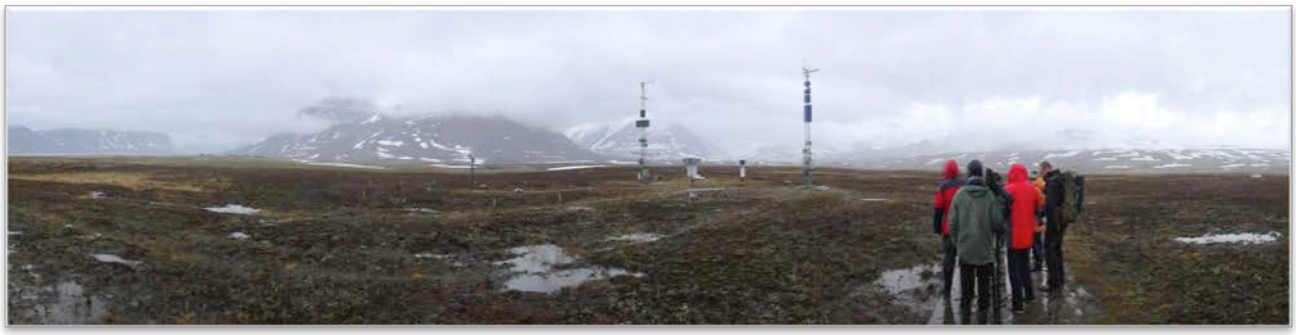

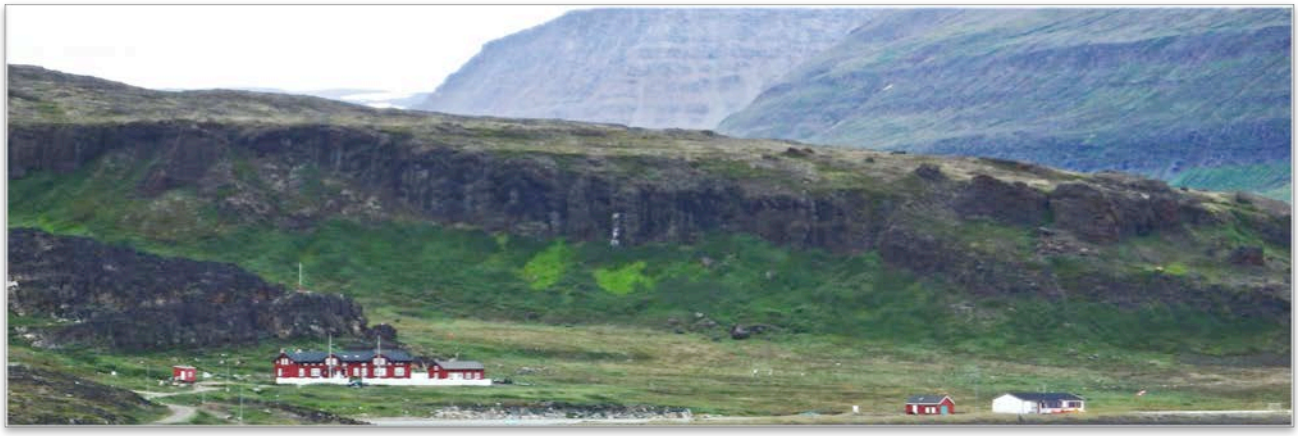

GREENLAND ECOSYSTEM MONITORING
GEM EVALUATION

Final Report
2014

Steve Albon **Jörn Thiede** **Kim Holmén**

The Evaluation Report is structured around the format of the Terms of Reference proposed by the GEM Steering Committee (see APPENDIX 2).

Within each section, the Panel has attempted to address all 26 primary questions posed by the Terms of Reference (these questions are in red italic text).

Furthermore, the Panel has addressed a substantial number of secondary questions (within the 'Scientific Questions') about the five thematic areas of the GEM Strategy and Working Programme 2011-2015, where we comment on all 13 fundamental questions.
These questions are in red italic text, framed in grey.

Where we felt the need to highlight our conclusions we have done so in bold blue. We have used the term RECOMMENDATION for the conclusions we considered most important, and these have been gathered in the Executive Summary. Points of lesser weight, but nonetheless worthy of careful deliberation, tend to be made as "suggestions".
All conclusions are highlighted in bold blue text, framed in grey.

Finally, our comments on the Basis sub-programmes (Monitoring) and Research Platforms (sites) can be found in Appendix 3.

Greenland Ecosystem Monitoring. GEM Evaluation 2014.

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The opinions, statements, conclusions and recommendations presented in this report are solely the responsibility of the three authors and may not reflect the position of the GEM Steering Committee, comprised of representatives from Danish Energy Agency; Danish Environmental Protection Agency; Danish Agency for Science, Technology and Innovation; Government of Greenland; Greenland Institute of Natural Resources; Aarhus University; University of Copenhagen; ASIAQ; and Geological Survey of Denmark and Greenland.

Front cover photos, top to bottom: The GEM climate station in central Zackenberg valley. Kobbefjord and the GEM monitoring site. Arktisk Station and the adjacent GEM site.
Back cover photos, top to bottom: Zackenberg GEM installations with Young Sund in background and Daneborg to far left. GEM installations in the central part of Kobbefjord valley. A panel member enjoys a moment of reflection near the GEM installation at Arktisk Station.

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Kim Holmén, Steve Albon and Jörn Thiede en route to GEM site Zackenberg.

GREENLAND ECOSYSTEM MONITORING

GEM EVALUATION 2014

Preface

In early 2014, the Danish Ministry for Climate, Energy and Buildings, in cooperation with the Environmental Protection Agency of the Danish Ministry of the Environment, commissioned an in-depth evaluation of the Greenland Ecosystem Monitoring (GEM) programme, on behalf of the GEM Steering Committee, which includes both ministries and participating research institutions. GEM is an interdisciplinary monitoring programme of the effects of climate change on ecosystems in Greenland, primarily focused on two comprehensive long-term monitoring stations in the Zackenberg Valley, Northeast Greenland (High Arctic) and in Kobbefjord, close to Nuuk, Southwest Greenland (Low Arctic). Recently, GEM activities have been complemented by similar, but less comprehensive, monitoring at Arktisk Station, Qeqertarsuaq (Disko Island), West Greenland, and glaciological as well as hydrological work at Sermilik, Southeast Greenland. Furthermore, in 2015 a new research station will open at Station Nord, 700 km north of Zackenberg.

The overall objective of the evaluation is to assess the scientific, economic and organisational effectiveness of GEM's 'Strategy and Working Programme 2011-2015' and its scientific and societal impact. Although the current programme has a further full year to run, the GEM Steering Committee decided to undertake an evaluation of the programme in order to assess the needs of a future 'GEM Strategy and Working Programme 2016-2020', as part of the continuing 'Kingdom of Denmark Strategy for the Arctic 2011-2020'.

A preparatory meeting in Copenhagen (March 19-21, 2014) introduced the Panel members to the general vision, mission and objectives of GEM, from both political and scientific perspectives. We met senior ministry officials and stakeholders as well as senior scientists responsible for leading and managing the GEM programme or related research efforts. Nonetheless, it was already clear before this meeting that the evaluation could not be carried out successfully without visits to the main GEM sites in Greenland. Consequently, a carefully prepared visit to Zackenberg/Daneborg, Nuuk/Kobbefjord and Arktisk Station, Qeqertarsuaq, took place July 13-24, 2014.

At the research stations we were met by logistics managers and many scientists, including postdocs, PhD and MSc students conducting measurements and field experiments within GEM. Most of them were very enthusiastic and motivated and left us with a very favourable impression of their commitment to the GEM work. Unfortunately, because of the intensive travel programme, we did not have the opportunity to visit the station at Sermilik, nor some of the auxiliary localities close to Nuuk, but it is our impression that they are not central to the current GEM activities and of interest only by association to some of the GEM partner institutions. All in all, the exposure to the East and West Greenland environments and ecosystems was an invaluable experience, both on a scientific level, as well as on a personal level.

Since we were only present in each of the three main sites for a few days we did not coincide with many of the lead scientists. Consequently, throughout August, we conducted a series of one-hour telephone interviews with all seven PIs of the five Basis sub-programmes, as well as the newly appointed GEM Scientific Leader, Torben Røjle Christensen, and Morten Skovgaard Olsen, Chair of GEM Steering Committee. These discussions, together with the participatory workshop held with a wider range of 30 scientists and stakeholders on September 8 in Copenhagen, and two further interviews with Morten Rasch (former GEM Scientific leader) and Bo Elberling (University of Copenhagen), have been helpful in formulating our ideas and recommendations.

Nonetheless, we found that organizing the evidence to answer many of the questions posed in the Terms of Reference was cumbersome. This was caused by the reporting structure still being based on the Zackenberg and Nuuk research platforms and being fragmented into the Basis programmes and the collaborative projects, rather than addressing the five central themes of GEM and the 13 specific questions nested within them.

Inevitably, some of our impressions are still coloured by our limited familiarity with the entire GEM programme but we hope that our attention to the feedback on our draft report has eliminated most factual errors. Any remaining will, naturally, be entirely due to our misunderstandings.

Finally, we would like to acknowledge the generosity of all the many people, both in Denmark and Greenland, who made this evaluation possible. Although there are too many to name everyone, two should be singled out for special thanks. First, Henning Thing was a marvellous travelling companion. With his encyclopaedic knowledge of Greenland, its culture, history, politics and recent science advances, and his amiable personality, he transformed our trip into a highly successful and very informative tour. Second, Lillian Magelund Jensen, who organised both our travel around Greenland and all the teleconferences. Also, she patiently dealt with our frequent requests for further information.

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October 24, 2014

EXECUTIVE SUMMARY AND RECOMMENDATIONS

The overall objective of the evaluation of the 'Greenland Ecosystem Monitoring Strategy and Working Programme 2011-2015' is to assess the scientific, economic and organisational effectiveness of GEM and its scientific and societal impact. This evaluation is timely, since it occurs shortly before a planned synthesis and the development of a 'GEM Strategy and Working Programme 2016-2020' – a contribution to the continuing 'Kingdom of Denmark Strategy for the Arctic 2011-2020'.

The review process involved the Panel members in a briefing in Copenhagen (March 2014) to familiarise them with the GEM programme and structure; a 12-day visit to Greenland (July 2014) to see the field operations (Bio-, Climate-, Geo-, Glacio-, and MarineBasis sub-programmes) and meet researchers at Zackenberg, Daneborg, Kobbefjord, Nuuk and Arktisk Station; a series of teleconferences (August-September 2014) with the Principal Investigators of the five Basis sub-programmes, the previous and the new GEM scientific leaders, and the chair of the GEM Steering Committee.

The evaluation was concluded with the presentation of a draft report at a participatory workshop involving 30 scientists and representatives of government institutions, including funding agencies, in Copenhagen on September 8, 2014. This helped facilitate an open, constructive discussion, including an analysis of strengths, weaknesses, opportunities and threats (SWOT) of the current work and ways to achieve a better integrated, and more holistic, work plan.

Much of the feedback from participants at the September workshop and their subsequent written comments, as well as further interviews, stressed that the GEM 'Working Programme' was evolving and should be viewed as "work in progress". While this may be true, it was not the impression the Panel gained, either in the field or from the teleconferences with the Basis PIs. Rather than the Work Plan tactically supporting the current innovative GEM Strategy, the approach seemed to be to largely continue the monitoring at Zackenberg, with its extensions to Kobbefjord and, in some cases, Arktisk Station too.

Unfortunately, the structure of both the websites and the annual reports around the research sites reinforces this view of being 'stuck-in-the-past', rather than having a clear focus on the five thematic areas of the 'GEM Strategy and Working Plan 2011-2015'. The key recommendations and additional suggestions of the Panel have been developed with the intention that the "whole (ecosystem programme) is more than the sum of its parts" (*i.e.*, Basis sub-programmes and research platforms). The Panel's intention is to help enhance the long-term research excellence, as well as increase the policy relevance and strategic impact of GEM.

Overview: Although the collective GEM activities are able to address only some of the pressing issues of climate change in a general way, at relatively few selected localities and using specific techniques, the Panel supports the overall strategic goals of the GEM programme. When compared with other Arctic monitoring programmes, the Panel considers the activities of GEM to be one of the most comprehensive schemes, with the scientific contributions demonstrably important at all scales, from the local to the global level.

RECOMMENDATION 1: The Panel views the GEM activities as producing much excellent science, published in leading international journals, and, as far as we can judge, comparatively good 'value-for-money'. In order that GEM can deliver its ambitious threefold mission, the Panel recommends it should be resourced for many decades to come. However, thought should be given to the GEM organisational structure, science focus and how the Work Plan maps onto the Strategic Plan to enable the programme to fully deliver its current objectives. Also, thought should be given to enhancing GEM's flexibility to meet future science policy needs.

Policy Relevance: The Panel is of the view that GEM activities make a very significant contribution to the knowledge base on Arctic ecosystems, thereby meeting a central objective in the 'Kingdom of Denmark Strategy for the Arctic 2011-2020', namely "*The Kingdom will pursue a vigorous and ambitious knowledge building on climate change in the Arctic, and its consequences, in order to foster global and local adaptation to far-reaching change.*"

RECOMMENDATION 2: The Panel recommends that GEM builds upon the upscaling workshop held in November 2013 and prioritises efforts in ecosystem modelling, in order to both achieve a meaningful regional synthesis, and contribute more fully to the Kingdom's policy objective.

The Panel notes that the Preface to the Kingdom's Strategy for the Arctic 2011-2020 states that "It is our common objective that the Arctic and its current potential must be developed to promote sustainable growth and social sustainability." and, elsewhere, states that "development must take place firstly to the benefit of the inhabitants of the Arctic and go hand in hand in safeguarding the Arctic's environment". If GEM were to rise to the challenges of the science underpinning these sustainable development aspirations, it would need to reconsider i) if its network of research platforms (sites) is fit-for-purpose, and ii) refining its focus on enhancing our understanding of Arctic ecosystem function and responses to climate change towards the outcomes for human well-being.

RECOMMENDATION 3: The Panel recommends that, given the Government of Greenland / Kingdom of Denmark's expectations that the current monitoring and research do underpin sustainable development, GEM should explore the opportunity of establishing a GEM site in South Greenland, where climate warming is permitting agriculture to diversify its crops, increase local production and expand northwards. Without this information predictive models of the impact of ecosystem change farther north are likely to be of less policy relevance.

RECOMMENDATION 4: The Panel recommends, that GEM review the opportunity to increase its policy relevance by monitoring how climate change, and its interaction with other drivers, impacts ecosystem functioning and, thereby, influences the resilience of natural capital assets, the delivery of ecosystem services and, through wider collaboration, the consequences for human well-being.

