Greenland, where the tidal range is 1-5 meter, a wide belt of intertidal vegetation appears at low tide (Fig. 1). In sheltered areas, this tidal vegetation is dominated by knotted wrack that forms a highly productive habitat supporting a rich fauna including blue mussels, snails and barnacles. Indeed, habitats of knotted wrack are known to generally enhance abundance and diversity of associated flora and fauna, including several commercially important species, as well as to contribute to nitrogen, and carbon storage (Schmidt *et al.*, 2011).

Knotted wrack forms a new knot (node) at the tip of its branches each year. The distance between the knots reflects the species annual growth rate (Fig. 2). As the branches often hold a long sequence of knots, the age and growth rate over past years can be assessed from a single sampling event. We sampled six Greenlandic and two Norwegian populations of knotted wrack, quantified growth over the period 1997/2002-2009/2011 and

Figure 1. a) Knotted wrack. b) Sampling knotted wrack at low tide in Kobbefjord, Greenland (Photos: Peter Bondo Christensen).

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Data source:

GEM MarineBasis-Nuuk, University of Copenhagen/Arctic Station

GROWTH OF INTERTIDAL MACROALGAE

examined growth of the species in relation to climatic forcing. Historic studies in the 1950s and 1980s (Wilce 1964; Hansen *et al.,* 2004), provided a >50 year long time series of growth rate of the knotted wrack population at the northern distribution limit of the species in Kronprinsens Ejland, Disko Bay. Specimens in the assessed populations grew between 2.0 and 9.1 cm year^{-1}. Variability in growth rate correlated with temperature and annual ice-free days (Fig. 3).

From the literature, we compiled additional estimates of growth rates of knotted wrack across its distribution range. On this basis, we examined large-scale growth patterns in relation to variability in summer seawater temperature across the species entire biogeographical distribution range. We found that populations grew at the slowest rates in the northern and coldest environments (Fig. 4). Our results demonstrate that arctic climate change enhances the growth of knotted wrack and suggest that its productivity will increase in response to projected global warming.

Given, the ecological importance of the North Atlantic Ocean tidal vegetation and recognition of the response of the growth and population dynamics of *Ascophyllum nodosum to* diverse temperature environments, this species is a significant indicator of tidal vegetation response to climate change.

Figure 2. The distance between annual knots of knotted wrack allows quantification of annual growth rate of the species. Reproduced from Marbà et al., 2017.

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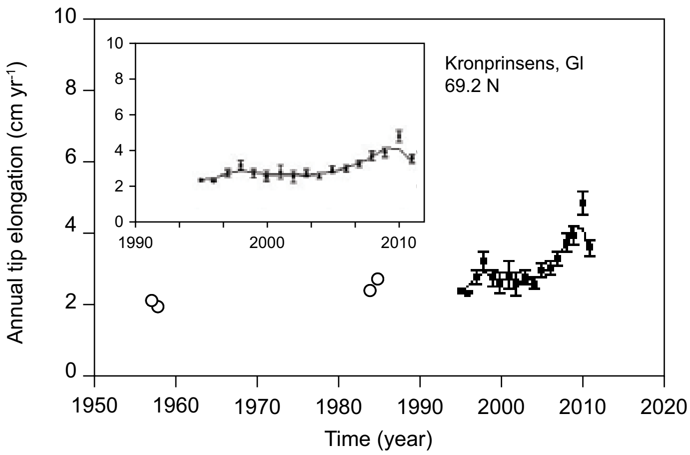

Figure 3. Annual growth rate of knotted wrack over >50 years at the northern distribution limit of the species in the Disko Bay. Reproduced from Marbà et al., 2017.

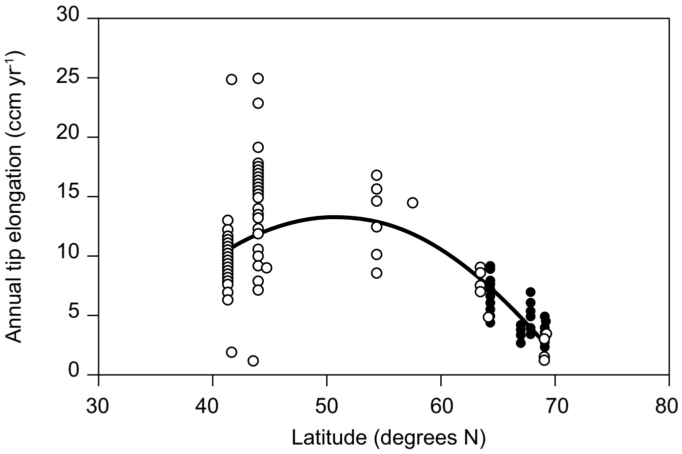

Figure 4. Annual growth of knotted wrack across latitudes. Filled circles from our study, open circles from the literature. Reproduced from Marbà et al., 2017.

