

Scientific evaluation of programme area 5

Nature and Climate (2013-2020) at the Geological Survey of
Denmark and Greenland (GEUS)

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Table of content

Summary	4
Introduction	5
Evaluation procedure	6
Personal interviews with selected staff	9
General observations	9
Marine Geology	11
Observations	11
Mapping habitats	12
Geological models	12
Marine and near-surface geological history	13
Marine data acquisition	13
Recommendations	13
Paleoclimate and Palaeoceanography	15
Observations	15
Natural climate and environmental variability	16
Modern analogues in past climate	16
Climate proxy development and calibration	17
Recommendations	17
Glaciology	19
Observations	19
Monitoring of glaciers and ice sheets	20
Glaciological Processes	20
Recent Climate Change	20
Recommendations	21
General recommendations across the Nature and Climate programme area	23
The evaluation process	26

Summary

Our role as a review panel was to provide a scientific evaluation of GEUS' programme area 5, 'Nature and Climate', with a view to providing a full assessment across the range of activities undertaken within the programme. This in itself necessitates commending areas that are thriving as well as perhaps the more critical role of making clear recommendations in areas where we believe that changes, if implemented, could improve the performance or working environment within the institute.

At the outset, we wish to make clear that we were, in the main, impressed with the performance and progress in the Nature and Climate programme over the assessment period (2013–2020). The research strength within the programme has been enhanced as evidenced through the excellent publication record (398 peer-reviewed publications during the reporting period (mean ~50/yr)), success at securing external competitive funding via strategic research grants (41) and consultancy grants (19) and the generation of critical, extensive and outstanding datasets about the natural environment in Denmark and Greenland. In addition, the ambition to promote the open availability of these datasets via web-platforms and dissemination through publications is commendable. The programme has also made important contributions to high-impact policy documents delivering clear and successful assessment and outreach products. Finally, our discussions with staff and tours of the infrastructure all allude to a positive work environment supported by excellent lab facilities.

While our assessment overall is positive, there are several areas where changes, if implemented, could further enhance the performance of the programme either more generally or specifically in relation to the marine geology, paleoclimate or glaciology research groups. These are outlined in detail within the documentation that follows but key areas include establishing a specialist technical computing-support working group, in order to address clear computing issues that are restricting the overall performance and research potential of the programme (and GEUS more widely). Furthermore, additional programme-wide recommendations include implementing an Early Career Advisor system, establishing a scientific innovation budget and taking meaningful steps to address the issue associated with the gender imbalance in leadership roles.

Overall, we were impressed with the professional preparation and the detailed documentation made available to us, which helped us considerably with the evaluation process.

Introduction

Following the Executive Order from the Danish Ministry of Climate and Energy on January 20, 2009, this document reports on an Evaluation of the research conducted by the Geological Survey of Denmark and Greenland (GEUS) in the Nature and Climate Programme Area (GEUS' programme area 5). The Evaluation Panel are tasked with an evaluation of research and dissemination activities over the period 2013-2020 with the aim of *identifying strengths, gaps and the need for amendments and improvements* in relation to GEUSs strategy and mission with the 'Nature and Climate' Programme Area. More specifically, the evaluation relates to the following primary research disciplines:

Marine Geology

Paleoclimate

Glaciology

Evaluation procedure

The members of the evaluation panel were:

- Lilja Rún Bjarnadóttir (PhD), Head of Quaternary Geology section, executive group member (lead: geology) of the MAREANO seabed mapping programme, Geological Survey of Norway.
- Tómas Jóhannesson (PhD), Senior Researcher, Coordinator of Glaciological Research, Division of Processing and Research, Icelandic Meteorological Office.
- Thomas Neumann (PhD), Research Scientist, Chief, Cryospheric Sciences Lab, NASA Goddard Space Flight Center.
- Peter Nienow (PhD), Professor of Glaciology, School of Geosciences, University of Edinburgh.

In addition, Lovisa Zillén Snowball, Head of Marine Geology Division/Researcher, Geological Survey of Sweden, was nominated to take part in the evaluation but she could not participate due to illness.

The evaluation was conducted according to the terms of reference and detailed programme (given below):

Tuesday, October 5th

- 9:00 Welcome coffee/tea.
The panel members introduce themselves.
- 9:15 Introduction to GEUS and the Research Evaluation,
General introduction to GEUS by Deputy Director Esben Auken
- 9:45 Uptake of recommendations from the previous evaluation by Deputy Director Esben Auken
- 10:00 Discussion on the role of the evaluation panel members, on the mission programme, the outcome of the mission, and the time frame for the evaluation etc.
- 10:20 Highlights of recent and ongoing activities on programme area 5 – Nature and Climate. Introduced by Heads of Departments Signe Bech Andersen and Jørn Bo Jensen
- 10:50 Questions
- 11:00 Coffee break

Presentation of main research areas (15 minutes presentation followed by 5 minutes for questions):

- 11:20 Seabed nature – diversity and habitats, by Senior Researcher Ziad Al-Hamdani
- 11:40 Coastal seabed geomorphology and habitats, by Senior Researcher Verner Brandbyge Ernstsen
- 12:00 The long-term history of ice-ocean-climate interaction in the Arctic North Atlantic region, by Professor Paul Knutz
- 12:20 The interaction of the Greenland Ice Sheet with climate and ocean changes in the North Atlantic: the multidecadal to millennial time scale, by Senior Researcher Camilla S. Andresen