Strategic Impact: The results of GEM activities have featured prominently in a number of major syntheses in recent years, including the 'Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere' (AMAP, 2011) and the 'Arctic Biodiversity Assessment' (CAFF, 2013). These publications reflect that the monitoring sites, especially Zackenberg, are well embedded in circum-Arctic networks. The added value of these international collaborations leads to ground-breaking research which is published in the highest impact journals, reinforcing the spirit of wider cooperation.

RECOMMENDATION 5: In order to maximize the impact of the planned synthesis in 2015/2016 of the GEM research, the Panel recommends that the synthesis focus primarily on cutting-edge, interdisciplinary research to address the mechanisms driving change in the structure and function of Arctic ecosystems, rather than what was done in each Basis sub-programme, or at a particular site. To do this will also require a major effort in synthesis of the existing data, subject to the database being complete, and rectifying the generally slow progress on upscaling models.

Science: The Panel observed a mixed effectiveness with regard to building a symbiosis between the long-term Basic/Basis measurements and the process-focused research studies, some of which are short-term. To some degree this varied between sites and the length of time the monitoring had been established.

RECOMMENDATION 6: The Panel recommends a deliberate effort to better integrate collaborative projects into the long-term observational monitoring, so that the new knowledge becomes a direct influence on planning of the continued long-term measurements. The Panel suggests that this could be achieved by a review of the current 13 questions (see RECOMMENDATION 7) and a more systematic implementation of the adaptive monitoring concept (see RECOMMENDATION 8). This approach may involve the active encouragement of projects at Kobbefjord, and elsewhere.

Although large portions of the GEM research effort are doing outstanding work within the five themes, the Panel considered many of the 13 questions too general to evaluate progress in answering them meaningfully. A weakness of such general questions is that almost any study can be argued to be working towards answering an element of the question, without necessarily making the programme effective in producing novel insights that can be linked easily with other sub-projects, apparently focused on the same question.

RECOMMENDATION 7: The Panel recommends that there needs to be more strategic thoughts about a SMART[1] set of the over-arching questions. The refinement of the central questions needs to be an on-going process and integral to the implementation of the GEM strategy through the concept of adaptive monitoring (see RECOMMENDATION 8).

[1] Here SMART is Specific, Measurable, Achievable, Realistic (though some suggest "Results-focused") and Time-bound.

The Panel was concerned that the number of measurements across the Basis sub-programmes has expanded to more than 3,500 and was of the view that there needed to be more focus on the (revised) questions, as well as on the consistent and iterative use of the adaptive monitoring concepts, in order to hone the monitoring regimes, both within and between the Basis sub-programmes and across the sites.

RECOMMENDATION 8: The Panel recommends that the adaptive monitoring approach is implemented more systematically and involves, where possible, the field staff responsible for the on-going data collection, several of whom told us they didn't feel connected to the outcomes.

With the exception of the glacial outbursts at Zackenberg, the Panel found little indication of progress in identifying potential threshold effects in either the terrestrial or marine ecosystems. In general where data series have been inspected, many relationships are linear within the range of variation in temperature and precipitation witnessed to date. One alternative approach would be to build process-based models and explore responses to sustained extremes – shifts in mean of explanatory variables.

RECOMMENDATION 9: The Panel recommends that GEM explores the scope for more specific experiments, as well as expending more effort on process modelling, in order to investigate the likelihood of thresholds in Arctic ecosystems and exploring their potential consequences.

The Panel is concerned that delays in delivering several of the Strategic Initiative projects has had the effect of retarding progress in developing the upscaling, modelling and prediction thematic area. In general, the Panel wishes to encourage more process understanding of internally consistent frameworks (*e.g.*, numeric models) in order to calculate future states based on a quantitative mechanistic understanding, this is particularly crucial for the approach of upscaling from local specific sites to regional scales.

RECOMMENDATION 10: The Panel recommends that GEM develops a collaborative (institutional) modelling and prediction 'group' where there is continuous interaction of fundamental thinking and curiosity to interrogate the incoming data, enhancing understanding and refining approaches to both the ongoing monitoring and research.

The Organisation: The 'coalition-of-the-willing' approach, both among the institutional supporters of Arctic ecosystem science and the passionate researchers themselves, means that GEM activities have achieved a tremendous amount in terms of improving our understanding of species biology, important elements of ecosystem function, and of their physical surroundings. However, the Panel concluded that to date there is little evi-dence of the more novel aspirations of the 'GEM Strategy and Working Programme 2011-2015' – a more holistic understanding of interacting terrestrial, limnic and marine eco-systems in Greenland, and the wider Arctic – being delivered by the current structure of a Steering Committee and a Coordination Group.

Although the Panel is very encouraged by the re-cent appointment of a new scientific leader, our view is that he and his team will need dedicated support. Whether this

support can be achieved without the current partner-ship of institutions creating a dedicated GEM Centre, including a stronger presence in Greenland, is a debatable point?

RECOMMENDATION 11: The Panel recommends that, as soon as possible, GEM establishes an independent (of the ministries and other stakeholders), international advisory board to provide the high-level overview and support to both the Science Leader and the stakeholders.

In terms of logistics, the Panel was of the view that all GEM research platforms should be more energy efficient and critical of current waste management practices. Neither the Danish Energy Agency nor the Danish Environmental Protection Agency should be in a position where their sponsored initiatives could be criticised for lack of 'best' practice.

RECOMMENDATION 12: The Panel recommends that there is an options review and feasibility assessment of green energy generation and utilisation efficiency, as well as dealing with all forms of human waste management, at all sites.

The Panel believed that the annual reporting structure by site (research platform) was no longer fit for the purpose, and impeded measuring the progress of GEM. Some of the Basis sub-programmes merely reported what was done year after year, just changing the dates between years. Often there was a lack of description of what was found, and, even where more specific results were described, there was little or no interpretation. Given that little of the specific GEM work, undertaken since 2011, has been published yet, the historical format of the reports made the job of the evaluation Panel considerably more difficult.

RECOMMENDATION 13: The Panel recommends the development of a 'corporate' GEM-brand, facilitated through a single GEM annual report and a unified website. Both the GEM annual report and the website should be structured by the five themes of GEM, disaggregated to the level of the re-evaluated set of the 13 questions. Also, the monitoring and the relevant science projects should be integrated accordingly under the relevant theme/question.

The Future – GEM 2.0: In addition to encouraging GEM to implement the previous 13 Recommendations over the next five years, the Panel identified two other areas to enhance the strategic impact of GEM: i) Join terrestrial and marine ecosystem studies together through a major effort in interdisciplinary process-modelling; ii) Consider how GEM fits within the wider effort to deliver Arctic research in the Kingdom of Denmark.

First, the Panel encourages GEM to focus increasingly on understanding the causes and consequences of ecosystem change and generate the capacity to predict, through mechanistic models, the outcome of future scenarios of environmental change at local, regional and global scales. To do so requires confidence about the representativeness of the sites at which measurements are conducted, and their appropriateness for upscaling to regional scales (see RECOMMENDATION 3). Further, since the regional importance of Greenland is due to its ice-dominated land mass surrounded by productive seas, more emphasis needs to be placed on the interaction of terrestrial and marine processes.

RECOMMENDATION 14: The Panel recommends a much stronger explicit link between the coastal marine work and the terrestrial/limnic research, through a stronger strand/theme of integrated conceptual thinking, observation and process models.

Second, the Panel was concerned about the fragmented approach to Arctic research in the Kingdom of Denmark, with interests and responsibilities widely distributed across many ministries and research institutions. Although, the 'Terms of Reference' questions are specific and only consider how GEM should be organised in the coming years and decades, we encourage the wider-than-GEM stakeholder community to think about a more joined-up approach to achieve greater added value and efficiencies.

Since our first meeting in Copenhagen in March, throughout our visit to Greenland in July, and in the weeks since returning, the Panel has spent a considerable amount of time pondering the important broader issue of how research in the Arctic is organised in the Kingdom of Denmark. The three Panel members all come from countries with dedicated polar research institutes (combining science and logistics), as well as nations with considerable strengths in polar research within the university sector. These nations maintain these institutions partly because many environmental changes are dramatic, fast in real time, with global effects, but also partly for political reasons, because these changes influence the well-being of their own societies. Given the geopolitical importance of the Arctic to the Kingdom of Denmark, it is unusual in not having a dedicated institution to ensure that its strategic needs are integrated across the science-policy interface. As indicated above the Panel believes that, at the very least, there is a need for greater co-operation between the universities and other relevant research institutes, as well as a cohesive partnership among the funders, including the different ministries with a stake in the Arctic, to achieve a virtual centre, at the very least.

RECOMMENDATION 15: The Panel recommends a wider review of the potential institutional structures to meet the Kingdom of Denmark's future needs for high-profile excellent and relevant research in the Arctic, recognising the considerable financial and political implications. Although it is not within the remit of the Panel's mandate to define specific proposals, one of several possible models is a 'centre' with two 'hubs'. One 'hub' would involve growing the capacity to implement the integrated monitoring, research and logistics from a base in Greenland. The other 'hub' involves creating a dedicated process modelling group which can draw on the expertise of Danish research institutes and universities in Denmark and more widely (see RECOMMENDATION 10). This second 'hub' would co-locate the relevant researchers in a single site. The two hubs can be linked by the two original GEM concepts: i) a holistic study of the Greenland ecosystem, but expanded to include other drivers in addition to climate change, and ii) the principles of adaptive monitoring, which integrates both science questions, data collection, analytical approaches (incl. modelling) and interpretation in an iterative way, as mentioned previously.

The central part of Zackenberg Valley with GEM's greenhouse gas monitoring.

1. Introduction, Background & Rationale

1.1 Purpose of the evaluation

The overall objective of the evaluation is to assess the scientific, economic and organisational effectiveness of the GEM programme and its scientific and societal impact (see Terms of Reference: Appendix 2).

1.2 Brief history behind inception of GEM and importance of Greenland in Arctic / Global research

The vision of the programme is to contribute substantially to the basic scientific understanding of Arctic ecosystems and their responses to climatic changes and variability, as well as the potential local, regional and global implications of changes in Arctic ecosystems.[2]

Greenland's global importance in terms of understanding climate change is huge because of the effect of prodigious rates of melting of its ice sheet and ice caps on sea level rise. Furthermore, at a regional scale the release of the ever-increasing amounts of freshwater may change the major currents flowing through both the Davis and Denmark Straits, with repercussions for the whole North Atlantic circulation. As a result we can expect profound change in all local aquatic and terrestrial ecosystems.

[2] Greenland Ecosystem Monitoring Strategy and Working Programme 2011-2015.

The GEM vision grew partly out of the success of a decade of ecological monitoring and research undertaken in the high Arctic at Zackenberg Basic (culminating in Meltofte *et al.,* 2008), and partly from the recognition of the importance of also working in the low Arctic, which saw the development of Nuuk Basic in 2007. Further, an international review of the first ten years at Zackenberg (Callaghan *et al.*, 2006) recommended, among other things, an improved integration of the different discipline-based monitoring (Basis) sub-programmes through both crosscutting questions and co-located measurements, as well as the development of an iterative system to review and modify the measurements and monitoring protocols. These particular recommendations were central to the development of the GEM strategy, which is based around a series of holistic ecosystem questions and an adaptive monitoring framework. However, as we note later, some of the other recommendations of the 2006 review were not implemented but recur as concerns in the current evaluation.

At Zackenberg, the three original Basis sub-programmes (BioBasis, ClimateBasis, Geo-Basis) were extended to include MarineBasis in 2003, and again in 2008 GlacioBasis to include glacier mass balance, its response to climate and contribution to the hydrology of the Zackenberg River catchment. When work began at Kobbefjord, Nuuk, all but the GlacioBasis sub-programme were implemented, with the added value that the Marine-Basis was based on research in the surrounding fjords and inner seas since the late 1950's. However, an extension of the current transects into the ocean boundary currents, which control many of the fjord processes, is lacking. Monitoring by the ClimateBasis team of a mountain glacier above Kobbefjord began in 2014 as part of a Strategic Initiative.

Since the inception of GEM, there has been an Evaluation of the Greenland Climate Research Centre (GCRC), a major partner of GEM, providing access to engagement in several terrestrial, limnic and marine projects under GCRC (Falkowski *et al*, 2013). Many of the conclusions and recommendations of the GCRC evaluation have parallels to our own observations of the strengths and weaknesses of GEM. Although we have seen the comments of the GCRC leading scientists about the review process and its recommen-dations, at the time of drafting this report, we are not aware of any implementation plan to act upon the GCRC evaluation.

Crossing the Zackenberg River.

1.3 The mission

i. To contribute to a coherent and scientific sound description of the state-of-the-environment, including its biodiversity in Greenland and the Arctic in relation to climatic changes with focus on ecosystem responses and on global impacts related to the feedback processes.

ii. 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 administration.

iii. To provide a platform for cutting-edge interdisciplinary research on the structure and function of Arctic ecosystems.

Although this evaluation is assessing the progress of GEM over the first few years since its formal inception in 2011, it builds upon nearly 20 years of research at Zackenberg.

RECOMMENDATION 1: The Panel recommends that, in order to deliver its threefold mission, GEM should run for many decades to come.

This length of time would 1) ensure that long time series of basic key physical, chemical and biological data are established (every year of measurement will make the preceding data more valuable), and 2) justify the major investments for infrastructure, incl. accommodation, communication, energy supplies, laboratories/ships (lifetime c. 30 yrs.) to sustain the necessary long-term monitoring and research.

1.4 Overall objectives 2011-2015

In the period 2011-2015, GEM intends to (i) strengthen the 'adaptive monitoring' (Lindenmayer and Likens, 2009) approach based on scientific key-questions, (ii) strengthen and elaborate the research component of GEM, (iii) strengthen the linkage between monitoring and research activities, (iv) extend its cooperation with other Arctic monitoring and research programmes and stations, (v) strengthen its capacity for upscaling and predictions, and (vi) strengthen the visibility and outreach of the GEM.

Although this review takes place before the end of the five years, and many of the results have yet to be synthesised, the Panel was, nonetheless, in a position to evaluate progress towards the overall objectives.

1.5 Thematic research areas

The comprehensive long-term interdisciplinary data collection carried out by GEM aims to allow the programme to provide data to address regionally and globally important scientific questions of relevance to the scientific community and decision makers in the understanding of how climate change will affect Arctic ecosystems, their services and feedbacks to the global system. In all, 13 questions are addressed across these five thematic research areas:

- Greenhouse gas exchange with the atmosphere and nutrient balance
- Ecosystem function and resilience

- Water balance, including glaciology and water circulation in the marine environment
- Snow and ice, including effects on phenology, energy and carbon balance
- Upscaling, modelling and prediction

For political, socio-economic and scientific reasons, the future of the Greenland ice sheet and its surrounding coastal lands and seas, is subject to intense debate and much speculation internationally. In the light of the continuing discussion about the potential instability of the ice, it is of paramount importance for humanity at local (habitats in Greenland), regional (fisheries, freshwater export from Greenland, port installations) and global scales (eustatic sea level rise) to study ongoing changes in real time.

