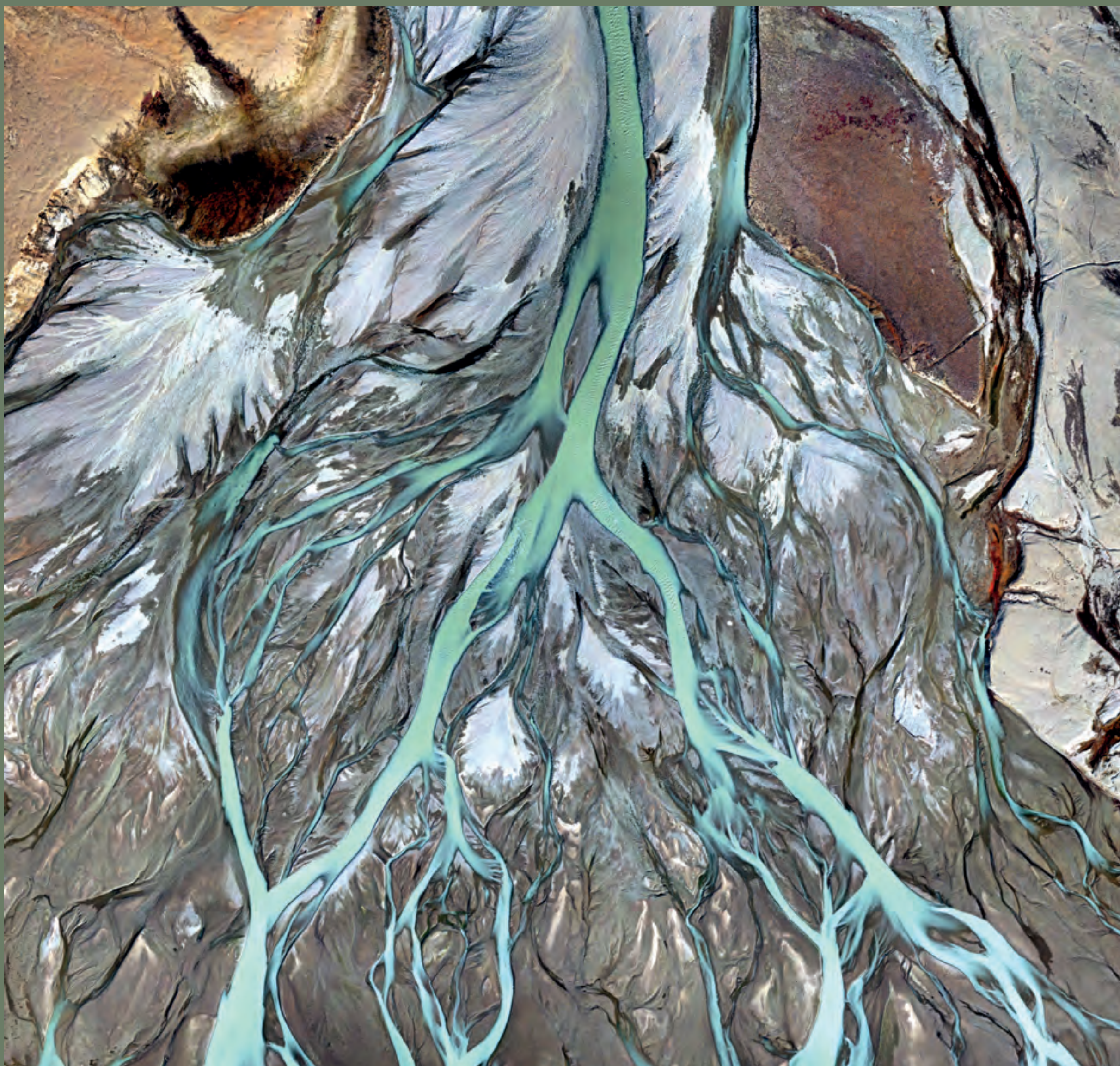
Greenland Ecosystem Monitoring

STRATEGY 2022-2026



AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

GEM
Greenland Ecosystem Monitoring

GREENLAND ECOSYSTEM MONITORING STRATEGY 2022-2026

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Data sheet

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Editors: Torben Røjle Christensen, Elmer Topp-Jørgensen & Marie Frost Arndal

Contributors: Andreas Westergaard-Nielsen[1], Arno Hammann[2], Birger Ulf Hansen[1], Elmer Topp-Jørgensen[3], Katrine Raundrup[4], Kirsten Seestern Christoffersen[1], Kirsty Langley[2], Marie Frost Arndal[3], Michele Citterio[5], Mie S. Winding[6], Mikael K. Sejr[3], Mikhail Mastepanov[3], Niels Martin Schmidt[3], Per Juel Hansen[1], Signe Hillerup Larsen[5], Thomas Friborg[1], Thomas Juul-Pedersen[3], Torben R. Christensen[3], Torkel Gissel Nielsen[7]

[1]University of Copenhagen
[2]ASIAQ
[3]Aarhus University
[4]Greenland Institute of Natural Resources
[5]GEUS
[6]Greenland Institute of Natural Resources
[7]Technical University of Denmark

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GEM STEERING COMMITTEE

Aarhus University, Denmark
Asiaq – Greenland Survey, Greenland
Greenland Institute of Natural Resources, Greenland
National Geological Survey of Denmark and Greenland, Denmark
University of Copenhagen, Denmark

INSTITUTIONS WITH OBSERVER STATUS:

Department of Nature, Energy and Climate, Ministry of Nature, Environment and Energy, Greenland
Environmental Protection Agency, Ministry of Environment and Food, Denmark
The Danish Energy Agency, Ministry of Climate, Energy and Building, Denmark
The Danish Agency for Science, Technology and Innovation, Ministry of Higher Education and Science, Denmark

GEM COORDINATION GROUP

Aarhus University, Denmark
Asiaq – Greenland Survey, Greenland
Greenland Institute of Natural Resources, Greenland
National Geological Survey of Denmark and Greenland, Denmark
Technical University of Denmark, Denmark
University of Copenhagen, Denmark

GEM SECRETARIAT

Scientific leader: Torben R. Christensen
Academic secretary: Marie Frost Arndal & Elmer Topp-Jørgensen
Database manager: Jonas Koefoed Rømer

Address:
The GEM Secretariat
c/o Department of Bioscience, Aarhus University
Frederiksborgvej 399
4000 Roskilde
Denmark
Phone: +45 61 66 77 02
E-mail: g-e-m@au.dk

More information about GEM can be found at www.g-e-m.dk.

Content

Executive summary

Greenland Ecosystem Monitoring is a monitoring and long-term research programme providing data on climate and ecosystem interactions in the Arctic. Operational since 1995, GEM has now completed 25 years of recording seasonal and interannual variability in a wide range of climate and ecosystem variables. The temporal scale is complemented by the spatial coverage across a climate gradient from high arctic Zackenberg in North East Greenland to Qeqertarsuaq, Disko Island, on the boundary of the high and low Arctic and further south to low arctic Nuuk. This continuous monitoring of the state of the ecosystems along this gradient cover both glacial, terrestrial, freshwater and near coastal marine environments.

A fundamental aim of GEM is to ensure the continuity and integrity of its long-term time series of monitored variables and to improve knowledge on ecosystem processes and connections. At the same time, GEM needs to continuously be able to adapt to changing science agendas and data needs, and stay at the forefront of technological advances. GEM therefore introduces new cross cutting programme components and a series of internal programme initiatives that will ensure that GEM remains a leading climate and ecosystem monitoring programme in the Arctic.

The GEM strategy 2022-2026 is responding to national and international concerns about climate and ecosystem change in the Arctic by addressing science agendas and data needs of the Arctic Council working groups (AMAP and CAFF) and global intergovernmental assessment organisations (IPCC and IPBES). Through its multidisciplinary approach to long-term monitoring and targeted research, GEM contributes to over 30 international scientific networks providing insight into the functioning of arctic ecosystems. The programme thus makes vital contributions to Greenland, panarctic and global scale studies of climate change impacts on, and feedbacks from, arctic ecosystems in a variable and changing climate.

To ensure the interdisciplinary nature of GEM and clear links to the efforts and priorities of intergovernmental organisations, the programme will in the coming years implement a thematic structure with multiple interconnections:

- Climate and Cryosphere
- Ecosystem Feedbacks
- Biodiversity and Populations

Panorama, Kobbefjord.

Photo: Efrén López-Blanco.

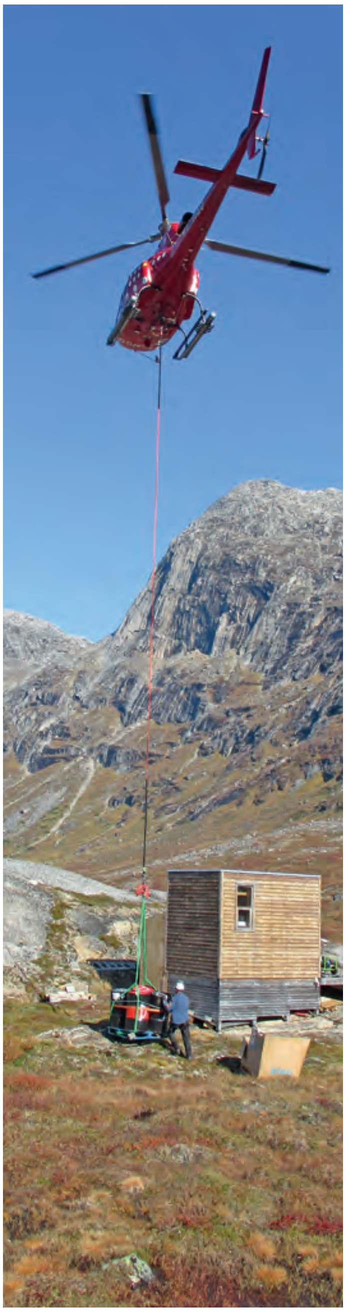


Photo: Henrik Phillipsen.

GEM operations have until now been build around five disciplinary sub-programmes called ClimateBasis, Glacio-Basis, GeoBasis, MarineBasis and BioBasis. In addition to introducing the thematic structure overlaying the subprograms, new initiatives also include the implementation of a remote sensing and numerical modelling component to strengthen the use of GEM data for upscaling and prediction efforts. The latter will use input data from *in-situ* and remote sensing data to improve our mechanistic understanding of ecosystem functioning and explore future projections of ecosystem changes in response to likely climate scenarios. GEM will further implement a range of new and emerging technologies, including an expanded use of molecular techniques for biodiversity studies and autonomous monitoring using remotely operated platforms including non-intrusive drone-based observations.

The strategy emphasizes the continued efforts to improve the free and open access to data using the FAIR principles and make data available for research and e.g. courses at high schools and universities. A green transition initiative is introduced to monitor and reduce carbon footprint and environmental impacts of GEM operations. Finally, the strategy also encompasses a communication strategy targeting GEM stakeholders from the scientific community, decision makers and the general public.

In this strategy period GEM will focus government funding on the long term monitoring while seeking to increase the contributions from external sources to expand efforts on process understanding gradient studies, data sharing, education and outreach. This will be achieved through continued efforts to attract external scientists and scientific networks as well as continue and develop existing national and international collaborations.

GEM at a Glance 2017-2020

Individual sub-programme proposals funded in 2020:	14 + Remote sensing
Average number of Scientists in the field/year:	73
Number of collected variables:	>2000
Average number of Scientific publications/year:	61
Avg. Conferences with GEM representations/year:	17
Avg.Conference presentations (poster)/year:	21 (9)
Avg. Courses using GEM data/year:	17

Acronyms used in the text

ABBCS	Arctic Breeding Bird Condition Survey
ACIA	Arctic Climate Impact Assessment
AMAP	Arctic Monitoring and Assessment Programme
APECS	Association of Polar Early Career Scientists
AWS	Automatic Weather Stations
CAFF	Conservation of Arctic Flora and Fauna
CBMP	Circumpolar Biodiversity Monitoring Programme
DMI	Danish Meteorological Institute
DOI	Digital Object Identifier
EBV	Essential Biodiversity Variables
ECV	Essential Climate Variables
ESA	European Space Agency
FEC	Focal Ecosystem Components
GCW	Global Cryosphere Watch
GEM	Greenland Ecosystem Monitoring
GCOS	Global Climate Observing System
GIOS	Greenland Integrated Observing System
GRDC	Global Run-off Data Centre
IASC	International Arctic Science Committee
ICARP III	International Conference for Arctic Research Planning III
ICOS	Integrated Carbon Observing System
INTERACT	International Network for Terrestrial Research and Monitoring in the Arctic
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
ITEX	International Tundra Experiment
IWG	Interactions Working Group
LIFEPLAN	A Planetary Inventory of Life
NDVI	Normalized Difference Vegetation Index
NUFI	Nationalt Udvalg for Forskningsinfrastruktur / National Committee for Research Infrastructure
PROMICE	Programme for Monitoring the Greenland Ice Sheet
SWIPA	Snow, Water, Ice and Permafrost Assessment
UArctic	University of the Arctic
UAV	Unmanned Aerial Vehicle
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organisation

1 Introduction

1.1 Background and rationale

Climate change is ongoing, and the effects of rising temperatures and altered precipitation patterns can be seen around the globe. In the Arctic, warming is amplified and the effects on ecosystem dynamics are more pronounced and happening at a faster pace than elsewhere.

The impacts of climate change have implications for arctic societies: a warmer climate may change species distribution thereby affecting natural ecosystems and the availability of natural resources; changing sea ice conditions and extreme weather may affect local and global transport, and permafrost melt may lead to infrastructure instability, to name a few. This is of concern for all arctic countries, including Greenland, and may have significant implications for Greenlandic culture and economy, both of which are largely built on natural resources. The changing dynamics of arctic ecosystems also influence the global climate through a number of feedback mechanisms. Climate change impacts in Greenland therefore have implications for the global climate system and hence also affect people living outside the Arctic.

Concerns about the effects of climate change on arctic ecosystems and societies led to the initiation of the Greenland Ecosystem Monitoring (GEM) programme in 1995. GEM was developed by research institutions in Denmark and Greenland as an integrated long-term monitoring and research programme on ecosystem dynamics and climate change effects and feedbacks in Greenland. The aim was, and still is, to provide insights into the functioning of arctic ecosystems in a highly variable and changing climate. The institutions committed to GEM include ASIAQ - Greenland Survey, Greenland Institute of Natural Resources, University of Copenhagen, Geological Survey of Denmark and Greenland (GEUS), Technical University of Denmark and Aarhus University.

The GEM 2022-2026 Strategy builds on the efforts and achievements of previous GEM strategies, national arctic and research strategies, and science agendas of international science organisations. Through its focus on national and international cooperation, GEM seeks to strengthen its position as a leading long-term ecosystem monitoring programme in the Arctic.

The present strategy describes how GEM will consolidate the core monitoring activities while at the same time introduce a new scientific structure focussing on the themes Climate and Cryosphere, Ecosystem Feedbacks, and Biodiversity and Populations. The aim of the new thematic structure is to achieve a clear alignment with priorities of Arctic Council working groups (AMAP, CAFF/CBMP) and international assessment and science organisations (including IPCC, IPBES, IASC/ICARP III), through addressing relevant priorities and integrating internationally recognised essential climate and ecosystem variables.