- 12:40 Arctic climate, cryosphere and ocean changes – Holocene records and new proxies, by Senior Researcher Sofia Ribeiro
- 13:00 Questions and discussion
- 13:20 Lunch at GEUS with the staff presenting in today's sessions.
- 14:20 Cryospheric monitoring programmes, by Chief Consultant Andreas P. Ahlstrøm
- 14:40 Cryospheric data products, by Researcher Anne Solgaard
- 15:00 Processes and modelling, by Senior Researcher Robert Fausto
- 15:20 Processes and modelling – continued, by Senior Researchers Nanna Karlsson and Robert Fausto
- 15:40 Questions and discussion
- 16:00 Coffee break
- 16:20 Pre-satellite era glaciology – Bridging modern and geological observation, by Senior Researcher Kristian K. Kjeldsen
- 16:40 GEUS scientific content in high level reporting, by Professor Jason Box
- 17.00 Questions and discussion
- 17.15 Review of the day, plans for the evaluation
- 18:00 Dinner

Wednesday, October 6th

- 9:00 Recollecting Day 1
- 9:15 Strategy and visions for the future on marine, paleoclimate, glaciology and cross-cutting issues: tasks introduced by Head of Dept. Signe Bech Andersen and Head of Dept. Jørn Bo Jensen followed by ultrashort presentations:
- Learning from past climate changes, by Senior Researcher by Senior Researcher Kasia Śliwińska
 - Mapping the shallow subsurface in the North Sea – Quaternary geological evolution and impact on present day usage, by postdoc Lasse T Prins
 - Marine and coastal geodiversity and geosystem services, by Senior Researcher Verner Brandbyge Ernsten
 - Seabed mapping – scale analysis and automation, by physical geographer Lars Øbro Hansen
 - Past ice sheet evolution: inputs from Greenland and Antarctica, by Senior Researcher Lara Perez
- 15 min break around 10.00
- Geocenter Greenshift, by postdoc Mimmi Oksmann
 - Modelling of outlet glaciers, by Researcher Signe Hillerup Larsen
 - Surface properties from remote sensing or meltwater retention, by Researcher Baptiste Vandecrux
 - Permafrost in rock, by Senior Researcher Michele Citterio
 - Operational data assimilation, by Professor Jason Box
- 15 min break around 11.00

- Sedimentary ancient DNA (sedaDNA) – a new tool in climate studies, by postdoc Sara Harðardóttir
 - Sea-level rise and coastal flooding in Denmark: past, future, and policy, by Senior Researcher Kristian K. Kjeldsen
 - Mathematical Modelling of Ice Sheets – G(EUS)MMI, by Researcher Anne Solgaard
 - Sharing is caring, by Kenneth D. Mankoff
 - Gender balance in geosciences, by Senior Researcher Nanna Karlsson
- 12:30 Lunch at GEUS with the staff members from the sessions today
- 13:30 Landslides and tsunamis coupled to climate (marine & DK), by Researcher Kristian Svennevig
- 13:40 Bibliometric analysis, by professors Jason E Box and Paul Knutz
- 14:00 Outreach via GEUS Department of Communications, by Senior Researcher William Colgan
- 14:15 Evaluation panel reflects on the day and decides which staff members to interview
- 14:30 Coffee break
- 15:00 Laboratory visit at ØV10:
Introduction and overview of equipment at storage facilities at Taastrup, by Professor Paul Knutz
- Weather stations at GEUS (roof) (Robert Fausto)
 - Weather station laboratory (Robert Fausto)
 - Paleoclimate laboratory / Palynology Lab (Sofia Robeira)
 - Organic geochemistry; (Jørgen Bojesen-Koefoed; climate/nature applications)
 - Geochemistry; focus on paleoDNA (Sofia Ribeiro)
- 17:00 Discussion including reflections on the day
- 17:30 End of day 2.

Thursday, October 7th

- 9:00 Preparation of draft report and/or interviews with staff members selected by the evaluation panel
- 12:00 Lunch at GEUS
- 13:00 Preparation of draft report, preparation of debriefing conclusions.
- 17:00 Debriefing
- 19:00 Dinner

Friday, October 8th

- 9:00 Preparation of final draft report.
- 12:00 Lunch at GEUS.
- 13:00 Delivery of final draft report to GEUS.
- 14:00 End of research evaluation mission

Personal interviews with selected staff

Marine geology department: Head of department Jørn Bo Jensen, Professor Paul Knutz, Senior researcher Verner Brandbyge Ernstsen, postdoc Lasse T. Prins

Glaciology and Climate department: Head of department Signe Bech Andersen, Senior researcher Camilla S. Andresen, Senior researcher Sofia Ribeiro, Senior researcher Nanna B. Karlsson, Senior researcher Robert S. Fausto, Senior researcher Kenneth D. Mankoff, Senior researcher Michele Citterio, Researcher Anne M. Solgaard, postdoc Sara Harðardóttir.

Department of Stratigraphy: Senior researcher Kasia Śliwińska

Management: Director Flemming Larsen, Deputy director Esben Auken, Senior Geologist, Scientific Coordinator Lisbeth Flindt Jørgensen.

General observations

Presentations from GEUS staff about current projects and research activities were well organized and gave a comprehensive overview of the activities of the agency during the reporting period.