Although the collective GEM activities have insufficient resources to tackle all these pressing issues, the Panel supports the overall strategic goals of the GEM programme. When compared with other Arctic monitoring programmes, the Panel considers it to be one of the most comprehensive, with the scientific contributions of the GEM research demonstrably important at all scales, from the local to the global level.

Visiting the snow cover monitoring setup at the Kobbefjord site.

2. POLICY RELEVANCE QUESTIONS

Within the realm of the 'Kingdom of Denmark Strategy for the Arctic 2011-2020', the evaluation panel is requested to address the following four questions:

2.1 Do GEM activities provide an adequate foundation for wider international cooperation, including support for the fulfilment of international agreements on climate change, environmental protection, and the protection of nature and biodiversity?

The Panel is of the view that the GEM activities are well integrated in a range of wider international co-operations, which help underpin the scientific evidence base upon which international agreements on climate change, protection of nature, biodiversity and the wider environment can draw (see also section 3. Strategic Impact Questions). The growing knowledge base from GEM about climate change impacts on ecosystem function and biodiversity contributes to a central objective in the Kingdom's Strategy for the Arctic 2011-2020: "*The Kingdom will pursue a vigorous and ambitious knowledge building on climate change in the Arctic, and its consequences, in order to foster global and local adaptation to far-reaching change.*"

RECOMMENDATION 2: The Panel recommends that GEM builds upon the upscaling workshop held in November 2013 and prioritises efforts in ecosystem modelling, in order to both achieve a meaningful regional synthesis and contribute more fully to the Kingdom's policy objective.

However, even with appropriate dissemination it is less clear how GEM will foster adaptation without developing appropriate adversarial skills and political partnerships. While the Kingdom of Denmark considers the Arctic Council as the primary forum for cooperation in the Arctic, it is noticeable that the Danish involvement in the Arctic appears ignored in a seminar on September 11, 2014 about *The EU in the Arctic, the Arctic in the EU,*[3] the last in a series on *Strategic Environmental Impact: Assessment of development of the Arctic.*

2.2 To what extent do GEM activities contribute to the fulfilment of a sound and solid scientific basis for the protection of nature and environment in Greenland?

GEM activities are helping generate knowledge to contribute to a more informed scientific basis for practical conservation and environmental management, as desired in another objective of the Kingdom's Strategy for the Arctic: "*The Arctic nature and environment must be managed based on the best possible scientific knowledge and standards for protection, and international cooperation in this endeavour must be promoted.*" However, success in applying the knowledge may require GEM partners collaborating with conservation institutions and developing additional work strands focused on adaptive management.

[3] www.arcticinfo.eu/en/

2.3 Do all the GEM activities provide value for money in terms of scientific and societal impact?

Evaluating 'value for money' is challenging since it depends on your assumptions. Given that working in the Arctic is so expensive, particularly at the more remote stations, where transportation and energy costs are significant components, any meaningful assessment would have to compare the cost of running similar operations elsewhere in the Arctic. The Panel was not provided with any relevant data. However, at an estimated operational cost of around 20M DKK per annum for the Basis monitoring sub-programmes at Nuuk and Zackenberg (c. 16M DKK per annum, excl. the cost of running Zackenberg c. 2.8M DKK) and the Strategic Initiatives (c. 1.5M DKK per annum), our 'gut-feeling' was that the return on this level of investment was probably quite good 'value for money'[4].

Nonetheless, given the 'apparent' leverage of funding from the suite of Collaborative Projects (totaling five times the monitoring budget!) one might have expected that there would be a greater output of scientific papers (The combined list of all Nuuk and Zackenberg publications only modestly exceeds the 'Deliverables' target of 30 peer-reviewed papers per annum). True, many of these Collaborative Projects are yet to complete their fieldwork but given most of them are based on large teams with earlier work at the sites, particularly Zackenberg, one could expect more.

Assessing the societal impact of GEM in terms of 'value for money' is even more challenging than the scientific achievement. While exploring the societal impact of climate change on Greenland's ecosystems is of considerable importance, given the Kingdom's recognition that "*development must take place firstly to the benefit of the inhabitants of the Arctic and go hand in hand in safeguarding the Arctic's environment*", this was apparently not a high priority in the development of the 'GEM Strategy and Working Programme 2011-2015'. Yet, when the Panel met in Nuuk with Kim Kielsen, Minister for the Environment and Nature, he stressed the need for research, which could underpin sustainable development.

RECOMMENDATION 3: The Panel recommends that, given the Government of Greenland / Kingdom of Denmark's expectations that the current monitoring and research do underpin sustainable development, GEM should explore the opportunity of establishing a GEM site in South Greenland, where climate warming is permitting agriculture to diversify its crops, increase local production and expand northwards. Without this information, predictive models of the impact of ecosystem change farther north are likely to be of less policy relevance. The Panel considers a site in South Greenland to be a higher priority than GEM contributing to the new development at Station Nord. Also, the Panel encourages GEM to explore the possibility of collaborative studies of the marine ecosystem function that are directly pertinent to ensuring the long-term sustainability of fisheries in the seas surrounding Greenland.

[4] Aksnes et al. 2014, Polar Research in the Kingdom of Denmark 2013: a mapping survey, gives comparative international statistics.

The Panel notes that the preface of the 'Kingdom of Denmark Strategy for the Arctic 2011-2020' states that "It is our common objective that the Arctic and its current potential must be developed to promote sustainable growth and social sustainability." If GEM were to rise to the challenges of the science underpinning these sustainable development aspirations, it would need to refine its current focus of enhancing our understanding of Arctic ecosystems and their responses to climate change.

RECOMMENDATION 4: The Panel recommends that GEM reviews the opportunity to increase its policy relevance by monitoring how climate change, and its interaction with other drivers, impacts on ecosystem functioning and, thereby, influences the resilience of natural capital assets, the delivery of ecosystem services and, through wider collaboration, the consequences for human well-being.

2.4 To what extent do GEM activities contribute to / form a basis for adaptation to a changing climate?

Although the second of the threefold missions of GEM refers to the provision of science-based input *"for Danish, Greenlandic and international policy development, adaptation and administration"*, the Panel could see little evidence that this connection was being made. Since 'adaptation' involves altering the way we do things to prepare for the potential effects of climate change, one might have expected to see some explicit research on both the potential risks and benefits, such as the increased opportunities for agriculture, of climate change. This work might be done in association with the Greenland Climate Research Centre (GCRC).

At the GEM climate station adjacent to Arktisk Station.

3. STRATEGIC IMPACT QUESTIONS

Within the realm of the 'Greenland Ecosystem Monitoring Strategy 2011-2015', the evaluation panel is requested to address the following five key questions:

3.1 Does GEM play a leading role in the circum-Arctic network of ecosystem field monitoring sites?

Zackenberg, as the longest established monitoring site, is particularly well embedded in circum-Arctic field site networks. For example, Zackenberg and Arktisk Station are participating in the continuous monitoring conducted by the International Tundra Experiment (ITEX) programme, a network of 50 sites. Although Kobbefjord is not formally part of ITEX, the same experimental chamber design has been adopted there to make more meaningful comparison with the other GEM sites, and more widely across the Arctic. The current permafrost work within the GEM programme is also well connected with other sites around the Arctic. The Centre for Permafrost (CENPERM) is working at all three main GEM sites, in addition to Sermilik, Station Nord and five other sites in Greenland, as well as in Svalbard and Abisko, Sweden. CENPERM also facilitates links to DEFROST (Impact of a changing cryosphere – depicting ecosystems-climate feedbacks from permafrost, snow and ice) and PAGE21 (Changing permafrost in the Arctic and its Global Effects in the 21st Century).

Arktisk Station, Kobbefjord and Zackenberg, along with Sermilik and Station Nord, are all part of INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic), an EU funded project with the objective of building capacity for identifying, understanding, predicting and responding to diverse environmental changes throughout the wide environmental and land-use envelopes of the Arctic.

3.2 How do you evaluate the overall impact from GEM/Zackenberg/Kobbefjord scientific publications over the past six years (2008-2013)?

There are, as yet, a limited number of publications specifically from the GEM activities at Kobbefjord, (seven in Web of Science search just using "Kobbefjord", July 23, 2014), and only one is in the terrestrial environment (*Camera derived vegetation greenness index as proxy for gross primary production in a low Arctic wetland area*, Westergaard-Nielsen *et al.*, 2013). Among the other six publications, five document work in the marine environment, and one deals with mercury in freshwater. Most of the publications, listed by the Nuuk website, relate to longer established research in neighbouring fjords and inshore waters monitored by Greenland Institute of Natural Resources (GINR).

The comparable Web of Science search on "Zackenberg" produced more than 40 papers published since the synthesis "*High-Arctic Ecosystem Dynamics in a Changing Climate*" (Meltofte *et al.*, 2008). Clearly, this reflects that Zackenberg has been established a decade longer and currently attracts many more projects, particularly those focused in the terrestrial environment; it also reflects the established links with other circum-Arctic networks as described above. The papers which present results across circumpolar sites, incl. Zackenberg, are often in the higher impact journals, and already some are

particularly highly cited. Interestingly the 21 papers in (Meltofte *et al.*, 2008), had been cited 308 times (209 excluding self-citations) up to September 7, 2014.

The results of GEM activities have featured prominently in a number of major syntheses in recent years, including the 'Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere' (AMAP, 2011) and the Arctic Biodiversity Assessment (CAFF, 2013). The Panel has every expectation that the planned Synthesis in 2015/2016 of the GEM research, over two decades at Zackenberg and the first ten years at Kobbefjord, will have a substantial impact in raising the profile of GEM.

RECOMMENDATION 5: In order to maximize the impact of the planned synthesis in 2015/2016 of the GEM research, the Panel recommends that it is primarily focused on cutting-edge, interdisciplinary research to address the mechanisms driving change in the structure and function of Arctic ecosystems, rather than what was done in each Basis sub-programme, or at a particular site. To do this will also require a major effort in synthesis of the existing data, subject to the database being complete, and rectifying the generally slow progress on upscaling models.

3.3 Has GEM published clear and unambiguous guidelines for field observations, data management and dissemination procedures? [5]

Through the manuals for the sub-programmes and stations, GEM has provided clear and unambiguous technical guidelines for the field observations. However, it is not so clear, if the selection of sampling sites has followed the principle of selecting locations that would make the datasets from the three main sites easily comparable. In some Basis sub-programmes it is unclear how and when the collected field data are validated, introduced into a data management system and interrogated. Presently, it seems that few of the relevant GEM data are easily available, even internally to GEM (after they have been validated), and it is unclear how and when they are released into the public domain. However, the data are supposedly available on request directly from the researchers.

The Panel is encouraged by the renewed effort to establish a functioning GEM database and suggests a rigorous policy on data treatment, archiving and their dissemination, without which a substantial investment of public funds is in danger of not being used optimally.

3.4 To what extent have GEM results been reflected in the IPCC WG I 5th Assessment Report?

There is limited reference to collaborative projects undertaken in Greenland in the Bio-geochemical chapter, and apparently none in the case of the Oceans chapter.

The Panel was of the opinion that answering this question is an exercise that the GEM Steering Committee might be better placed to undertake.

[5] The Panel considered this question mis-placed in the sense that it is about Organisation rather than Strategic Impact.

3.5 To what extent have GEM results been reflected in "milestone" reports and activities within the Arctic Council?

Overall, the profile of results arising from GEM activities featuring in the reports and work of the Arctic Council is good, especially in the AMAP and CAFF Working Groups.

Eddy covariance tower at GEM's Kobbefjord site.

4. SCIENTIFIC QUESTIONS

Within the realm of the 'GEM Strategy and Working Programme 2011-2015', the evaluation panel is requested to address the following key questions:

4.1 To what extent are results of GEM (monitoring) activities used for scientific analyses?

In recent years, results of GEM activities have featured prominently in a number of major syntheses, including the 'Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere' (AMAP, 2011) and the 'Arctic Biodiversity Assessment' (CAFF, 2013). Since the 'GEM Strategy and Working Programme' was established, ground-breaking research has been published in leading international journals, incl. *Nature Climate Change* (Elberling *et al.*, 2013a, Elmendorf *et al.,* 2012a*,* Hoye *et al.*, 2013), *Global Change Biology* (Hollesen *et al.*, 2011; Krause-Jensen, 2012; Tagesson, 2012; Wassmann, 2011; Wu, 2011) and *Ecology Letters* (Elmendorf *et al.*, 2012b).

The Panel views these science outputs as compelling evidence of researchers responding to two specific recommendations of a previous review of the Zackenberg Ecological Research Operations (Callaghan *et al.*, 2006) "*Facilitate and increase the impact of the research*" and "*Increase the international involvement of Zackenberg staff*".

The Panel noted that, while the BioBasis and GeoBasis sub-programmes at Zackenberg, in particular, contribute research at local, regional and global scales, the MarineBasis work tends to be more locally focused, possibly because it appears to be less well networked to wider Arctic initiatives. However, this may change as the Arctic Science Partnership (ASP)[6] programme expands. Nonetheless, a major constraint for MarineBasis is that logistics of studying the connections of local and regional marine systems requires bigger vessels. For example, relating the fjord measurements in the vicinity of Nuuk or Zackenberg / Daneborg (*i.e.*, Young Sund / Tyrolerfjord) to their adjacent W and NE Greenland respective seas and currents, requires sea-going ships; this is possible from Nuuk through the involvement of GINR, but would require expensive specific campaigns in NE Greenland.

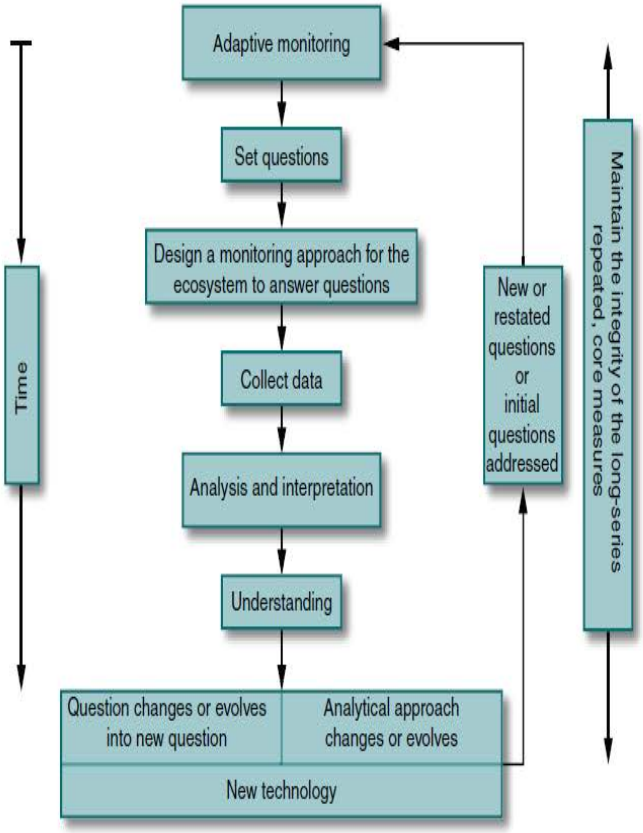
4.2 To what extent do GEM activities and results serve as basis for other research activities?

