20 years of methane measurements has sharpened our understanding

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Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2016

GEM

Greenland Ecosystem Monitoring

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

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2016

GEM
Greenland Ecosystem Monitoring

GEM
ANNUAL REPORT

About GEM and the new GEM Strategy 2017-2021

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 new GEM strategy 2017-2021 seeks to expand the program with an additional main site, supplemented with single disciplinary sites, campaigns and a remote sensing initiative 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 made freely available through http://data.g-e-m.dk/. GEM data are submitted to more than 10 thematic data repositories and GEM researchers participate in over 35 international scientific networks, programmes and projects.

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

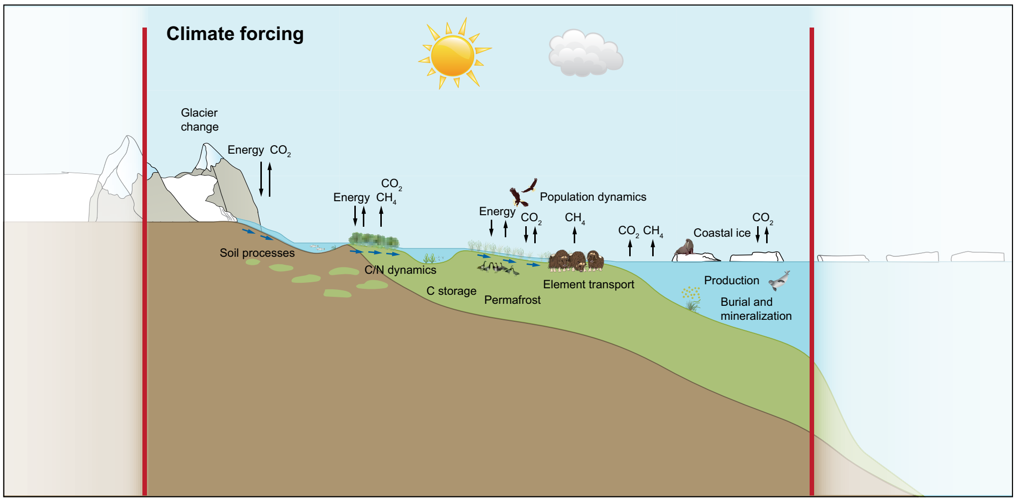


Figure 1. The GEM domain.

GEM
Greenland Ecosystem Monitoring

CARDS 2016

GEM Annual Report Cards 2016

This publication presents some of the significant findings of the 2016 field season and interesting time series analysis spanning several years. We call this GEM Annual Report Cards and this is the first edition. Report cards are produced by all five Basis programmes, some in collaboration with external partners.

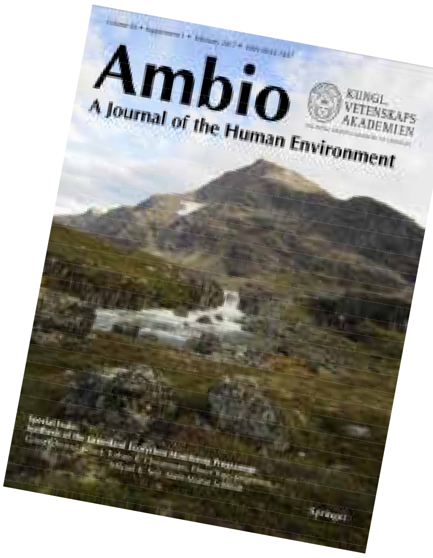
The reports in this issue include, among others, slushflow avalanches, long-term effects of a larval outbreak, plant phenology across scales, freshwater discharge effects on coastal ecosystems as well as glacial meltwater contribution to sea level rise.

The report cards will be supplemented with information on the website, e.g. description of data, research projects, disturbances in the study areas, logistics, publications lists, etc.

Earlier comprehensive annual reports have been produced from each of the main study sites in GEM. These are available on http://g-e-m.dk/gem-publications/.

GEM Synthesis

GEM has produced a synthesis of the first 20 years as a special issue of AMBIO. The issue presents papers from all scientific disciplines covered by GEM and seeks to put results into an arctic or global context. The issue is public access and is available from http://link.springer.com/journal/13280/46/1/suppl/page/1.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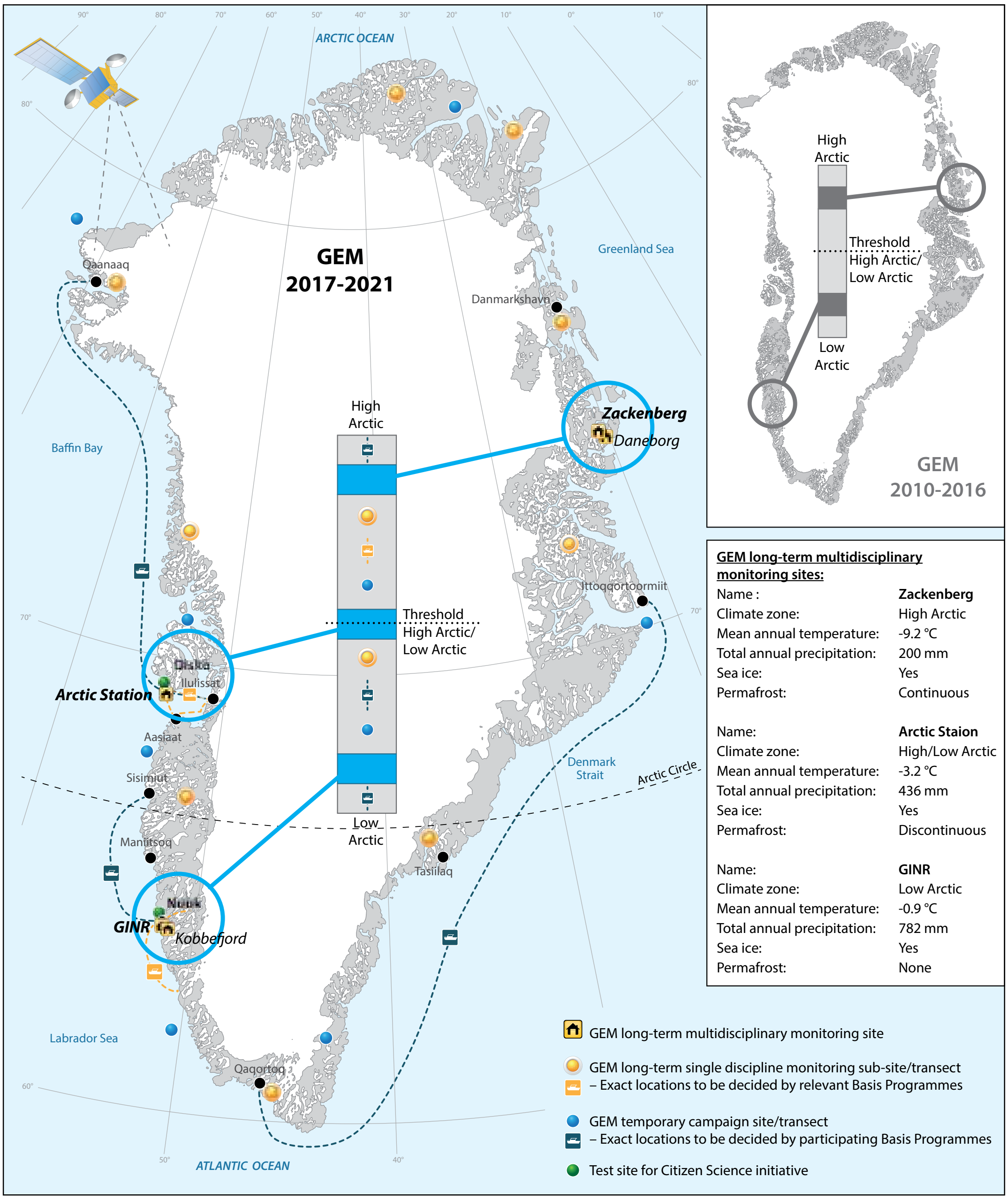

GEM long-term multidisciplinary monitoring sites:

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.

Annual Report Card 2016

WARM
SPRING IN THE WEST, WARM

The year 2016 was an abnormally warm year with an unusually warm spring on the west coast and a record warm autumn on the east coast. A recent publication puts this into a larger spatio-temporal context defining hotspots and key periods of change in Greenland.

Kapisillit, west Greenland (photo: Elmer Topp-Jørgensen).

This year, 2016, was a good example for the often different temperature anomaly at the East vs the West coast of Greenland. While Disko and in Kobbefjord (GEM main sites in west Greenland) both experience average temperatures from May to December, the Spring was several degrees warmer than usual (Fig. 1, left and middle). In Zackenberg (GEM main site in east Greenland), it was the other way round with monthly air temperatures around the long-term average in the first half of the year and way above average in the second half (Fig. 1, right). The timing of the temperature anomalies is crucial for the ecosystem response as it hits the biosphere in differing phases (spring/autumn).

A recent study investigated the climate trends in a spatio-temporal perspective for the Zackenberg reference period (1996-2014). The strongest warming happened during February at the West Coast (up to 0.6 °C yr^{-1}), weaker but consistent and significant warming occurred during summer months (up to 0.3 °C yr^{-1}) both in West and in east Greenland. Statistically significant cooling happened on a monthly basis in April, May and December at some stations along the west coast (Fig. 2). Further details are summarized in Abermann *et al.* (2017)

GEM monitoring efforts are designed to study ecosystem response to such changes in the climate system (e.g. temperature, snow, clouds, precipitation) and several of the stories in this publication address changes in ecosystem functioning and processes in a changing climate.

Story by:

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[2]Deutscher Wetterdienst, Germany

*Corresponding author, jab@asiaq.gl

Data source:

GEM ClimateBasis – Monitoring component in Kobbefjord, Disko and Zackenberg, east and west Greenland

AUTUMN IN THE EAST

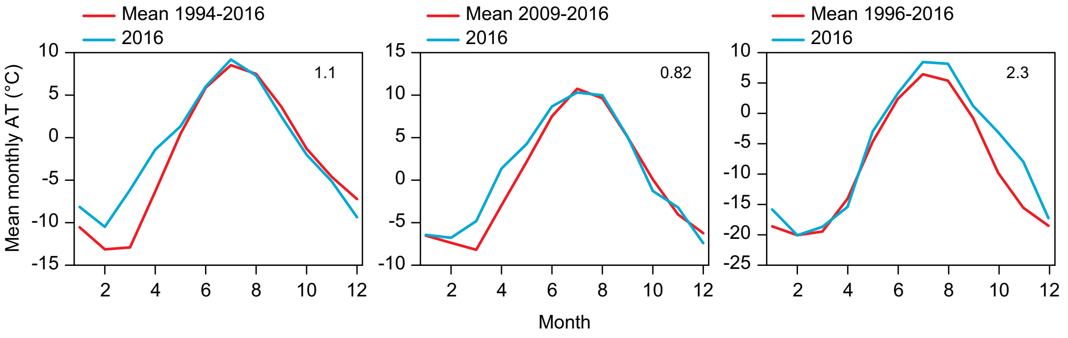

Figure 1. Average monthly air temperature for the three GEM-sites Disko (left), Kobbefjord (middle) and Zackenberg (right) for the average reference period (red, note that the length of the reference period depends on the site) and the year 2016 (blue).