- GEUS management and the GEUS board have a clear ambition to increase the emphasis of the institute on the publication of research results in peer-reviewed scientific journals and on applications to competitive funding agencies. Part of GEUS government funding is provided to the departments as own-funding or matching funding in such projects. This funding model has recently been revised to make such internal contributions more transparent.
- The publication record of Programme Area 5 has been excellent with authorship on 398 peer-reviewed publications during the reporting period (mean ~50/yr).
- The Nature and Climate programme area has been successful at securing fundamental and strategic research grants with 41 large to small projects active over the reporting period divided between Glaciology (19), Paleoclimate (9), Marine Geology (8) and 'Other environments' (5).
- Consultancy provides a key component of the Area 5 income, in particular within Marine Geology, which has secured 13 of the 19 consultancy projects funded during the reporting period.
- GEUS has acquired extensive and outstanding data sets about the natural environment in Denmark and Greenland and these data have a considerable, and as yet only partly realised, potential for delivering scientific research led both from within GEUS and more widely. The greater emphasis on published research at GEUS is in part centred around finding interesting research opportunities in these data and exploiting them in research applications to funding agencies. This implies a shift from a more consultancy-based operation and may require hiring of new researchers or refocusing the work of existing staff towards science aimed at publication in reviewed scientific journals.
- GEUS has implemented an open data policy for sharing observations and results of research and has embedded this policy within the 'GEUS' strategy 2020–2023' via the "Value-adding data" strategic topic. These data are therefore not generally withheld or

sold on to end users in order to claim back some of the institute's operating costs. The data are increasingly made available via web-based platforms (e.g. dataverse) and reported to the community via publications in journals such as *Earth System Data Science*. This policy and approach should be commended highly; it is providing an outstanding service to the wider community and increases greatly both the value of the data and the impact of GEUS's wider scientific contribution.

Marine Geology

The Marine geology department is located in Aarhus. The department has a staff of 17 persons, divided on three main scientific themes (paleoclimate, raw materials and nature and environment). In general, communication is good within the Marine geology group and on larger projects/tasks the whole group participates (e.g. fieldwork). A few persons commute from Copenhagen and occasionally have some office time in Copenhagen. This provides some degree of communication with colleagues at GEUS-Copenhagen.

The Marine geology department grew out of an agency and has historically undertaken a large amount of consultancy work mapping raw materials on the seabed. The main tasks and scientific focus of the department at the moment include offshore habitat mapping, palaeo-environmental reconstructions, studies of coastal processes and sediment dynamics, sea level change, fluid flow-related seabed features, geoarchaeology, the Quaternary development of the North Sea and marine-environmental baseline for platform decommissioning.

The department runs a public database for marine geological data called MARTA. The data are freely available for download in commonly used formats (excluding classified data). Datasets include sediment maps, raw material distribution, sampling points, seismic lines, images and videos and reports. Datasets are also available as Web Map Services and Web Feature Services. MARTA is much used by governmental agencies and companies as a tool for spatial planning. Data is delivered to several other European portals such as EMODnet and EGD.

By direction, the panel considered the Paleoclimate research component of the Marine Geology department separately. This section therefore relates to the department with the exception of Paleoclimate.

Observations

- The Marine geology department has the necessary skills and equipment for conducting high quality seabed mapping (sediments, aggregates, shallow geology). They have many years of experience with mapping marine raw materials and habitats in shallow coastal areas / according to Natura-2000.
- Denmark does not have a national seabed mapping plan/programme. The offshore mapping done by GEUS is mostly tender-based. Despite a high success rate winning bids this funding model is not ideal for continuity and long-term planning.
- The department is developing its range of remote sensing approaches, allowing a multiscale approach to mapping.
- The department is developing methods to bridge the gap between land and sea, taking a holistic approach to describe the coastal environments including the geosystems and processes at play in these environments, on both sides of the shoreline.
- The department has had only limited research output in the form of scientific publications in recent years but is actively working to increase the amount of research.
- There is a strategy to increasingly make reporting of the results from consulting work more effective, with an ambition to replace long reports with scientific publications and digital products.

- The department is working to increase the visibility and importance of geology in seabed ecosystems, both in terms of geodiversity and geosystem services.
- The department is starting to use machine learning techniques for semi-automated seabed (geo)morphology mapping, with the aim to move away from expert interpretation to less time-consuming methods and reproducible products.
- The department has access to a wealth of marine acoustic data from external sources. Data is organised in a database (Marta) with seabed sediment maps and information on the distribution of raw materials, sampling points, images and video, as well as reports. The data are freely available for download, and are also provided as map services (WMS, WFS).

Mapping habitats

For the last about 15 years, the Marine geology department has conducted benthic habitat mapping in numerous locations. Benthic habitats include the physical, biological and chemical seabed environment and mapping them requires a multi-disciplinary approach and co-operation with other institutions. GEUS's main role has been mapping the geology of the benthic ecosystems such as the seabed substrate and morphology, both of which greatly influence the distribution and diversity of benthic fauna communities. The geological mapping includes acoustic surveying with a range of equipment (such as sidescan sonar, single- and/or multibeam echosounders and sub-bottom sediment profilers), followed by visual inspection (photo/video) and physical sampling of the seabed.

Geological models

A common practice in Marine geology projects includes compiling existing and/or new data and knowledge and building a geological model. Such models describe the geological composition, stratigraphy and age, as well as key geological processes at play in the past and present. The geological models are used for multiple purposes including e.g. for mapping and estimating raw material resources and mapping benthic habitats.

The detail in the geological models can be further enhanced and GEUS already plans to include information on for example geodiversity variables and geosystem functions and services. This will be a valuable addition to the fundamental knowledge necessary to ensure sustainable marine spatial planning and management of the seabed. A national seabed model including such information will be very useful for multiple purposes concerning issues such as nature conservation, siting of wind/fish farms, resource exploitation and geoheritage to name a few. This is important work which should be continued.