The GEM Strategy 2022-2026 provides a framework and guidance that will help GEM align its resources and objectives with its long-term vision. As such, it guides GEM scientists and communicates to external scientists, decision makers and other stakeholders what they can expect from GEM.

International organisations and networks

Today GEM is one of the most comprehensive long-term ecosystem monitoring programmes in the Arctic, collecting and openly sharing information on more than 2000

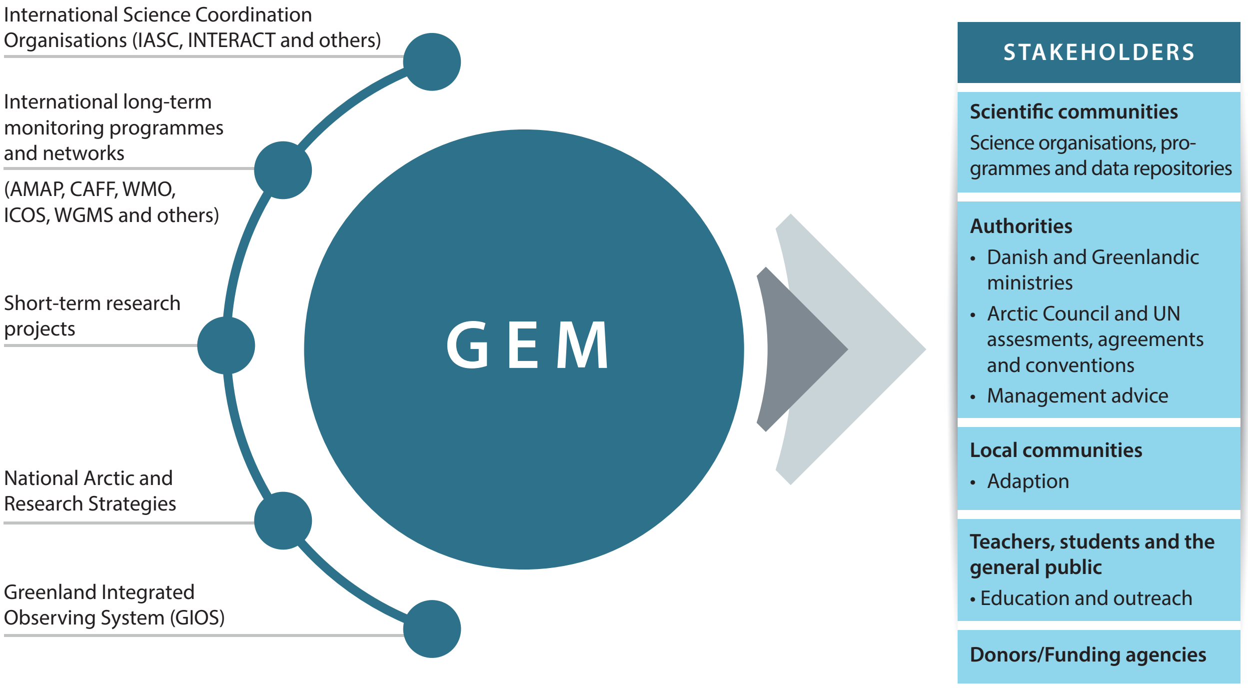


Figure 1. *GEM-centric view with interface towards external programs, strategies and activities left and key stakeholders outputs at the right.*

internationally relevant variables, including 'Essential Climate Variables' and 'Focal Ecosystem Components' identified by international organisations, e.g. WMO and CBMP (Appendix A). The GEM programme is a key provider of expertise and data to Arctic Council working groups (AMAP and CAFF), global intergovernmental assessment organisations (IPCC and IPBES) addressing societal challenges and serving the need of decision makers. On a global scale GEM contributes to more than 30 scientific networks, ensuring that GEM is at the forefront of scientific developments and that its data are utilized widely to assess climate and ecosystem change and feedbacks on a local to global scale.

A major part of the GEM rationale lies in facilitating free and open access to all monitoring data collected since 1995 through the continuously updated GEM database. The scientific value of the time series of data grows markedly year by year. It allows increasing numbers of scientists, scientific networks, intergovernmental organisations, and others to explore and exploit GEM data to assess past, present, and forecast future impacts of climate change on arctic and specifically Greenlandic ecosystems. GEM data are increasingly used in educational materials and also in courses offered in both national and international contexts (e.g. through UArctic).

With this five-year strategy period, GEM is approaching the conventional 30-years period of WMO Climatological Normals[1]. This 30-year 'Climate Normal', provides an opportunity to assess gradual and abrupt ecosystem changes in relation to this standard. In an international context, GEM will also aim to expand the use of remote sensing and regional climate simulations in order to integrate in situ observations with the larger-scale dynamical context. Understanding the local-to-regional scale linkages is essential to provide locally adapted versions of future climate projections, including reliable forecast on how climate change will affect local ecosystems and thereby also the next generation of the Greenlandic society.

[1] https://www.wmo.int/pages/prog/wcp/wcdmp/GCDS_1.php

GEM domain

The GEM programme is designed to study entire ecosystems to identify change and understand ecosystem processes and linkages from glaciers, across land, to the near coastal sea (GEM domain figure). The focus is thus on biodiversity and climate-induced interactions with glacial, terrestrial, freshwater and near coastal processes with linkages to other monitoring programmes that cover the Greenland ice sheet (PROMICE) and the open ocean (such as mapping and population assessment surveys by the Greenland Institute of Natural Resources).

The integrated nature of GEM provides a unique opportunity for studying the abiotic and biotic systems and their interactions over a gradient from glaciated environments, over terrestrial and freshwater habitats to the coastal zone, including feedbacks with local to global implications. The long-term monitoring across a range of disciplines also provides the foundation for mapping, analysing and predicting climate and ecosystem change through documenting variability, averages, extreme events, tipping points, etc. and their implications for arctic ecosystems.

Disko Island, micrometeorological tower.

Photo: Charlotte Sigsgaard.

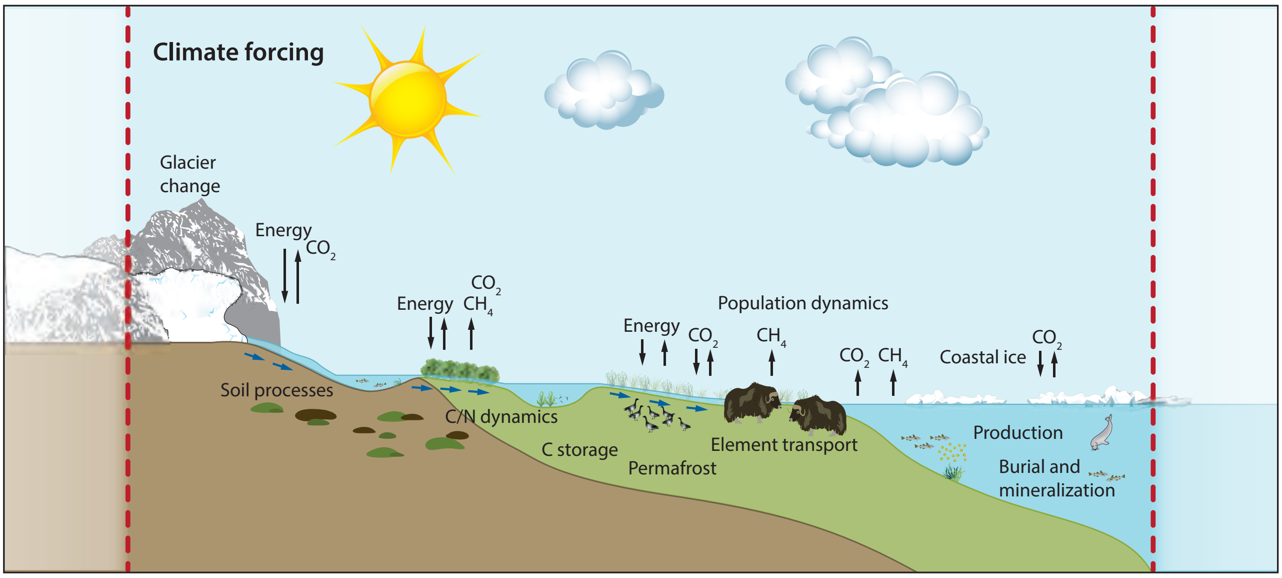


Figure 2. *The GEM domain covers the gradient from land ice, through terrestrial and freshwater environments, to near coastal processes.*

1.2 Vision

- Focusing on Greenland, GEM will contribute substantially to the basic scientific understanding of arctic ecosystems and their responses to climatic changes and variability as well as their potential local, regional, and global implications.
- GEM will consolidate and expand its position as an internationally leading integrated long-term arctic ecosystem monitoring and research programme.
- GEM will maintain the continuous update and safeguard the integrity and use of the GEM long-term data series.

1.3 Mission

In support of mission statements of the Arctic Council Working Groups, AMAP and CAFF, the GEM 2022-2026 Strategy will continue to provide reliable science-based information on the status of arctic ecosystems and its associated drivers of change, and provide scientific advice to arctic governments. In particular, this relates to the efforts of the governments of Denmark and Greenland to take preventive and mitigation actions relating to adverse effects of climate change in the Arctic. The mission of GEM is threefold:

- To contribute to a coherent and science-based description of the state of the environment, including its biodiversity, in Greenland and the Arctic in relation to climatic change with focus on ecosystem responses and feedbacks to the global system.
- To provide science-based input on the state of the environment in Greenland and the Arctic for Danish, Greenlandic and international policy development, adaptation, and governance.
- To provide a platform for cutting-edge interdisciplinary research on the structure and function of arctic ecosystems.

2 GEM organisation and coverage

2.1 Organisation

GEM is operated as an interdisciplinary centre without walls and established as a collaboration between Danish and Greenlandic institutions. The GEM organisation consists of a Steering Committee, a Secretariat, a Coordination Group and sub-programme leaders. The specific roles and responsibilities are described in the GEM Terms of Reference[2].

The **GEM Steering Committee** consists of representatives from the leadership of the science institutions contributing with principal investigators in the GEM sub-programmes, with observers from relevant authorities in Denmark and Greenland. The Steering Committee endorces the overarching strategy and oversees the work carried out by the GEM Secretariat and Coordination Group.

The **GEM Secretariat** consists of a Scientific Leader, an Academic Secretary and a Database Manager. The Scientific Leader is responsible for the development of the GEM strategy and for promoting a high quality and standard of scientific outputs from the program. The Scientific Leader is also responsible for the coordination across sites and sub-programmes and for advocating GEM in an international context. The Academic Secretary supports the Steering Committee and the Scientific Leader, and coordinates activities within GEM, produces outreach materials and maintains the website (www.g-e-m.dk) and social media with relevant contents. The Database Manager is responsible for the operation, maintenance and development of the GEM database and ensures that data is regularly updated and made available via the website (http://data.g-e-m.dk).

Røde Elv, Qeqertarsuaq.

Photo: Charlotte Sigsgaard.

[2] Kommissorium available (in Danish only): https://g-e-m.dk/fileadmin/g-e-m/Kommissorium_for_Greenland_Ecosystem_Monitoring_-_2016.pdf

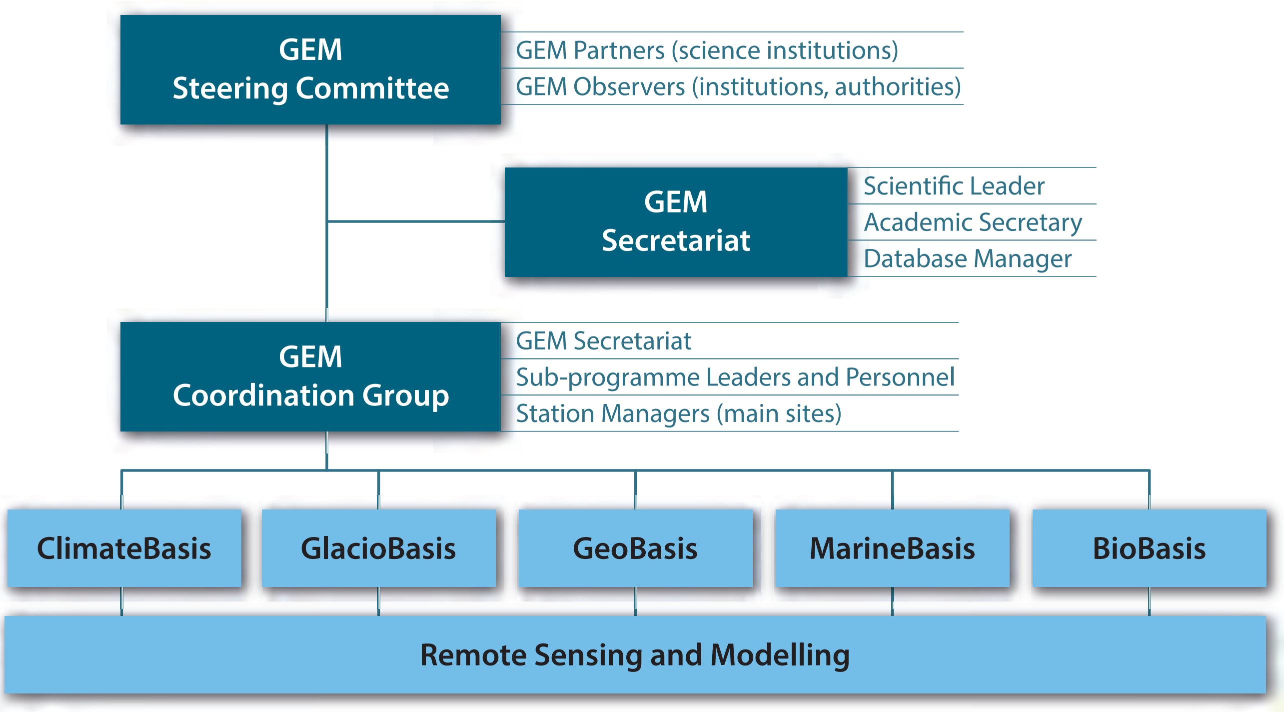


Figure 3. *GEM operational structure. The six light blue boxes in the lower part represents the sub-programmes in GEM 2022-2026. Note for all sub-programmes (except Remote Sensing and Modelling) there are site specific operations at the three GEM Main Sites.*

The **GEM Coordination Group** consists of the Scientific Leader, Academic Secretary, Database Manager, Sub-programme Leaders and station managers from each of the GEM three main long-term monitoring sites (Zackenberg, Disko and Nuuk). As observers, the Coordination Group may include personnel involved directly on the payroll of GEM at any point in time. The Coordination Group contributes to the development of the five-year GEM strategies and is responsible for coordinating scientific fieldwork activities and facilitating implementation of interdisciplinary initiatives.

Sub-programme Leaders (Principal Investigators - PI's) coordinate efforts of the GEM sub-programmes: ClimateBasis, GlacioBasis, GeoBasis, MarineBasis, and BioBasis as well as the Modelling/Remote Sensing efforts. The PI's are responsible for addressing the scientific aims of the GEM strategy 2022-2026 across the GEM main sites (Nuuk, Disko, Zackenberg), distal sites (Niaqornaa, Upernerviarsuk and in Qaanaaq with automatic weather stations) and within the remote sensing and modelling efforts.