Tasiilaq, east Greenland. (Photo: Elmer Topp-Jørgensen).

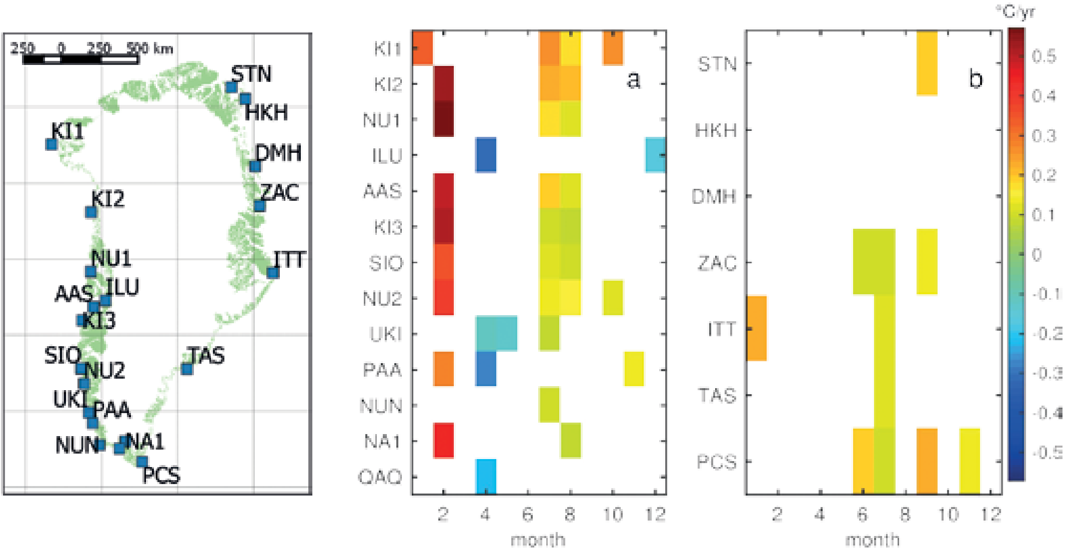

Figure 2. Left: Greenland with the Automatic Weather Stations (AWS) used. Monthly temperature trends for the weather stations at the West (a) and East (b) coast for the period 1996-2014. Statistically non-significant trends are white.

Reference:

Abermann, J., *et al*. 2017. Hotspots and key periods of Greenland climate change during the past 6 decades. Ambio, 46(1), pp. 3-11.

Annual Report Card 2016

EXTREME
SLUSHFLOW AVALANCHE

On 11 April 2016 we observed a high occurrence of slushflow avalanches in Kobbefjord. Air temperatures above freezing in combination with rain in the days prior and on 11 April 2016 were presumably the triggering factors pointing towards the release of wet snow avalanches and slushflows.

Slushflow avalanche, Kobbefjorden catchment area (Photo: Jakob Abermann).

Heavy precipitation (ca 27.5 mm) along with an impressive temperature rise (27 °C in 56 hours) and a maximum 30 minute average of 17.8 °C was recorded between 9 April and 11 April 2016 in Kobbefjord (Fig. 1). Within 24 hours, the water level of Badesø in Kobbefjord rose by 0.85 m and thus reached its second highest water level since the start of the measurements.

As a consequence of the combination of heavy rain, abrupt temperature rise and a thin, unstable snow pack, we observed a number of avalanches that in parts also destroyed some of our monitoring installations. Automated cameras recorded a significant amount of mud/rocks that got transported during the process (Fig. 2).

The type of avalanches is best characterized as a 'slush flow', defined as a 'mudflow-like flowage of water-saturated snow' (c.f. Washburn and Goldthwait, 1958). Prerequisites are heavy precipitation and high temperatures. The avalanches impacted vegetation and eroded soil. In addition to the observations in Kobbefjord, we have reports from avalanches/landslides that occurred during this event on Nordlandet, in Amitsuloq and Buksefjord. We are currently investigating the spatial extent using Sentinel satellite data and found a large number of avalanches that we can connect to this. Such mass movements are clearly a hazard for infrastructure and along with the recent warming in Greenland (e.g. Mernild *et al.*, 2014; Abermann *et al.*, 2017) there are indications that their frequency increases (Bokhorst *et al.*, 2016) with significant implications for affected ecosystems.

Story by:

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*Corresponding author, jab@asiaq.gl

Data source:

GEM ClimateBasis Monitoring component in Kobbefjorden, west Greenland

EVENT IN KOBBEFJORD IN APRIL 2016

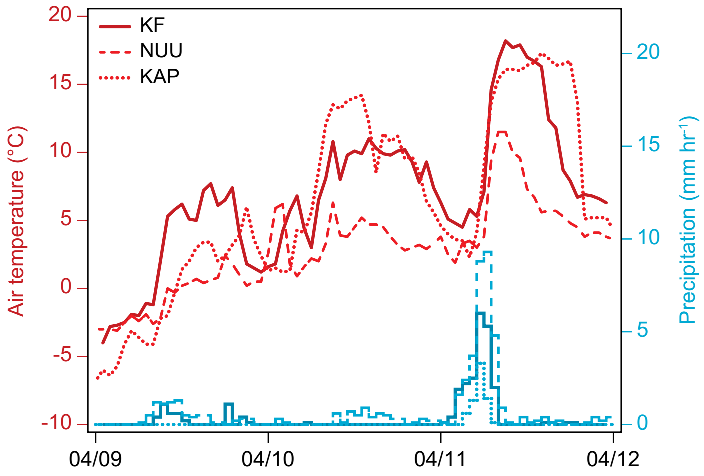

Figure 1. Air temperatures and precipitation in April 2016 in Kobbefjord (KF), Nuuk (NUU), and Kapisillit (KAP). Nuuk and Kapisillit data: Courtesy Asiaq, Greenland Survey.

References

Abermann, J. *et al*. 2017. Hotspots and key periods of Greenland climate change during the past 6 decades. Ambio, 46(1), pp. 3-11.

Bokhorst, S. *et al*. 2016. Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. AMBIO, 45 (5), 516–537, doi:10.1007/s13280-016-0770-0.

Mernild, S.H. *et al*. 2014. Coastal Greenland air temperature extremes and trends 1890–2010: annual and monthly analysis. Int. J. Climatol., 1487(34), 1472-1487, doi:10.1002/joc.3777.

Washburn, L. & Goldthwait, R.P. 1958. Slushflows. Bull. Geol. Soc. Am., 69, 1657–1658.

10-04-2016

11-04-2016

Figure 2. Time-lapse image from Badesø, Kobbefjord before and after the heavy slushflow event. Courtesy: GEM GeoBasis.

SNOW AS A KEY REGULATOR OF

Snow is a major driver for arctic ecosystem functioning, influencing surface energy balance, permafrost thaw, hydrology, plant growth and greenhouse gas exchange. Therefore, one of the most important tasks for the GEM GeoBasis and ClimateBasis programmes is to monitor temporal and spatial variability in snow cover, snow depth and snow density, in order to advance knowledge on climate change related effects in arctic ecosystems.


Photo: Kirstine Skov.

GEM use multiple methods for measuring snow characteristics in Zackenberg, Nuuk-Kobbefjord and Disko. Point-based measurements of snow depth provide useful information for assessing temporal variation (Fig. 1). In addition, we perform snow surveys along various transects as well as making use of time-lapse photography for assessing daily snow coverage, allowing for computation of snow depletion curves (Fig. 2).

The spatial variation in snow characteristics in Greenland is large, owing to the complex topography in near-coastal Greenland tundra ecosystems. During winter 2015/2016, the observed snow depth was close to the long-term mean in Zackenberg (Fig. 1). However, in Kobbefjord, there was relatively little snow whereas at Disko Island record amounts of snow were measured. The inter-annual variation in snow depth in Zackenberg is strong and a recent investigation of the long-term monitoring record indicated little evidence for significant trends in observed snow characteristics, except for a decrease in the snow cover fraction observed 10 June each year (Pedersen *et al.* 2016).

With the ongoing, rapid warming of the Arctic, it is expected that the hydrological cycle will be intensified with associated increases in

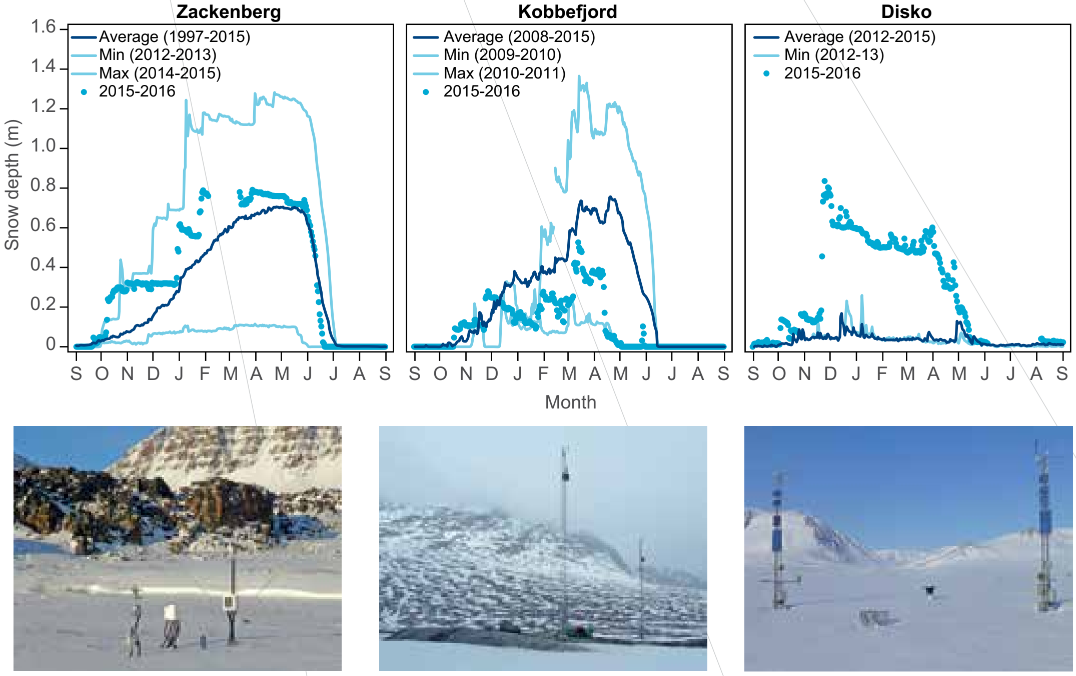

Figure 1. Snow depth measurements in Disko (top left panel), Kobbefjord (top middle panel) and Zackenberg (top right panel) with photos from each site below.