Extending geological models from sea to shore to allow seamless mapping is becoming more important in a rapidly changing environment. More recent efforts to map the coastal environments on both sides of the shoreline using a combination of different data types such as multibeam bathymetry and red/green laser (topographic/topobathymetric LiDAR) look very promising. A better understanding of the interplay of processes in this highly dynamic zone is increasingly important and should be continued. Making use of machine-learning techniques

and semi-automated mapping methods will be important to ensure reproducibility as well as cut processing time and costs.

Marine and near-surface geological history

The Marine geology department studies the palaeogeography of the Danish marine sector, particularly the postglacial evolution. Seismic data provide regional framework for choosing good coring locations. Seabed sediment cores provide information on both sedimentology and age. Also the department has in-house expertise on biostratigraphy, providing another layer of environmental information. Different data are combined to reconstruct the extent of different palaeo-sedimentary environments at different times. The resulting palaeogeographical maps are useful in different ways, such as identifying sand and gravel resources, understanding postglacial changes to species distribution in Scandinavia and identify potential submarine archaeological sites of different ages.

Marine data acquisition

The department owns and operates the 31 foot research vessel *Maritina* that is well suited to short (1-day) cruises surveying the inner Danish waters. *Maritina* is equipped with a range of acoustic instruments and sampling equipment. The acoustic instruments include sidescan sonar, single- and multi-beam echosounders, sub-bottom sediment profiler and seismic systems (sparker/boomer). Physical sampling gear include different corers (vibro-, gravity-, piston, box) and grabs. GEUS has licences for necessary software for acquiring, processing and interpreting the different data.

GEUS is well-equipped for multiple types of seabed surveys, including amongst others raw material and/or habitat mapping, palaeo-environmental studies and submarine construction work.

Recommendations

- GEUS should have a strategy for seabed mapping. The Marine geology department is well positioned and has the necessary skills to take a leading role in acquiring geological seabed data in Denmark.
- GEUS should actively advocate and work for the establishment of a national programme for seabed mapping.
- GEUS should establish a Framework Programme including R&I in relation to seabed habitat mapping.
- GEUS should aim to build an operational, multifunctional, cross-sectorial seabed model.
- GEUS should actively promote geological seabed information (e.g. on seabed substrate, the sub-surface, geological processes, geodiversity, geosystem services) as an integral part of the knowledge fundament needed for ecosystem-based ocean management.

- GEUS should work for the establishment of a national plan for storing and managing marine data. Ideally, it should be mandatory to send all seabed data to GEUS. The data should be compiled in a national database that is freely available to all.

There are many existing models for mapping programmes that may be helpful to explore in relation to the aforementioned recommendations. While some of them primarily focus on mapping the depth and seabed terrain (multibeam bathymetry surveying), others are multi-disciplinary and include holistic mapping of benthic ecosystem (including e.g. geology, biology, sediment chemistry). Successful national seabed mapping programmes that may provide inspiration include e.g. Infomar (Ireland), AusSeabed (Australia) and MAREANO (Norway).

- The green transition brings new opportunities e.g. related to platform abandonment, windfarm siting and potential carbon storage sites. GEUS should continue promoting their geological expertise and knowledge with respect to such topics, and work to re-establish their supervisor role for agencies and departments.
- GEUS should explore new topics e.g. marine geohazard mapping, and providing seabed substrate maps to fisheries.
- GEUS should continue working with a range of remote sensing approaches, taking a multiscale and holistic approach to mapping the coastal zone. In addition to providing important insights on environments subject to climate change and human impact, mapping the coastal gaps will allow production of seamless land-seabed maps.
- GEUS should continue developing their map making methods, increasing the use of machine learning/semi-automated prediction tools where possible.
- The Marine geology department should consider measures to improve the gender balance.

Access to science-based seabed knowledge is a prerequisite for proper management of marine areas. This includes management of seabed ecosystems and resources, as well as coastal and offshore area planning. GEUS has an important role to fill as a knowledge provider in this regard.

Paleoclimate and Palaeoceanography

The Paleoclimate and Palaeoceanography group is composed of researchers, postdocs, and students from the Department of Marine Geology and the Department of Glaciology and Climate. Within the Department of Marine Geology, research is focused on the evolution of climate and oceanography over deep time, spanning tens of millions of years. Within the Department of Glaciology and Climate, research is focused on the evolution of climate and oceanography over the Holocene and the recent past. In addition, one researcher in the Department of Reservoir Geology brings expertise in inorganic chemistry and biostratigraphic analyses across both time scales.

The group has developed collaborations among researchers within, and to a lesser extent, between departments. The group has significant collaborations with other research groups in Denmark, as well as the wider international community, as evidenced by (among other efforts) playing a leading role in securing the upcoming International Ocean Discovery Program 400 cruise and coring efforts. Through interviews, the scientists noted that the formation of a cross-department Paleoclimate Group has great potential to foster inter-departmental collaboration once the immediate disruption of the current global pandemic has passed. Scientists based at Aarhus University (Department of Marine Geology) make efforts to stay connected to colleagues at the main GEUS campus in Copenhagen.

The overall quality of the research among this group has been excellent during the review period. Although an imperfect metric the publication rates, and citation metrics of those publications are commensurate with the career stages of group members. Two observations are worth noting in particular: 1. the transition of the Marine Geology group from a primarily consultancy-based Department to a research-focused department is ongoing, and 2. the group has been extraordinarily successful in securing external funding to develop laboratory facilities that significantly expanded the breadth of analyses that can now be done in-house.