2.2 GEM geographical coverage

GEM operates with a focus on three intensively monitored main sites from the low to high Arctic, as well as three climate stations on the West coast to facilitate Greenland-scale gradient studies. At these main sites, GEM collects comprehensive data sets on selected key variables within the three new overarching science themes (3.2). In close collaboration with Greenland Integrated Observation System (GIOS; see section 2.2.2), the GEM programme also intends to cover the Greenland scale for a sub-set of key GEM variables on the East coast using mobile platforms for gradient studies. While the remote sensing and ecosystem modelling efforts will be an integrated component in GEM 2022-2026, new mobile platforms with selected autonomously measured parameters represent an externally funded complimentary extension of the core GEM activities through GIOS. The monitoring at GEM main sites will form long-term reference points for the mobile platforms to be developed as part of GIOS, and combined, they will produce data and ground truthing for the GEM sub-programme on remote sensing and modelling.

Nuuk Kobbefjord.

Photo: Katrine Raundrup.

2.2.1 GEM main sites

Nuuk, low Arctic West Greenland

The Nuuk monitoring site is located in low arctic West Greenland. The research station in Kobbefjord and associated infrastructure is owned and operated by Greenland Institute of Natural Resources. The mean annual temperature is -0.1 °C for Nuuk city (1991-2020). The main terrestrial study area encompass the catchment area at the head of Kobbefjord, a well-confined fjord without branches, approximately 20 km from Nuuk. The setting is diverse and includes numerous glaciers at higher elevations and the most typical vegetation types of a low arctic ecosystem. There is no permafrost in the core monitoring area. In addition to monitoring Kobbefjord, the marine component is focused in Nuup Kangerlua, which is also the location for one of the distal climate stations. The Kobbefjord and Nuup Kangerlua area offers easy access from Nuuk to a rich variety of low arctic landscape elements over short distances (lakes, wetlands, heaths, fjord).

Kobbefjord.

Photo: Katrine Raundrup.

Arktisk station.

Photo: Regin Rønn.

Disko, low Arctic West Greenland

Arctic Station is located on the south coast of Disko Island, in central West Greenland and is owned and operated by University of Copenhagen. The location is characterised by a low arctic coastal climate with a mean annual temperature of -2.4 °C (1994-2020). The surroundings of Arctic Station are characterised by a large variety in landscapes with plateau mountains, valleys, coastal zone and hot springs with a unique flora and fauna, as well as a productive marine environment in the Disko Bay. The station and the nearby town Qeqertarsuaq are situated on a ridge of Precambrian gneisses overlain by massive basalts from the Tertiary. Arctic Station was established in 1906 and hence holds valuable old data records (although as broken time-series). In the GEM context a meteorological station, established in 1990, is being used with a full record of climate data since 1991.

Zackenberg, high Arctic Northeast Greenland

Zackenberg Research Station is owned by the Government of Greenland, and Aarhus University is responsible for running the station. The Station is located in the high Arctic in Northeast Greenland in an area of continuous permafrost. A branch facility is situated at Daneborg, 25 km east of Zackenberg, mainly supporting the marine monitoring programme. The mean annual temperature is -8.9 °C (1996-2020). A great variety of biotopes like ponds, fens, heaths, fell field plateaus and grasslands occur within the core study area. The study area comprises the drainage basin of the river Zackenbergelven, with a total size of c. 500 km^2.

Zackenberg Station.

Photo: Daniel Alexander Rudd.

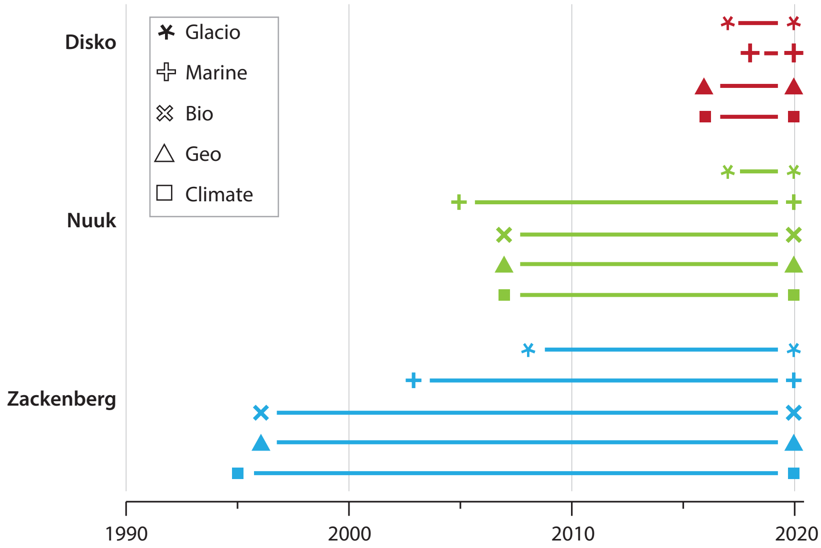


Figure 4. *The GEM programme was initiated as the Zackenberg Ecological Research Operations, ZERO in 1995. The programme developed from there with a gradually broader scientific and geographic scope. In the years 2005-2007 a new main site was established around Nuuk (as Nuuk Ecological Research Operations, NERO), and in 2016-2018 Disko area was included as a new main site. Five sub-programmes are now funded at all three main sites, except for BioBasis at Disko.*

2.2.2 Linking GEM with wider research infrastructures

The Greenland Integrated Observing System (GIOS) forms a national cross-institutional collaboration on research infrastructure supporting environmental observations in Greenland. It is a national network of physical research infrastructure encompassing existing and new key monitoring and research sites across Greenland, which allow the characterisation of temporal and spatial climate gradients and how these affects ecosystem structure and functioning. Initially GIOS is granted for five years until 2026, but with a ten-year implementation plan (National roadmap, NUFI).

GEM is a central contributor and GIOS forms an opportunity both for integration with other monitoring efforts in Greenland as well as adding value to GEM data when combined with data gathered with a larger geographical coverage, hence supporting GEM extrapolations and upscaling initiatives. New and improved observation infrastructure combined with a more efficient logistic collaboration is central and shared between GEM and GIOS, as is the wish to expand opportunities for national and international collaborations.

Through GIOS, GEM will also be closer connected with the monitoring of the Greenland Ice Sheet under the auspices of the PROMICE project (www.promice.dk) and better integrated with the National Centre for Climate Research at the Danish Meteorological Institute (DMI) to find and explore common ground between the local scale field observations and the regional climate simulations.

Arctic hares in Zackenberg.

Photo: Charlotte Sigsgaard.

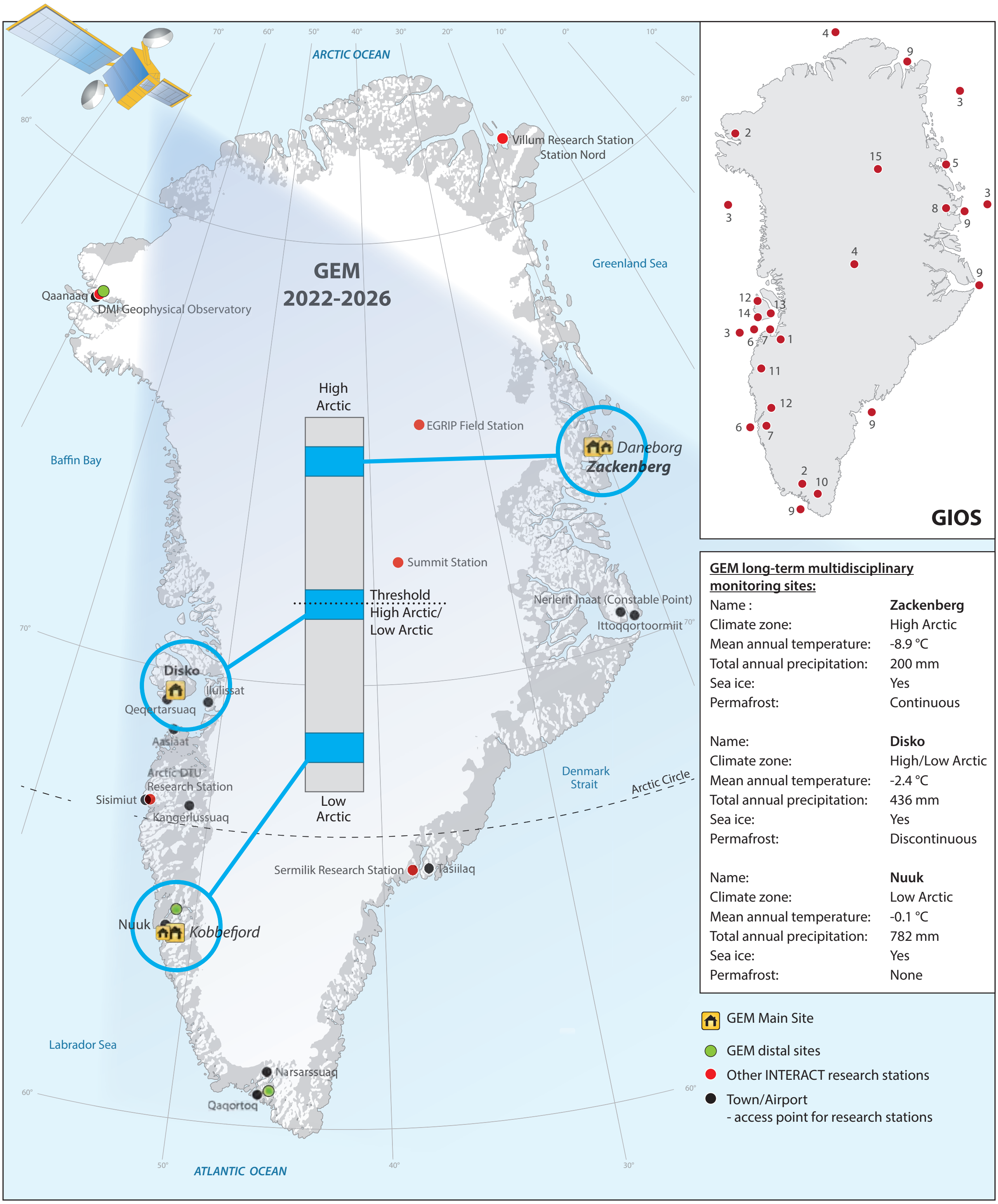


Figure 5. *GEM focus on three intensively monitored main sites from the low to high Arctic, as well as three climate stations (distal sites) on the West coast to facilitate Greenland-scale gradient studies. Greenland Integrated Observing System (GIOS) inserted showing positions of linked monitoring efforts (see www.gios.org for details).*

3 GEM Science Plan

3.1 Structure of the science plan and objectives

The GEM Strategy 2022-2026 has been developed cooperatively by all institutions involved in the GEM programme. The process has been led by the scientific leader supported by the GEM Secretariat and the coordination group including principal investigators from all subprograms. The resulting document has been reviewed, edited and finally endorsed by the GEM Steering Committee. Building on previous strategic plans and priorities of international scientific networks and organisations, the strategy will provide a forward looking framework for all GEM operations until 2026.

In the following, the GEM strategy introduces a new thematic structure that will facilitate integration within GEM and with clearly defined linkages to intergovernmental monitoring and assessment organisations (section 3.2). The strategy also describes the approach taken by GEM and the concomitant programme development initiatives carried out across main sites and activities (section 3.3). The science themes and approaches feed into international collaboration and societal engagements (section 4) and provide the overall framework for the descriptions of the operational sub-programmes of GEM (section 5).

Objectives

Building on the GEM vision and scientific agendas of international organisations and research communities, a set of key objectives have been identified to provide a framework for the monitoring operations under GEM. These objectives, and the new thematic structure of GEM introduced below, will support interdisciplinary initiatives within the

Photo: Henning Thing.

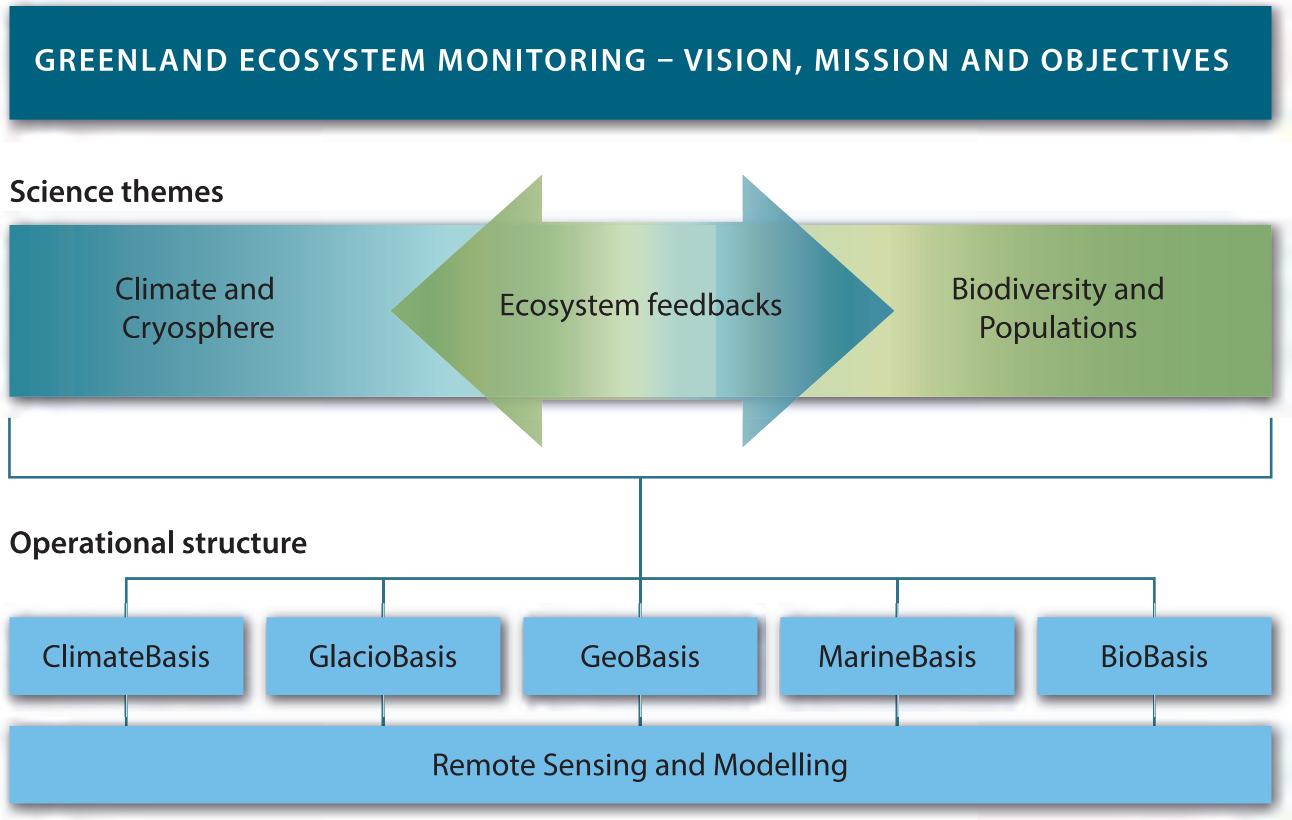


Figure 6. *Schematic illustration showing overarching entry to the GEM strategy (described in section 1 and 2), the three GEM Science themes (section 3.2) and the operational structure (section 5).*

sub-programmes in answering key scientific questions on an ecosystem and Greenland scale. The objectives are:

- To study the state and spatiotemporal variability of key components of the climate, cryosphere, freshwater, ice free land and near coastal ecosystems in Greenland.
- To provide data-based analyses revealing the connections between these key components and how their inherent spatial and temporal variability influence each other.
- To document the effects of climatic variability and long-term change on a wide range of key ecosystem components and processes in Greenland.
- To identify key indicators of change as they emerge as detectable significant trends of change from the monitoring data.