MELT WATER IS A KEY

COASTAL CARBON FLOW AND

Arctic warming results in accelerated ice melt increasing inflow of meltwater to Greenland fjords. The freshening and coupling to the melting ice sheet has important consequences for coastal carbon cycling.

(Photo: Mikael K. Sejr).

Based on summer measurements in Young Sound from 2003 to 2015 the change in salinity and freshwater content was analyzed for the fjord and the coastal ocean outside the fjord (Fig. 1a). Salinity was found to decrease both in the fjord (Fig. 1b) and outside, with the largest drop taking place at 30-50m (Sejr *et al.*, 2017). When the integrated, increase in salinity was converted to a water column height of pure freshwater, it showed an increase from 1 m to more than 3 m during the sampling period demonstrating the fast rate of physical change in the marine habitat (Fig. 1c). Surprisingly, the main source of freshwater in the fjord was not the local catchment, but rather increasing freshwater content of coastal water outside the fjord. This suggests meltwater from the melting ice sheet and sea ice north of Young Sound is being contained in the coastal current and that this freshening signal is being transported "downstream" with the East Greenland Current along the coast.

(Photo: Jens W. Hansen).

(Photo: Mikael K. Sejr).

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Data source:

GEM MarineBasis, ClimateBasis and GeoBasis

FACTOR INFLUENCING

COUPLE OCEAN DYNAMICS TO CRYOSPHERE CHANGE

The two fjords in the GEM program are coupled to the Greenland Ice Sheet in different ways; the Godthåbsfjord system (near Nuuk) is linked to the Ice Sheet through several marine tidewater glaciers, whereas Young Sound receives meltwater through rivers connected to glaciers on land. Since sub-glacial discharge beneath marine-terminating glaciers act as a nutrient pump replenishing surface water with nutrients in summer; fjords with marine tidewater glaciers are significantly more productive and important fishing ground (Meire *et al.,* 2017). In the low productive Young Sound, a seasonal study revealed that the phytoplankton production in the fjord could not sustain the bacterial carbon demand thus indicating that glacial rivers were an important source of organic carbon (Paulsen *et al.,* 2017). Organic carbon concentration in the rivers was low but the bioavailability was higher than in the coastal water. Combined the three studies highlight how important meltwater from the Greenland Ice Sheet is for marine carbon cycling in Greenland fjords with potential significant reduction in ecosystem production if glaciers retract to land or ocean circulation changes freshwater input to fjords.

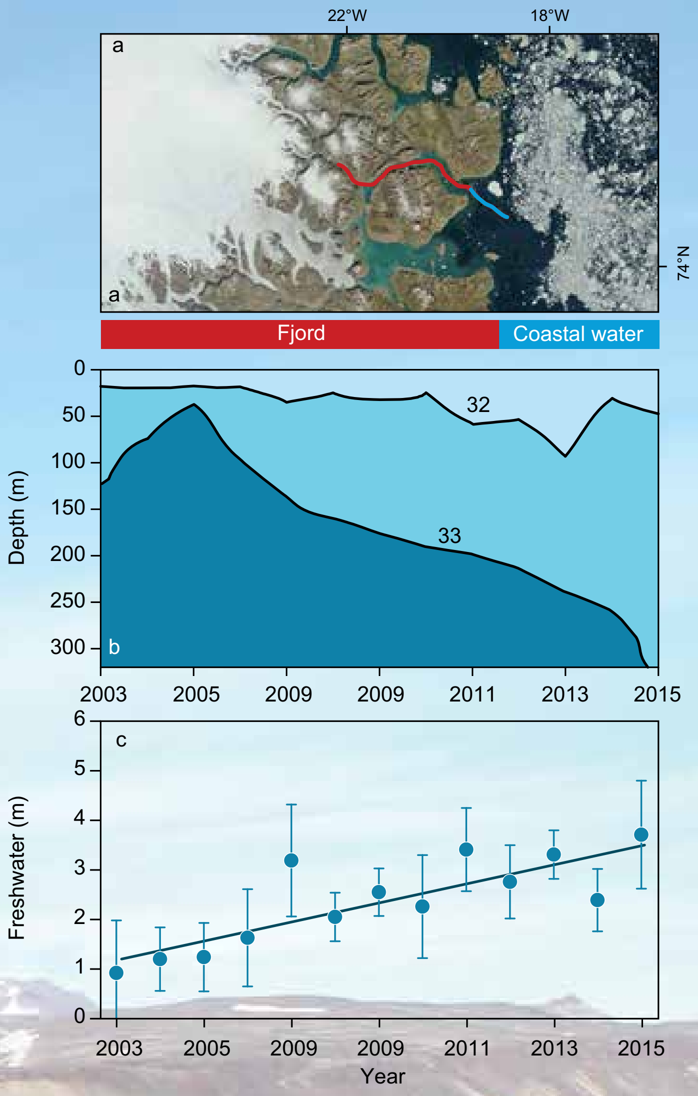

Figure 1. a) The studied hydrographical transect in Young Sound. b) Changes in salinity in Young Sound during early August from 2003 to 2015 (32 and 33 isohaline shown, Sejr et al., 2017). c) The increase in freshwater content in the upper 50 m of the water column in Young Sound.