Story by:

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[2]Asiaq

[3]University of Copenhagen

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Data source:

GEM ClimateBasis
– Precipitation

GEM GeoBasis
– Automatic Photo Monitoring

GEM GeoBasis
– Meteorology

GEM GeoBasis
– Snow Properties

ARCTIC ECOSYSTEM PROCESSES

precipitation (Collins *et al.* 2013). This may lead to more snowfall, but at the same time, warming will increase melt rates and the combined effect on the length of snow cover period is uncertain. This confirms the need for continued monitoring of snow variables, especially in the light of numerous, recent publications indicating the importance of GEM snow observations for various climate feedback related processes.

In the recently published GEM special issue in AMBIO, Lund *et al.* (2017) found that snow depth and timing of snow melt control arctic surface energy balance. Longer snow-free period increase melting of glaciers and may promote tundra permafrost thaw. In addition, Pirk *et al.* (2017) showed the importance of the timing of snowmelt for tundra methane emissions in Zackenberg and Kobbefjord, which has also been found to regulate arctic CO_2 exchange dynamics (Lund *et al.* 2012). Likewise, snow characteristics regulate inter-annual variation in vegetation phenology and greenness (Westergaard-Nielsen *et al.* 2017).

Data from the GeoBasis and ClimateBasis programmes are used in international initiatives such as the Global Terrestrial Network for Permafrost (GTN-P), FLUXNET and World Hydrological Cycle Observing System (WHYCOS).

References:

Collins, M., *et al.* 2013. Long-term climate change: Projections, commitments and irreversibility. In Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report on the intergovernmental panel on climate change. Ed. Stocker *et al.*, 1029–1136. New York: Cambridge University Press.

Lund, M., *et al.* 2012. Trends in CO_2 exchange in a high Arctic tundra heath, 2000-2010. Journal of Geophysical Research 117: G02001. DOI:10.1029/2011JG001901.

Lund, M, *et al.* 2017. Spatiotemporal variability in surface energy balance across tundra, snow and ice in Greenland. Ambio, vol 46, no. Suppl. 1, pp. 81-93. DOI: 10.1007/s13280-016-0867-5

Pedersen, SH, *et al.* 2016. Spatiotemporal characteristics of seasonal snow cover in Northeast Greenland from in situ observations. Arctic, Antarctic, and Alpine Research, vol. 48, no. 4, pp. 653-671.

Pirk, N, *et al.* 2017. Toward a statistical description of methane emissions from arctic wetlands. Ambio, vol. 46, no. Suppl 1, pp. 70-80.

Westergaard-Nielsen, A., *et al.* 2017. Transitions in high-Arctic vegetation growth patterns and ecosystem productivity tracked with automated cameras from 2000 to 2013. Ambio, vol. 46, no. Suppl. 1, pp. S39-S52.

Figure 2. Snow depletion curves from the Zackenberg valley (left panel), computed based on oblique RGB images derived from an automatic photo monitoring system overlooking the valley (right panel). The photo was taken 16 June 2016 – indicated by arrow in top panel – indicated by arrow in the graph below – with an associated snow cover of 47 %.

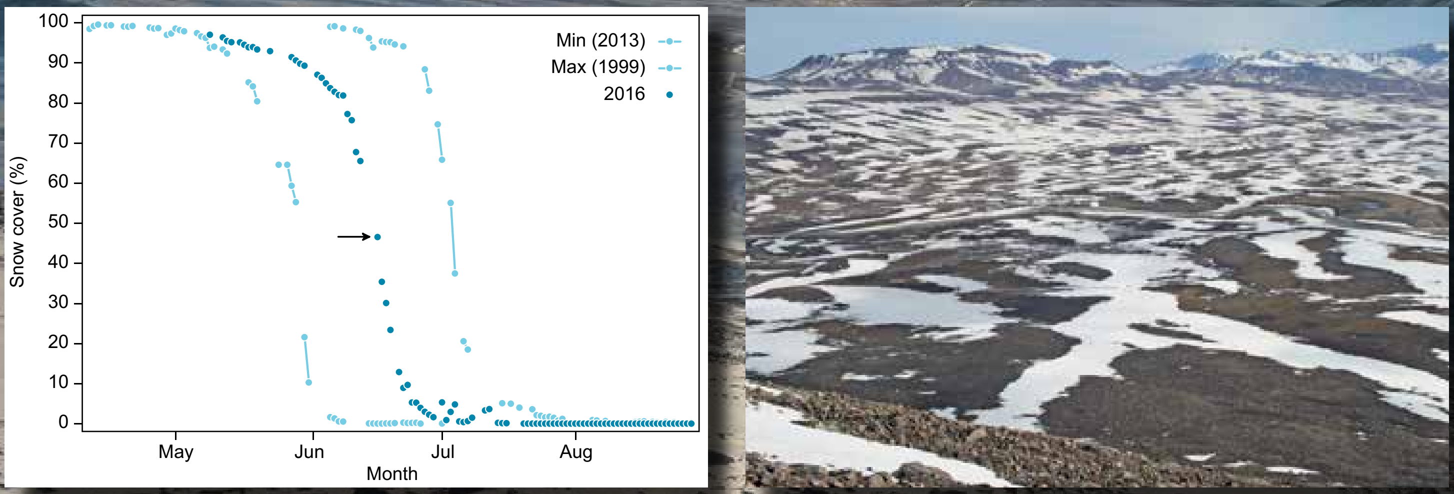

Photo: Kirstine Skov.

DRIVERS AND SCALE OF VEGETATION

Vegetation phenology (periodic plant life cycle events) is very sensitive to climatic changes and influences climate feedbacks by affecting surface properties such as albedo, energy balance fluxes and surface roughness. Here we report general trends of phenology along gradients at a greenlandic scale, combined with local observations in order to identify key differences and drivers.

The annual cycles in vegetation phenology occur simultaneously at a number of scales from the burst of individual buds to large-scale gradients along elevations or east- and west coasts of Greenland. Therefore GeoBasis and BioBasis monitor the vegetation dynamics with both in-situ plot scale measurements in Nuuk, Zackenberg, and Disko (GeoBasis only), and at regional scale with remotely sensed vegetation indices.

On a regional spatial scale, the vegetation phenology is closely linked to temperature. The latitudinal gradients are marked, which results in a shorter growing season and an earlier fall when moving north. The east coast has a less variable start of season along the latitudinal gradient mainly due to the vegetated areas being close to glaciers and more exposed to open sea from 68 °N and southwards (Fig. 1). Secondly, the consistent southward transport of sea ice along the east coast also results in less latitudinal variation in the start of the growing season, combined with an overall shortening of the growing season. The influence of sea ice on the west coast is more spatially variable between years, with the strongest link between sea ice concentration and vegetation phenology from 67-71 °N (Fig. 2). Thirdly, local factors such as elevation affects phenology (e.g. shorter growing seasons at higher altitudes), but this effect seems to diminish when moving northward (Karami *et al.* 2017)

At the site-specific scale, vegetation greenness patterns can also be used to estimate the general seasonality. Working on a site also allows for direct comparisons between vegetation greenness patterns and the ambient biotic and abiotic conditions. The start of the growing season is closely linked to the winter snow regime, specifically the timing of snowmelt. In years with a late snowmelt we observe a relatively higher peak value in greenness for a *Cassiope* dominated heath. Since the greenness pattern is linked to gross primary productivity, it suggests that the vegetation to some extent compensates for a shorter growing season (resulting from a later start of season in snow-rich years) by increasing the productivity in peak summer.

From the site-specific data in Zackenberg, it is also evident that parts of the vegetation communities are water-limited in the late growing season (Fig. 3) (Westergaard-Nielsen *et al.* 2017). Increased temperatures might increase the potential growing season length, but the actual growing conditions will be highly dependent on water availability throughout the summer and autumn, both directly and indirectly by mobilising nutrients.

Most of the vegetation phenology data is freely available through the GEM database, and the remotely sensed metrics will be available in the future through the GEM remote sensing initiative.

Story by:

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[2]Greenland Institute of Natural Resources

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*Corresponding author, awn@ign.ku.dk

Data source:

GEM ClimateBasis – Meteorology

GEM GeoBasis – Automatic Photo Monitoring

GEM GeoBasis – Meteorology

GEM GeoBasis – Soil water

GEM BioBasis – In-situ phenology metrics

PHENOLOGY IN GREENLAND

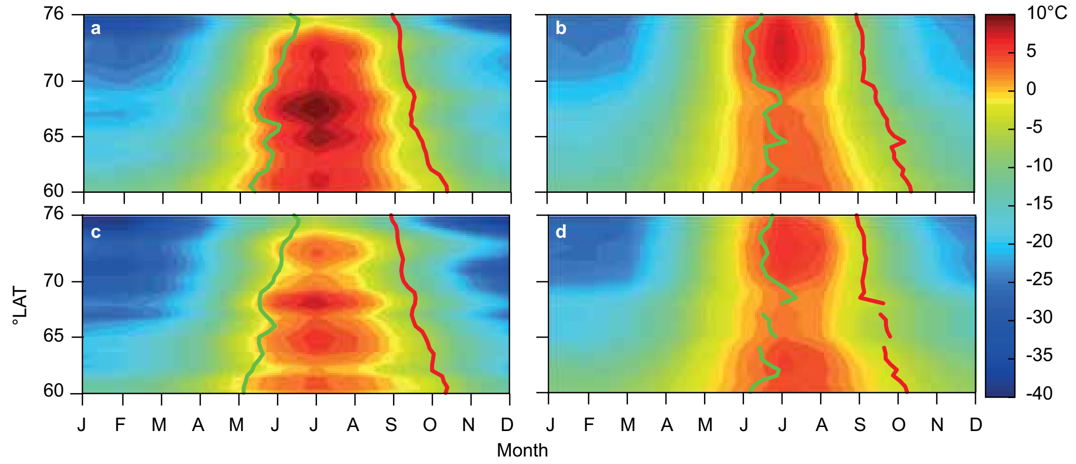

Figure 1. Annual variations of surface temperatures for west Greenland (a, c) and east Greenland (b, d) . Average start of the growing season is marked by the green line, average end of growing season is marked by the red line. a and b are direct measurements, while c and d are topographically standardised to avoid biases related to mean altitude at the different latitudes.