3.2 GEM science themes

With the strategy for 2022-2026, GEM introduces a thematic structure for the scientific activities. The themes are shaped by insights from the 25 years of GEM operation and the challenges ahead as defined by a broad consensus in the scientific community. The objective is to advance integration across disciplines within GEM, and to clearly communicate and advertise the contents and relevance of GEM data for a wider scientific and stakeholder audience. The basis of the new thematic structure is a division into three fundamental themes:

- Climate and Cryosphere
- Ecosystem Feedbacks
- Biodiversity and Populations

The specific objectives of each theme are detailed below.

Qasigiannguit glacier in Kobbefjord near Nuuk.

Photo: Asiaq

3.2.1 Climate and Cryosphere

Global average atmospheric and oceanic temperatures are increasing due to human activities, and the rate of near-surface atmospheric warming in the Arctic is nearly twice that of the global average. These changes have implications for the local ecosystems, where the cryosphere (including seasonal snow cover) in particular, mediates the availability of liquid water in the Arctic, a key variable for a wide range of abiotic and biotic processes. With the 'abiotic' environment, we refer to the inanimate components of the atmosphere, cryosphere, terrestrial, freshwater and marine environments. Much of the dynamics of biotic systems (3.2.3 Biodiversity and Populations) are directly affected by the state and variability of abiotic parameters. In turn, biotic systems have the ability to affect the physical environment, potentially creating feedback loops (3.2.2 Ecosystem Feedbacks).

Abiotic variables which are key drivers for biotic processes include temperature, precipitation, radiation, and clouds. Across all spatial scales, from individual catchments to the Arctic as a whole, the cryosphere interacts with the energy exchange of the landscapes, thereby creating feedback loops in the climate system. Furthermore, the duration of the growing season on land and primary productivity in near-costal water are modulated by the seasonal cycle between cold and dark winters and relatively warm, sunlit conditions in summer. Surface and ground hydrology, glacier mass balance, permafrost stability, sediment and nutrient mobilization, transport and deposition are also all factors influenced by the timing and length of the un-frozen conditions. While the broad seasonal cycle is determined by predictable astronomical factors, the timing of water and light availability during the transitional seasons is strongly impacted by clouds and seasonal snow cover, as well as the associated feedbacks. Snow cover is highly sensitive to temperatures, precipitation and local factors such as snowdrift, which are difficult to model, whether on land, glaciers, or sea ice. At the multi-year scale, oscillations of atmospheric circulation patterns add a further source of variability which needs to be accounted for when quantifying trends in time series.

Many abiotic parameters have been identified as "Essential Climate Variables" (Appendix A), with the goal to provide a long-term baseline on which to monitor changes and thereby better understand the key processes, feedbacks, and potential tipping points. GEM will continue to measure these parameters at sufficient spatial and temporal resolution by implementing internationally recognized protocols. Increased temperatures, increased fraction of liquid vs. solid precipitation and reduced meltwater retention capacity of glaciers may give rise to more frequent extreme events – slush events, landslides, glacial lake outburst flood (GLOF), increased erosion, sediment transport and leaching of nutrients into the rivers and fjords. All these events have a very strong influence on the arctic landscape and ecosystems. The change of water from frozen to liquid phase, both on land and in lakes and rivers, intensifies the hydrological coupling between land and sea. In the coastal ocean, the impact of changes on land combines with marine drivers to produce very complex dynamics resulting in strong physical and chemical gradients in space and time.

The physical process understanding developed through the detailed monitoring at the GEM sites allows the climate sensitivity of abiotic and biotic processes to be quantified. This is a necessary step to be able to project what effect future climate scenarios, based on different greenhouse gases emissions, may have on the ecosystem. Assessing the representativeness of GEM sites at the Greenland and Arctic scales also becomes possible when combining in situ observations, process understanding, regional climate modelling and remote sensing.

Changes in abiotic variables can be predicted by models once the underlying physical processes are understood and their local expression is quantified through in situ observations. Climatological time series are among the longest datasets produced by GEM, and some are now approaching the conventional 30-year period of WMO Climatological Normals3. GEM will expand the use of projections from regional climate models in order to link in situ observations of both abiotic and biotic parameters with larger scale climate dynamics. A better scientific understanding of current linkages between local and global scale processes will further aid in the application of future climate projections to local contexts, including the prediction of extent and frequency of local extreme events and the identification of tipping points with the potential for causing fast ecosystem changes.

Key science questions:

- What is the current mean state and short-term variability of atmospheric, hydrological and glaciological variables at the GEM sites, and how representative are they for Greenland and the Arctic as a whole? Can long-term trends be detected in the measurements?
- What is the climate sensitivity of atmospheric, hydrological and glaciological processes at the GEM sites and how do ecosystems react to the occurring changes?
- Combining the process-level understanding developed through GEM research with climate projections, what can we say about the future evolution of the climate, hydrosphere and cryosphere at GEM sites?

[3] https://www.wmo.int/pages/prog/wcp/wcdmp/GCDS_1.php

Fen in the central Zackenberg Valley.

Photo Marie Frost Arndal.

3.2.2 Ecosystem Feedbacks

Biotic processes are often controlled by abiotic factors, but changes in the biological system may also feed back to the climate – this is called a feedback mechanism. These climate ecosystem interactions have a large impact on the global climate systems, especially in the Arctic. Stronger warming in the Arctic compared to the rest of the planet can primarily be explained by a number of feedbacks between climate forcing and processes closely coupled to the ecosystems of the Arctic.

The Ecosystem Feedback theme deals with budgets of energy balance (radiation) and carbon balance (greenhouse gas fluxes), how these are affected by ecosystem dynamics including biota and their interactions with climate. These feedbacks alter both land and sea ecosystems, and cause reinforcing or in some cases a dampening of the ongoing changes in climate. Understanding these processes at the regional to local scale and their magnitude is therefore important for predicting climate change from the global to the local scale. In support of these efforts GEM is making significant contributions in representing the northernmost stations in regionally distributed networks of measurements such as the Integrated Carbon Observing System (ICOS).

One of the most important feedbacks in the climate of the Arctic are associated with the reflectance of the surface and the effect that this has on radiation budget and surface temperature. Higher temperatures in combination with increased algal blooms and deposition of dust affect the albedo of the snowpack and glaciers. As such the dynamics of annual snow- and ice cover and duration are seen in the context of the surface radiation budget linking and impacting both surface and air temperatures. Likewise, vegetation dynamics, greening and browning of tundra and ecosystem composition also influence albedo and, hence, may act to influence the temperature and/or precipitation.

The exchange of the greenhouse gases H_2O, CO_2 and CH_4 between terrestrial, freshwater or marine surfaces and the atmosphere is another example of a link between biology and abiotic factors influencing climate through the influence it has on greenhouse gas concentrations of the atmosphere. Studies of these linkages provide detailed insight into the soil carbon and vegetation dynamics. The ecosystem-atmosphere flux measurements of CO_2 and CH_4 are strongly linked to processes within biota, cycling of nutrients and organic matter in the soil. The plant growth in turn is changing in response to both climate and increased CO_2 in the atmosphere leading to both a greening and in some cases tendency for browning of the vegetation caused by draining/drying of habitats. It is important to understand that while these biotic/abiotic feedbacks are complex, the connections between them in turn constitute important feedbacks in the climate and make long time series documenting interannual variability and long-term trends important in the context of modelling future climatic scenarios.

Marine CO_2 content determines the potential for air-sea exchange, which is presently not well understood, despite accounting for about half of the global atmospheric CO_2 sink. In the marine environment changes in sea ice cover, melt water and ocean temperature together with constantly rising CO_2 concentration in the atmosphere cause acidification of the sea, which can be a driver of ecosystem change. Therefore, CO_2 exchange data are important for describing ecosystem interactions including primary production and food web structure. Knowledge of these processes and their magnitude are important for understanding the dynamics of the marine ecosystem, but also draw obvious links to socioeconomic factors of the society in Greenland where marine resources make up a significant part of the BNP.

Key science questions:

- Can trends in the structure and functioning of the Greenlandic ecosystems be linked to climate feedbacks such as changes in radiation properties or exchange of greenhouse gasses?
- How does duration and dynamics in snow, lake-ice and sea-ice cover interact with ecosystem productivity including higher trophic levels and what influence does this in turn have on ecosystem carbon and nitrogen cycling?
- How does variability in the amount of freshwater flow and chemical composition influence ecosystem productivities in both freshwater and near-coastal ecosystems?

View from Arctic Station, Disko.

Photo: Charlotte Sigsgaard.

*Labrador Tea (*Ledum palustre*) in Kobbefjord, Nuuk.*

Photo: Katrine Raundrup.

3.2.3 Biodiversity and Populations

Biodiversity, populations, and biological processes are influenced by abiotic factors (3.2.1 Climate and Cryosphere) and biotic interactions. In some instances, biological processes also feed back to impact the climate system altering radiation and carbon budgets (3.2.2 Ecosystem Feedbacks).

In arctic ecosystems, a number of biodiversity-related parameters are known to respond to changes in the abiotic conditions, either directly or indirectly, for instance through interactions between plants, insects, birds and mammals (biotic interactions). Pronounced increasing temperatures in the Arctic means that ecosystems here may depict what global ecosystem may experience later. Understanding the effects and interplay between climate and biodiversity in the Arctic is therefore crucial for understanding and predicting changes on a local to global scale.

Keeping track of arctic biodiversity in glacial, marine, freshwater, and terrestrial ecosystems is a central focus area within GEM. Arctic ecosystems are often regarded as being rather simple compared to lower latitude ecosystems, but recent studies of biotic interactions have changed that view by revealing a high degree of complexity also within the arctic interaction webs. The biotic responses to environmental change may thus be equally complex. The biodiversity monitoring encompasses a large variety of species and processes across microbial, plant and animal populations as well as their interactions, with the main focus on diversity, abundance and composition, phenology, and demographic rates across the arctic ecosystems.

In the terrestrial ecosystem, biota mainly respond to changes in precipitation and temperature. Inter-annual variability in plant flowering versus insect abundance may ultimately have major implications for the food -web and hence also population dynamics of birds and mammals. The timing of the snow season and the amounts of winter precipitation are impacting most of these terrestrial species and processes (e.g., predation or fecundity rates), whilst the growth of arctic vegetation is additionally controlled by moisture from melting snow packs and summer precipitation (rain). At decadal scale, climate-induced changes in e.g., nutrient availability and soil properties are furthermore expected to alter the competitive interactions between plant species, with implications for e.g. carbon fluxes and surface energy balance. To capture the complexity of biodiversity in the arctic ecosystems, GEM conducts biodiversity monitoring across scales, from plot-level to landscape-level using a variety of methodologies, from direct in-situ observations to automated, drone and remotely sensed observations.

In the freshwater ecosystems, biota are mainly controlled by the duration of the ice cover, which in turn is directly affected by temperature, snow and wind during winter, and in the spring also by incoming melt-water from the surrounding terrestrial landscape. Together, these abiotic conditions determine the water temperature and the concentration of inorganic ions during the ice-free season, which regulates the abundance and biomass of auto- and heterotrophic populations.

The marine ecosystem is largely controlled by the strong seasonality in incoming solar radiation combined with duration of the ice cover and incoming meltwater from glaciers and the ice sheet. Hence, inter-annual variations in the pelagic food web and distribution of macro-algae in the photic zone are mainly driven by changes in the onset of the ice-free period and discharge of meltwater. The duration of ice cover is expected to decrease as the climate warms and the meltwater discharge increase. This will impact the pelagic community structure leading to longer ice-free periods dominated by low nutrient concentrations, and thus a food web dominated by small primary producers and a complex pelagic food web. The increased ice-free period also promotes the growth, and in some areas also depth-distribution, of macro-algae. Changes in coastal waters and currents driven by climate changes, i.e., the fraction of water from the Atlantic and Arctic oceans, is expected to also impact fjord ecosystems, affecting species composition, community structure and overall biodiversity of arctic fjord ecosystems, for instance by introduction and favouring of new (boreal) species.

Key science questions:

- What is the interannual variability in community structure and species abundance of terrestrial, freshwater and near-coastal ecosystems in the Arctic?
- How does the dynamics of species and populations respond to interannual variability in climate, and in particular snow, freshwater and sea ice dynamics?
- Can trends and variability in species and population abundance as well as other attributes be linked to environmental conditions?

3.3 GEM approaches and programme development

The scientific advancement of GEM is founded in an increased understanding of impacts of climate change and variability on arctic ecosystems. This in turn is based on interdisciplinary and integrated long-term monitoring coupled with an improved understanding of ecosystem dynamics. It allows for analyses of trends and variability across a vast set of variables from across the entire ecosystem that, coupled with an understanding of ecosystem processes and relationships, enables GEM to model and predict ecosystem responses to future scenarios. While GEM core monitoring activities are focused on catchment scale observations along a climate gradient, GEM also intends to enable up-scaling of selected variables through combining core monitoring data with gradient studies, remote sensing and modelling.

International cooperation is key to advancing scientific developments, and it is central to the strategy of GEM to maintain and develop collaboration with external scientific projects, networks and organisations (Appendix B). This will allow GEM to promote the ecosystem-based approach to monitoring, provide novel insights into climate and ecosystem functioning and stay at the forefront of new scientific developments. GEM provides free and open access to all data that are also DOI indexed and shared with thematic repositories and global data search engines. Applying standardized methodologies and internationally recognised essential variables furthermore allows GEM to contribute to arctic and global assessments, relevant for the scientific communities and societies at large.

The range of strategic developments in GEM approaches and activities envisioned over the period 2022-2026 are grouped in those relating to methodologies, to database/ data management and to activities relating to the green transition of the monitoring activities. These are detailed below.

3.3.1 Methodological developments

Technological advances provide new opportunities for improved data sampling, i.e., accuracy, geographical coverage, frequency, automatisation and data transfer. GEM will aim to closely connect modelling efforts with the field activities in the initial stage of new monitoring designs, ensuring that the data collected in the field meet the needs of the modelling community. GEM therefore has a strong focus on the testing and implementation of new technologies, while maintaining comparability in data series. Efforts to apply state of the art technologies to improve and facilitate data collection including documentation and repeatability are integrated in the five operational sub programmes, and their specific ideas related to methodological and technological development. Here they are described in general terms for GEM as a whole:

Sample preparation for field measurements of phytoplankton primary production in Nuup Kangerlua (Godthåbsfjord) as part of the MarinBasis-Nuuk programme.