The Panel observed a mixed effectiveness with regard to building a symbiosis between the long-term Basis measurements and the process-focused research studies, some of which are short-term. To some degree, this varied with sites and the length of time the monitoring had been established. At Zackenberg, both monitoring activities and research projects are well represented, but the impression is that, to a large part, the two elements live their separate lives. When queried, the research project participants emphasized mainly the logistics as the reason for their presence in Zackenberg and to a lesser extent the long-term datasets.

[6] The Arctic Science Partnership (ASP) involves the University of Aarhus – Arctic Research Centre, Greenland Institute of Natural Resources and the University of Manitoba, which began cooperating in June 2012.

RECOMMENDATION 6: The Panel recommends a deliberate effort to better integrate collaborative projects into the long-term observational monitoring, so that the new knowledge becomes a direct influence on planning of the continued long-term measurements. The Panel suggests that this could be achieved by a review of the current 13 questions (see RECOMMENDATION 7) and a more systematic implementation of the adaptive monitoring concept (see Figure 1 and RECOMMENDATION 8). This approach may involve the active encouragement of projects at Kobbefjord, and elsewhere.

Figure 1. The cascading steps and iterations involved in applying the principles of adaptive monitoring concept (from Lindenmayer and Likens, 2009).



At Kobbefjord, there is a strong set of Basis sub-programmes present but apparently little project activity. Nuuk has an underutilised potential as a research location for developing monitoring techniques (see more under upscaling discussions).

The Panel suggests that for cost and logistical reasons there should be a critical evaluation of whether some of the projects attracted to Zackenberg could be re-directed to the other GEM sites.

At Arktisk Station, the GEM programme is to a large degree still at the inception stage, with some of the Basis sub-programmes still to be conceived. Also, the Panel thought there might be significant opportunities to explore the scope for linking with some of the

historical monitoring and specific projects undertaken since the station was established in 1906. This could be of particular interest for MarineBasis, but also for some aspects of the BioBasis (ITEX) and GeoBasis.

The Panel concluded that there was some urgency to establish the common GEM Basis protocols more widely than the current GeoBasis work at Disko. Also, the Panel suggests that if Arktisk Station is to be fully integrated in GEM, the University of Copenhagen might want to reconsider the role of the Station Manager and the way 'station activities' are organised.

All three sites can contribute to education in environmental sciences at all levels, though at Zackenberg the pressure on accommodation may make it appropriate only for post-graduates.

Arktisk Station already facilitates up to twelve MSc students undertaking field courses for three weeks. There may be scope to engage students at Kobbefjord, too. However, accommodation is limited at Kobbefjord (but facilities in Nuuk may be available through GINR) so student groups, involved in projects that require extended work, either have to camp or make return trips every day from Nuuk.

Both Arktisk Station and Kobbefjord connect with schools in Qeqertarsuaq and Nuuk, respectively, which over time may stimulate more indigenous interest in studying environmental sciences at tertiary levels. The Panel members were struck by the fact that, while we met many inspired young Danish MSc and PhD students, we did not encounter junior scientists from Greenland during our visit. It seems of paramount importance for the acceptance of GEM in Greenland to involve more people with roots in Greenland.

The Panel suggests that the GEM Steering Committee makes a concerted effort in Greenland educational institutions, as well as Danish and international universities, to canvass for candidates to get involved in environmental monitoring and research, supported by bursaries and educational programmes at appropriate Greenlandic institutions.

4.3 Has GEM provided data analyses that have substantially contributed to the understanding of the broad thematic themes?

The five broad thematic areas (4.3.a - 4.3.e below) are all fundamentally important to understanding ecosystem change in Greenland, and the 13 questions nested under these five themes are rightly ambitious. Although large portions of the GEM research effort are doing outstanding work within these themes, the Panel considered the questions too general to evaluate progress in answering them meaningfully. A weakness of such general questions is that almost any study can be argued to be working towards answering one of these questions, without necessarily making the programme effective in producing novel insights that can be linked easily with other sub-projects apparently focused on the same question.

RECOMMENDATION 7: The Panel recommends that there needs to be more strategic thoughts about a SMART[7] set of the over-arching questions. The refinement of the central questions needs to be an on-going process and one that is integral to the implementation of the GEM Strategy through the concept of adaptive monitoring (see Figure 1 above, and also RECOMMENDATION 8).

4.3.a Greenhouse gas exchange with the atmosphere and nutrients balance

*How does climate change, and variability, control the annual and seasonal exchange of greenhouse gases (H_2O, CO_2, CH_4 and N_2O) between Arctic terrestrial ecosystems and the atmosphere? (**GEM Question 1**)*[8]

Carbon dioxide, water vapour (latent heat) and sensible heat exchange are all measured through eddy covariance stations at all three sites. Methane fluxes are studied with automatic chambers in Zackenberg and Kobbefjord, whereas methane studies at Disko are intermittent studies with chambers. As posed, the question is general and will not be fully answered in the foreseeable future. The CO_2 and CH_4 flux measurements at Zackenberg have global fame and are state-of-the-art (Elberling *et al.*, 2013; Mastepanov *et al.*, 2008). The installations at Kobbefjord and Arktisk Station are drawing on this experience and know-how but there are nevertheless questions regarding how one proceeds from there to answering the question.

Currently, the measurements are conducted only during part of the year but there are plans to make them year-round, if the power problems can be addressed. The flux measurements can be related to entities like soil moisture and temperature at INTERACT masts close-by. Research over a decade shows that snow cover is a major factor controlling CO_2 exchange (Lund *et al.*, 2012). The Panel was concerned about the representativeness of the sites since both Zackenberg and Arktisk Station are placed in locations that are exciting biodiversity locations but, from a Greenland-wide perspective, are rather unusual. But, more generally, the limited wetland areas in Greenland suggest that, compared to continental Arctic sites, fluxes in these greenhouse gases are unlikely to be a major concern.

Preliminary work on nitrous oxide flux measurements has revealed very small exchanges to date (Elberling *et al.*, 2010).

Since the soils vary in terms of their physical, chemical and biological properties both within and between sites, the Panel suggests a careful assessment of the comparability of measurements at the three GEM sites.

*How does climate change, and variability, affect the CO_2 exchange between Arctic marine ecosystems and the atmosphere? (**GEM Question 2**)*

[7] Here SMART is Specific, Measurable, Achievable, Realistic (though some suggest "Results-focused") and Time-bound.

[8] The Panel has attempted to evaluate progress on each of the 13 Questions identified in the GEM Strategy and Working Programme 2011-2015.

In contrast to the terrestrial studies, the MarineBasis sub-programme, which appears to work and plan independently, has given low priority to flux measurements of (all) gases, until the recent Arctic Science Partnership (ASP) consortium work in 2012 in Young Sound. MarineBasis in Zackenberg is developing carbon dioxide exchange studies but it was attempted only in Nuuk for the first time in 2013, as part of the ASP field campaign there. However, there are issues regarding the frequency of measurements and ability to transform concentration measurements to fluxes. In practice, the CO_2 exchange in the fjords and near-shore waters of Greenland is probably of much larger significance than the wetland fluxes on land, and yet is poorly known since most North Atlantic studies are based on blue water oceanographic studies.

Although this clearly points to this area being an important niche for GEM studies, it is not delved into with full force. Methane in fjord waters is an area that likewise is of relevance to pursue and it was pleasing to see the exploratory study measuring concentrations within sea ice and sea water in the Nuuk ASP campaign in 2013. It would be very interesting to also learn something about methane concentrations under the sea ice during late winter / early spring.

The Panel suggests that seasonal patterns of gas fluxes (both with and without ice cover) are measured in the fjords and lakes across the GEM sites.

The greenhouse gas monitoring setup at GEM's Kobbefjord site.

4.3.b Ecosystem function and resilience

*How does global change, including stronger climatic variability and change, affect the species composition and function of Arctic ecosystems? (**GEM Question 3**)*

GEM monitors the biological components of terrestrial, limnic and marine ecosystems with emphasis on species abundance and composition/diversity, phenology and reproduction across trophic levels, and how these biological attributes respond to variability in climate (weather) and hydrological parameters. Thus, monitoring in the ClimateBasis and GeoBasis sub-programmes, in particular, forms the basis for potentially explaining temporal patterns observed in species performance and ecosystem function. Although the data series of abundance, reproductive phenology/success of a wide range of plant and animal species are tabulated in the NERO and ZERO Annual Reports, relatively little analysis has taken place to date and few high-profile publications have appeared (Høye *et al.*, 2013, 2014; Iler *et al.*, 2013).

Unfortunately, there are rather few species common to all three sites but the Panel suggests that relatively more effort could be expended on those that are, including the possibility of exploring genes by environment interactions, using molecular tools.

Some of the longer established ecosystem function work, particularly projects networked to other Arctic sites, have started to appear in leading publications (Elmendorf *et al.*, 2011, 2012a, 2012b; Legagneux *et al.*,2014; Riisgaard *et al.*,2014). However, much of the work on ecosystem function is more recent, and yet to be published, but it is good to see some accounts starting to appear in the Annual Reports. For example, *Collaboration on permafrost-soil-vegetation* (Elberling *et al.*,2013b), *Responses of soil organic carbon to climate manipulations in Salix arctica heath in Zackenberg, Greenland* (Lee, 2013), and *Ecological function of aquatic mosses in Arctic lakes* (Riis, 2013), all in the ZERO 2012 Annual Report. Similarly, in the Draft ZERO 2013 report: *Three years exclusion of large herbivores in a high Arctic mire changed vegetation structure and greenhouse gas balance* (Falk *et al.*, in press), *Trophic interactions, temperature and greening in a changing climate* (Finstad *et al.*, in press) and *Nutrient fluxes and biotic communities in Arctic rivers with different water source contributions* (Milner *et al.*, in press).

Since it is possible to study mammalian herbivore-plant interactions only at Zackenberg, the Panel suggests that the importance of invertebrate herbivore-plant interactions, undoubtedly sporadically important at Arktisk Station and Kobbefjord, could be studied at all three sites.

The Panel understands that more could be published, if it were not the desire to produce a synthesis of 20 years of data collection at Zackenberg, and the first decade at Kobbefjord, following an international workshop in 2015 (GEM Strategy and Working Programme 2011-2015: Milestone M 2015: A). However, the Panel is concerned that the adaptive monitoring principles are not being applied and the interrogation of whether the data is fit-for-purpose is not being reviewed as it accumulates.

RECOMMENDATION 8: The Panel recommends that the adaptive monitoring approach is implemented more systematically and involves, where possible, the field staff responsible for the on-going data collection, several of whom told us they didn't feel connected to the outcomes.

*Are there important thresholds in Arctic ecosystems that might lead to sudden and significant shifts of their overall biodiversity and function? (**GEM Question 4**)*

The on-going GEM monitoring may identify extreme events that, if they were to become more frequent, might signal potential threshold effects influencing future species composition and/or ecosystem functioning. From our inspection of the publications and Annual Report project descriptions for the years 2011-2013, the Panel found little indication of progress in identifying potential threshold effects in either the terrestrial or marine ecosystems, with the exception of the observations of the glacial-lake outbursts at Zackenberg. In general, where data series have been inspected many relationships are linear within the range of variation in temperature and precipitation witnessed to date.

One alternative approach would be to build process-based models and explore responses to sustained extremes – shifts in mean of explanatory variables, as it has been done recently with the impact study of the decline of lemmings on the abundance of Long-tailed Skua in Northeast Greenland (Barraquand *et al.*, 2014). Another approach is to instigate or enhance experimental manipulations of key factors, though often this may be constrained to varying temperature and/or snow in terrestrial environments (*e.g.*, the ITEX experiments). Finally, insights on thresholds may come from work across climate gradients, though caution may be required in translating spatial differences to their equivalence in temporal trends.

RECOMMENDATION 9: The Panel recommends that GEM explores the scope for more specific experiments, as well as expending more effort on process modelling, in order to investigate the likelihood of thresholds in Arctic ecosystems and exploring their potential consequences.

4.3.c Water balance, incl. glaciology and water circulation in the marine environment

The Panel noted the significance of the inclusion of the A.P. Olsen Iskappe at Zackenberg in CryoNet, a network of 14 *in situ* monitoring sites of the Global Cryosphere Watch programme, coordinated by the World Meteorological Organization (WMO).

*How does the climate variability and change affect the water balance (incl. availability of water in terrestrial ecosystems, glacier mass balance and extreme run-off events) of Arctic ecosystems? (**GEM Question 5**)*

The GlacioBasis mass balance measurements on the A.P. Olsen Iskappe potentially permits modelling of the quantity of freshwater from the glacier into the Zackenberg river system. Coupled with the wider snowmelt measurements and hydrological flow measurements of the ClimateBasis and GeoBasis sub-programmes, it may be possible to relate the within and between season patterns in the overall water balance to the detailed meteorological measurements made across the whole catchment.

Although analysis of extreme events (*i.e.*, glacial-lake outbursts) can be elucidating, understanding the long-term effects of single episodes may require a highly modified sampling scheme and strategy.

The Panel is concerned that, so far, there seems to have been little attempt to undertake exploratory analysis and modelling and suggests this should be a priority.

*How does climate variability and change affect the discharge of sediments, organic matter, solutes and carbon from the terrestrial to the marine compartments of Arctic ecosystems? (**GEM Question 6**)*

Freshwater discharge is monitored at all three sites. Whereas measurements at Arktisk Station and Zackenberg are routinely on single rivers, at Kobbefjord four rivers, draining into the fjord, are monitored. At Zackenberg, the hydrological monitoring includes twice daily measurements of suspended sediment transport and water conductivity, which potentially can be related to continuous measures of river discharge and climate variables.

Dissolved organic carbon is measured weekly. Although there is some systematic ongoing work to relate these measures to fluctuations in the discharges and/or variations in weather, both within seasons and between years, this has yet to be published. However, there was work published on climatic influences on discharge simulations that precedes the inception of GEM (see Mernild, 2008).

The Panel suggests that the analysis of hydrological monitoring data series at Zackenberg is prioritised and linked to the GlacioBurst project reported in the ZERO 2012 Annual Report (Binder *et al.*, 2013).