The overall quality of the research outreach activities among this group was not highlighted as prominently as the academic and technical successes of the group. The group publishes their research in professional journals and at appropriate conferences.

Observations

- In terms of research, the overall productivity as reflected by proposals, funded projects, papers and collaborations is of very high quality, regardless of time period (deep time, Quaternary, or Holocene) or department.
- The group is split between two departments. At times this has led to administrative challenges when it's not clear which department has responsibility, and issues can take longer to resolve, as two administrative units are involved.
- In general, separation between departments has not prevented collaboration across researchers; the recent formation of a cross-department Paleoclimate Group has been a positive element.

- Unlike other review elements, Paleoclimate has no significant stabilising budget line item and the work is proposal- and project-based. This has resulted in longer-term uncertainty about institutional commitment to the research element.
- The group is dependent on physical laboratories and has been reasonably well supported in terms of laboratory space and colocation of facilities.
- The organic geochemistry lab has outstanding potential, given the existing facilities and equipment. A current limitation is the lack of lab staff (chemist) and long-term vision and funding for research.
- The gender balance in this cross-departmental group is remarkable, with women in more than half of leadership roles.
- The development of laboratory capability in the review period was driven by the success of the group in writing competitive proposals.

The Paleoclimate and Palaeoceanography group can be further subdivided by three main focus areas of scientific research as described below. Collectively, during the review period group members led 59 peer-reviewed publications and were co-authors on an additional 102 peer-reviewed publications. The number of times these works have been cited (a metric of how relevant the research has been) averages around 10 for the first authored papers, and somewhat higher (around 20) for co-authored papers. The panel acknowledges the imperfect nature of citation indices but noted that group members have citations and related scores commensurate with others at similar career stages.

Natural climate and environmental variability

This research element focuses on the climate and environmental variability of the recent past at the multi decadal to millennial scale through the use of climate proxies. Primarily, these projects have focused on the recent evolution of the Greenland ice sheet, based on proxy records derived from short sediment cores. These records are then related to larger-spatial scale climate indicators, such as the Atlantic Multidecadal Oscillation, in order to better understand the physics of the interrelationships in the climate system. Ultimately, such insights will lead to improved confidence in predictions of ice sheet change in a warming climate.

Modern analogues in past climate

During the review period, there have been several research efforts to leverage insights from past climate as prologue for the world we are entering in the coming decades. Such research leverages both deep time analogues from the past several million years and insights from the more recent past. GEUS research and projects in this area have been scientifically relevant and of wide interest among the larger community. The panel appreciates the complexity in establishing compelling quantitative relationships between elements of the climate that resulted in the sedimentary sequences and associated geochemistry we can observe today. There is every indication that this will remain a fruitful research theme in the coming decades, and GEUS has established itself as a leader in this topic through strategic hires and competitive

science projects. Maintaining such scientific expertise requires ongoing thoughtful leadership and an institutional commitment to sustain a well-qualified research team.

Climate proxy development and calibration

Common to both elements above, the Paleoclimate and Palaeoceanography group maintains and develops the laboratory techniques to generate proxy records from sediment cores and samples. During the review period, entirely new paleo proxies have been developed and implemented (notably ancient DNA extraction and classification). This group has taken advantage of a number of technical advances to maintain state-of-the-art facilities and also continue to move the field forward, and this remains an active area of development scientifically. Notably, GEUS scientists have primarily funded the acquisition of new technical equipment via grant proposals. The panel recognises that keeping such facilities occupied and operating is a significant challenge, and to date the group has been remarkably successful in this regard.

Recommendations

- Consider establishing paleoclimate as a separate administrative entity

While the research group has had success in intra-departmental collaborations, GEUS could foster wider collaborations by elevating this research topic. The purpose of such a change would be two-fold: 1. facilitate collaboration among researchers who share interests in similar processes and drivers, even though the timescales in question may be disparate, and 2. demonstrate GEUS' commitment to pursuing these lines of research on an equal footing with other scientific elements within Program Area 5. There exists sufficient scientific momentum within the group (recently funded projects, a healthy cohort of postdocs, students, state of the art laboratory facilities) to consider such a realignment. The review panel notes there was significant, though not universal, support for such a change, as there are valid arguments related to funding and management for maintaining the current departmental structure. In further discussion with the GEUS Managing Director, it was noted that Paleoclimate had been an independent unit in the past. However, without the stabilising force of significant directed funding, the group was entirely funded through competitive proposals, and the current arrangement was designed to mitigate the risk posed by the prior organisational structure.

- Consider commitment to laboratory facilities associated with this research group

While the group has been successful at winning competitive proposals to acquire significant new laboratory capabilities and securing science projects to utilise those facilities, the long-term viability and interest in these facilities is unclear. First, the organic geochemistry lab is clearly in a state of transition. While the laboratory equipment in this lab is substantial and reasonably state-of-the-art, the lab lacks a chemist to leverage these investments and a longer-term scientific vision to carry this facility into the next decade. GEUS should consider its commitment to such capabilities and either promote this capability by hiring a chemist or repurpose this space. Second, the development of DNA-based stratigraphic techniques is an emerging scientific development and provides unique capability within Denmark if not a wider

geographic region. GEUS should consider its commitment to this line of research and develop the last pieces of the process that prevent a complete end-to-end analysis capability from sample or sediment core to scientific data. At the moment, the group depends upon external facilities for extraction. Completing support for the end-to-end process would establish GEUS as a significant international leader in ancient sedimentary DNA and enable new science and collaborations with external entities. Third, GEUS should consider its financial model for the long-term success of these laboratories. Currently, there is a lack of administrative structure and funding to carry labs through lean periods and promote the involvement and training of students. Fourth, while GEUS may not have a programmatic mandate for education as a university would, the nationally unique resources of GEUS present an opportunity for education and training of students at both university and graduate student levels. A commitment to fostering these connections by clear guidance and financial support for student training and researcher supervision and involvement would elevate GEUS' profile nationally, and potentially internationally.