Photo: Thomas Juul-Pedersen.

Molecular techniques
Molecular techniques (e.g., eDNA and mitogenomics) offer new opportunities for monitoring species composition exploring the hidden and unknown diversity, tracking seasonal and annual changes in biodiversity of entire communities and studying food web interactions across terrestrial, freshwater, and marine habitats. Sequencing species that are not yet in the global DNA reference databases will further expand the possibility for understanding the Arctic diversity and functioning. Pilot studies already conducted within GEM have shown that the methodology offers potential in GEM's monitoring of e.g., terrestrial arthropods. Hence the expanded use of these techniques will be a central development in GEM Strategy 2022-2026.

Sensors
Sensor developments include many new possibilities for GEM in the coming years with lower weight and less power consuming devices. New sensors considered for this strategy include lasers for use in the ecosystem flux measurements and optical imagery for estimating discharge in potentially difficult rivers. GEM will increase its use of biologging to monitor and decipher animal movements and interactions, cross-boundary interactions, and their impacts in population dynamics.

To increase the robustness and accuracy of glacier accumulation measurements, new techniques will be implemented including water equivalent retrievals from counting of cosmic-ray induced neutrons, snow depth retrievals from GNSS reflectometry, and compact rain sensors suitable for use on glaciers. With the emerging operational capabilities of drones, these have become instrumental in providing digital elevation models and monitoring key variables across entire GEM catchment areas. Improved flight times and heavier pay loads mean that the application of drones for carrying advanced sensors and taking samples will continue to expand during the GEM 2022-2026 strategy. Examples of sensors that will be applied under GEM are hyperspectral and other sen-

Pittfall traps are used to collect Arthropods in Kobbefjord.

Photo: Katrine Roundrup.

sors for mapping, e.g. snow, blooms of snow algae, acquiring vertical profiles of air temperature, NDVI and plant diversity. In combination with satellite remote sensing, these techniques allow for catchment or Greenland scale assessments.

Automatisation

A general benefit of automation is to make observations more resilient to disruption of the fieldwork when adverse ground conditions prevent reaching and safely working at monitoring installations (particularly for remote stations, on glaciers, under water, during extreme weather, etc.), and in case of pandemics as experienced in 2020/2021. In the coming years GEM will focus on automatization to improve data standardisation and quality, for example by securing year-round data coverage with more focus on winter processes, increase frequency and accuracy of observations, and implement gradient studies through mobile platforms. Such efforts will improve the data forming the basis for upscaling from the GEM sites.

While acknowledging that many aspects of the biological monitoring still remain far beyond automatisation, GEM has introduced image recognition techniques and machine learning in different parts of the programme and plans to expand its use in this strategy period, e.g. for monitoring flowering phenology and pollination, snow cover, arthropod identification, wildlife and fish abundance, etc. The automation efforts also relate to a tighter integration of remote sensing products with the operational monitoring, to facilitate and continuously improve annually produced remote sensing products.

Mobile platforms

Mobile platforms are used to operate sensors where there is no need or possibilities for human presence. Such platforms include satellites, remotely operated vehicles (drones/ROVs) or fixed (but movable) measuring masts/buoys. Over the past decades GEM has made use of sensors in fixed locations and during the last strategy period implemented the use of remote sensing, drones and ROVs. GEM will further develop and integrate mobile platforms across disciplines and habitats in the strategy period 2022-2026. A mobile autonomous mini-GEM platform for gradient studies within and beyond GEM main sites is being developed and applied as part of GIOS. Using GEM as the long-term data backbone this developing infrastructure for gradient studies on the East coast of Greenland will represent an external development during 2022-2026 as a direct offspring from and in close collaboration with the GEM programme.

Kobbefjord Hydrostation.

Photo: Asiaq.

Marine habitat studies in Nuup Kangerlua (Godthåbsfjord), SW Greenland using a remotely operated underwater vehicle (ROV) as part of the MarinBasis-Nuuk programme.

Photo: Thomas Juul-Pedersen.

Analytical tools

While GEM scientists have ongoing activities to develop and implement process-based models addressing ecosystem-atmosphere interactions, there is a need to explore further more complex relationships through the application of model-data fusion techniques and also to improve the mechanistic, capacity of the program. New tools within machine learning and computer cloud-based processing power provide new opportunities for data analysis across vast data sets difficult to digest using traditional methods. This strategy period will therefore see increased focus on these analytical approaches.

Key methodological goals

- Develop, test, and implement new methodologies, technologies, and analytical tools through cooperation with scientists, scientific networks, organisations, and industry, including new sensors, instrumentation, and field methodologies for delivering reliable, accurate, standardized, state-of-the-art monitoring data.
- Mobile platforms (e.g., buoys, ships, mobile terrestrial measuring stations, drones) will be integrated across sub-programmes. This will be part of the studies at GEM main sites and contribute to gradient studies.
- Expand automatisation efforts to maximize spatio-temporal coverage, focusing on e.g., winter season coverage, improved data quality, areas difficult to access or areas sensitive to human disturbance.
- Implement wireless data transfer efforts to the widest possible extent for remotely located sensors on fixed or mobile measuring stations. This will reduce workload and environmental impact from people in the field.
- Application of new analytical tools, like molecular examinations, machine learning and modelling for assessing past, present and future climate and ecosystem change.

3.3.2 Database and management

The GEM database is managed in accordance with the FAIR principles – Findability, Accessibility, Interoperability and Reusability. Free, open and timely access to quality assured data is the heart of the GEM programme. Over 2000 variables are collected in the field and are quality checked by the scientists and by the GEM database manager. All individual data sets receive a DOI (digital object identifier) to enable data citation.

GEM data are collected using methodological standards following accepted protocols by international scientific networks and organisations, and subsets of data are shared with thematic and multidisciplinary repositories and search engines. This ensures that GEM data are used in relevant national, arctic, and global assessment organisations and modelling groups and are detectable for all with an interest in arctic ecosystem and climate change data.

The GEM database is continuously developed to adhere to efforts in international data standardization fora, incorporate new data, facilitate data quality controls, and improve visibility and usability of the data. GEM will aim to continue and further strengthen efforts to provide free and open access to all GEM data collected since 1995.

GEM will increase efforts in wireless transferring of data from existing measuring stations to local data hubs and live streaming of selected data sources where possible.

Musk-oxen population dynamics are influenced by the interannual variability in snowcover.

Photo: Charlotte Sigsgaard.

Key goals:
- Operate the database after the FAIR principles (Findable, Accessible, Interoperable and Reusable), adhering to international standards for improved data sharing and interoperability with other systems.
- Increase use and visibility of GEM data by sharing data sets (all, subsets or meta-data) with international repositories operated by scientific networks, organisations, or data sharing platforms/search engines.
- Further increase the use of GEM data by external scientists and organisations by promoting the GEM database in relevant fora and continuously improve usability functions easing access to free data and data products.

3.3.3 Green Transition and the local environments

Being a monitoring programme focused on climate change and its impacts, GEM scientists are very aware of the environmental impact of the monitoring work. New technologies and coordinated logistics are key to minimizing the ecological footprint of GEM scientists and field operations. Therefore, as part of the strategy GEM will during 2022-2026 also be monitoring the climate footprint of the fieldwork activities and seek ways of reducing emissions where possible. GEM will actively support the main research stations at the GEM sites in their efforts to improve the climate footprint of operations through green energy solutions.

Likewise, with respect to implications of the monitoring activities themselves on the local environment, GEM has a self-evident interest in monitoring potential impacts on wildlife and vegetation from drone-based monitoring, vehicle transport of equipment for monitoring purposes and the shear traffic caused by field personnel. GEM will support and recommend the research stations we use as platforms to register the traffic and monitor the use of potentially disturbing elements for wildlife such as drones.

Key goals:
- Reduce carbon and environmental footprint of GEM operations.
- Continuously seek means to adjust operations to reduce carbon footprint of activities.
- Monitor and minimise impact of GEM field activities on local environments.

Solar panels in Kobbefjord.

Photo: Katrine Raundrup.

4 Collaboration and societal engagement

4.1 International cooperation

With over 25 years experience of an ecosystem approach to studying the effects of climate change in the Arctic, GEM is in a position to take a leading role in international organisations and projects seeking to coordinate arctic science and assessments. GEM scientists will therefore continue to play central roles in AMAP, CAFF, IPCC, IPBES, WMO and further scientific networks. GEM will also continue to develop its involvement in current important circumarctic initiatives and projects of IASC (T-MOSAiC), UArctic, EU (INTERACT, EU-PolarNet, Arctic Passion) and other relevant international contexts.

Key goals:

- Promote long term monitoring, an integrated ecosystem approach, standardization, harmonization and data sharing.
- Address international science agendas and priorities and ensure integration of international recognized essential and focal variables in GEM monitoring efforts.
- Make GEM data available for scientists, students, scientific networks, governments, intergovernmental organisations, and others with an interest in climate and ecosystem change in Greenland.
- Engage actively in international projects, scientific networks, comparable arctic monitoring programmes to improve and standardize methodologies, harmonise data sets and improve our understanding of climate change and ecosystem dynamics and feedback mechanisms in the Arctic.

4.2 Supporting advisory function

Climate change, pollution and resource use impact arctic ecosystems, and knowledge about the inferred changes is needed for societies to adapt. While national input to arctic and global assessment organisations is the cornerstone of GEM, the knowledge and data generated by the programme can also be used in other advisory functions.

Kobbefjord.

Photo: Efrén López-Blanco.

Platelet or Pancake ice observed in the inner-part of Nuup Kangerlua (Godthåbsfjord), SW Greenland during an annual fjord transect by the MarinBasis-Nuuk programme.

Photo: Thomas Juul-Pedersen.

GEM data are witnessing arctic ecosystem change and will be used further during this strategy period to make Greenland scale assessments and predictions. The understanding of ecosystem processes and dynamics are used in species management advice by other institutions to the Government of Greenland, and GEM knowledge and the free and openly available data may be relevant for other advisory tasks requested by governments, institutions, organisations, etc.

Key goals:
- Make up-to-date information about climate and ecosystem change available for decision makers and institutions providing government advice.
- Provide national input to national arctic and global assessments (including AMAP, CAFF/CBMP, IPCC, IPBES)
- Respond to political requests for advice or data.

4.3 Coupling of knowledge systems and Citizen Science

Whilst GEM has a strong focus on scientifically robust and standardised measurements, GEM also sees a potential in engaging local communities in data collection via so called Citizen Science programmes. Citizen Science projects can potentially help collect data on specific variables, and help map and classify species distributions and communities that can e.g. be used to increase GEM data series or act as ground truthing for remote sensing efforts. GEM data also holds potential for engaging in socioeconomic projects to assess climate change and its impacts on local communities. GEM will remain vigilant to explore this potential through collaboration with external partners.

Key goals
- GEM will engage in externally funded Citizen Science projects, where this is relevant to GEM.
- GEM will be open for engaging in externally funded projects on climate change impacts on local communities.

Students collecting water samples in Nuup Kangerlua (Godthåbsfjord), SW Greenland on the graduate course "Arctic Marine Ecosystems in a Changing Climate". This course is part of the Arctic Science Study Programme (ASSP) offered in Nuuk, which collaborates with the Marin-Basis-Nuuk programme.

Photo: Thomas Juul-Pedersen.

4.4 Education

GEM will continue to promote the use of GEM data for educational purposes and use field sites and activities as a way of educating students in a range of skills from research to technical sciences and engineering.

There is a general lack of climate and ecosystem-relevant teaching material for the science subjects within the secondary education. The unique data material of real and continuously updated observations from the GEM programme provides unique opportunities for use in high school teaching materials and university level courses on the impact of climate change on ecosystems in the Arctic. GEM scientists will work with teachers to develop educational materials and virtual tools, and promote university level courses through for instance UArctic and APECS to engage and educate young scientists.

GEM data and outputs are already used in university courses in Greenland, Denmark and beyond, and GEM will continue to develop educational resources to the widest extend possible through external funding.

Key goals:

- Develop educational materials on climate change and ecosystems in Greenland in biology and geography teaching at high school levels in Denmark and Greenland.
- Developing university level educational programmes and thereby using GEM data to educate the next generation of scientists.
- Encourage the use of GEM data by young scientists through Bachelor, Master, PhD, and Post doc projects.


Photo: Katrine Raundrup.

4.5 Outreach

With the collection of locally and globally relevant data and knowledge, GEM is keen on communicating observed changes and potential impacts to the scientific community, decision makers and the public using a variety of platforms, including scientific peer reviewed journals, joint assessment reports, GEM Annual Report Cards, social media and newspaper articles.

Increasing the awareness of climate change and its impact, is important for people to comprehend the challenges that lie ahead, and to take informed decisions on how to mitigate potential negative consequences on local, national, regional, and global level. GEM will expand and broaden the platforms used for communicating science to the public both in Greenland, Denmark and beyond. We will work with the new International Arctic Hub on communication with the public in Greenland and beyond using multiple languages including Greenlandic.

Key goals:

- Ensure that scientific findings are communicated wider than in scientific journals alone - using accessible and plain language.
- Work with the International Arctic Hub in Greenland to increase public outreach for people in Greenland.
- Arrange and participate in outreach events in Greenland like Cultural Night and Greenland Science Week. GEM will also seek to hold outreach events in communities located near GEM main sites.
- GEM staff will to the widest extend possible allow visits to GEM sites to explain aims, fieldwork activities and results of the GEM programme to school classes, VIPs and other relevant groups.
- Use of social media through continuous updates via Facebook, Twitter and LinkedIn.
- Publish GEM Annual Report Cards and seek wider media coverage upon their annual releases.

5 Operational programme

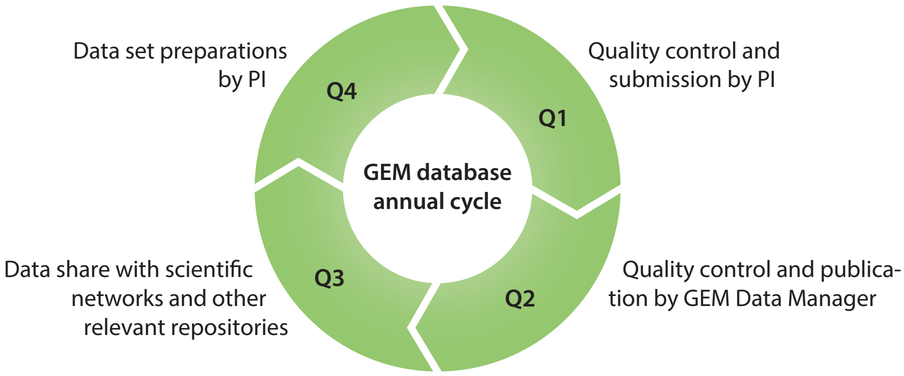
5.1 Coordination and Data Management

The GEM Secretariat facilitates the overall programme coordination and integration across sub-programmes. This includes coordination of funding applications, coordination of activities and monitoring of progress in relation to strategy aims.