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Annual Report Card 2017

MELTWATER RE-

– IMPROVING MODELS FOR

Mountain glaciers and ice caps around Greenland lose mass relatively more quickly than the ice sheet due to their higher sensitivity to climate change. GEM GlacioBasis Nuuk, Asiaq – Greenland Survey and PROMICE are assessing how the refreezing of meltwater in seasonal snow affects glacier mass balance, what the main drivers of refreezing are and how well the process is represented in a sophisticated subsurface model.

Current mass balance calculations estimate that 14 % of the total mass loss from Greenland stems from ice caps and mountain glaciers (Noel *et al.*, 2017), that cover only 5 % of the glaciated area (Rastner *et al.*, 2012). However, models struggle with spatially resolving these comparatively small ice masses, and observations of surface conditions on these glaciers are limited, causing a high uncertainty in mass loss estimates.

Our project aims to reduce the uncertainty in surface mass balance estimates of Greenland glaciers by improving the understanding of a scantly studied feature in Greenland: the formation of ice lenses and superimposed ice in a glaciers' seasonal snowpack. This is done by detailed analysis of in-situ weather observations, mass balance measurements, snow pit data, and output of an observation-fed model calculating meltwater percolation and refreezing in snow, for the small mountain glacier Qasigiannguit in southwest Greenland (51.36°W, 64.16°N) (Fig. 1).

Qasigiannguit has been monitored since 2012. In the spring of 2015 a 5 cm layer of superimposed ice, which forms when meltwater refreezes at the base of the winter snow layer, was found on the glacier. This prompted a thorough investigation of the formation of superimposed ice, with the installation of a stake farm and five snow pit loggings during spring 2017.

The 2017 field study revealed that superimposed ice had also formed on the glacier in the accumulation season of 2016/17, and remarkably that it had formed in autumn when the snow cover was still thin at about 1 m. In spring, when the snow cover was more than 2 m thick, the meltwater refroze as horizontal ice layers within the snowpack (Fig. 2). Up to 0.22 m of solid ice was found to have formed within the 2.2 m snowpack, either as ice lenses or as superimposed ice directly on the glacier surface, amounting to 19% of the snow water equivalent of the total winter accumulation recorded on 26 May 2017 (Fig 3).

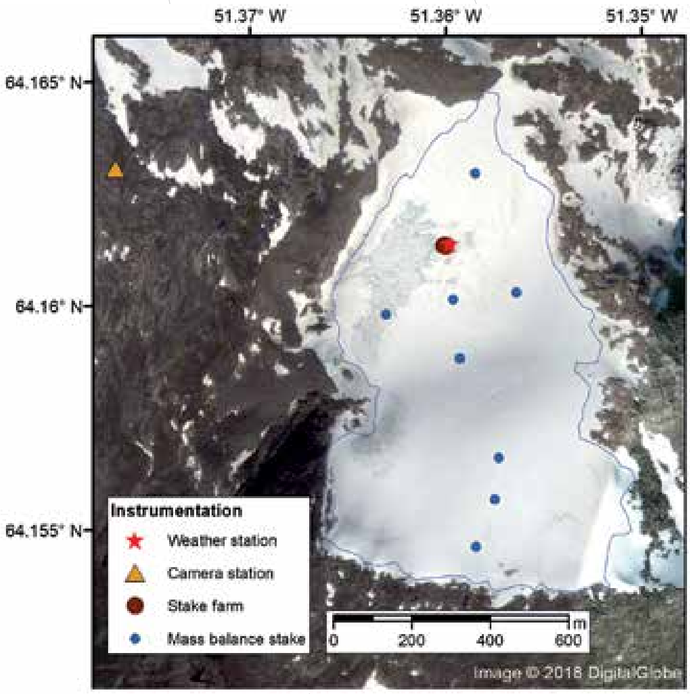

Figure 1. Outline of and monitoring infrastructure at Qasigiannguit glacier, southwest Greenland.