*How does river discharge affect the water circulation in Arctic fjord systems? (**GEM Question 7**)*

To provide a more comprehensive picture of the effects of freshwater discharge into Young Sund, three smaller rivers were monitored in August 2012 to complement the continuous recording from the largest, Zackenberg River (GEM SI 3 – *Freshwater run-off to Young Sund/Tyrolerfjord (2012)* – see Larsen *et al.*, 2013). Since the discharges at the Arktisk Station and Kobbefjord sites are small, attempts to relate the effect of freshwater discharge on the fjord water circulation is now only a specific objective at Zackenberg / Young Sund. However, GINR does continue its year-round monitoring of hydrological conditions in Godthåbsfjord, as part of the other activities.

Nonetheless, at Zackenberg/Daneborg the plan is to combine the oceanographic data from the 2011 campaign (GEM SI 2 – *Land-ocean coupling in Young Sund*), which have already been analysed (GEM A6 – *High arctic marine production: quantifying controls by terrestrial melt-water),* with observations from this year's extended campaign (GEM SI 14 – *A seasonal marine study at Zackenberg 2014*). The current project at Young Sund also includes three months prior to the rivers start flowing and when the fjord is ice-fast.

The Panel is concerned that, since the water circulation of fjord systems are highly variable processes in time and space, influenced by offshore ocean water exchange as well as freshwater inputs, the present programme is insufficient to generalise and contribute to upscaling (see section 4.3.e).

4.3.d Snow and ice, including effects on phenology, energy and carbon balance

*How do climate-induced changes and variability of snow, lake ice and sea ice distribution change the biodiversity and function of marine, terrestrial and limnic ecosystems in the Arctic? (**GEM Question 8**)*

The installation of Snow Pack Analysing Systems at both Kobbefjord and Zackenberg in 2013 should significantly enhance the previous work on terrestrial snow depth and extent, because it provides automatic and continuous measures of snow density, snow water equivalents, and liquid water and ice, at three levels (10, 35, 55 cm), as well as overall snow depth. These measurements should prove particularly useful for the *Establishment of a snow model for the Zackenberg and Nuuk areas* (GEM SI 4/13) related to the variability of winter weather.

Also, strengthening the snow measurements will potentially improve the understanding of temporal variation in snow pack on the winter and spring ecology of animals (*e.g.*. GEM A5: *Snow conditions controlling muskoxen distribution at Zackenberg*) and plants (*e.g.*, *The role of plant interactions on plant recruitment along a snow depth gradient* (Grau and Ninot, 2012).

Considerable effort has been made to also address questions about the variability of ice cover in both limnic and marine environments through specific projects. Examples in limnic systems include *Winter ecology of lakes / Ecology of Arctic lakes* (Christoffersen 2012, in press) and *The influence of climate change on the growth of submerged macrophytes in low Arctic lakes* (Mønster and Olsen, 2013). Examples in marine systems include *Seasonal study on benthic metabolisms in a low Arctic area* (Sørensen *et al.*, 2012) and *The function of a polynya?* (Rysgaard *et al.*, in press).

The Panel acknowledges that the generic issue of "ice-cover effects" on biodiversity and ecosystem function are likely to be incredibly important but viewed the question as far too broad given the very limited data available because of the current constraints on sampling.

*How does the energy balance of Arctic ecosystems (marine, terrestrial and limnic) change with climate change and variability? (**GEM Question 9**)*

The network of automatic weather stations at all three sites enables the complete surface energy balance to be computed for the terrestrial environment. Comparative studies of land-atmosphere energy exchange have been conducted across a range of habitats within a low Arctic tundra ecosystem (Stiegler *et al.*, 2013). This work at Kobbefjord can be scaled up to a regional level through the strategic initiative GEM SI 9: *Surface energy budget at two additional sites in West Greenland*, maintained by ASIAQ, as well as to Zackenberg, and to the circumpolar scale through the INTERACT network of sites.

The DEFROST initiative also includes limnic and marine cryospheric systems, providing energy balance measurements that have the potential to elucidate the role of these ecosystems in climate feedback mechanisms. The extent to which the planned direct measurements of CO_2 fluxes from marine water surfaces, through the deployment of mobile towers, had been achieved was not clear.

The analytical synthesis project *Water, energy and radiation feedback changes in the Arctic* (GEM A8) suggested changes in summer-time surface energy balance partitioning in Arctic ecosystems may be of importance for the climate system (Lund *et al.*, 2014).

The Panel is encouraged to learn of the plans 1) to investigate year-round energy budgets by making use of Snow Model outputs, and 2) catchment-scale energy budgets using weather stations covering various surfaces and altitudes in Zackenberg. Nonetheless, the Panel is of the view that an enhanced understanding of the energy balance and feedback to the climate needed exploration of process models alongside further analysis of data.

The evaluation panel on site visit in Zackenberg Valley.

*How do climate-induced changes of permafrost-affected landscapes/soils (mainly thickness of active layer, thermal and moisture regime) affect the function of Arctic ecosystems and specifically their carbon balance? (**GEM Question 10**)*

Soil studies are limited in extent albeit part of the observational programme at all sites, and soil carbon does not seem to be measured on an annual basis. However, the research project *Collaboration on permafrost – soil – vegetation studies* (Elberling *et al.*, 2013b) includes the measurement of the spatial distribution of soil carbon, nitrogen storage and permafrost characteristics within the top 1-2 m of the ground. This is a key issue of PAGE21 and builds on measurements carried out sporadically since 1996, which have then contributed to recent major publications (Hugelius *et al.*, 2013; Schädel *et al.*, 2013) and the training of several PhD students.

This work is complemented by two other recent projects. First, on *The sensitivity of carbon in Arctic permafrost soils to climate change* (Björk *et al.*, 2013), which is exploring the current gap in knowledge of the extent to which permafrost-protected carbon is available for microbial metabolism once the soil thaws. Second, on *Effects of climate manipulations on soil organic matter under Cassiope tetragona dominated heath in Zackenberg, Greenland* (Jung *et al.*, 2012), which aims to understand the characteristics of soil organic carbon (SOC) and the effects of climate manipulation on SOC in two high Arctic heaths. The analytical synthesis project on *Tempo-spatial trends in soil water chemistry: plant soil interactions and controls by permafrost thawing* (GEM A 3), collected since 1996, has shown that although the active layer increased with more than 1 cm per annum, that there was no significant loss of carbon (Elberling *et al.*, 2013a). However, laboratory experiments showed consider-able losses of carbon depending on drainage.

The Panel is concerned that in order to acquire a relationship between landscape changes and the local carbon balance requires considerably more data and/or far reaching assumptions. Given the constraints on resources (funding, personnel and time) the Panel suggests that some prioritisation needs to be made about which of these generic questions, or specific elements within them, to prosecute immediately, in the short-medium term or longer term. Also, the Panel believes that more could be learned from the ClimateBasis and GeoBasis sub-programmes taking a historical perspective, say the last two centuries, which might allow some judgement of whether the modern situation is a consequence of previous trends or a modern anomaly which lacks any precedent. Information on landscape evolution, cryo-related processes, or temperature/weather records revealed in the understudied historic lake records may carry some clues.

4.3.e Upscaling, modelling and prediction

The 'GEM Strategy and Working Programme 2011-2015' is rightly upbeat about the challenges of developing the upscaling, modelling and prediction thematic area. However, it is disappointing that two of the Strategic Initiative projects on upscaling *Establishment of a vegetation upscaling and prediction model for Zackenberg* (GEM SI 7) and *Upscaling climate change effects to the Greenland scale* (GEM SI 11) appear to still be 'in progress' because they are both part of PhD studies. Also, since the report on the *International workshop on upscaling of ecosystem function data* (GEM SI 18) held in November 2013 has not been produced yet, it is unclear how much progress has been made in this theme.

*To what extent can results from GEM be used for upscaling and prediction to address GEM Questions 1-10 on a regional scale covering Greenland and seas around Greenland (now and in the future) and what are the constraints for such upscaling and prediction efforts? (**GEM Question 11**)*

Upscaling requires an understanding of the representativeness of the sites and the relevance of the studies performed. In the rationale presented, there is little discussion regarding the extent of different ecological systems around Greenland, yet it appears that much of the coastline differs significantly from the current three study sites. One could adopt a strategy to create an envelope around Greenland environmental states by

studying extremes which could produce many useful results, but one is still not coming closer to understanding the transient problem (*How one state is transformed into another, upon a change in forcing?*), since the pathway from the one balanced state into a new one is unlikely to be linear. Also, it is debatable if there are balanced states since climate has always changed (and will always change) at variable timescales but it does not alter the main strategic discussion. Variants looking at transects across different states are likewise hampered by not necessarily leading to an understanding of the time-dependence problem.

The three sites have different historic and scientific arguments for their inclusion. Zackenberg, it is argued, is on the high Arctic / low Arctic boundary and is thus placed where climate change may make the largest impact. Kobbefjord is situated close to Nuuk, the main population centre in Greenland, and thus potentially provides useful policy relevant information. Arktisk Station has the heritage of 100 years of studies and was originally chosen because it is in the vicinity of one of the (botanical) biodiversity hotspots of Greenland. These diverse arguments are difficult to reconcile as a strategy for choosing the best locations for upscaling to Greenland or regional conclusions. GEM long-term measurements have evolved but are still strongly inhibited in their development by heritage from the initial priorities at the locations. To create opportunities for more original discoveries regarding how entities are interlinked and influenced by each other or external forcing, more care is needed regarding creating congruent measurements in space and time. This is true within the Basis sub-programmes but, in particular, between the Basis sub-programmes and between the three sites.

The Panel suggests that, in the light of the refined (SMART) questions (see RECOMMENDATION 7), there is a comprehensive review of the matrix of Basis sub-programmes, collaborative projects and sites in order to refine and strengthen the GEM Working Programme, in general, and specifically plan the modelling and data collection required to achieve the desired upscaling.

Predictive capacity can be acquired mainly through two fundamentally different pathways. One approach is the utilisation of historic analogues where one can return to a previous state, given that all 'forcings' are identical to the historic instance. Long-term measurements can then provide the data on how different entities previously adjusted themselves. This can be a sound approach within the envelope that previous variations (in 'forcing') encompass (*i.e.*, interpolation). However, present perturbations in the system, notably climatically active agents in the atmosphere but also atmospheric deposition, particularly of nitrogen, and pollutants, direct human disturbances (*e.g.*, tourism, scientists), introduced species, hunting and fishing are probably outside previous perturbations or in combinations of pressures previously not seen, making the historic analogue strategy inadvisable. The alternative approach comprises gaining process understanding of some internally consistent framework (*e.g.*, numeric models) to calculate future states based on quantitative mechanistic understanding.

Therefore, a prerequisite for such studies is that long-term measurements are sufficient not only to detect change but also the basis for a parallel fundamental (basic) research activity of what lies behind the observed change. This is where the symbiosis between the

long-term measurements and the process studies is of paramount importance for the success of GEM (and all other 'monitoring' work). The Panel was encouraged to learn that the GeoBasis sub-programme had initiated an upscaling project focusing on the land-atmosphere exchange of CO_2 and CH_4 with simulations using the dynamic vegetation model LPJ-GUESS (Smith *et al.*, 2001). Preliminary results are promising but also indicate some specifics of the high Arctic environment that need to be resolved. The intention is to pursue 'local' modelling (Zackenberg valley), and then scale up to a regional level (*i.e.*, entire coastal Greenland), making use of observations at other sites, combined with remotely sensed data.

RECOMMENDATION 10: The Panel recommends that GEM develops a collaborative (institutional) modelling and prediction 'group' where there is continuous interaction of fundamental thinking and curiosity to interrogate the incoming data, enhancing understanding and refining approaches to both the ongoing monitoring and research.

It is noteworthy that GEM is presently addressing only *climate* amongst all the perturbations mentioned above. The effects of climate change and ability to build predictive capacity cannot be studied in isolation. A weakness is the little attention given to quantifying the effects of all other ongoing changes. If interpretation only seeks relations to climate variability there are risks of missing the impacts of other potential drivers.

While a comprehensive monitoring scheme of all drivers of change would be beyond current resources, the Panel suggests that it would be important for a modelling and prediction collaborative group to have the interdisciplinary capacity to develop a holistic, system-level model which considers the potential interactions with other drivers, in addition to climate change.

Since upscaling involves generalising to a larger region, some kind of model is needed (the discussion of which is deferred to GEM Question 12 below) but also an understanding of the region or area one is upscaling to. The latter requires an understanding of how the local measurements at a long-term observation site apply to the surroundings. Maps are a static beginning, remote sensing can capture both distribution and time dependence of some entities, drones can give some regional detail and entities that remote sensing is unable to produce and other measurements (*e.g.*, weather stations or other restricted entity probes) could be placed in further places to aid in the upscaling. To some extent meteorological parameters are measured in a finer grid but for most other entities we are presently limited to (at best) the three GEM locations. Work to identify key parameters (entities) through the above auxiliary methods that can give significant support for upscaling, needs careful consideration.

The Panel views that such an analysis of network design should be an essential part of the suggested GEM modelling and prediction group. This group should lead the synthesis between the Basis sub-programmes as well as within Basis sub-programmes between the sites.

*What models shall be developed to address the above questions on a regional scale (Greenland and surrounding seas)? (**GEM Question 12**)*

There is a multitude of efforts around the world working on global modelling in Earth system science. It is advisable to work in close cooperation with such institutions to be able to relate what happens in Greenland to changes in the rest of the world and likewise how Greenland influences its surroundings. GEM, and in particular the people working with GEM, does, however, harbour detailed knowledge on the regional and local scale.

Some issues regarding the details of how the global scale interacts with the regional or local scale require biogeochemical modelling of the Greenland system. This includes fjord circulation models, atmospheric models that can resolve valleys, for example katabatic flows, and a snow model that can make valid use of the three dimensional wind fields. From there, one could pursue how different ecosystems respond to changes in physical parameters. Such modelling will always be best done in close collaboration between the observational design hub and the modelling community hub.

The Panel suggests that modelling should be actively integrated in the adaptive monitoring concept.

*How can current monitoring and long-term research efforts in GEM be adjusted most effectively to meet current and future scientific needs and policy-related demands? (**GEM Question 13**)*

This question is best addressed by the modellers concentrating on entities that can be utilised as initialisation data or verification data for the models. Likewise, the models should actively work towards identifying entities that have large variability in space or time (therefore requiring higher-resolution measurements in a given realm) and thus lending support to the monitoring design. With the models, one can identify uncertainty (as given by the model variability in an entity as function of initial conditions) and thus aspire to a knowledge (and cost) effective design of the monitoring system development.

By placing the monitoring design work in the Greenland hub it should ensure that the link to understanding the measurements in the regional context is ensured. Importantly, this also gives a direct link to policymakers' needs in Nuuk. The hub would both be capable of responding directly to what is possible to say (including uncertainty estimates) with the existing monitoring and models, and also have a direct link to what needs to be done with the monitoring and/or models in order to provide the information necessary for the policymakers.