GEM data management strive to adhere to the FAIR principles (Findable, Accessible, Interoperable and Reusable) and data are provided with open access to all files generated within the GEM programme. The GEM Database Manager and sub-programme leaders continuously update quality assured data following a standard annual procedure from field data acquisition through quality assurance to publishing of DOI referenced datasets. Metadata are shared with relevant data search engines and subsets of the database are shared with thematic repositories operated by scientific networks and organisations.

Operational programme elements – cross cutting initiatives and disciplinary sub-programmes are described in the following sections 5.2 and 5.3 respectively.

Figure 7. Annual wheel of GEM database operations.



5.2 Cross cutting sub-programme elements

5.2.1 Remote Sensing

Remote sensing has become a nexus in the GEM ambition of upscaling local ecosystem processes to larger regions or the entire Greenland. Alongside modelling, remote sensing is the only way of quantifying processes across a full spatial domain from site to landscape and regional scale. These spatiotemporal data are moreover critical to capture the magnitude of unforeseen extreme events, and we have put an effort in developing data with a wide range of applications within the sub-programmes. It is in the interest of GEM to continue focusing on developing automated workflows to activate remotely sensed data across all sub-programmes, and the exceptional time-series of in-situ observations from sub-programmes serve as valuable independent validation of remote sensing data, similar to their role in our ecosystem modelling ambitions. Having remote sensing, together with numerical ecosystem modelling, as specific topics in the strategy is therefore expected to catalyse studies cutting across all sub-programmes. Moreover it allows for synergy-effects when installing in-situ sensor types and decisions on sensor location, as remote sensing data can guide placements, and sensor types can be aligned with validation needs.

Efforts will be put in advancing our ability to use combinations of multi-spectral image data and modelling. As examples this is expected to lead to improved estimates of e.g.

snow density and cloud cover. These efforts will be supported by photogrammetry based on UAV and time-lapse camera imagery and extend our precision in monitoring glacier changes. Moreover, it will improve quantification of hydrology through the glacier-land-freshwater-fjord domain. Snow cover on sea and lake ice shuts off light from reaching through and below the ice and will be investigated by building upon similar methods as used in the former strategy period. Chlorophyll-based measures of marine biological productivity in the top water column will be explored from satellites, with implications of studies linking freshwater hydrology to fjord system biology. Biological processes like snow algae blooms that impact and reduce albedo and accelerate snowmelt can be detected from space and will be mapped from imagery, using the blooms known to occur at some of the GEM sites to relate the strength of their peculiar spectral signature to the concentration of algae measured in snow samples. As part of the sub-programmes, GEM will explore the use of LiDAR and hyperspectral data from UAVs for estimating land surface properties of relevance for the exchange of water and energy between land and atmosphere. These novel approaches link to measures of biodiversity, as a function of structural and spectral complexity of a surface or plant canopy. Biodiversity is linked to local moisture regimes, and efforts will be put on monitoring surface temperature and vegetation change and phenology with remote sensing, as these are linked to soil- and canopy moisture through thermal inertia and indicator plant species. Efforts in monitoring e.g., soil moisture is linked not only to ongoing measurements of in-situ soil moisture but also the ambition of increased focus on precipitation in the Geo-, Climate-, and Glacio sub-programmes.

New initiatives:

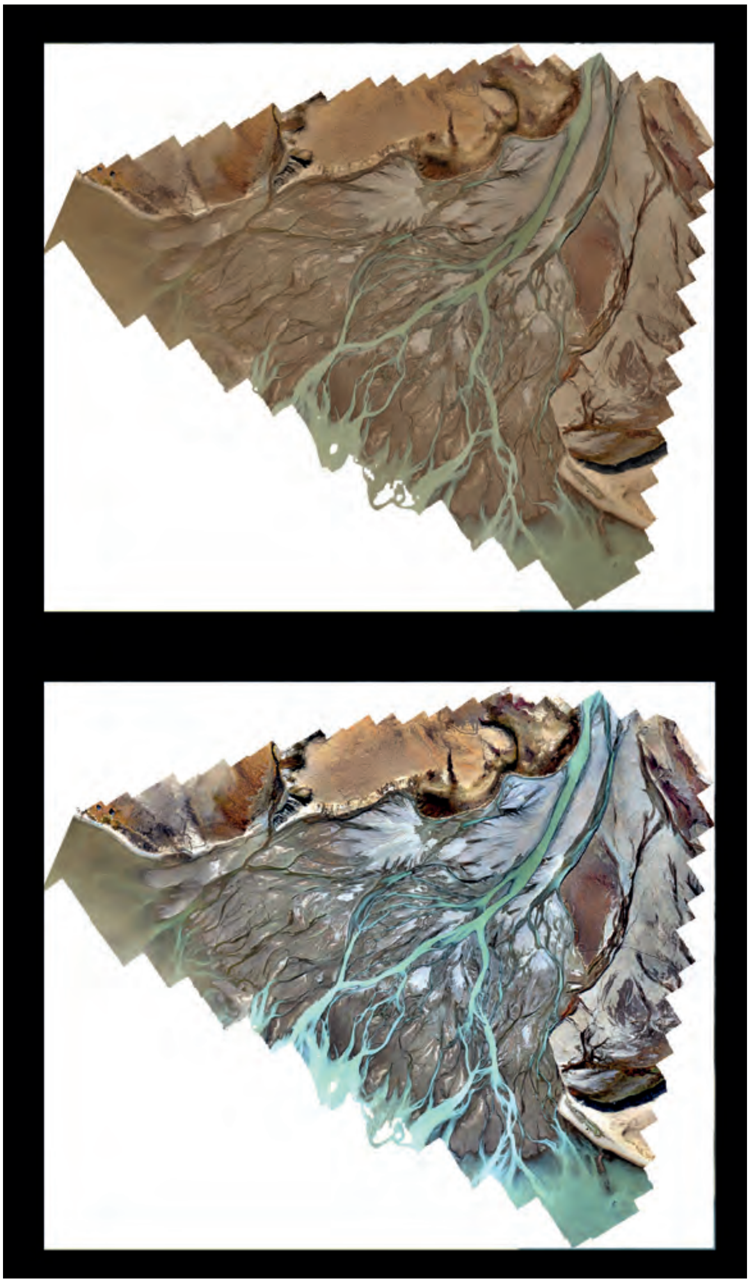
- Workflows will be optimized to minimize time spent on operational work, and be enhanced with novel and cutting-edge techniques in photogrammetry, image processing, machine learning and online cloud processing.
- The remote sensing efforts will be expanded to include marine components. This involve near-shore surface water temperature and chlorophylls.
- Remote sensing will be used to explore a higher degree of functional phenology through optical measures of vegetation productivity and multispectral data of plant canopy changes from satellites, UAVs, and time-lapse cameras. In combination with in-situ biogeochemical measurements of e.g., soil nutrient status and carbon fluxes, they are key to moving beyond descriptive changes in e.g. NDVI, towards the phenology of functional traits.

View from camera installation at the mountain Zackenberg overlooking the Valley, Young Sund and Daneborg in the distance.

Photo: Charlotte Sigsgaard.

Drone images of Zackenberg River delta.

Photo: Daniel Rudd, GeoBasis Zackenberg.



5.2.2 Ecosystem modelling and ecological forecasting

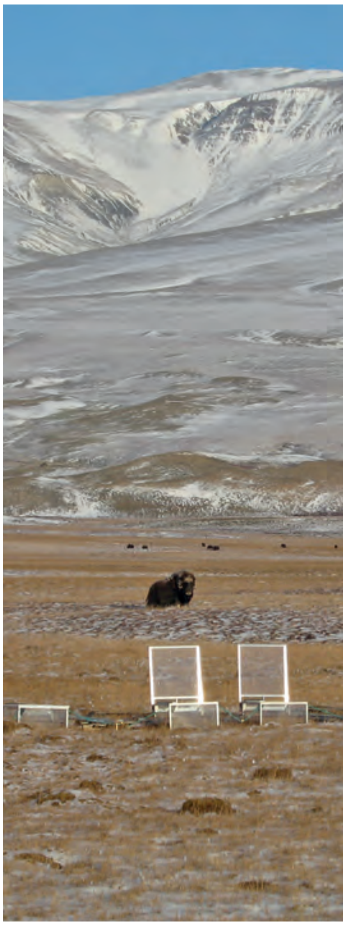
A new operational modelling component cutting across all three science themes and operational sub-programmes of GEM 2022-2026 will have an extended focus on improving understanding of spatiotemporal trends, variability and feedbacks through the close integration of in-situ data from all sites with numerical models. While in-situ measuring techniques are widely used in long-term ecosystem monitoring, their temporal and spatial coverage is limited mainly due to remoteness and harsh conditions challenging the creation of continuous datasets. There is also a challenge in analysing very heterogeneous landscapes, with components beyond the reach of monitoring locations. Conveniently, ecosystem modelling and remote sensing are key tools to understanding these neighboring to distal areas and providing forecasts. GEM's new efforts will support the assessment of data quality and homogeneity and the identification of extreme events, potential tipping points as well as exploration of likely future climate scenarios for ecosystem change. Moreover, these initiatives will feed into the development of more realistic (and less uncertain) ecosystem models of different complexities based on quality-controlled field data.

Process-based models are tools that allow the representation of dynamic vegetation and soils, hydrology, and ecosystem biogeochemistry (addressing complex carbon-, water-, energy- and nutrient-related interactions) as well as animal population dynamics. Such models have been recently adapted for use at different GEM sites with explicit representations of tundra vegetation, soil thermal dynamics, snow cover and frozen depth. Soon GEM will incorporate the challenging CH_4 emissions using recently published techniques, and an integrated joint use of snow and discharge models covering the entire composite landscapes. Linked to these efforts will be work on partitioning water and energy fluxes and the non-trivial interactions between large herbivores and the carbon and nitrogen cycles. A complimentary approach is the model-data-fusion systems. These are heavily data constrained techniques that retrieve optimal model parameters that statistically reduce the difference between model outputs and observations. Such modelling frameworks will allow for dynamic adjustments of the model parameters assimilating multiple data streams provided by GEM (e.g., different C fluxes and CN stocks, air temperature, soil temperature, snow depth, thaw depth, water table, soil moisture, and vegetation greenness) as well as spatially explicit remote sensing products such as leaf area index and soil moisture. In the biodiversity context, GEM will apply Hierarchical Modelling of Species Communities (HMSC) and other community-approaches to analyse and predict community-level dynamics, also in combination with molecular data (see below).

Finally, by using extensive quality-controlled measurements in conjunction with state-of-the-art ecosystem models, GEM will not only be able to facilitate a solid foundation for model calibration and validation, but also stimulate robust ecological forecast experiments. Thus GEM's cross cutting effort will be linked with the newest downscaled regional climate products and Earth System Models (ESM) following the 2021 IPCC sixth assessment report (AR6) and its most recent climate change scenarios based on different socioeconomic assumptions.

Auto chambers measuring fluxes in Zackenberg.

Photo: Charlotte Sigsgaard.



Using state-of-the-art energy-based modelling, GEM will facilitate the development of predictive modelling of the population dynamics of key tundra species.

New initiatives:

- Different data-model approaches will diagnose and upscale past, present and future ecosystem processes (both biotic and abiotic) and their links to associated climate feedback effects in all GEM sites. Some examples of such modelling efforts will address 1) the status and exposure of arctic greenhouse gas exchange (both CO2 balance and CH4 emissions) to current warming trends, 2) the ecosystem response to intensified hydrological cycles and run-off, 3) the rate of permafrost degradation in relation to temperature, snow dynamics and energy balance, and 4) the unexplored interactions between animal movement and carbon and nitrogen cycling.
- GEM will serve as ground-validation points for local-to-large scale modelling efforts. Strong efforts will be put to establish and consolidate strategic partnerships with leading scientific communities such as COPERNICUS Climate Change Service (CS3) and the Coupled Model Intercomparison Project version 6 (CMIP6; future contributor to the 2021 IPCC AR6 report).
- Data emerging from GEM will help to reduce widespread model uncertainties and improve forecasts. GEM can implement a dynamic iterative framework that will assimilate various data streams into different ecosystem models to improve model calibration and future projections at annual basis.

5.3 Disciplinary GEM sub-programmes

5.3.1 ClimateBasis

The overarching aim of the ClimateBasis programme is the long-term monitoring of climate and hydrological variables identified as essential by the scientific community and intergovernmental bodies (e.g. WMO, AMAP). The program focusses on high quality, continuity, high temporal resolution and year-round coverage. To ensure quality and as much continuity as possible, a double sensor set up is used together with a two-tier quality control procedure. Collected data is delivered to relevant WMO networks as well as to the GEM, Asiaq and DMI databases, thus providing baseline input to the GEM programmes as well as information on climate change and variability to the scientific community and society at large.

For the ground-based measurements at the core of GEM activities, the new strategy period will include the following focal points:

- Monitoring of climate and hydrology (in collaboration with GeoBasis) to maintain the continuity of the high temporal resolution, year round data series from the established main and distal sites.
- The role of clouds and precipitation in the Arctic climate system. Clouds are a poorly understood, sparsely observed element of the climate system, important for understanding climate sensitivity to warming. The recently implemented cloud cameras, atmospheric profiler and remote sensing efforts will be fundamental to this. Precipitation, in its liquid and solid form, continues to be one of the most difficult, but equally most important, parameters to measure. This focus compliments GlacioBasis, Promice, GIOS and Asiaq collaborations.
- Extending and improving winter measurements of challenging parameters (e.g. clouds, snow, discharge).

Zackenberg Hydrostation.

Photo: Asiaq.

Ecosystem processes are affected by the state and variability of the atmosphere and the hydrological cycle, including the spatiotemporal distribution of snow on the ground. Biological systems, in turn, modify the abiotic environment through material fluxes and their impact on surface properties such as albedo and aerodynamical roughness. The data collected by ClimateBasis on physical parameters is therefore needed as a basis for scientific work in all three GEM thematic areas.

The detection of trends and their separation from inter-annual variability, as well as the identification of extreme events is an essential aim of climate monitoring and requires continuous long-term observations of high quality. The strategic expansion of single-site observations to improve representation of spatial gradients and variability in horizontal and vertical dimensions is a first step towards answering the question of how representative the GEM research sites are for the climate and ecology of Greenland and the Arctic as a whole. The GEM main sites and distal climate sites provide an anchor point for up-scaling and gradient studies, feeding directly to the remote sensing and modelling efforts within GEM.

A natural extension of this is to use the data sets as validation for model-based approaches (e.g. regional climate models, regionalized snow models, local-scale process models), in collaboration with partners, that will allow projections of the future evolution of the climatic and ecological processes monitored by GEM. Understanding the process-based relationships between variables and the interactions between climate and ecosystems is essential in order to be able to predict future changes and their timing better. A process-based perspective will further aid in identifying observational gaps to be addressed by future monitoring activities.