References:

Karami, M., *et al*. 2017. Vegetation phenology gradients along the west and east coasts of Greenland from 2001 to 2015. Ambio, 46(1), 94-105.

Westergaard-Nielsen, A., *et al*. 2017. Transitions in High-Arctic vegetation growth patterns and ecosystem productivity tracked with automated cameras from 2000 to 2013. Ambio, 46(1), no. Suppl. 1, pp. S39-S52.

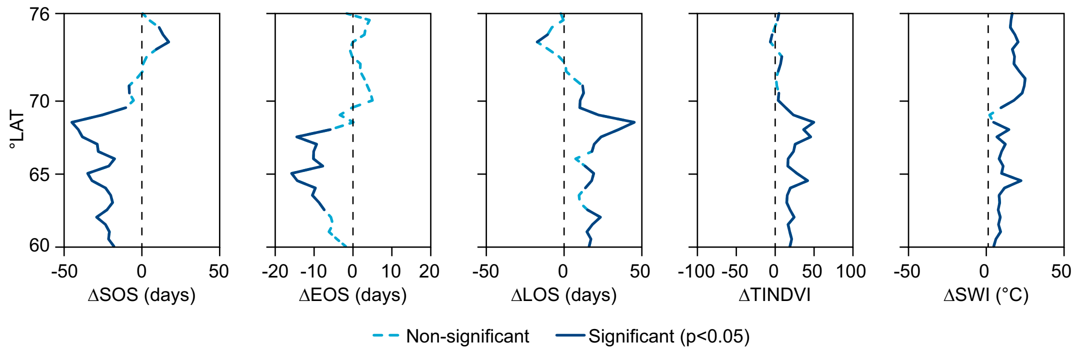

Figure 2. Discrepancies (Δ) in start of season (SOS), end of season (EOS), length of season (LOS), time-integrated NDVI (TINDVI), and summer warmth index (SWI) between the east and west coast of Greenland. The values, here exemplified by SOS, are computed as (SOSWEST – SOSEAST), meaning that negative values indicate earlier SOS in west Greenland. Dotted lines are not significant, full lines are significant ($p < 0.05$).

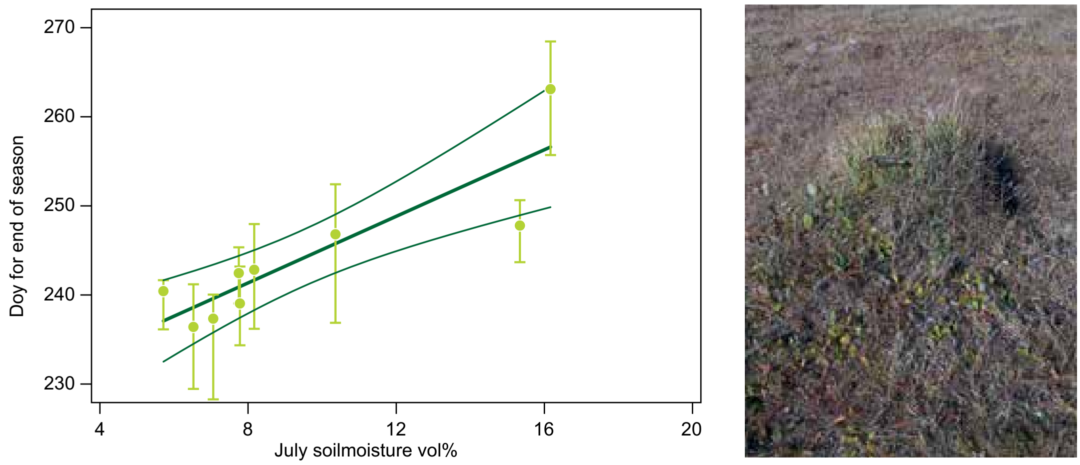

Figure 3. Timing of end of fall and soil moisture in July with a linear model fit and 95% confidence intervals. Error bars indicate model uncertainty in end of fall estimation. The photo is showing the breakdown of a muskox head, and how the nutrients released stimulates the growth of grasses, i.e., not only water affects the phenology (photo: A. Westergaard-Nielsen).

20 YEARS OF METHANE MEASUREMENTS

When measurements of methane fluxes started 20 years ago in Zackenberg only rudimentary knowledge existed about the controlling processes and what role the permafrost played. Since then, both the techniques and our understanding has developed to a level where we can explain most of the seasonal pattern, and estimate the effects of changing climate on the production.

For several decades methane (CH_4) production in cold soils of the Globe has attracted interest. The strong greenhouse effect and the potential effect that increasing temperatures in the Arctic, and the associated thawing of permafrost, may have on the emissions (climate feedback mechanism), makes CH_4 interesting in an arctic context. These connections were also the reason why CH_4 flux measurements started 20 years ago in the High-Arctic environment at Zackenberg research station. In 1997 bi-weekly measurements of CH_4 flux where carried out in the summer using both static chambers (Christensen *et al.*, 2000) over different landscape components and using the, for that time, advanced eddy covariance technique (Friborg *et al.*, 2000), integrating the flux from the wet fen in the valley.

The interpretation of the data from that time, allowed establishing a connection between CH_4 flux and seasonal temperature trends, active layer and water table position, which, in combination, also explained most of the variability in CH_4 exchange between the different plant communities in the valley.

Due to prolonged field season measurements in 2007, we now know, that summer measurements alone do not tell the full story about methane production in the cold soils of the Arctic and that fluxes during autumn may in some years surpass that magnitude of summer time fluxes, and due to different mechanisms than those considered in the earliest measurements. In 2008, Mastepanov *et al.* (2008) published results from automated chambers that revealed surprisingly high CH_4 emission rates during autumn, which could not be explained by the conventional understanding of methane production in the soil. The autumn measurements emphasised the role of permafrost in the emission pattern, and could explain the high release as a squeeze out of CH_4 trapped between the permafrost and the frozen surface. The prolonged measurement campaign in 2007 allowed this discovery, which could not have been made from summer season measurements alone.

The same year, an identical automatic chamber system was installed at the GEM site in Kobbefjord, close to the greenlandic capital Nuuk. The site does not have any permafrost present and annual temperature is on average 10 °C warmer than at Zackenberg. As shown in a recent publication by Pirk *et al.*,(2017), the different environmental conditions has a distinct impact on the measured methane emission (see Fig. 1). The lack of permafrost at Kobbefjord is the likely reason for the "missing" autumn burst. The autumn burst appears as component C (Fig. 2). Pirk *et al.* divide the seasonal flux pattern into three components, where A is related to the spring thaw period, B to the mid-summer production and C being the above mentioned freeze-in component.

Despite that inter annual variation in total CH_4 emissions still remains a challenge to model and predict, the long data series from the two GEM sites has enabled us to find and characterise the methane emission over the three warmest seasons. This would not have been possible without GEMs systematic and long term approach.

Story by:

Thomas Friborg[1]*, Norbert Pirk[2], Magnus Lund[3], Birger U. Hansen[1], Charlotte Sigsgaard[1], Kirstine Skov[3], Mikhail Mastepanov[2,3] & Torben Christensen[2,3]

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Data source:

GEM GeoBasis – Flux monitoring

GEM GeoBasis – Meteorology

GEM GeoBasis – Soil Properties

HAS SHARPENED OUR UNDERSTANDING

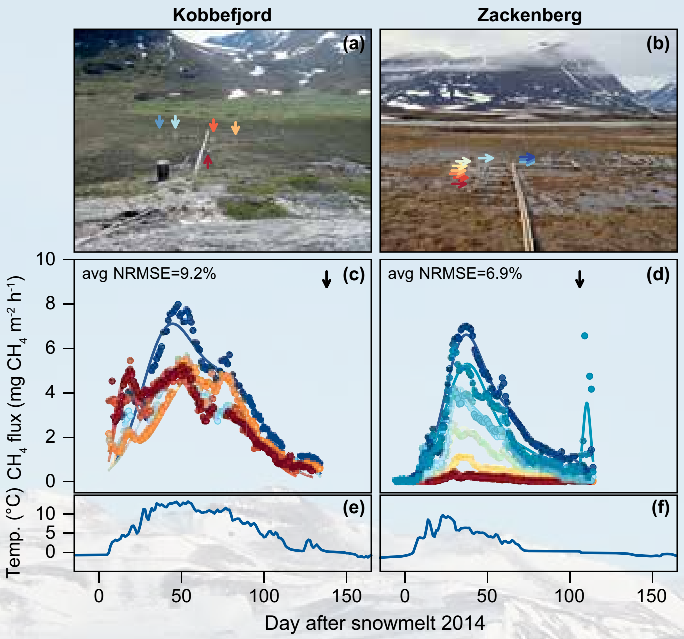


Figure 1. Site photos, fluxes, and soil temperatures. Kobbefjord (left column) on July 14, 2015 (Photo: Hanna Axén). Zackenberg (right column) on July 4, 2012. Modified from(Pirk et al.,2017).

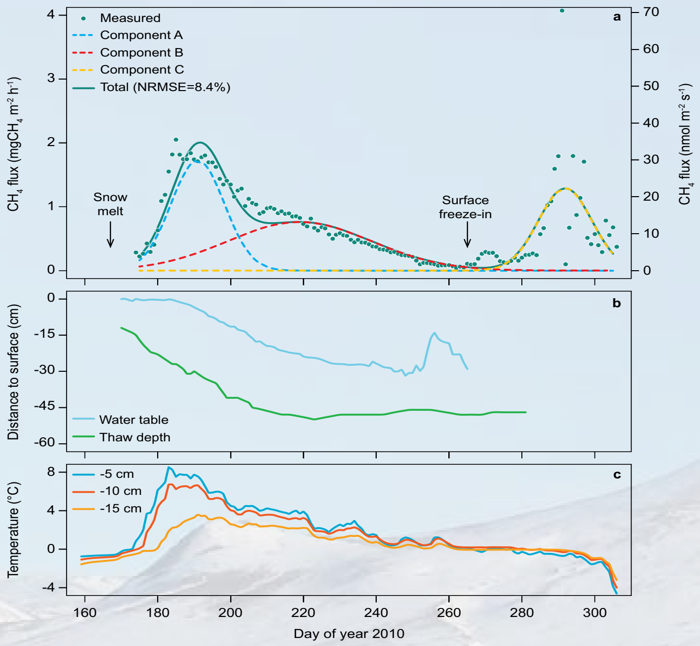


Figure 2. (a) CH_4 chamber flux measurements at Zackenberg, 2010, show a steep rise of fluxes in the first month after snowmelt, which is largely attributed to the first Gaussian component A. Figure 2b shows that the thaw depth was increasing fastest during this period. The much wider component B describes the fluxes in the second half of the growing season. Finally, component C describes the autumn emissions during the freeze-in period, where large emission bursts occurred. (c) soil temperatures at different depth. (Pirk et al.,2017)

References:

Christensen,T.R., *et al*. 2000. Trace gas exchange in a high-arctic valley 1: Variations in CO_2 and CH_4 fluxes between vegetation types. Global Biogeochem. Cycles Vol. 14, No. 3.