Story by:

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[2]Geological Survey of Denmark and Greenland, Denmark

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Data source:

GEM GlacioBasis – surface mass balance and near surface weather datasets

FREEZING IN SNOW

ESTIMATING GREENLAND GLACIER MASS BALANCE

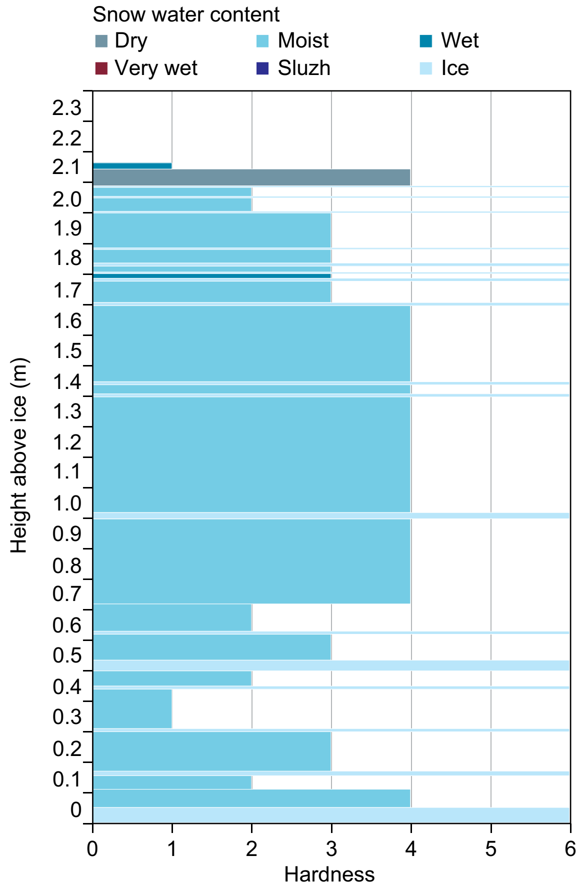

Figure 2. Ice lenses in the snowpack on 26 May 2017, formed in the cold wintertime snowpack.

A model using weather station observations (Vandecrux *et al.,* submitted) is used to calculate the energy fluxes at the surface and water movement through the snowpack for the period 2014 to 2017 (Fig. 4). Preliminary results show the ability of the model to reproduce surface melt, and to some degree to redistribute and refreeze meltwater at appropriate depths. However, the timing of the arrival of meltwater at the bottom of the snowpack, and subsequent refreezing as superimposed ice, depends on factors that are still not well known. Improvements such as a better quantification of the heat flux from the snowpack to the underlying ice are currently being included in the model.

Once the model is able to match field observations in the study period, it will be used to estimate refreezing during the preceding years for which no snow pit measurements are available, and for different elevations across the glacier. Our study helps determine the role of meltwater refreezing (also as superimposed ice) in the total mass balance of Qasigiannguit glacier, enabling application to other small glaciers around Greenland.

The project is funded by the Greenland Research Council and carried out in cooperation with GEM ClimateBasis.

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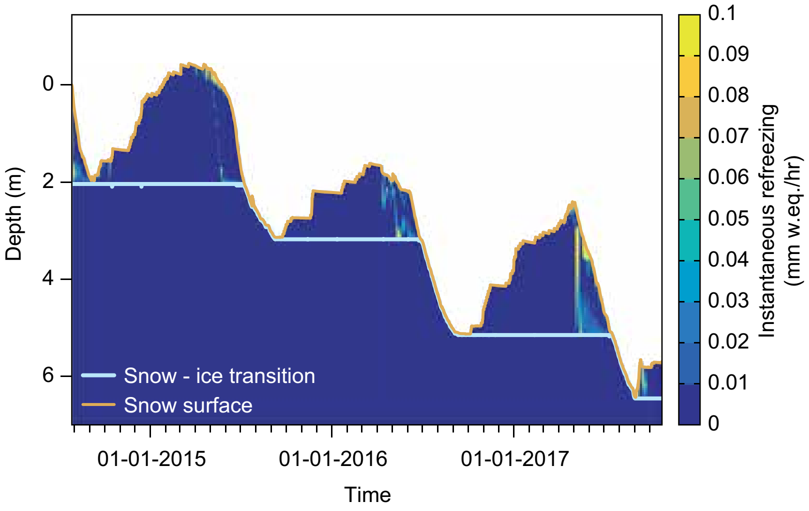
Vandecrux, B.R.M. *et al.,* Submitted. Drivers of Firn Densification on the Greenland Ice Sheet Revealed by Weather Station Observations and Modelling. JGR: Earth Surface.

Figure 3. Snow pit log from 26 May 2017 showing ice adding up to a total thickness of 0.22 m (Photo: Sille Marie Myreng).

Figure 4. Preliminary model results of refreezing in snow on Qasigiannguit glacier, with inputs of surface height changes and atmospheric observations from the automatic weather station. Refreezing occurs in the snowpack, but also at its base (the ice level of the previous year) as superimposed ice. Note the superimposed ice formation in autumn 2017.



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 ice dynamics, mass balance and surface energy balance in glaciated environments.

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