New initiatives:
- UAV-based snow distribution maps, incorporated into the long-running annual snow survey will a be a new data product. If the pilot deployments for alternative continuous snow measurements are successful, these will also feed into an improved understanding of the evolution of the winter snow pack.
- Clouds decrease the amount of incoming solar radiation by reflecting it back into space, but emit longwave radiation toward the surface. The net effect is poorly constrained by existing observations in the Arctic but important to understand physical feedbacks to climatic warming and effects on ecosystems. To address this knowledge gap, hemispherical sky cameras are in operation at several GEM sites, and the algorithm to derive cloud fraction and properties from the optical images is being improved and validated against other data sources (including remote sensing) to provide fractional cloud cover datasets at the sites.
- Understanding the vertical structure and temporal development of the atmospheric boundary layer is important for understanding the dynamics of clouds and the energy balance at the earth's surface, both of which affect ecosystems. A microwave radiometer is collecting temporally highly resolved atmospheric profiles of temperature and humidity at Arctic Station in Qeqertarsuaq and quality control procedures are being developed to deliver its data to the GEM database.

5.3.2 GlacioBasis

The overarching aim of GlacioBasis is to monitor mass balance of arctic glaciers and quantify the processes that governs the mass balance and the impact of arctic glaciers melt processes on future sea-level rise, fresh water inputs into fjord systems and impact on the fjord ecosystem. The efforts directly address several of the essential variables, knowledge gaps and research needs identified by AMAP and international scientific networks and organisations (e.g., IPCC, WMO-GCW, WGMS).

Snow pit and buried weather station at A.P. Olsen Ice cap close to Zackenberg.

Photos: Michele Citterio.

To achieve its aims, the primary focus of GlacioBasis is the monitoring of glacier surface mass balance and of its climate drivers. Operationally, these key monitoring tasks are:

- Monitoring of surface mass balance, including more robust snow measurements on glaciers
- Monitoring of near-surface weather to calculate the surface energy balance
- Monitoring of area and volume changes supported by the Remote Sensing component

The results will produce in situ observations for calibration and validation of modelling and remote sensing products in collaboration with ESA, DMI and others.

By addressing the glacier and glacial meltwater runoff components of changing Arctic climate systems, GlacioBasis contributes to the hydrological monitoring in GEM, which is essential for understanding linkages between glaciated, freshwater, terrestrial and marine ecosystems (e.g. physical properties and nutrient fluxes). GlacioBasis will continue the development of the snow modelling activities to contribute to GEM modelling efforts. The impact of snow on the abiotic and biotic components of the ecosystem cuts across all three science themes in this strategy, and will therefore support GEM as a whole in addressing the shifts in terrestrial ecosystems linked with snow-land type-hydrologic changes coupled with ecological feedbacks that together transform Arctic landscapes.

The *in situ* monitoring in GlacioBasis is used for validation of GEM remote sensing products, and combined with quantification of glacial processes it will be used in GEM modelling efforts. GlacioBasis hence enables the use of climate models and downscaling techniques to link with in situ observations and address the overarching knowledge gap on the timing, magnitude and risk of future Arctic change involving multiple feedbacks.

New initiatives

Spatial distribution of snow cover and melt will be a new data product based on the satellite, UAV and automated camera data and supplemented by new automated GNSS reflectometry snow depth and cosmic ray snow water equivalent measurements. The product will be further developed through the Ecosystem Modelling component, as part of the snow and discharge models. If pilot deployments are successful, liquid precipitation on glaciers will become part of the standard package carried by the GlacioBasis automatic weather stations (AWS).

- In collaboration with PROMICE we are developing an automated and fully reproducible processing toolchain from raw data, including realtime AWS satellite transmissions, to publicly delivered datasets for the GEM database and the WMO Information System (both directly and through DMI), as well as near-realtime updated outreach channels like PolarPortal, and PROMICE and Asiaq websites.
- On the modelling side, the ongoing snow and ice melt model development work at GEUS will continue and incorporate albedo and snow extent products from the GEM Remote Sensing Initiative. This model can also use weather fields produced by regional climate models (RCM), enabling studies both beyond the local scale of the GEM sites and beyond the temporal coverage of our time series to predict changes in response to different greenhouse gas emission scenarios.

5.3.3 GeoBasis

GeoBasis focuses on abiotic characteristics in order to describe the state of Greenlandic terrestrial environments and their potential feedback effects in a changing climate. The GeoBasis programme provides an active response to recommendations in international assessments organisations and scientific networks (e.g., ACIA, SWIPA, AMAP, ICOS, GRDC, CALM).

Preparations for camera installation. Kobbefjord.

Photo: Laura Hauch Kaufmann.

The backbone of the GeoBasis programme consists of three components that will be maintained and further developed in the strategy period:

- Water cycle components – through monitoring of permafrost, river discharge and water chemistry, evapotranspiration and soil water and snow and rain measurements in collaboration with ClimateBasis
- Radiation - four component radiation measured at all sites provided a robust measure for the available energy. As a new initiative a further integration between drone surveys and radiation components will be initiated during the coming strategy period.
- Greenhouse gases - the exchange of water vapour, CO_2 and CH_4 between the ecosystem and the atmosphere is fundamental for understanding the climatic feedbacks of the Arctic and a long-term important program component. The efforts in this field will in the coming project period be further aligned and adapted to the best international standards. Most of the flux stations will be integrated in the ICOS network and workflow in the processing of data will be aligned further to increase the comparability of the data, ease the workflow and increase the exchange of expertise between the GeoBasis team.

To improve the understanding of the differences and similarities between the three main GEM sites the new strategy period will improve the mapping of the sites with respect to vegetation (in collaboration with BioBasis) and with respect to soil and morphological properties. This initiative will also be of benefit to the general user of the GEM database and will allow a more qualified use of the already available data.

The Ecosystem Feedbacks theme has a strong focus on the effect of climate change on radiation budgets, exchange of greenhouse gases and permafrost thawing. All of these are measured in the GeoBasis programme and therefor a backbone in this specific theme. By linking the physical environment of snow and ice prevalence (the Cli-

Erosion gully associated with permafrost thaw. Zackenberg Valley.

Photo: Charlotte Sigsgaard.

Organic soil profile. Zackenberg Valley.

Photo: Daniel Rudd.

mate and Cryosphere theme), over the temperature of the surface, to ecosystem composition and dynamics (the Biodiversity and Populations theme), the theme and the GeoBasis activities are building a bridge between the abiotic and biotic Worlds of Greenland.

By integrating *in-situ* measurements, remote sensing products, and ecosystem modelling, GEM will be in a privilege position to find and explore common ground between the local scale field observations and the fine-to-large scale modern climate simulations focusing on Greenland, typically left behind in global modelling analyses due to its complexity and lack of data. The activities within GeoBasis will explore synergies with the new crosscutting ecosystem modelling and remote sensing programmes to advance our understanding of spatiotemporal variability shaping greenhouse gas exchange, energy and water cycles trigged by changes in meteorology and extreme events, plant phenology, nutrient availability, and permafrost degradation. GeoBasis data will play a key role calibrating process-based models, validating and benchmarking large-scale downscaled climate products, and establishing the initial conditions for ecological forecasting efforts.

GeoBasis will implement a new initiative of a more detailed description of landscape scale vegetation, soil types and functioning, and morphology, through in-situ observations and use of both satellite and drone data. The initiative will be realized in combination with expertise from BioBasis and ClimateBasis. The GeoBasis efforts in monitoring parameters such as soil moisture, energy-fluxes, nutrient status and surface hydrology are thus fully aligned with the crosscutting modelling and remote sensing initiatives, leading to improved process understanding and scalability of terrestrial ecosystem functioning.

New initiatives:

- The greenhouse gas flux data will undergo a streamlining, and improvement after international protocols provided by the European research infrastructure ICOS. This increase the visibility, quality and comparability of the data, from a region of the World which has a limited data coverage. This improvement requires calibration and renewal of instrumentation.
- GeoBasis will seek funding for new instrumentation for the CH_4 flux measurements that, if funded, will increase the comparability between the other micrometeorological measurements.
- The proposed mapping of the sites in Nuuk and Disko requires a wider use of drone data and therefore calls for new drones and sensors/cameras. Likewise a mapping of soil properties and morphology would benefit from dedicated sampling and analyses campaigns combined with e.g. georadar surveys which would improve the interpretation of the subsurface layers and visualize the presence of shallow permafrost layers.

5.3.4 MarineBasis

The MarineBasis programme collects key physical, chemical and biological data from the Greenland coastal zone, primarily at the three main field stations: Nuuk, Disko and Zackenberg. The programme began in 2003 at Zackenberg and has since been implemented at Nuuk (2006) and Disko (2018), and the evolving time series provide unique baselines for quantifying impacts of climate change now and in the future in marine

Sampling for fish, shrimp and crab larvae using a Bongo-net near the Narssap Sermia glacier in Nuup Kangerlua (Godthåbsfjord) as part of an annual fjord transect by the MarinBasis-Nuuk programme.

Photo: Thomas Juul-Pedersen.

ecosystems. Marine Basis addresses key variables and research needs identified by intergovernmental and scientific networks and organisations, (e.g. CAFF/CBMP).

The MarineBasis programme delivers baseline data that allows us to identify long-term trends in key parameters such as sea ice coverage, water temperature, salinity, CO_2 uptake, nutrient concentrations, sinking flux, phytoplankton biomass and primary production, species composition of phytoplankton and zooplankton, macroalgal growth and marine mammals and seabirds. Combined with integrated research projects, the program increases our knowledge of how climatic drivers influence the structure and function of marine ecosystems.

The MarineBasis programme collects data on species composition and community structure of phytoplankton and zooplankton. In addition the programme also collects data on macroalgae, marine mammals and seabirds all under the GEM theme of Biodiversity and populations. The Climate and Cryosphere theme is supported through the collection of data on the effects of a changing climate, meltwater and effects of glacial processes. Many physio/chemical parameters are collected including sea-ice cover, water temperature, salinity, CO_2 uptake and nutrient composition. This links to the theme on Ecosystem Feedbacks where the MarineBasis programme collect data relevant for describing ecosystem interactions including primary production, food web structure, seasonal variations/patterns, temporal variations/patterns and CO_2 fluxes.

New initiatives

- eDNA sampling will be added as a new tool to monitor species composition of microplankton, i.e., phytoplankton and microzooplankton, along with mesozooplankton based on microscopic analysis, targeting the lower- to mid-trophic level organisms. This will provide a broader insight into the presence, diversity and ecological role of species in these coastal ecosystems. Collection of eDNA data is intended as a pilot study supplementing, rather than replacing, the ongoing quantitative plankton method.

Research vessel "Porsild". Arctic Station, Qeqertarsuaq.

Photo: Torkil Gissel.

Marine sampling. Young Sund, Zackenberg.

Photo: Mie Winding.

- GEM will introduce the use of lipids as a marker in the marine ecosystems. Pronounced seasonal variations in light intensity, ice cover and productivity amplified by climate change will further prolong the ice-free period of the year. This influences the timing and duration of the spring bloom of lipid rich diatoms affecting the presence, quantity and quality of food supplies for pelagic predators. Consequently, Arctic pelagic ecosystems will become more unpredictable and the animals are forced to adapt to these environmental changes, since most elements in the arctic marine food web rely on lipid for successful overwintering and reproduction. GEM aims to incorporate monitoring of the lipid content in key plankton size groups and selected animals.
- The carbonate system in seawater is not easy to analyse, but is essential to monitor since acidification can be a driver of ecosystem change, while the CO_2 content determines the potential for air-sea exchange of CO_2. Both parameters are influenced by changes in sea cover, melt water flux and ocean temperature. We aim to improve the MarineBasis monitoring of the carbon dioxide system, by standardizing methods across the three monitoring sites and updating the instrumental quality of the collected field data.


Photo: Lars Holst Hansen.


Photo: Henning Thing.

5.3.5 BioBasis

BioBasis monitors key communities, species and processes across plant and animal populations and their interactions within the terrestrial and freshwater ecosystems, thereby documenting the intra- and inter-annual variation, resilience and long-term trends. BioBasis thus addresses essential variables and research needs identified by intergovernmental and scientific networks and organisations (e.g., CAFF/CBMP, ITEX, ABBCS, IWG, LIFEPLAN).

BioBasis documents changes in the arctic biodiversity, and thus monitors a large variety of populations, species and processes across plant and animal taxa, with main focus on diversity, abundance and composition, phenology, reproduction and predation rates in the arctic ecosystems. The key taxonomic groups include flora (phytoplankton, lichens, mosses, and vascular plants), invertebrates (zooplankton and arthropods) and vertebrates (fish, birds and mammals).

With its specific focus on biodiversity, populations, and species in the terrestrial and freshwater ecosystems, BioBasis makes major contributions to the GEM theme Biodiversity and Populations by documenting status and trends of the key biotic components of the ecosystem, as well as the interactions between these. Collating data from across sub-programmes allows GEM to target cross-boundary interactions to decipher how these may influence ecosystem structure and function.

Hydrology is thus a common denominator for all GEM sub-programmes: Snow, ice, rain, and moisture are key drivers in terrestrial, freshwater ad marine ecosystems, impacting a suite of diversity-related parameters, including abundance, composition, phenology, as well as the biotic interactions in the ecosystems; all of which are monitored closely by BioBasis.

Processes within the biotic components of the ecosystem may impact other biotic but also abiotic processes. For instance, element cycling may be impacted by herbivory and decomposing rates, or by shifts in the community composition. Incorporating biotic feedbacks into ecosystem-modelling enables GEM to make better predictions about ecosystem processes.

BioBasis will work closely with the sub-programme on remote sensing and modelling to allow for up-scaling of key elements (e.g. vegetation patterns) and for better predictions of biotic responses to on-going and future environmental changes.

New initiatives

BioBasis envisions a number of new pilot studies or fully implemented initiatives. The new initiatives aim primarily to improve the spatio-temporal coverage of key parameters, and to improve the link between biodiversity-related data from plot-scale, over the landscape-scale (UAV products) and to regional-scale (remote sensing products). The initiatives include:

- To increase the spatio-temporal resolution of the BioBasis monitoring, the sub-programme will increase the use of data-loggers for continuous measurements of e.g. soil moisture and freshwater temperature, and of UAVs for monitoring of e.g. plant growth patterns and wildlife distributions.
- To improve the workflow within BioBasis, the sub-programme will increase the use of molecular tools or automatic image-based solutions to monitor community composition, species abundance and their interactions.
- To increase the predictive capacity of BioBasis, the sub-programme will continue to integrate various mechanistic models and statistical frameworks to analyse and predict community-level dynamics within the arctic ecosystems.

The gear needed for a lake sampling day. Zackenberg Valley.

Photo: Kirsten Christoffersen.

Disko Bay.

Photo: Charlotte Sigsgaard.