Friborg,T., *et al*. 2000. Trace gas exchange in a high-arctic valley 2: Landscape CH_4 fluxes measured and modelled using eddy correlation data. Global Biogeochem. Cycles Vol. 14, No. 3.

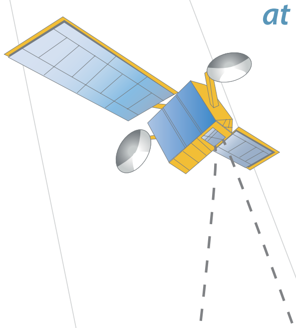
Mastepanov,M., *et al*. 2008. Large tundra methane burst during onset of freezing. Nature 456.7222: 628-30.

Pirk,N., *et al*. 2017. Toward a statistical description of methane emissions from arctic wetlands. Ambio 46.1: 70-80.

Photo: Kirstine Skov.

GEM LAUNCHES
NEW REMOTE SENSING INITIATIVE,

As part of a new GEM remote sensing initiative, calibrated and gap-filled skin temperatures will be produced and made publicly available. The temperature products will consist of daily gridded values for the whole ice-free part of Greenland, as well as site-specific skin temperatures at high spatial resolution.



Skin temperature recordings from satellites offer spatially gridded temperatures with a very low modelling component, thus offering measured reference data. Processes at the surface and vegetation canopy will in some cases be closer linked to skin temperature than air temperatures, such as release of biogenic volatile organic compounds, metabolism in organisms living in the canopy, leaf thermal regime, and temperature exchange between the ground and lower atmosphere (Körner 2006). The datasets will also allow for unique studies at landscape to regional spatial scale of changes in temperature trends, and related processes and feedback mechanisms.

Remotely sensed skin temperature will however be limited by cloud cover, which for e.g. MODIS-based data results in a severe cold bias in high northern regions (Westermann *et al*. 2011) since the temperature signal is from cloud free days only. The aim of the GEM-based surface temperature products is to correct for potential biases by gap-filling the satellite-based data series during days with cloud cover. This is achieved by implementing empirical relationships between in-situ skin temperature from the GEM stations, and the net shortwave radiation (Karami *et al*. 2017). Two different products will be initiated: a MODIS-based dataset at daily temporal resolution covering the ice-free part of Greenland at 250 or 1000 m resolution, and a site-specific product based on Sentinel-2 at a spatial resolution of 20 m, and bi-monthly or better temporal resolution.

Here we present an early draft based on daily values from Nuuk (2010-2012), at 1000 m spatial resolution (Fig. 1). It can be seen from the time series, that the original dataset suffers from data gaps, as well as a cold bias during the winter, and a slight warm bias during summer. The coming steps will consist of a downscaled version at 250 m spatial resolution, based on in-situ measurements of skin temperature and surface class relationships, as well as a longer time-series covering the period 2001-2016.

Read more about the GEM Remote sensing initiative in the GEM Strategy 2016-2021 (http://g-e-m.dk/gem-publications/gem-reports/).

Story by:

Andreas Westergaard-Nielsen[1]*, Mojtaba Karami[1], Michele Citterio[2] & Jakob Abermann[3]

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*Corresponding author, awn@ign.ku.dk

Data source:

GEM ClimateBasis – Meteorology

GEM GeoBasis – Meteorology

INCLUDING SKIN (SURFACE) TEMPERATURE PRODUCTS

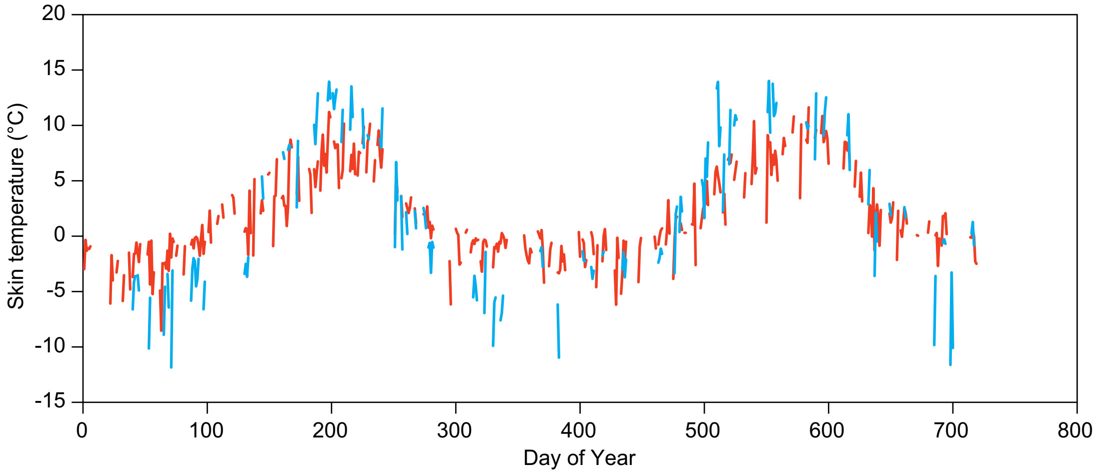

Figure 1. Annual variations of skin temperatures for Nuuk, Greenland. The blue lines depict the original dataset, while the red lines are gap-filled where possible and de-biased from cloud cover effects.

References:

Körner, C. 2006. Significance of temperature in plant life. Book chapter 3 in *Plant Growth and Climate* Change. Blackwell Publishing Ltd.

Westermann, S. *et al*. 2011. Systematic bias of average winter-time land surface temperatures inferred from MODIS at a site on Svalbard, Norway. *Remote Sensing of Environment 118*, 162-167.

Karami, M. *et al*. 2017. Vegetation phenology gradients along the west and east coasts of Greenland from 2001 to 2015. Ambio, 46(1), 94-105.

The flux measurements and energy exchange stations (here from Kobbefjord) with surface temeprature sensors and radiation pyranometers (rightmost mast) are central for the correction of remotely sensed skin temperatures, especially in cloudy conditions (Photo: Antti Lauri).

Annual Report Card 2016

ARCTIC FOOD WEBS ARE MUCH MORE

Untangling the interactions between organisms in ecosystems is crucial for our understanding of how ecosystems work and how they may respond to environmental change.

Since the establishment of Zackenberg research station in 1995, mapping out the interactions between species has been a major focal point. Through the standardized monitoring effort over the past decades at the GEM sites, we have acquired a unique insight into how the abundance of species and communities in the arctic ecosystem varies both with season and between years. The on-going monitoring thus keeps track of the status and trends of the various species and communities. However, only by merging the knowledge acquired through the monitoring with knowledge obtained via process-oriented research studies we will eventually arrive at the most complete understanding on how the arctic ecosystem actually works.

A number of interesting insights into species interactions have emerged from the research and monitoring conducted particularly at Zackenberg in High-Arctic Greenland. Though High-Arctic interaction webs traditionally are regarded as being very simple compared to the very complex interaction webs at lower latitudes, our in-depth mapping of these has revealed that the High-Arctic interaction webs are actually much more complex than previously envisaged: as shown in the figure, the biotic interactions surrounding a single plant species (*Dryas octopetala* × *integrifolia*) is indeed rather complex and includes multiple trophic levels and ecosystem processes. Moreover, as observed in most ecosystems, the High-Arctic interaction webs are dominated by their arthropod component, but the dominance is much more pronounced in the High-Arctic. Furthermore, the dynamics of the individual species in the interaction webs are affected by the changing environmental conditions, and the interactions at one trophic level may cascade onto other trophic levels. Finally, as species may respond differently to common environmental drivers, the on-going environmental change in the High-Arctic may decouple interacting between species, thus hampering ecosystem services such as pollination.

During the process of dissecting the interactions webs, we applied both traditional and novel approaches. Particularly the use of molecular tools has expanded our knowledge about the interactions between species in the interaction webs, and such tools will ultimately feed back into the monitoring program and improve our capacity for species identification and thus understanding of the ecosystem.

Story by:

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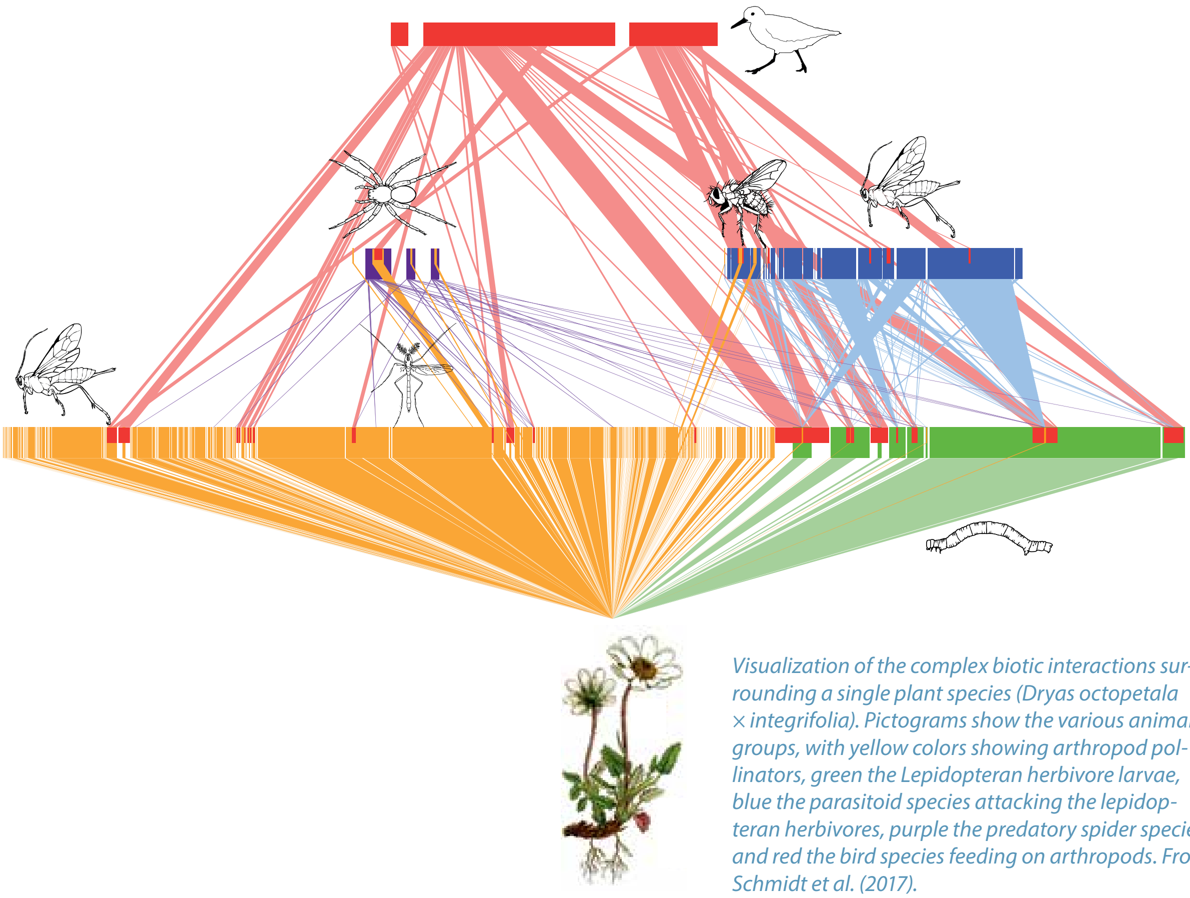
Data source:

GEM BioBasis – Arthropod emergence, Plant flowering phenology, Avian breeding phenology, Lemming Abundance, Muskox abundance, Arctic fox abundance and reproduction, Numerous research projects

COMPLEX THAN PREVIOUSLY ENVISAGED



Visualization of the complex biotic interactions surrounding a single plant species (Dryas octopetala × integrifolia). Pictograms show the various animal groups, with yellow colors showing arthropod pollinators, green the Lepidopteran herbivore larvae, blue the parasitoid species attacking the lepidopteran herbivores, purple the predatory spider species, and red the bird species feeding on arthropods. From Schmidt et al. (2017).

Sticky flowers mimicking real Dryas flowers used to map out the plant-pollinator network surrounding this species (Photo: Malin Ek).

Reference

Schmidt *et al*. 2017. Interaction webs in arctic ecosystems: Determinants of arctic change? Ambio 46: S12-S25. http://link.springer.com/article/10.1007/s13280-016-0862-x

Annual Report Card 2016

INSTANT AND SUBSEQUENT EFFECTS OF LARVAL OUTBREAKS

Defoliation, changes in CO_2 exchange, changes in the production of catkins and changes in greenness visible from space are some of the effects of a larval outbreak in Kobbefjord in 2011.

Eurois occulta larvae (Photo: Katrine Raundrup).

Eurois occulta is a noctuid moth with a Holarctic distribution and in Greenland it is found northwards to Ilulissat and Qeqertarsuaq on the west coast and to Skjoldungen on the east coast. In 2011, an outbreak of the moth larvae was observed in the Kobbefjord monitoring area in west Greenland and though outbreaks have been known to occur historically, the instant and subsequent effects have not been studied previously.

As a direct effect of the outbreak, the vegetation was grazed and e.g. most *Salix* (willow) plants were left without any foliage. This resulted in an immediate reduction of photosynthesis and hence a reduced uptake of CO_2 from the atmosphere corresponding to a decreased carbon uptake of more than 1000 tonnes C at the catchment scale (32 km^2). Furthermore, the larvae grazed the catkins leaving the *Salix* without reproductive seeds. The defoliation of the vegetation resulted in plummeting measurements of the vegetation greenness, i.e. the normalised difference vegetation index (NDVI).

The *E. occulta* larvae disappeared as abruptly as they appeared and in 2012 none were found. But the effects of the outbreak were still evident. *Salix* regrew with more foliage than before (evident from the NDVI measurements), but did not produce any catkins. With the excessive regrowth, the CO_2 uptake more than compensated for the lowered uptake in 2011.

During the following years, *Salix* started producing catkins again and in higher numbers than ever seen before. The compensatory growth as a response to the intense grazing and the resulting changes in CO_2 exchange indicate the ecosystems ability to recover rapidly after the larvae attack. The tundra ecosystem may therefore, not be as vulnerable as anticipated when it comes to these extreme outbreak events.

We were able to use satellite derived NDVI measurements as a proxy for outbreak events both in Kobbefjord and in the Kangerlussuaq inland area further north. This is the first time that remote sensing has been used to detect and map insect outbreaks in tundra ecosystems. Using remote sensing tools to detect these types of extreme events is highly valuable, but without long-term monitoring, ground truthing to identify drivers (e.g. larvae, fire, etc.) and data collection on plot scale to understand processes it would be impossible to connect the two realms without losing relevant information on the underlying causes.

Salix glauca (Photo: Katrine Raundrup).

Story by:

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[2]Aarhus University

[3]University of Copenhagen

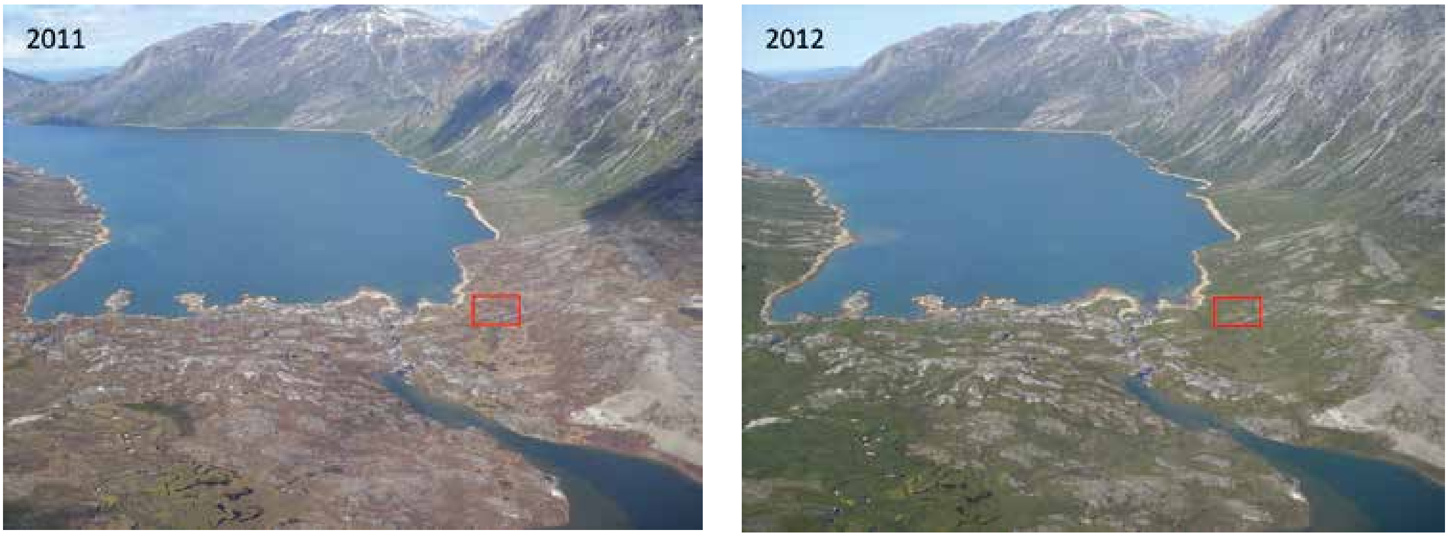
*Corresponding author, kara@natur.gl

Data source:

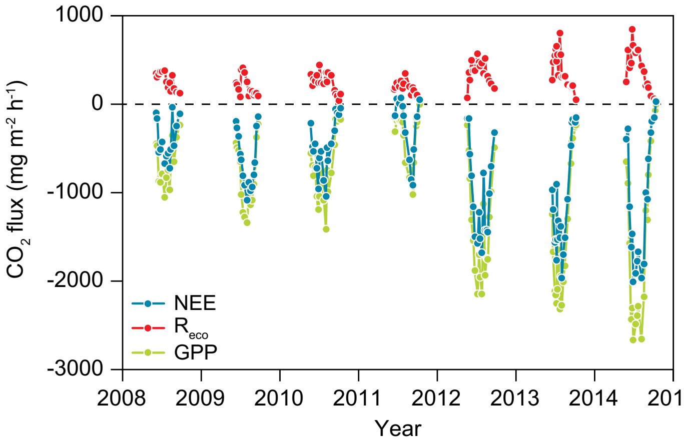
GEM BioBasis – Arthropod emergence, Plant phenology, Plot level CO_2 flux measurements

GEM GeoBasis – Automatic photo monitoring

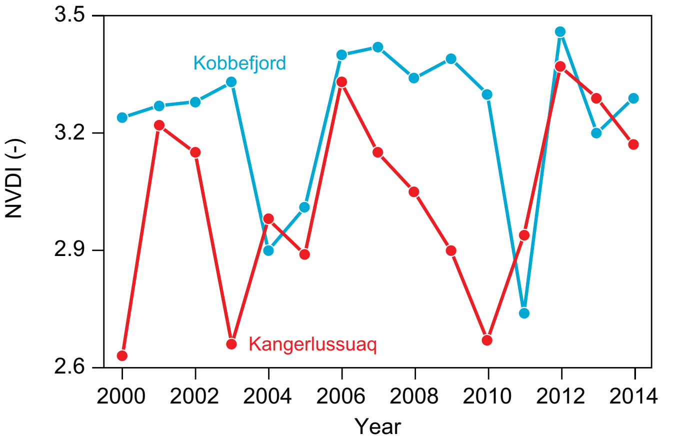
ON ECOSYSTEM PRODUCTIVITY AND CO$_2$ EXCHANGE



Direct effects of the Eurois occulta outbreak in 2011. Photos from an automatic camera in Kobbefjord. The red square indicates the approximate location of the experimental plots.



Daytime CO$_2$ flux measurements of net ecosystem exchange (NEE) and ecosystem respiration (R$_{eco}$) in 2008-2014. Gross primary production (GPP) calculated as the difference between NEE and R$_{eco}$.



Normalized difference vegetation index (NDVI) in Kobbefjord and Kangerlussuaq derived from MODIS sensor on board the Terra satellite platform. The monitoring programme in Kobbefjord was initiated in 2007.

Reference:

Lund *et al.* 2017. Larval outbreaks in west Greenland: Instant and subsequent effects on tundra ecosystem productivity and CO$_2$ exchange. Ambio 46: S26-38. http://link.springer.com/article/10.1007/s13280-016-0863-9

Annual Report Card 2016

MARINE TERMINATING GLACIERS

The GEM marine monitoring programme links prolonged annual summer phytoplankton productivity to discharge of glacial meltwater at the base of marine terminating glaciers.