4.4 How likely is it that GEM will achieve the scientific goals set out in the 2011-2015 working programme?

GEM has made considerable progress in delivering its general vision to "contribute substantially to the basic scientific understanding of Arctic ecosystems and their responses to climatic changes and variability, as well as the potential local, regional and global implications of changes in Arctic ecosystems". However, progress to date in achieving the scientific goals of the GEM Mission and GEM Objectives 2011-2015 has

been more mixed. For example, the coherence across the five Basis sub-programmes is patchy and variable within the three sites. The apparent lack of integration constrains the desire for cutting-edge interdisciplinary research needed to address some of the chosen research questions.

More focus is needed on the conceptual models that are fundamental to answering the 13 questions to ensure that the correct information/data is being collected and, in particular, the concept of adaptive monitoring needs to be implemented more widely. The modelling capability to deliver the predictive capacity, and to achieve the desired up-scaling, is currently limited to some particular Basis sub-programmes and needs to be prioritised more generally in the coming years.

In the view of the Panel, achieving the more holistic outcomes posed by the scientific goals requires stronger scientific leadership, both in coordinating the integration of the research and in directing the interdisciplinary, collaborative modelling approach.

4.5 Has GEM provided any unanticipated scientific results over the past six years?

Since 2008, some unanticipated scientific results have appeared. A particularly prominent example is the discovery of the widely cited ground-freezing methane burst revealed by the extension of the methane measurements into the autumn/early winter (Mastepanov *et al.*, 2008), a phenomenon that has also been observed in other Arctic regions (*e.g.*, Siberia). The GlacioBasis monitoring of the A.P. Olsen Iskappe, together with a complementary project led by the Austrian Central Institute for Meteorology and Geodynamics, has provided insights into the mechanisms influencing glacial-lake outburst floods (Binder *et al*., 2013).

The BioBasis has been monitoring the flowering response to the significant warming at Zackenberg and found what appears to be a non-linear response in the timing of flowering where, despite the warmer temperatures, plants can't flower earlier; this indicates that plants may be approaching their limits of phenological change (Iler *et al.*, 2013b).

The field station at GEM's Kobbefjord site.

5. THE ORGANISATION

Within the wider realms of other national and international Earth science monitoring programmes and strategies, the evaluation panel is requested to address the following key questions.

5.1 To what extent does GEM apply an adaptive monitoring approach?

The 'GEM Strategy and Working Programme 2011-2015' proposes to *"strengthen its analytical component"*… *"by following the paradigm of adaptive monitoring"* (*sensu* Lindenmayer and Likens, 2009). Adaptive monitoring provides a framework for incorporating new questions into a monitoring approach for long-term research while maintaining the integrity of the core measures. Initial key steps are the development of critical questions and a robust statistical design, followed by data collection, analysis and interpretation. New understanding feeds back into a synergistic evolution of the ques-tions, modification of core data collection and analytical approaches etc. in an iterative way.

Field personnel running the Basis sub-programmes across the sites was unaware of the concept and somewhat skeptical about the extent to which it was implemented, if at all. Indeed, as commented upon earlier in this report, there was a specific concern that, if there was any data interrogation going-on beyond the immediate quality control, the outcomes were not being fed back to the field assistants. During our series of telecon-ferences with all the PIs of the sub-programmes we found a very patchy awareness of the specific concept and a variable degree of its use. While some PIs gave examples of their *ad hoc* use of the principles of adaptive monitoring to refine questions and modify data collection, there was little sign of systematic application of the concept.

As commented upon earlier (see RECOMMENDATION 8), the Panel is of the view that the adaptive monitoring approach should be implemented more systematically and involve, where possible, the field staff responsible for the on-going data collection, the modelling colleagues, and other participants in the research and, where appropriate, stakeholders.

5.2 Is the current management structure of the programme efficient in terms of:

5.2.a Scientific guidance and leadership to GEM activities

The 'coalition-of-the-willing' approach, both among the institutional supporters of Arctic ecosystem science and the passionate researchers themselves, means that the GEM activities have achieved a tremendous amount in terms of improving our understanding of species biology and ecosystem function as well as their physical environments in Greenland and the wider Arctic. However, to meet the aspirations of the GEM pro-gramme, continual strategic thinking needs to be more prominent, and coupled with appropriate implementation of more coherent and holistic ecosystem projects. The Panel concluded that, the strong interdisciplinary thematic approach, advocated in the 'GEM Strategy and Working Programme 2011-2015', has not been delivered by the current structure of a Steering Committee and a Coordination Group. The collective effort needs

dedicated, full-time visionary scientific leadership and direction to achieve the potential added-value intended from the work across the sites, as well as better integration between the sub-programmes within sites. Also, stronger leadership and direction might help generate a more corporate identity for GEM: Currently, too much of the ethos is linked to a place-based identity, with Zackenberg overly dominant, which partly undermines the generic questions, especially issues of upscaling. While the Panel is very encouraged by the recent appointment of a new scientific leader, our view is that he and his team will need dedicated support. Whether this support can be achieved without the current partnership of institutions creating a dedicated GEM Centre, including a stronger presence in Greenland, is a debatable point?

RECOMMENDATION 11: The Panel recommends that, as soon as possible, GEM establishes an independent (of the ministries and other stake holders), international advisory board, to provide the necessary high-level overview and support to both the Science Leader and the stakeholders.

5.2.b Logistical organisation of GEM activities

The Panel was impressed with the logistical organisation at all sites, and found them exemplary in terms of their thoughtfulness in support of the welfare of scientists, and the overall tidiness of the station buildings and compounds. However, the challenges of maintaining Zackenberg, in particular, are significant since there everything is ferried in by air. Arktisk Station and Kobbefjord have the benefit of being close to settlements providing immediate resources, and are also accessible throughout the year, though Kobbefjord has limited overnight accommodation. Although, in recent years, the research and monitoring at Zackenberg/Daneborg have been extended into spring and autumn, there is still a need to consider investments in infrastructure that would potentially enable vital winter work. In general, Zackenberg/Daneborg, needs improved living (study space) and working (laboratory, internet connection) facilities as well as a 'greener' energy provision.

The Panel was of a view that all GEM research platforms should be more energy efficient and critical of current waste management practices. Neither the Danish Energy Agency nor the Danish Environmental Protection Agency should be in a position where their sponsored initiatives could be criticised for lack of 'best' practice.

RECOMMENDATION 12: The Panel recommends that there is an options review and feasibility assessment of green energy generation and utilisation efficiency, as well as dealing with all forms of human waste management, at all sites.

5.2.c Facilitating interfaces between long-term monitoring and research efforts

Currently, there seems to be a gulf between the two components because each realm largely functions independently, though it was more integrated at Zackenberg were there are many more researchers and collaborative projects. Even so, it was noticeable that the research assistants, while technically very able and dedicated to conducting the specific measurements, often seemed to have little awareness or understanding of the GEM research questions their monitoring was aimed at addressing.

As commented earlier, the Panel suggests there should be more interaction between the PIs, their technical assistants, and the more independent collaborative researchers, through using the adaptive monitoring concept.

5.2.d Adjusting activities to meet knowledge needs

The current GEM conceptual framework is sufficiently general that it can be adjusted to accommodate new knowledge needs both in terms of direct scientific understanding and indirect policy relevance. However, in the latter case there is now probably an increased need for closer engagement with the relevant policy stakeholders and environmental managers. There is still a relative dearth of understanding of winter ecology and the extent of the dormancy of ecosystem function. These gaps in our understanding may be overcome if the logistical issues of personnel over-wintering can be solved, or more remote sensing can be deployed, though this still requires power and mobile telecommunication solutions.

In terms of both scientific impact and policy relevance, the Panel suggests that more could be done to explore additional drivers of change and, in particular, the interaction with climate change.

5.3 Has GEM obtained a clear role in comparison with other similar monitoring programmes addressing current Arctic challenges?

The Panel is not aware of any research and monitoring initiatives in the Arctic which are as comprehensive as GEM in terms of systematic measurements in terrestrial, limnic and marine ecosystems, or of the physical framework. However, there are a large number of initiatives in the terrestrial environment, which are conducting closely related work, similar in breadth and depth. The most extensive of these is the Long-Term Ecological Research (LTER) network established in 1980, which has two sites in Alaska but is also connected to many more temperate sites across North America. Other ecological monitoring in the Arctic is typically based on single sites some of which have been running much longer, including Kluane Lake, Yukon Territory, Canada, since 1961, or a century at Abisko, Sweden. The comprehensiveness of the terrestrial measurements at Zackenberg, and the fact that they been running since the mid-1990s, are reasons why it is so well-networked with international collaboration in circum-Arctic activities.

5.4 Does GEM provide online access to monitoring data (temporal and spatial resolution, timeliness, ease of use)?

Given that eight years ago a key recommendation of the review of Zackenberg was to "*Increase support to the data management system"* (Callaghan *et al.*, 2006), the Panel was disappointed to find that no one in the field in Greenland or any of the PIs of the Basis sub-programmes knew about the progress in delivering a database that would enable on-line access to the monitoring data.

The Panel views this failure to deliver a working data management system as a major impediment to joining the research up across the Basis sub-programmes, thereby constraining progress towards answering the GEM questions.

However, we were informed that the GeoBasis data system is being adapted to provide a central facility for GEM data management, and that the new Science Leader plans to make this happen, as a top priority.

The Panel is encouraged by the apparent progress on the GEM database presented at the workshop on September 8 but suggests that the GEM Steering Committee pays special attention to this issue (the database is promised to function by the end of 2014!).

5.5 Is there a need to revise or adjust the current set-up and implementation plans for the GEM programme?

Although the Panel views the GEM strategic plan to work across ecosystems and develop a holistic Greenland-wide understanding, to be truly innovative, we are concerned that it may fail to meet the aspirations of its vision. We are not aware of specific implementation plans between the insights of the *Working* element of the 'GEM Strategy and Working Programme 2011-2015' and the technical Basis manuals, which describe how the measurements are taken. However, working through the conceptual framework and the adaptive monitoring approach systematically would effectively enable a review of the current set-up.

5.6 Some further thoughts on the organisation of GEM

The panel was of the view that the annual reporting structure by site (*i.e.*, research platform) was no longer fit for the purpose, and impeded measuring the progress of GEM. Some of the Basis sub-programmes reported merely what was done year after year, just changing the dates between years. Often there was a lack of description of what was found, and, even where more specific results were described, there was little or no interpretation. Given that only a little of the specific GEM work, undertaken since 2011, has yet been published, the historical format of the reports made the job of the evaluation Panel considerably more difficult.

RECOMMENDATION 13: The Panel recommends the development of a 'corporate' GEM-brand, facilitated through a single GEM annual report and a unified website. Both the GEM annual report and the website should be structured by the five themes of GEM, disaggregated to the level of the re-evaluated set of the 13 questions. Also, the monitoring and the relevant science projects should be integrated accordingly under the relevant theme/question.

Inside the Kobbefjord field station. Briefing of the evaluation panel by the PIs Josephine Nymand (GINR) and Jakob Abermann (Asiaq).

6. THE FUTURE: GEM 2.0

During the workshop in Copenhagen time was devoted to an analysis of Strengths, Weaknesses, Opportunities and Treats (SWOT). This engaged all the participants, except the Panel who listened before revealing their own SWOT, done prior to the workshop (both sets of SWOT analyses are shown in Appendix 4).

There were some similarities between the two exercises, including issues of funding and selection of sites. However, there were also many differences arising from the fact that the workshop participants who had little warning that they were to conduct the exercise, tended to think 'tactically', presumably reflecting their close connections with GEM, whereas the Panel had 'stepped-back' and produced a more 'strategic' analysis. While this sort of exercise can be interesting as a one-off 'brain-storm', both the GEM Steering Committee and the GEM Coordinating Committee might usefully repeat it.

Within the widest possible realm of future *"unknown unknowns"* (*e.g.*, rapid cryospheric changes, biogeochemical feedbacks and their impacts on Arctic ecosystems), the evaluation panel is requested to address the following key questions:

6.1 Does GEM provide the flexibility to adjust to rapidly changing physical conditions in the Arctic (loss of sea ice, etc.)?

Although it has effectively been in operation for six years, the evolution of GEM to a holistic ecosystem-based strategy benefiting from strong interdisciplinary cooperation still seems to be constrained by its origin as a site-based ecological, and largely terrestrial,

research operation. Add to this the historical aspects and the site-based institutional affiliations with their different cultural backgrounds and objectives, particularly at Arktisk Station. Accordingly, the Panel was concerned that the current structure could be unlikely to be flexible and 'fleet-of-foot' in adjusting to the research needs driven by rapidly changing physical conditions in the Arctic. As commented upon earlier in this document, the Panel viewed strong leadership, unambiguous implementation of the adaptive monitoring principles, and adequate resources, as also essential to underpin the future success of GEM. Monitoring change in real time is highly interesting, but it really makes sense only if lessons can be learned for the future (*i.e.*, predictive capabilities), which seems impossible, presently, because of the underdeveloped modelling efforts.

6.2 Should GEM include and/or coordinate activities with other ongoing monitoring efforts in and around Greenland to provide a more coherent and trans-disciplinary monitoring programme for all of Greenland?

The Panel was convinced that there is considerable scope for GEM to have a wider role than the current core efforts at Nuuk and Zackenberg. In particular, the work at Arktisk Station, which is already receiving funding from DANCEA, should be more clearly aligned with all relevant Basis sub-programmes from the other sites. Currently, this is largely confined to the GeoBasis work undertaken by CENPERM and ,potentially, to the ITEX-based work (BioBasis) on vegetation responses to perturbation. It was unclear to the Panel how well either the freshwater or marine environment work at Arktisk Station was connected to the respective Basis sub-programmes at Nuuk and Zackenberg, but certainly there was huge scope in the marine environment, including the potential exploitation of historical records. Also, Arktisk Station offers the scope to expand the limited effort currently expended on the GlacioBasis network.

As stated earlier, the Panel is of the view that there should be a monitoring site in South Greenland, where rapid climate change is driving agricultural expansion, which may have relevance to upscaling of what could happen at other sites on the west coast. This would increase the strategic relevance of GEM and offer the opportunity of exploring the consequences for human well-being locally (see RECOMMENDATIONS 3 and 4). The necessary trans-disciplinary work could be achieved in partnership with GINR and GCRC.

6.3 Should GEM be considered as a core activity guiding others, or as a marginal activity closing the gaps between research projects?

The Panel was convinced that the GEM should be a core activity unifying the work to gain added value from systematic approaches to all monitoring. As the connectivity of the sites increases, and the time series extends, the number of projects attracted to collabo-rate with GEM, many of which will inevitably be short-term, will grow and increasingly *'the whole should become greater than the sum of the parts'*.