6 Financing and implementation

GEMs long-term monitoring efforts is envisioned to continue with base funding from the Arctic science support programmes of the Danish Ministry of Climate, Energy and Utilities, and the Ministry of Environment of Denmark (Klimastøtte and Miljøstøtte til Arktis) with additional support provided by the Government of Greenland and the participating research institutions. The GEM strategy 2022-2026 is ambitious and intends to develop and initiate a range of new initiatives and the programme is therefore expected to expand over the coming five year period. GEM will seek to achieve this

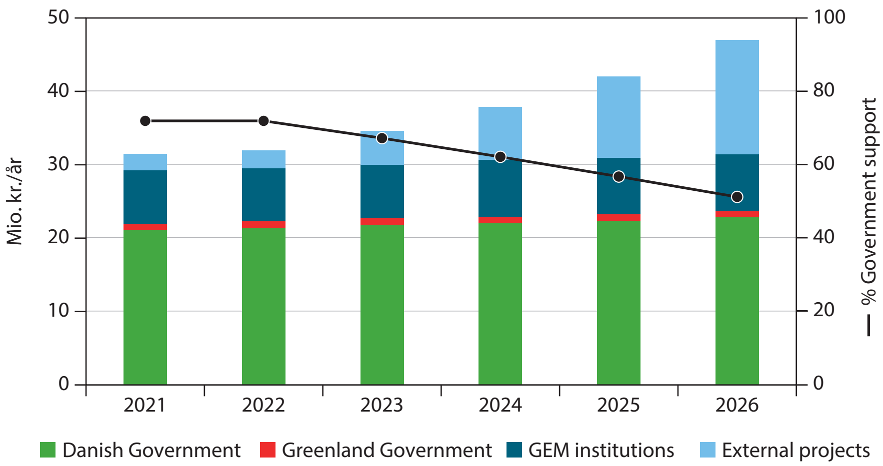
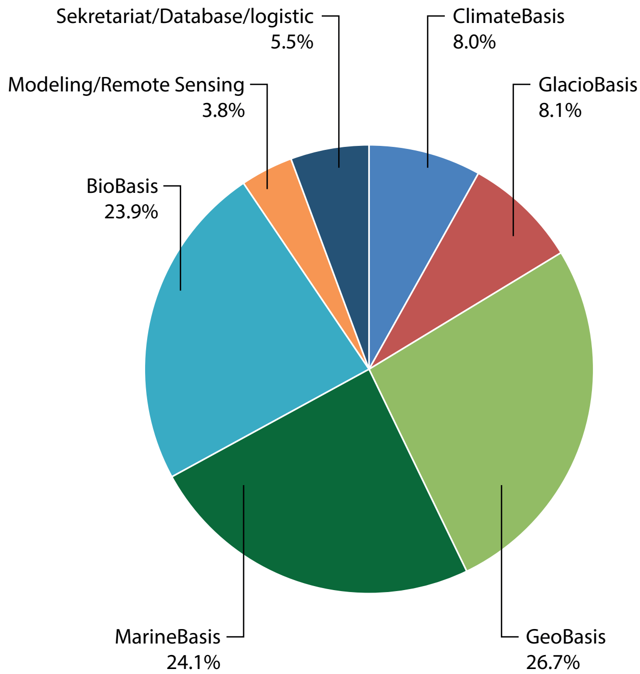


Figure 8. *The envisioned approximate composition of GEM funding over the strategy period 2022-2026. The existing composition as in the GEM proposals for 2021 is included for reference. The governmental support forms the stable foundation (red and green part of bar diagram, left axis) but the relative contribution it makes is decreasing with time as GEM associated external project contributions increase (black line, right axis). The level of 50/50 contribution of governmental sources versus other contributions to GEM is expected to stay at a stable level after 2026. Hence, the proposed growth rate of the program over the period is expected to cease and the size of GEM to stay at a stable level from 2026 and onwards.*

expansion by increasing the contribution of external non-government funds to the programme. Hence, the core funding from the Danish ministries and the Government of Greenland is expected to support a decreasing share of the operational budget for GEM from 72% in 2021-22 entering the new strategy period to 52% in 2026. Similarly, the contributions from participating GEM institutions will remain at the same level throughout the strategy period.

Figure 9. *Operational sub-programme's share of the Government support.*



The governmental support and the contributions from GEM institutions are intended to secure the monitoring and long-term research efforts, while externally funding will be sought for short-term projects and collaborations to e.g. improve our knowledge of ecosystem processes and connections, contribute to gradient studies, improve data sharing and develop education and outreach initiatives. This will be achieved through continued efforts to attract external scientists and scientific networks, and continue and develop existing national and international collaborations.

The operational sub-programme's share of the GEM programme budget (pie diagram below) is expected to stay at the same relative level as in the 2017-2021 strategy with only one new addition in relation to the previous strategy being one separate cross cutting sub-programme on Modelling and Remote Sensing.

7 Budget

The budget depicted below constitutes the total financial means needed from internal and external funding sources for implementing the GEM Strategy 2022-2026. The budget has been produced with input from the GEM Secretariat and operational sub-programmes.

Budget is in million Danish Crowns (mio DKK).

	%	2021	2022	2023	2024	2025	2026
KlimaBasis	**100,00**	**2,56***	**2,60**	**2,84**	**3,14**	**3,51**	**3,96**
Disko	27,26	0,70	0,71	0,78	0,86	0,96	1,08
Nuuk	46,73	1,20	1,21	1,33	1,47	1,64	1,85
Zackenberg	26,01	0,67	0,68	0,74	0,82	0,91	1,03
GlacioBasis	**100,00**	**2,19***	**2,22**	**2,37**	**2,54**	**2,75**	**3,01**
Disko	29,75	0,65	0,66	0,70	0,76	0,82	0,89
Nuuk	15,35	0,34	0,34	0,36	0,39	0,42	0,46
Zackenberg	54,90	1,20	1,22	1,30	1,39	1,51	1,65
GeoBasis	**100,00**	**6,85***	**6,95**	**7,33**	**7,79**	**8,35**	**9,02**
Disko	21,71	1,49	1,51	1,59	1,69	1,81	1,96
Nuuk	25,04	1,71	1,74	1,84	1,95	2,09	2,26
Zackenberg	53,25	3,65	3,70	3,90	4,15	4,45	4,80
MarinBasis	**100,00**	**7,63***	**7,74**	**8,46**	**9,33**	**10,41**	**11,74**
Disko	26,96	2,06	2,09	2,28	2,52	2,81	3,16
Nuuk	40,98	3,13	3,17	3,47	3,82	4,27	4,81
Zackenberg	32,06	2,45	2,48	2,71	2,99	3,34	3,76
BioBasis	**100,00**	**7,65***	**7,76**	**8,49**	**9,39**	**10,49**	**11,85**
Disko	28,04	2,14	2,18	2,38	2,63	2,94	3,32
Nuuk	27,88	2,13	2,16	2,37	2,62	2,92	3,30
Zackenberg	44,07	3,37	3,42	3,74	4,14	4,62	5,22
Modeling/RS	**100,00**	**1,35**	**1,37**	**1,52**	**1,71**	**1,94**	**2,23**
Sekretariat/logistik	**100,00**	**2,53***	**2,57**	**2,80**	**3,10**	**3,50**	**3,90**
Koordination	60,00	1,52	1,54	1,68	2,10	2,50	2,90
Nuuk logistics	40,00	1,01	1,03	1,04	1,06	1,07	1,09
Total GEM costs		**30,8**	**31,2**	**33,8**	**37,0**	**40,9**	**45,7**
Danish Government		20,34	20,66	20,97	21,28	21,60	21,93
Greenland Government		0,91	0,91	0,93	0,94	0,96	0,97
GEM Institutions		7,11	7,22	7,33	7,44	7,55	7,66
External projects		2,39	2,43	4,60	7,30	10,80	15,10
Total projected income		**30,8**	**31,2**	**33,8**	**37,0**	**40,9**	**45,7**

Obs 2021 marked with * is calculated from collected GEM proposals for 2021. Percentages as also in 2021.

Appendices

Appendix A. Essential variables by international organisations

GEM is delivering data on a wide range of parameters and indicators identified as essential for the monitoring and detection of climate change impacts and feedbacks in the Arctic. This provides the direct linkage of GEM to a number of international programmes. The key essential variables and organisations are summarized in the tables below.

Essential variables by international organisation	Group	Products
Essential Climate Variables – WMO GCOS	ECV atmosphere / surface	Temperature, precipitation (liquid and solid), air pressure, surface radiation budget (long- and shortwave components), humidity, wind speed and direction
Essential Climate Variables – WMO GCOS	EVC Atmosphere / upper atmosphere	Tropospheric profiles of temperature and humidity, fractional cloud cover, water vapour, radiation budget
Essential Climate Variables – WMO GCOS	ECV atmosphere / atmospheric composition	Carbon dioxide, methane and other greenhouse gases
Essential Climate Variables – WMO GCOS	ECV Land / Hydrosphere	Lake water level, lake surface temperature, river discharge,water level and flow velocity, cross section, surface soil moisture
Essential Climate Variables – WMO GCOS	ECV Land / Cryosphere	Area covered by snow, snow depth, snow water equivalent, snow extent, water flow (level and discharge), water parameters (temperature, conductivity, turbidity, chemistry), glacier mass change, glacier elevation change, permafrost and active layer thickness
Essential Climate Variables – WMO GCOS	ECV Land / Biosphere	Albedo, land surface temperature, Above-ground biomass, soil carbon, soil moisture, Land surface temperature, evaporation from land, energy budget
Essential Climate Variables – WMO GCOS	ECV /Ocean Physical	Temperature, salinity, sea ice cover

Essential variables by international organisation	Group	Variable
Focal Ecosystem Components (CBMP)	Focal Ecosystem Components (FEC) / Essential Biodiversity Variables (EBV)	Diversity and composition of communities and species
Focal Ecosystem Components (CBMP)	Focal Ecosystem Components (FEC)	Abundance of species and species-groups
Focal Ecosystem Components (CBMP)	Focal Ecosystem Components (FEC)	Phenology of life-history events
Focal Ecosystem Components (CBMP)	Focal Ecosystem Components (FEC)	Demographics and vital rates , Spatial distribution

Footnote:
Global Climate Observing System Essential Climate Variables (by WMO et al.) https://gcos.wmo.int/en/essential-climate-variables/table
CAFF - Focal Ecosystem Components
Terrestrial and Freshwater: https://interact.caff.is/index.php/fec-s
Marine: https://www.caff.is/marine/marine-monitoring-publications/3-arctic-marine-biodiversity-monitoring-plan

Appendix B. International organisations and networks GEM contributes to

Scientific network (with data repository)		GEM repre-sentation	Geographical Coverage	Link
Acronym	**Name**			
ABDS	Arctic biodiversity Data Service	BioBasis	Arctic	https://www.abds.is/
ACD	Arctic Coastal Dynamics	GeoBasis	Global	http://arcticcoast.info/
Arctic Birds	Arctic Birds	BioBasis	Arctic	http://arcticbirds.net
CALM	Circumarctic Active Layer Monitoring	GeoBasis	Arctic	https://www2.gwu.edu/~calm/
CBMP	Circumpolar Biodiversity Monitoring Programme	BioBasis MarineBasis	Arctic	http://www.caff.is/monitoring
EFD	European Fluxes Database Cluster	GeoBasis	European	http://www.europe-fluxdata.eu/
FLUXNET	Fluxnet	GeoBasis	Global	https://fluxnet.ornl.gov/introduction
GBIF	Global Biodiversity Information Facility	BioBasis	Global	http://www.gbif.org/
GLORIA	Global Observation Research Initiative in Alpine Environments	BioBasis	Alpine	http://www.gloria.ac.at/
GRDC	Global Runoff Data Centre	ClimateBasis GeoBasis	Global	http://www.bafg.de/GRDC/EN/Home/homepage_node.html
GTN-G (GTOS/GCOS)	Global Terrestrial Network for Glaciers	GlacioBasis	Global	http://www.gtn-g.ch/
GTN-G GlaThiDa	Global Terrestrial Network – for Glaciers, Glacier Thickness Database	GlacioBasis	Global	https://www.gtn-g.ch/glathida/
GTN-P	Global Terrestrial Network - Permafrost	GeoBasis ClimateBasis GlacioBasis	Global	http://gtnp.arcticportal.org/
ICOS	Integrated Carbon Observation System	GeoBasis	European	https://www.icos-ri.eu/
IHP - UNESCO	International Hydrological Programme - UNESCO	GlacioBasis	Global	http://en.unesco.org/themes/water-security/hydrology
ITEX	International Tundra Experiment	BioBasis	Arctic	http://ibis.geog.ubc.ca/itex/
PDC	Polar Data Catalogue	BioBasis	Polar	https://www.polardata.ca/
Promice	Programme for Monitoring the Greenland Ice Sheet	ClimateBasis MarineBasis GlacioBasis	Greenland	http://www.promice.org/home.html
WGMS	World Glacier Monitoring Service	ClimateBasis GlacioBasis	Global	http://wgms.ch/
WHYCOS	World Hydrological Cycle Observing System	ClimateBasis GeoBasis	Global	http://www.whycos.org/whycos/
WMO - GCW	World Meteorological Organisation - Global Cryosphere Watch	GlacioBasis GeoBasis	Global	http://globalcryospherewatch.org/

Scientific network (with no data repository)		GEM representation	Geographical Coverage	Link
Acronym	**Name**			
Arctic Wolves	Arctic Wildlife Observations Linking Vulnerable Ecosystems	BioBasis	Arctic	http://www.cen.ulaval.ca/arcticwolves
CAFF/C-Bird	Conservation of Arctic Flora and Fauna/ Seabirds	Biobasis	Arctic	https://www.caff.is/seabirds-cbird
CAFF/Flora	Conservation of Arctic Flora and Fauna/ Circumpolar Flora Group	Biobasis	Arctic	https://www.caff.is/flora-cfg
CARMA	Circum Arctic Rangifer Monitoring and Assessment Network	Biobasis	Arctic	https://carma.caff.is/
Herbivory Network	Herbivory network	Biobasis	Arctic	http://herbivory.biology.ualberta.ca/
IPA	International Permafrost Association	GeoBasis	Global	http://ipa.arcticportal.org/
MWRNET	International Network of Ground-based Microwave Radiometers	GlacioBasis	Global	http://cetemps.aquila.infn.it/mwrnet/
NeAT	Network for Arthropods of the Tundra	BioBasis	Arctic	https://tundraarthropods.wordpress.com/
NordSnowNet	Nordic Snow Network	ClimateBasis	Arctic	https://nordsnownet.fmi.fi/
PerCS-Net	Permafrost Coastal Systems Network	GeoBasis	Arctic	https://permafrostcoasts.org/
PCN	Permafrost Carbon Network	GeoBasis	Global	http://www.permafrostcarbon.org/
SEDIBUD	Sediment Budgets in Cold Environments	GeoBasis	Global	http://www.geomorph.org/sedibud-working-group/

Greenland Ecosystem Monitoring

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

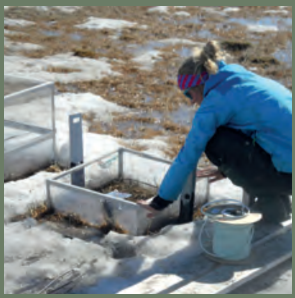
www.g-e-m.dk

ClimateBasis Programme

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

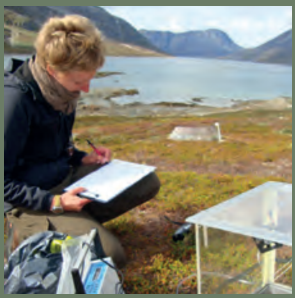
GeoBasis Programme

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



BioBasis Programme

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



MarineBasis Programme

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

GlacioBasis Programme

The GEM GlacioBasis Programme studies ice dynamics, mass balance and surface energy balance in glaciated environments.

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