Greenlandic Fjord (Photo: Mie S. Winding).

Story by:

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[2] Aarhus University

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Data source:

GEM MarineBasis-Nuuk (Particulate Pelagic Primary Production, Water Temperature)

GEM ClimateBasis-Nuuk (Short wave incoming radiation)

Fjords in Greenland constitute a transition zone between land and the Greenland Ice Sheet, and the ocean. Fjords are characterized by sustaining a rich and diverse plant and animal life mainly fuelled by microscopic phytoplankton, displaying a photosynthetic productivity (i.e. primary production) highly depended on light and nutrient availability.

Marginal light availability during winter, due to the low solar angle at high latitudes, therefore limits phytoplankton productivity in winter. Increasing light conditions in spring combined with high nutrient concentrations in the water results in a rapid increase in phytoplankton productivity (phase I, Juul-Pedersen *et al.* 2015). This annual phytoplankton spring bloom event is characteristic of high latitude marine ecosystems leading to a depletion of nutrients in the upper part of the water column, where light conditions can sustain phytoplankton production. The intense spring bloom is therefore often followed by a decrease in productivity due to nutrient limitations, despite high light availability in summer (phase II).

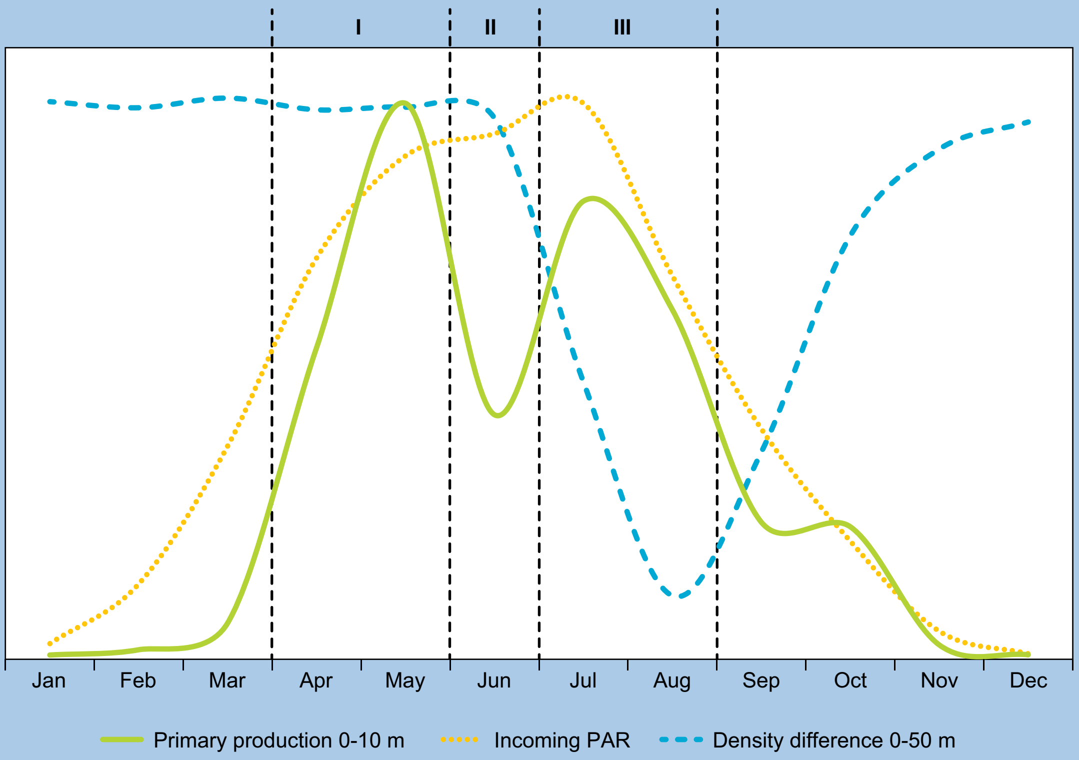
Phytoplankton production often shows a moderate increase again during summer, i.e. a summer bloom, as regenerated nutrients in the water or new nutrients from land becomes available. The time series on phytoplankton productivity collected by the GEM Marine monitoring program displayed a prolonged annually reoccurring summer bloom (phase III, Juul-Pedersen *et al*. 2015).

Studies of the physical oceanographic conditions of the fjord revealed that sub-glacial melt water introduced into the fjord at the base of marine terminating glaciers, i.e. subglacial discharge (Mortensen *et al.* 2011, 2013), entrained large amounts of ambient nutrient rich bottom water on its way towards the surface. The introduced nutrients resulted in the prolonged summer bloom observed in the marine time series (Juul-Pedersen *et al.* 2015), a process that has later been described in greater detail (Meire *et al*. 2015). Decreasing light levels during autumn reduces primary production towards the winter conditions.

Marine sampling (Photo: Helle Torp Christensen).

The extended summer phytoplankton productivity relies on the sub-glacial discharge unique to marine terminating glaciers found in many of the Greenlandic fjords. In the last decade, warming has increased the release of melt water from the Greenland Ice Sheet (Bamber 2012). As exemplified by the data from Nuuk, this likely influence nutrient availability and production of these systems. If these glaciers retreat and eventually become land terminating glaciers, it is likely to affect the summer productivity of these fjord systems with subsequent effects on the coastal ecosystems.

PROLONG FJORD PRODUCTIVITY IN SUMMER



A conceptual illustration based on monitoring data of primary production (0–10 m), incoming light (PAR) and water density difference between 0 and 50 m as a measure of freshwater (melt water) in the upper water column. The figure is adapted from Juul-Pedersen et al. 2015. Note that the density difference is displayed on a reverse scale.

References:

Juul-Pedersen, T. *et al*. 2015. Seasonal and interannual phytoplankton production in a sub-arctic tidewater outlet glacier fjord, west Greenland, Mar. Ecol.-Prog. Ser. 524: 27–38. doi:10.3354/meps11174.

Meire, L. *et al*. 2015. Glacial meltwater and primary production are drivers of strong CO_2 uptake in fjord and coastal waters adjacent to the Greenland Ice Sheet. Biosciences 12: 2347-2363. doi: 10.5194/bg-12-2347-2015

Bamber, J. *et al*. 2012. Recent large increases in freshwater fluxes from Greenland into the North Atlantic. Geophysical Research Letters 39: 8–11. doi:10.1029/2012GL052552.

Marine terminating glacier (Photo: Helle Torp Christensen).

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GLACIAL MELT

WATER AS A POTENTIAL KEY

Freshwater runoff from the Greenland Ice Sheet can be an important driver influencing zooplankton community structure in greenlandic fjords.

Seasonal sea ice melting combined with runoff from the Greenland Ice Sheet results in large summer freshwater input to the coastal marine environment. The freshwater input influences the physical features of greenlandic fjords and coastal zone oceanography with potential consequences for the biological processes in the area.

Zooplankton is a very important food chain component in the marine areas of the Arctic and is an important prey item for fish, sea birds and marine mammals. The copepod community structure and species composition is largely dependent on hydrographic, physical and chemical factors and therefore changes in these parameters would affect energy flow through the entire food web. Changes of energy flow through the food web may lead to dramatic changes in ecosystem structure and function in the future.

Physical, taxonomic and functional differences in the plankton community in Young Sound,

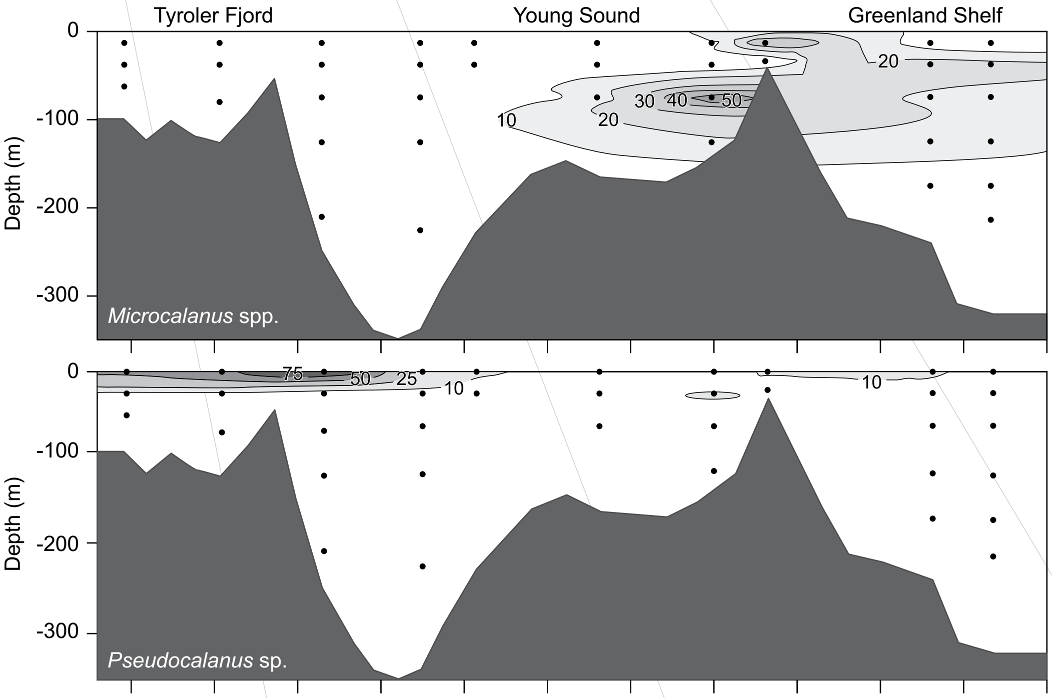

Figure 1. Distribution of Microcalanus spp. and Pseudocalanus spp. as abundance (Ind m^3) from the inner part the fjord, close to the Greenland Ice Sheet to the coastal region. Dots represent sample interval sampled with a 45 mm net. The figure is adapted from Arendt et al. 2016.

Story by:

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Data source:

GEM MarineBasis-Zackenberg (zooplankton species composition)

DRIVER FOR COASTAL ECOSYSTEM CHANGE

NE Greenland, was investigated along a transect from the inner fjord close to the Greenland Ice Sheet towards the coastal region in late summer (Arendt *et al.* 2016). The fjord is influenced by runoff from land-terminating glaciers that separate the surface layer from cold underlying more salty waters.

Along the transect both taxonomic and functional differences were found in the zooplankton communities. The stations along the transect show a gradual change and can be divided into fjord stations and coastally affected stations based on the mesozooplankton composition, as observed by a gradual change in copepod species composition from the inner fjord towards the coastal region.