The Panel encourages GEM to focus increasingly on understanding the causes and consequences of ecosystem change and generate the capacity to predict, through mechanistic models, the outcome of future scenarios of environmental change at local, regional and global scales. To do so, will require confidence about the representativeness of the sites at which measurements are conducted, and their appropriateness for upscaling to

regional scales (see RECOMMENDATION 4). Also, since the regional importance of Greenland is due to its ice-dominated land mass surrounded by productive seas, more emphasis needs to be placed on the interaction of terrestrial and marine processes.

RECOMMENDATION 14: The Panel recommends a much stronger explicit link between the coastal seas work and the terrestrial/limnic research, through a stronger strand/theme of integrated conceptual thinking, observation and process models.

6.4 Should GEM continue its strategy with a clear and long-term focus on two core areas in NE and SW Greenland?

The Panel was not convinced that focusing on just the Zackenberg and Kobbefjord sites, which are compromised by several confounding differences, was justified. GEM has already partially integrated related work at Arktisk Station, and while there is a risk of spreading both financial and human resources too thinly, the Panel recognised that there were opportunities to strengthen the research considerably by expanding to a network of sites across Greenland, while still maintaining a long-term focus.

The Panel suggests that a new GEM site be established in South Greenland (see RECOMMENDATION 3) but, under the theme of ecosystem monitoring, the Panel is hesitant about encouraging GEM to join the new Station Nord (even though desirable and attractive as it may be). Additional GEM sites would require substantial extra financial, logistic and human resources and the GEM leadership will have to judge if this can be accommodated.

6.5 Should GEM reduce its core activities and extend its monitoring activities to other carefully selected field sites in Greenland?

However, the Panel concluded that to make such gains would require a very different structure: one that could consolidate human-operations and expand automated/remotely sensed monitoring. There is a range of options for doing so; for example, limnic research opportunities are huge in West Greenland, north of Nuuk.

6.6 Should GEM reduce its core activities in general and provide a more flexible, dynamic and adaptable monitoring strategy?

The Panel was concerned that the number of measurements across the Basis sub-programmes had expanded to more than 3,500 and were of the view that there needed to be more focus on the questions and, as repeatedly stated, the implementation of the adaptive monitoring concepts to hone the monitoring regimes.

The Panel recommends that GEM makes a review of the overly ambitious 13 questions and an immediate priority so that they might be adjusted or revised to become more tractable (RECOMMENDATION 15). To do this will also require a major effort in synthesis of the existing data subject to the database being complete and rectifying the generally slow progress on upscaling models.

6.7 How could GEM best contribute to emerging and/or yet un-explored scientific questions?

The Panel is of the view that GEM should avoid over-focussing on climate change at the expense of other potential drivers of change, *sensu* AMAP, which, while not yet important in their own right, could be interacting with climate change.

6.8 Some further thoughts on delivering Arctic research

Finally, the Panel is of the view that Terms of Reference are often very specific and rather ignore the bigger, more generic question of *"How should GEM be organised in the coming years and decades?"*. Since our first meeting in Copenhagen in March, throughout our visit to Greenland in July, and in the weeks since returning, the Panel has spent a considerable amount of time pondering the important broader issues of how research in the Arctic is organised in the Kingdom of Denmark.

The three Panel members all come from countries with dedicated polar research institutes (combining science and logistics), as well as nations with considerable strengths in polar research within the university sector. These nations maintain these institutions partly because many environmental changes are dramatic, fast in real time, with global effects, but also partly for political reasons, because these changes influence the well-being of their own societies.

Given the geopolitical importance of the Arctic to the Kingdom of Denmark, it is unusual in not having a dedicated institution to ensure that its strategic needs are integrated across the science-policy interface. As indicated above, the Panel believes that, at the very least, there is a need for greater co-operation between the universities and other relevant research institutes, as well as a more cohesive partnership among the funders, incl. the different ministries with a stake in the Arctic, to achieve a virtual centre, at the very least.

RECOMMENDATION 15: The Panel recommends a wider review of the potential institutional structures to meet the Kingdom of Denmark's future needs for high-profile excellent and relevant research in the Arctic, recognising the considerable financial and political implications. Although it is not within the remit of the Panel's mandate to define specific proposals, one of several possible models is a 'centre' with two 'hubs'. One 'hub' would involve growing the capacity to implement the integrated monitoring, research and logistics from a base in Greenland. The other 'hub' involves creating a dedicated, process modelling group which can draw on the expertise of Danish research institutes and universities in Denmark, and more widely This second hub would co-locate the relevant researchers in a single site. The two hubs can be linked by the two original GEM concepts i) a holistic study of the Greenland ecosystem, but expanded to include other drivers in addition to climate change, and ii) the principles of adaptive monitoring, which integrates the science questions, data collection, analytical approaches (incl. modelling), and interpretation, in an iterative way, as mentioned, previously.

Operationally, it would be important for the two hubs to have high-tech videoconferencing for day-to-day interactions, as well as regular mixing of personnel either in the field sites and/or at either hub, because the majority will be engaged in one or more collaborative project. Established scientists should lead both hubs, with the Greenland hub prioritising the implementation of the field research and monitoring, while the Danish hub prioritises the theoretical and model developments. The leaders of both hubs would assist the overall science leader in developing the science questions and cutting-edge approaches to answering them so that GEM evolves into a world-class 'institution' renowned for its excellence, scientific impact and policy relevance.

The GEM hub in Greenland could be located on the research campus being developed at the site of the Greenland Institute of Natural Resources (GINR) in Nuuk, from where the whole MarineBasis sub-programme and the field operations across the BioBasis and GeoBasis sub-programmes in Kobbefjord are coordinated already. Clearly, there may be lessons to be learned from the experience of establishing the Greenland Climate Research Centre within GINR (Falkowski *et al.*, 2013). Since the ClimateBasis sub-programme is also based in Nuuk, at ASIAQ, it can also contribute to a hub which drives both science and logistics, and also provides potential capacity building through tertiary education programmes in association with Ilisimatusarfik – the University of Greenland - which currently has no environmental courses but which GINR is exploring developing.

Twin Otter aircraft has arrived at Zackenberg.

7. APPENDICES

Appendix 1. The panel members

Professor Steve Albon (James Hutton Institute, UK)
Steve Albon (*1954) began his research career at the University of Cambridge in 1976. After 15 years he joined the Institute of Zoology, London, where he spent 5 years establishing an Ecology Group, which worked all around the Globe. In 1997 he moved to Scotland as Director of the Institute of Terrestrial Ecology research station at Banchory (latterly the Centre for Hydrology and Hydrology (CEH)). After seven years at ITE/CEH he moved to the Macaulay Land Use Research Institute (renamed the James Hutton Institute following a merger in 2011) to be Head of Science.

Since 2009 Steve has been a Co-Chair for both the UK National Ecosystem Assessment and its Follow-on project. He was part of the team developing the Valuing Nature Network and coordinated the Environment - Land Use and Rural Stewardship research programme for the Scottish Government between 2006 and 2011. Steve is internationally renowned for his contribution to the long-term research on the population ecology of red deer on the Isle of Rum, Soay sheep on St Kilda and, more recently, reindeer on Svalbard, where he has worked for 20 years. He was elected a Fellow of the Royal Society of Edinburgh, Scotland's National Academy of Sciences and Letters, in 2008. Steve has held an Honorary Chair at the University of Aberdeen since 1997.

Professor Jörn Thiede (School of Earth Sciences, St. Petersburg State University, RF)
Jörn Thiede (*1941) worked in academic positions (from Amanuensis to Full Professor) 1967-1982 at the universities of Aarhus (Denmark), Bergen (Norway), Oregon State University in Corvallis (USA), and Oslo (Norway). He learned to sail the worlds' oceans attempting to understand the history of their shape, waters and life. In 1982, he moved to Kiel University (Germany), to create a new research institution in marine geosciences (GEOMAR). After fusing with the Kiel Institute of Marine Sciences it is now a world famous research institution. During 2008-2011, he was a professor for "Geology and Climate" at the Geocenter Danmark in Copenhagen, He also spent three years as Adjunct Professor at UNIS, Svalbard and he was the Director of the AWI (Alfred-Wegener-Institute, the HGF Centre for Polar and Marine Research) in Bremerhaven (Germany), 1997-2007. He is now working as leader of the KÖPPEN-Laboratory of Geochronology at the State University of Saint Petersburg, Russian Federation.

Professor Kim Holmén (Norwegian Polar Institute)
Kim Holmén is an atmospheric chemist, currently International Director at the Norwegian Polar Institute, and based in Longyearbyen, Svalbard. He has also been an Adjunct Professor at the University of Tromsø, since 2011. His research career began as a post-doc in the University of Miami (1987-1989), before he moved back to his native Sweden to take up a position as an Associate Professor in the University of Stockholm (1989-2003). Kim moved to Norway in 2003 as a Senior Scientist at the Norwegian Institute for Air Research (NILU), before moving to the Norwegian Polar Institute in Tromsø as Research Director in 2005.

Appendix 2. Terms of reference

(Version provided by the GEM Steering Committee and accepted by the Panel in a teleconference on February 10, 2014).

Evaluation of the Greenland Ecosystem Monitoring Programme

Background
The Greenland Ecosystem Monitoring (GEM) is an interdisciplinary monitoring programme of effects of climate change on ecosystems in Greenland. Currently the programme consists of two comprehensive long term monitoring stations in the Zackenberg Valley in Northeast Greenland and in Kobbefjord close to Nuuk in Southwest Greenland.

During the past few years, GEM efforts have been complemented by similar but less comprehensive long term monitoring efforts on Disko Island in West Greenland and at the Sermilik Station in Southeast Greenland. A new monitoring station is about to be built up at Station Nord in the ultimate Northeast corner of Greenland.

The background, history and organization of the GEM programme is described in Appendix 6.

Rationale
A five year strategy for the GEM programme (2011-2015) and work-programme was approved by the steering committee in 2011. Given its 5 year perspective the GEM steering committee has decided to undertake an evaluation of the strategy and the work-programme in order to evaluate the needs for revision of a future GEM programme.

The Steering Committee wishes to take into account the development that has happened since the establishment of the GEM in 2011 in terms of the understanding of climate change and climate variability and the effects on arctic ecosystems and biodiversity as well as the conceptual understanding and logistic and methodological developments. Three milestone reports from the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) and the programme for Conservation of Arctic Flora and Fauna (CAFF) published in 2005 (ACIA) , in 2010 (SWIPA) and in 2013 (Arctic Biodiversity Assessment) as well as a forthcoming Circumpolar Biodiversity Monitoring report series constitute major resources in this regard.

Objective
Overall objective

The overall objective of the evaluation is to assess the scientific, economic and organizational effectiveness of the GEM programme and its scientific and societal impact.

The GEM steering committee has developed the following framework and questions to guide the evaluation.

Policy relevant questions

Within the realm of the Danish *Strategy for the Arctic 2011-2020*, the evaluation panel is requested to address the following questions:

1. Do GEM activities provide an adequate foundation for wider international cooperation, including support for the fulfillment of international agreements on climate change, environmental protection, and the protection of nature and biodiversity?
2. To what extent do GEM activities contribute to the fulfillment of a sound and solid scientific basis for the protection of nature and environment in Greenland?
3. Do all the ongoing GEM activities provide "value for money" in terms of scientific and societal impact.
4. To what extent do GEM activities contribute to/form a basis for adaptation to a changing climate?

Strategic impact questions

Within the realm of the Greenland Ecosystem Monitoring Strategy 2011-2015, the evaluation panel is requested to address the following key questions:

1. Does GEM play a leading role in the circum-Arctic network of ecosystem field monitoring sites?
2. How do you evaluate the overall impact from GEM/Zackenberg/Kobbefjord scientific publications over the past 6 years (2008-2013)?
3. Has GEM published clear and unambiguous guidelines for field observations, data management and dissemination procedures?
4. To what extent have GEM results been reflected in the IPCC WG I Fifth Assessment report?
5. To what extent have GEM results been reflected in "milestone" reports and activities within the Arctic Council?

Scientific questions

Within the realm of the Greenland Ecosystem Monitoring working programme 2011-2015, the evaluation panel is requested to address the following key questions:

1. To what extent are results of GEM activities used for scientific analyses?
2. To what extent do GEM activities and results of the GEM serve as basis for other research activities?
3. Has GEM provided data analyses which have substantially contributed to the understanding of:
   a. Greenhouse gas exchange with the atmosphere and nutrients balance
   b. Ecosystem functioning and resilience
   c. Water balance, including glaciology and a freshwater circulation in the marine environment
   d. Snow and ice, including effects on phenology, energy and carbon balance
   e. Upscaling, modelling and prediction of ecosystem aspects
4. How likely is it that GEM will achieve the scientific goals set out in the 2011-2015 working programme?
5. Has GEM provided any un-anticipated scientific results over the past 6 years?

Organisational questions

Within the wider realms of other national and international Earth science monitoring programmes and strategies, the evaluation panel is requested to address the following key questions:

1. To what extent does GEM apply an adaptive monitoring approach?
2. Is the current management structure of the programme efficient in terms of:
3. Scientific guidance and leadership to GEM activities
4. Logistical organization of GEM activities
5. Facilitating interfaces between long term monitoring and research efforts
6. Adjusting of activities to meet knowledge needs
7. Has GEM obtained a clear role in comparison with other similar monitoring programmes addressing current Arctic challenges?
8. Does GEM provide online access to monitoring data (temporal and spatial resolution, timeliness, ease of use)?
9. Is there a need to revise or adjust the current set- up and implementation plans for the GEM programme?

Questions about the future

Within the widest possible realm of future “unknown unknowns”, such as rapid cryo-spheric changes, biogeochemical feedbacks and their impacts on Arctic ecosystems, the evaluation panel is requested to address the following key questions:

1. Does GEM provide the flexibility to adjust to rapidly changing physical conditions in the Arctic (loss of sea ice etc.)?
2. Should GEM include and/or coordinate activities with other ongoing monitoring efforts in and around Greenland to provide a more coherent and trans-disciplinary monitoring programme for all of Greenland?
3. Should GEM be considered as a core activity guiding others, or as a marginal activity closing the gaps between research projects?
4. Should GEM continue its strategy with a clear and long-term focus on two core areas in NE and SW Greenland?
5. Should GEM reduce its core activities and extend its monitoring activities to other carefully selected field sites in Greenland?
6. Should GEM reduce its core activities in general and provide a more flexible, dynamic and adaptable monitoring strategy?
7. How could GEM best contribute to emerging and/or yet un-explored scientific questions?

Methodology

Under the guidance of the GEM Steering Committee, an international panel of experts will be appointed to assist with a thorough and independent evaluation of the GEM programme. The evaluation will take place from January through December 2014.