- Model for core funding for Paleoclimate

Unlike the other elements considered in this review, the larger paleoclimate group has no core funding (from either directed work or tender-based competitions) to provide continuity or a backstop for labs and researchers. GEUS should consider what possibilities exist to develop such a resource. Two possibilities include: 1. recognition and support of research labs as national assets. To the panels' knowledge, several of the facilities used by the Paleoclimate group are unique in Denmark. There may be an opportunity to request state-level support for these state-level assets. 2. consider a model of project-based tax return to a common pool for this group to manage. This could be done at the department level with significant input from the participating researchers.

Glaciology

GEUS employs 23 researchers and 3 technicians working on the glaciology and changing climate associated with the Greenland Ice Sheet. This field of monitoring and research has expanded greatly within the agency during the evaluating period and this activity of GEUS has very clear international prominence and become an important part of the climate-change programme of the Danish government. GEUS scientists make substantial contributions to international collaboration in this research area and have participated in several IPCC and AMAP assessments during the evaluation period. The establishment of the PROMICE network of 25 automatic stations and its recent expansion with the inclusion of the 18 GC-Net weather-station network into a comprehensive observational system of snow/ice melt, climate and ice motion is a major achievement of the Glaciology Group.

The Glaciology Group also works on traditional mass balance (a data set of historical mass-balance measurements), surface energy balance, snow and ice optical properties, ice velocity from remote sensing, solid ice discharge, mass balance estimates for the entire ice sheet and individual glacier catchment basins, fresh-water runoff, melting at the base of the ice, ice borehole temperature profiles, terminus and calving front variations and glacier outlines, dynamic ice-flow modelling and reconstruction of the ice sheet over different time-scales since the end of the Little Ice Age. In short, GEUS is responsible for supporting an extremely impressive range of glaciological research investigating the world's second largest ice mass.

Observations

- GEUS has, in collaboration with Danish, Greenlandic and international collaborators, successfully established a comprehensive system of automatic weather stations on the Greenland Ice sheet.
- Data from this system are openly available and are accessible through a new data sharing system based on the “dataverse” concept which is a major new development of the programme.
- The PROMICE/GC-Net station network is operated independently from the DMI weather station network in Greenland and observations from PROMICE have so far not been integrated into the WMO data flow for sharing meteorological observations between national weather services.
- GEUS glaciologists have been involved with general studies of climate and climate change in the Arctic and contributed with data and analyses to the main international climate-change assessments in recent years.
- The Glaciology Group has an impressive publication record during the reporting period, both in glaciological and environmental technical journals and in high-profile scientific journals such as *Nature*. The open distribution of GEUS data through the new GEUS dataverse repository will increase the visibility and usefulness of GEUS data and scientific results through doi-references that document the use of the data in a transparent manner.

- The Glaciology group have made significant authored contributions to scientific ‘high level’ reporting and to key summary documents such as the AMAP (Arctic Monitoring and Assessment Program) and IPCC reports.
- The Glaciology Group, and GEUS in general, have carried out substantive outreach activities including through publishing ‘glossy’ internal reports about glaciology and the Greenland Ice Sheet, producing a brochure in Greenlandic, interacting with numerous news and mainstream media outlets and releasing videos/news feeds on social media.

Monitoring of glaciers and ice sheets

The operation of the PROMICE weather station network is the main monitoring activity of the Glaciology Group but regular reporting about the mass balance and ice flow of the Greenland Ice Sheet are also important activities. The reporting about the status and changes of the ice sheet to the Danish and Greenlandic governments, the international research community and to the public has increased during the reporting period and will become even more important in the future because of the increasing importance of the Greenland Ice Sheet in the context of global climate change.

Glaciological Processes

GEUS’ scientists carry out processing of remote-sensing data to produce ice-velocity maps, model glacier mass balance and carry out glaciological process studies. The process studies are important to complement the glaciological monitoring results and ensure that the unique data obtained for example from the meteorological stations is utilised properly to enhance understanding of key glaciological processes.

The Glaciology Group plans to expand its activity in dynamic modelling of the Greenland Ice Sheet, with both paleoclimatic modelling of the history of the ice sheet through the ice ages and modelling of current and future developments of the ice sheet. The aim is to combine results from ice-flow models with well-constrained (temporally and spatially) geological observations, including the wealth of available data from sediment cores and other sources, in order to validate and force the models.

Recent Climate Change

Analysis of meteorological measurements, remote sensing data and historical information about glacier extent and ice surface elevation creates baseline information against which current changes and trends can be compared. Participation in international reanalyses projects for the Arctic are an essential part of this activity. “Data archaeology” centred on archival aerial imagery that can be processed and interpreted using modern GIS technology and hitherto little used historical data, are also invaluable in providing constraints on ‘recent’ (centennial) ice-sheet margin change prior to the onset of the satellite era.

Reporting and outreach activities regarding recent climate change are an essential aspect of GEUS' activity in this area. Maintaining a pan-Arctic scope in this work by considering a larger area than Greenland alone, as has been done in some recent studies at GEUS, gives this activity more weight than it would otherwise have.