Differences in copepod species composition between the inner fjord and the coastal region can be explained by the occurrence of key species like *Microcalanus* spp., *Pseudocalanus* spp., *Oncaea/Triconia* sp. and *Oithona similis*. The most profound difference in the mesozooplankton community structure along the transect was seen in the abundance of the copepods *Microcalanus* spp., which were present in the coastal region in the upper 100 m (Greenland Shelf, Fig. 1), and *Pseudocalanus* spp., which only occurred in the surface layers and mainly in the inner part of the fjord (Tyroler Fjord, Fig. 1). Likewise, functional differences in grazing pressure and top down control of primary production differ with microzooplankton grazing in the inner part of the fjord, whereas *Calanus* copepods played an important role in the coastal region (Arendt *et al.* 2016).

The presence of glacial melt water has also been shown to influence zooplankton community structure at the Nuuk monitoring site (Arendt *et al.* 2010) 51 degrees W, as well as benthic diversity (Sejr *et al.* 2009) and local patterns of primary production (Sejr *et al.* 2009). Increasing evidence thus suggests that rapid increase in the melting of the Greenland Ice Sheet could directly influence several components of the coastal ecosystem and thus may be a more important driver of ecosystem change than for examples change in seasonal ice cover.

References:

Arendt, K.E., *et al.* 2016. Glacial meltwater influences on plankton community structure and the importance of top-down control (of primary production) in a NE Greenland fjord. Estuarine, Coastal and Shelf Science 183: 123-135

Arendt, K. E., *et al.* 2010. Differences in plankton community structure along the Godthåbsfjord, from the Greenland Ice Sheet to offshore waters. Marine Ecology-Progress Series 401: 49–62. doi:10.3354/meps08368.

Sejr, M. K., *et al.* 2009. Macrobenthic species composition and diversity in the Godthåbsfjord system, SW Greenland. Polar Biology 33: 421–431. doi:10.1007/s00300-009-0717-z.

(Photos: Mie S. Winding).

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GREENLAND
GLACIERS SHRINKING

Approximately 19,000 glaciers and ice caps exist in the stretch of land between the Greenland Ice Sheet and the sea. These glaciers are much smaller than the ice sheet but their average mass loss per unit area is higher. They have been found to account for up to 10% of the world's glaciers contribution to global sea level rise. The GEM GlacioBasis programme monitors 3 of the 5 glaciers currently monitored in Greenland.

Glaciers and ice caps independent from the Greenland Ice Sheet extend over 88,000 km^2, equivalent to 5% of the area covered by ice sheet (Citterio & Ahlstrøm, 2013). Since the earliest known observations in 1892/1893, surface mass balance has been measured at least once at 24 of these ca. 19,000 glaciers (Machguth *et al.*, 2016). Just 5 glaciers were monitored as of 2015, two of them by GEM: A.P. Olsen ice cap near Zackenberg and Qasigiannguit glacier near Nuuk. Lyngmarksbreen near Arctic Station was added as a third site in 2016 to close a gap in the regional coverage.

Extended in situ time series of glacier mass balance and near-surface climate are needed to calibrate and validate Greenland-wide estimates of glacier mass balance from climate models and remote sensing. This is particularly important when regional climate models need to be downscaled in regions characterised by steep elevation and mass balance gradients (Citterio *et al.*, 2017). Recent studies found that Greenland's glaciers and ice caps have been losing mass at a rate of 27.9 ±10.7 Gt per year to 38 ±11 Gt per year, and thus constitute about 14% of the entire ice mass loss from Greenland, while they only cover less than 5% of the total glacierised area (Bolch *et al*. 2013, Colgan *et al*. 2015).

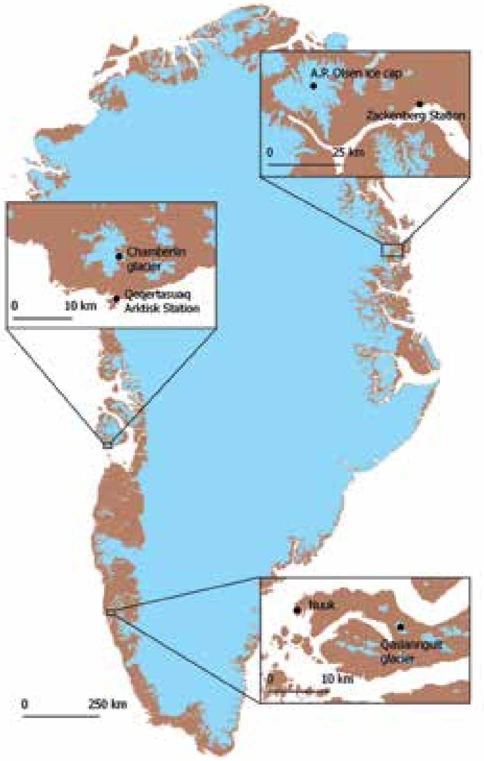

Figure 1. Map of Greenland showing the ice caps and glaciers surrounding the ice sheet. The inserts provide enlarged maps over the locations of the three glaciers monitored by GEM GlacioBasis.

Story by:

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Data source:

GEM GlacioBasis surface mass balance and near surface weather datasets, PROMICE glaciers map

FASTER THAN THE ICE SHEET

Compared to the Greenland Ice Sheet, the faster response and higher sensitivity to climate forcing is a result of the smaller size, lower average elevation and closer proximity of glaciers and ice caps to ice-free land and sea. It is also becoming clear that a tipping point has been crossed and that their smaller and shallower firn layer has lost much of its meltwater refreezing capacity, resulting in higher runoff which is irreversible under the current climate (Noël *et al.*, 2017).

The GEM GlacioBasis timeseries, combined with glacier and ice sheet maps produced by PROMICE, contributed to these studies and are freely available online through the GEM and PROMICE databases and websites (www.data.g-e-m.dk, www.promice.org).

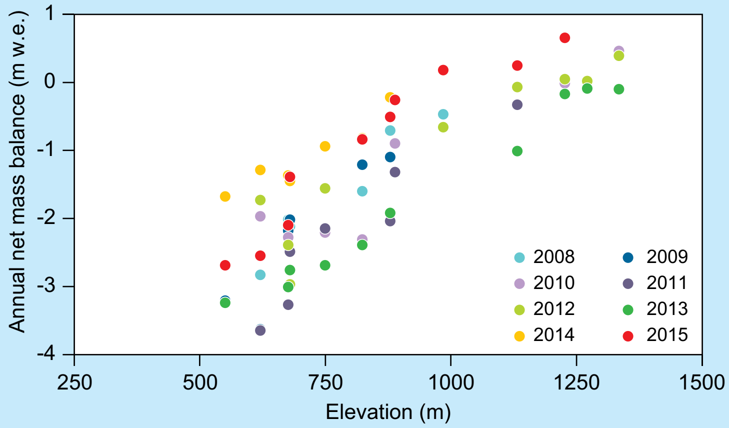


Figure 2. Surface mass balance observations from the GEM GlacioBasis ablation stakes network on A.P. Olsen ice cap, NE Greenland. Data for 2016 becomes available after the 2017 field campaign.

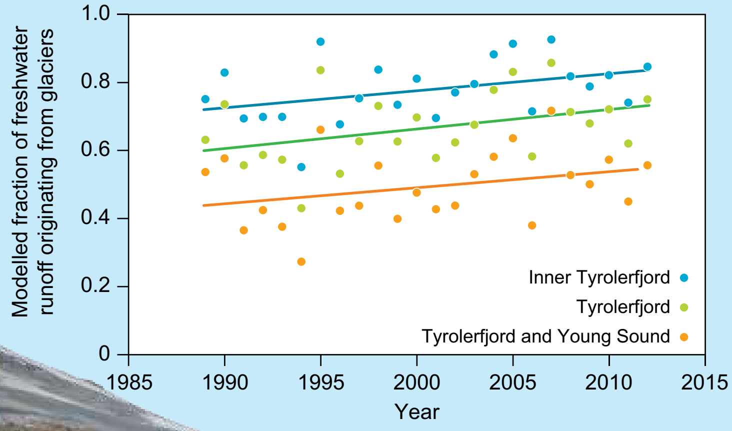


Figure 3. Modelled terrestrial freshwater runoff into Tyrolerfjord – Young Sound, NE Greenland, showing statistically significant trends of growing runoff fraction originating from glaciers (n=24, one-tailed p<0.05 solid lines, one-tailed p<0.10 stippled line). Based on downscaling 0.05° by 0.05° HIRHAM5 grids to a cell size of 110 by 110 m and correcting for omission and commission errors in glacier vs. land surface type at the coarser grid cell size as described in Citterio et al. (2017).

References:

Bolch, T., *et al*. 2013. Mass Loss of Greenland's Glaciers and Ice Caps 2003-2008 Revealed from ICESat Laser Altimetry Data. Geophysical Research Letters 40, no. 5: 875–81. doi:10.1002/grl.50270.

Citterio, M. and Ahlstrøm, A.P. 2013. Brief communication "The Aerophotogrammetric Map of Greenland Ice Masses". The Cryosphere 7, no. 2: 445–49. doi:10.5194/tc-7-445-2013.

Citterio, M., *et al*. 2017. Towards Quantifying the Glacial Runoff Signal in the Freshwater Input to Tyrolerfjord–Young Sound, NE Greenland. Ambio 46, no. 1: 146–59. doi:10.1007/s13280-016-0876-4.

Colgan, W. *et al*. 2015. Hybrid Glacier Inventory, Gravimetry and Altimetry (HIGA) Mass Balance Product for Greenland and the Canadian Arctic. Remote Sensing of Environment 168: 24–39. doi:10.1016/j.rse.2015.06.016.

Machguth, H. *et al*. 2016. Greenland Surface Mass-Balance Observations from the Ice-Sheet Ablation Area and Local Glaciers. Journal of Glaciology: 1–27. doi:10.1017/jog.2016.75.

Noël, B. *et al*. 2017. A tipping point in refreezing accelerates mass loss of Greenland's glaciers and ice caps. Nature Communications. doi:10.1038/NCOMMS14730.

Photo: View of the terminus and tongue of Chamberlin glacier, belonging to Lyngmarksbræen. GlacioBasis monitoring at this site started with a pilot project in 2016 and will be expanded in 2017 (Photo: Michele Citterio).

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

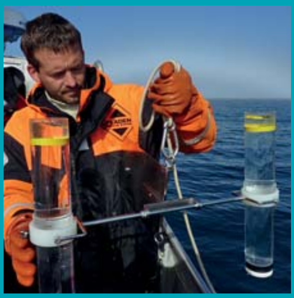
The GEM GeoBasis Programme studies abiotic characteristics of the terrestrial environment and their potential feedbacks in a changing climate.

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.

www.g-e-m.dk

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