Recommendations

- Work on integrating the PROMICE/GC-Net network with the WMO Information System for the sharing of atmospheric observations in collaboration with DMI should be continued (already in progress).
- Continue collaboration with Danish and international meteorological agencies and research institutes to make maximal use of the data obtained with the PROMICE network. As GEUS does not employ meteorologists, this data set will only be used to its full potential in collaboration with other researchers that carry out atmospheric modelling, reanalyses and other relevant meteorological interpretation. Maintaining and even enhancing the current links with DMI should therefore be an essential and ongoing ambition.
- The development of a dynamic ice-flow modelling capability for the Greenland Ice Sheet requires a substantial in-house development effort to establish the fundamentals for such modelling. There is already considerable experience and expertise to deliver on this work within the current GEUS staff. However, in order to realise its potential, a clear and strong vision for this work needs to be established including provision of the appropriate technical support (see below).
- Specialist technical computing support (hardware, software and personnel). The commitment to operate the open dataverse data distribution system for GEUS data, for example, needs to be implemented with a good plan to run this system in the future (platform, backup, continuation of the requisite in-house expert knowledge) after the initial installation effort which has now been successfully completed.

The research delivered by the glaciology group has evolved and increasingly requires the use of and access to high-level computing support. This requirement is primarily associated with the use and analysis of large data-sets (both field-based and remotely-sensed satellite data) and the developing modelling directions within the group (via G(EUS)MMI). The current computing set-up is inadequate to support this work, primarily due to the lack of hardware (e.g. servers/CPUs/Linux etc.) and specialist expertise to support the systems. This lack of support ensures that research productivity from the group is reduced either because work simply cannot be undertaken or very costly time-consuming workarounds need to be found. The top-down IT state support does not provide the level of specialist support required; this could potentially be found 'in-house', but a budgeted time commitment would need to be found to enable this (with agreement/support from line managers/relevant personnel). As noted below, this issue is not in fact unique to the Glaciology group within GEUS and we therefore suggest establishment of a wider Working Group to address this issue as a matter of urgency.

- Funding to support fieldwork safety.

The field research on the Greenland Ice Sheet and adjacent margins by the Glaciology Group has inherent risk and requires clear and strong fieldwork safety procedures and protocols. This requires personnel to be trained in a range of safety techniques. In the past, this training has been covered by overheads coming directly to the research group. The new GEUS model for distributing overheads means that these funds are now not directly available to the group. We recommend that this safety-cost commitment is guaranteed through overheads from the 'centre' in order to ensure that field safety is not compromised in any way.

In addition, ESA Worldview Imagery is invaluable for providing field-safety support via the ability to check the safety or otherwise of field conditions at short-notice (e.g. to check whether it is safe for planes or helicopters to land for fieldwork/weather station maintenance). Free access to Worldview requires high-level (Ministerial?) support and we would recommend that the GEUS management take action on this to support (for free) the field safety of the ground-based research teams.

- Roof-based weather-station platform

The group are continually developing and testing new equipment for the weather stations for deployment on the Greenland Ice Sheet. In order to improve the testing facilities, it would be invaluable to have a better platform on the GEUS roof for mounting their 'trial' weather stations. The current set-up does not allow for the most appropriate test environment. This limitation needs to be addressed to ensure that the key data, which is subsequently collected on the Greenland Ice Sheet, is of the best possible quality.

- Keep lab space near to the fieldwork academics

The current set-up for the Weather Station laboratory works exceptionally well because of the close proximity between the lab/technicians and academic field workers. We would like to stress the importance of maintaining this proximity of the lab to academic staff in order to support the effective interaction between the technicians and academics.

General recommendations across the Nature and Climate programme area

The panel noted six potential corrective actions in response to issues the panel noted from presentations, tours, and interviews that spanned both departments and all three research focus areas.

- Create a GEUS specialist technical computing support Working Group

It is clear that the issues flagged above regarding effective high-level computing resources are not unique to the Glaciology Group. As such, we recommend that a GEUS Working Group is set-up in order to consider the best way to address these limitations and thus help deliver more timely, valuable and impactful research. In particular, this group needs to consider: i) what hardware, software and technical support are needed across the groups; and ii) how this resource could be funded within GEUS's current financial model. We are not in a position to say exactly what is needed under these two headings. It may for example become clear that different groups need different servers/set-ups/support; what we want to ensure however is that the relevant users can use such a Working Group to make an informed decision on what is needed and be vested in the process of making those decisions. It is increasingly clear that the work of 'computing intensive' groups will be limited by the current set-up; furthermore, the new funding model without access to overheads, means that it is hard for individual research groups to address this problem alone.

- Implement an Early Career Advisor system

The Nature and Climate Program Area has a number of 'in-house' PhD students but as far as we can tell, there is no PhD 'Advisor', just the formal academic Supervisor(s). We think it is important to implement an 'Advisor' system where each student has an additional external PhD Advisor. The role of the Advisor is to provide mentoring support to ensure that all is going smoothly with the PhD across a range of issues; e.g. the academic progress; PhD timeline; publication plans (where appropriate); technical support etc. The role is designed to ensure that the PhD is guided properly by the Supervisor team and to provide a 'safety-net' for the student; in our experience, on the rare occasions when PhDs start to go wrong, for a whole range of reasons, an Advisor can be invaluable in supporting the student (and indeed on occasion the supervisor(s)) to help minimise the problem and ensure smoother progress. The Panel Members have access to more detailed documentation about the nature of the Advisor role from their own institutions if that would be useful. The role of an Advisor is very rarely onerous but can be invaluable to the success of a project. We also note that the Advisor should come from outside of the student's immediate research group. We note that while the above is specific to PhD students, this may also be relevant for any early career researcher (postdoc or otherwise).

- Consider development of a scientific innovation budget item

A common theme from researchers was the understandable need to trace their efforts to specific funded work packages. This clearly makes sense from an accounting and accountability perspective. However, this may present a barrier to innovation, collaboration, and development of new science and proposals. As there is already a means for researchers to request support for professional paper writing, we recommend a similar mechanism for

scientific innovation. This mechanism could be as prescriptive as administrators desire in order to foster the scientific outcomes that GEUS desires. For example, scientific innovation support could require cross-disciplinary groups, cross-career stage groups, cross-gender groups, or cross-departmental groups. In the review panel's experience, developing a competitive proposal idea from inception to submission takes considerable effort and seed funding to support conversion of a casual conversation over coffee into a compelling science proposal would aid the process. GEUS could foster innovation and send a strong message to its workforce encouraging forward-looking collaborative science by introducing a system where a certain proportion of researcher time could be spent on innovation or self-motivated research which in the long term would lead to new projects and funding. The panel notes that this issue was raised by the last review panel 8 years ago as well.

- Researcher demographics and inclusiveness

The panel welcomed the presentation on researcher gender imbalances and the apparently different experiences of men and women in leadership roles and scientific collaborations. The data presented do suggest that at GEUS, men and women do have different experiences in terms of scientific collaborations and co-authorships, while the data conclusively showed that there is a glaring gender imbalance at the Professor level. Through interviews with GEUS leadership, there was clear awareness and motivation to rectify the gender leadership imbalance. The panel recommends GEUS develop a plan and commit to addressing this issue prior to the next review. Some possible aspects of such a plan may be to establish career pathways beyond the purgatory of Senior Researcher to additional Research Professorships; if internal candidates for such roles are not currently appropriate, consider external hires. The panel appreciates the current workforce demographics are a consequence of the state of science and hiring decisions in past decades. However, it is clearly time to proactively address this issue. Although a common problem across the sciences, GEUS needs to find opportunities to implement changes in this arena.

The information presented on collaboration and co-authorships was also compelling though not as clear cut as the above demographic issue. The panel appreciates that such gender-specific disparities may not be intentional and reflect hidden preferences or biases. However, there are a few concrete steps GEUS should consider to improve on the current situation. First, the scientific literature demonstrates that metrics such as *h*-scores and publication metrics are an incomplete and at times inaccurate measure of scientific excellence and productivity. Yet these metrics remain a key consideration in hiring and promotion decision making, often to the detriment of women who disproportionately are impacted by childcare and are more often given supporting tasks that lead to fewer publications or co-authorships. This should be addressed in hiring decisions, promotion decisions, and task delegation by group leaders. Such considerations should promote gender-neutral decision making and help reveal and correct biases. Second, two of the panel's other recommendations (regarding early career mentoring and a science innovation line item) could be used to correct gender imbalance in tasking and collaboration. Third, while the data presented were compelling, the panel appreciates that this was a first analysis and applauds GEUS for supporting this effort. However, it is merely a first step, and the panel recommends collecting data from across GEUS related to scientific collaboration (as evidenced by co-authorships), tracking anonymized demographics of applicants to research positions, and related metrics. The panel appreciates that collaboration can't (and shouldn't) be mandated, but an organization can't manage what

it can't (or chooses not to) measure. Collecting and reflecting on such data in the coming years should provide the opportunity for self-assessment at an individual and organizational level.

- Communication of Natural-Hazards Research

GEUS has carried out natural hazard research related to landslides and permafrost in Greenland after a fatal tsunamigenic landslide that killed four people at Nuugaatsiaq in western Greenland in 2017. We recommend that dissemination of the results to local authorities is carefully considered in the planning and execution of such natural-hazards research. This is non-trivial since GEUS does not have a formal role in the civil-defence governance of Greenland. As the usefulness of natural-hazards research only comes through the implementation of planning decisions or increased awareness of the local people or authorities, it is essential that communication of practical results is an integral part of this type of research.

- Workforce engagement and education

A recurring comment from the panel's interviews was confusion about administrative processes and for lack of a better term, the business side of the house. While many researchers expressed either support or indifference to such matters (being content to work on science projects and pursue knowledge) others were unclear yet interested in such topics as overheads, support for labs, and the logic behind certain hires. While these matters are rightly the domain of the director(s) and department chairs, providing the opportunity for interested members of the workforce to educate themselves periodically and discuss such matters would promote cohesion among all GEUS employees.

The evaluation process

The panel found that all preparations for the evaluation process were excellent. This includes all communication before, during and after the evaluation period (4–8 Oct. 2021). The compendium that the panel was presented with upon arrival (containing presentations, researcher profiles, overview of projects and employees, overview of laboratories and equipment, publications list, previous evaluations, executive orders and acts) was very useful throughout the evaluation process.

The panel found the order, length and number of talks to be suitable. The round of shorter talks during day two were useful to the panel as they provided a more nuanced view of the different ongoing projects. It was nice and important to see researchers at different career stages represented, and it was helpful to be able to pose questions directly to the researchers involved in the showcased projects.

The interview rounds were well co-ordinated, and the staff were forthcoming,

While some members of the panel would have appreciated receiving parts of the general information about GEUS (structure, board, programme areas and departments) beforehand, others appreciated the fact that no additional preparation or reading was required in advance of the evaluation week.