The panel will address a number of scientific questions, as outlined in the Terms of Reference. In addition, the panel will receive a number of source documents provided by the Steering Committee in order to fulfill their task of evaluating the efficiency and impacts of the programme. These include:

- Danish Strategy for the Arctic 2011-2020
- Greenland Ecosystem Monitoring Strategy 2011-2015
- Greenland Ecosystem Monitoring working programme 2011-2015
- Annual Reports from the GEM programme 2008-2013
- Mapping of ongoing research projects in Greenland
- List of publications authored by GEM scientists and/or building on GEM data/results
- List of international scientific and other networks of relevance to GEM activities

The Evaluation Panel should acknowledge and take into account that the five year working programme has not been concluded at the time of evaluation.

The panel will be invited to three meetings in order to fulfill their task. One of these meetings will take place in Greenland in order to visit key monitoring sites maintained by the GEM programme.

The first meeting will address to what extent the GEM programme is designed and implemented to respond to actual and future “burning questions” related to ongoing and future changes in the Arctic. The second meeting will focus on the methodologies applied and the management structure of the programme. The third meeting will summarize and evaluate the impacts and the efficiency with which the programme is about to meet its current targets. This involves a judgment of the scientific quality and relevance of the output.

The panel will provide a draft evaluation report prior to the third meeting, which will also allow time for a structured dialogue with scientists and managers involved in the GEM activities.

The panel will be given the authority to finalize their evaluation report with the aim of providing a state of the art, independent and forward-looking assessment of the ongoing GEM programme with a view to strengthen the Danish contribution to planned international monitoring activities in the Arctic.

The Steering Committee will publish the final evaluation report.

Appendix 3. Monitoring and Infrastructure

1. The Basis sub-programmes

The five (Bio, Climate, Geo, Glacio, Marine) Basis sub-programmes are integral components of GEM. However, although many of the central questions posed by GEM require integration between the Basis programmes, the Panel found comparatively little evidence of this influencing the conceptual framework, and vice versa. Levels of awareness of the interdisciplinary interactions, and cooperation to integrate the ongoing collection of data, among the field assistants varied between sites. Interestingly, although there was a perception among PIs that this was better at Zackenberg, our observation was that it was better at Kobbefjord, where BioBasis, ClimateBasis, and GeoBasis, were particularly interactive.

Building on the work in Young Sund in 2014, the Panel suggests that the linkages between GeoBasis and MarineBasis in the area of flux measurements could be strengthened.

In general, the Panel found little evidence that the concept of adaptive monitoring (*sensu* Lindemeyer and Likens, 2009)' which was a central element of the 'GEM Strategy and Working Programme 2011-2015', was systematically implemented. The processes adopted by GEM in the annual update of the Basis manuals could not be explained by the technical staff, and only a few PIs seemed to apply it, and then largely on an *ad hoc* basis, even when it was appreciated that it might help focus on fewer important measurements.

The Panel suggests that:

- **Integration across the Basis programmes within and between sites could be strengthened by i) better articulation of the main five GEM research themes, ii) where possible a single PI should lead each Basis programme with responsibility for all sites, iii) greater feedback on what the data is showing, and iv) exchange of technical staff between sites.**
- **The monitoring of the disturbance caused by the research at Zackenberg should be reviewed and extended more comprehensively to Nuuk, as well as initiated at Disko.**
- **A project to contrast the impact of wider human activities across the sites, could both enhance the understanding of the resilience of marine, freshwater and terrestrial ecosystems, and also strengthen the policy relevance of GEM to the Greenland Government.**

BioBasis

BioBasis monitors the dynamics of a variety of organisms (*e.g.*, phyto- and zooplankton, fish, flora, arthropods, birds, mammals) and biological processes, though apparently not microbial ones, in the terrestrial and limnic ecosystems at Zackenberg and Kobbefjord. Freshwater dynamics and water chemistry monitoring is also carried out at both sites. BioBasis aims to document the inter-annual variation in species abundance, phenology and reproduction, as well as changes in biodiversity, all important components in the structure and functioning of the Arctic ecosystems. However, not all groups or species are

represented at both sites. For example, mammals are missing from Kobbefjord, and also Disko, although there is a Strategic Initiative (SI) for work on caribou herbivory in Akia, West Greenland (GEM SI 6 - from 2014). While among birds, only the snow bunting is present at all sites. The potentially important impact of invertebrate herbivores had been studied at Kobbefjord, and noted at Disko, but apparently attracted little attention at Zackenberg.

As noted earlier under the Scientific Questions (Section 4), the Panel suggests that the influence of invertebrate herbivore-plant interactions on ecosystem processes, undoubtedly sporadically important at Disko and Kobbefjord, could be studied at all three sites.

More importantly the Panel was concerned about the lack of routine below-ground monitoring of biological processes, and in particular, microbial processes so important a part of the biogeochemical interactions.

In addition, BioBasis appears to be important in contributing to several new Strategic Initiatives, including GEM SI 4: snow models for both Kobbefjord and Zackenberg; GEM SI 7: Establishment of a vegetation upscaling and predictive model for Zackenberg; GEM SI 11: Upscaling climate change effects to the Greenland scale – joint with GeoBasis, as well as, Analytical Synthesis projects (*e.g.*, GEM A1: Influence of local climate and geophysical conditions on lake ecosystem dynamics at Zackenberg; GEM A5: Snow conditions controlling muskoxen distribution) funded for a year.

However, the Panel was concerned that progress on several of these initiatives had stalled, either because of interdependencies on one, which was delayed, and/or because they involved PhD students or external collaborators over whom the PI had little influence.

ClimateBasis

ClimateBasis monitors the essential climatic parameters at Zackenberg and Kobbefjord. Both sites have a dual-mast, fail-safe system established and maintained by ASIAQ, who have the lead responsibility for the sub-programme. This robust standard seems highly appropriate given the dependency of most of the GEM research and monitoring programme on reliable measures of weather, and their impact on ecosystem processes. There are other un-replicated meteorological measurements undertaken by some of the other sub-programmes, particularly GeoBasis, or specific collaborative projects at both these sites. Although ASIAQ has a single mast system, part of a historical set-up in the village of Qeqertarsuaq, Disko Island, it has no involvement at Arktisk Station, 2 km away. At Arktisk Station, a meteorological station has been established recently as part of GeoBasis/CENPERM activities. The new station supplements the one located for some time on the roof of the Station Manager's house, which, because of the chimney, was liable to overestimate the temperature in winter! ASIAQ was recently invited to install a meteorological station at the new Station Nord but, because of limited funding, the redundant sensor setup was installed on a single mast only.

The Panel encourages GEM to unify the collection of meteorological measurements, through ASIAQ, across all sites thereby ensuring common protocols and standards.

The ClimateBasis sub-programme is also responsible for hydrological measurements at both Kobbefjord and Zackenberg, which measure discharge (water level), temperature, conductivity and turbidity. Again, this work could be extended to include the limited monitoring at Arktisk Station. ClimateBasis has also recently started monitoring the alpine glaciers in Kobbefjord.

The published outputs specific to ClimateBasis, as opposed to other sub-programmes and collaborative projects using meteorological measurements, have been limited to date. However, the new sub-programme leader has drafted a manuscript specifically reviewing *Climate gradients and trends along Greenland's East coast*, the knowledge of which will be essential to the upscaling thematic area.

The Panel encourages ClimateBasis to undertake a similar exercise for the West coast of Greenland, especially using their additional site at Narsaq, South Greenland, to provide possible insights into trends further north.

GeoBasis

GeoBasis monitoring is conducted at Zackenberg, Kobbefjord and Disko. The GeoBasis sub-programme aims to describe and monitor the physical and chemical processes which link climate with landscape development by collecting data which can be used to quantify and model temporal and spatial variations. Measures at Disko, Kobbefjord and Zackenberg, include the 1) Snow and Permafrost Monitoring, 2) Energy Balance and Greenhouse Gas Flux Monitoring, 3) Soil Water Moisture and Chemistry Monitoring, 4) Hydrology and Sediment Transport Monitoring, and 5) Geomorphological Monitoring (not Disko).

The work of GeoBasis interacts with a substantial number of collaborative research projects funded from external sources, including CENPERM, DEFROST, PAGE 21, Glacioburst. These projects have helped the development of many of the GeoBasis protocols at Disko, too. Across all Basis sub-programmes, the Panel regarded the GeoBasis as the most systematic in its measurements and protocols. However, it is astonishing that the GeoBasis programme does not include geophysical approaches (heat flow, seismic methods).

In addition, there are several GEM Strategic Initiatives (SI) which GeoBasis leads, including Establishment of eddy covariance measurements at Kobbefjord (GEM SI 5), as well as Analytical Synthesis Projects (A), such as *Methane emissions: a paradigm shift in the high Arctic?* (GEM A 2). Although there are considerable differences between the three sites, GeoBasis addresses themes of central importance for understanding the physical and chemical dimensions of ecosystem function, as well as the spatial variability between habitats and temporal variability over comparatively short time scales.

The GeoBasis manual provides substantial technical details clearly on how to make measurements and handle the instruments deployed in the field, in order to consistently collect the data. However, the Panel considered the absence of any information about the background history of the area in terms of short pertinent explanations (including maps,

of geology, geomorphology and the fluvio-glacio processes that shaped the landscape, soils, permafrost, vegetation, etc.) a real missed opportunity.

The Panel wishes to encourage the addition of this basic information so that the junior (and/or foreign scientists) who are conducting the measurements in the absence of the PI´s (most of the time) have virtually no knowledge about the context, which is of such importance in making the "right" measurements.

The Panel also made the following observations that the GeoBasis sub-programme might like to consider:

- **The Fens" monitored at the three stations for methane production etc. are quite different in size and hence the gas productions rates may not be so comparable.**
- **Temperature measurements, pore water movements and the geochemical properties of the pore waters will be highly dependent upon composition and geotechnical properties of the soils. The knowledge of the junior scientist of these parameters was fragmentary at best and the extent to which the PIs have considered this was not apparent.**
- **Soils at Disko are mostly volcanic in origin and partly under the influence of homeothermic waters. No knowledge was available on heat flow through the soils and temperature anomalies in the soils. The acquisition of these parameters would be easy and cheap to obtain.**
- **Most of the GEM people we spoke to were not really aware of the fact that they were dealing with very "young" landscapes which had been ice covered not too long ago, and which are still subject to continuous change due to ongoing glacial rebound and small scale climate variations (Little Ice Age).**
- **We have been unable to learn much about the limnic studies going on at the three stations (nature of parameters measured, historic variability stored in lake sediments) and the integration of lake studies into the GeoBasis sub-programme. The lakes at the three sites are of very different size and may not be compared easily, and hence may not be very attractive for study.**

GlacioBasis

GlacioBasis tries to monitor the dynamics, behaviour and response of relatively small (outlet) glaciers (marginal to the Greenland Ice Sheet) in the hinterland of Zackenberg. At Nuuk (Kobbefjord), the ClimateBasis team plans to start monitoring the small mountain glacier above the fjord. Currently, there is no work on the glaciers above Arktisk Station (Qeqertarsuaq) but these are comparatively easily accessed.

Methods employed are ablation stakes, snow radar and repeated GPS surveys along traverses across the glaciers in addition to satellite data, measurements of the melt water

run-off and retention. Upscaling will be attempted through cooperation with the EU-funded 'Ice2Sea' project and other scientific efforts.

There are many international (and national, in terms of the Kingdom of Denmark) observation and monitoring programmes of the Greenland Ice Sheet in its entirety, but it is unique that GEM concentrates on monitoring small marginal glaciers (on the time line of years to decades) which may be much more susceptible to short-term, real time climatic change than the ice sheet itself. None of the glaciers at the three GEM locations are directly connected to the fjords. Even though this type of local/regional monitoring may not be so important in the overall global picture, it is probably addressing some regions of the Greenland ice cover most sensitive to climate change and hence, for this type of monitoring programme, particularly interesting (cf. Olsen *et al.*, 2012)[9]. The review Panel endorses this approach!

GlacioBasis is probably the youngest member of the GEM-Basis programmes with modest beginnings in 2008, but really only coming into effect after 2011. Clearly, it is absolutely indispensable since the glaciers behind the GEM-sites control much of the hydrology of the actual sites in Zackenberg, Kobbefjord as well as at Arktisk Station, with the observations of the glacial lake outburst from A. P. Olsen ice cap west of Zackenberg of particular interest. Any monitoring programme at the GEM sites would probably not be meaningful without GlacioBasis data.

Therefore, the Panel encourages GEM to explore how the GlacioBasis work can be mainstreamed at all three current sites.

Since it began late, the Glaciobasis publication record is still modest, listing a few papers, which obviously have been produced under the framework of other projects, in addition to annual reports and abstracts of presentations at scientific meetings.

MarineBasis

The Greenland fjords are conduits for ocean waters far inland, where they interact with the freshwater drainage from the adjacent continent (terrestrial) and glaciers (icebergs, meltwater from small glaciers and the Greenland ice sheet). It is here where the 'continent with its high seasonality' competes with the 'ocean with comparatively low seasonality' resulting in terrestrial and marine ecosystems with very special properties. At present, the land-ocean transects do not really extend into either the East Greenland Current (off Zackenberg/Daneborg) or the West Greenland Current (off Nuuk and Qeqertarsuaq) and, hence, the current MarineBasis sub-programme can tell only part of the story. However, the GINR which is responsible for MarineBasis, has been conducting multi-year surveys of the marine living resources in the Greenland waters (mostly off West Greenland) including some oceanography. Many of the data are pertinent to the GEM programme and can probably be collected from the archives of GINR.

[9] Olsen, M. S. (& 17 co-authors) 2012: The Changing Arctic Cryosphere and Likely Consequences: An Overview.- Ambio 40: 111-118.

The GEM MarineBasis sub-programme monitors the 'marine environments and ecosystem function' and tries to establish correlations with datasets (*i.e.*, gas fluxes), which have been collected at the nearby terrestrial stations. Elements of MarineBasis are conducted both at Zackenberg/Daneborg and Kobbefjord/Nuuk, as well as to a limited degree at Arktisk Station/Qeqertarsuaq, though the Panel believes there is lots of scope for a tighter cooperation. MarineBasis tries to 'monitor the physical, chemical and biological parameters conditions and processes in the marine environment and their variability for possible changes related to climatic forcing' (cited from the GEM Strategy 2011-2015 document). The working conditions, at the three stations considered, are very different largely because of logistic reasons and because the relatively low priority given to MarineBasis.

The most advanced part of MarineBasis is run out of Nuuk with its comprehensive study of the Godthaabsfjord and Kobbefjord systems, which are either repeatedly surveyed at defined stations covering the entire year (Godthaabsfjord), or at individual hydrologic stations mounted at fixed points, served from the beach and deployed throughout the year (Kobbefjord). In this area, the sub-programme has easy access to its areas of investigations and it can draw on the resources of the GINR with ships, laboratories and specialised scientists present throughout the year. MarineBasis studies at Arktisk Station are modest but it could be highly interesting to monitor a sea bight, which is dominated by icebergs throughout the entire year. The usefulness of Daneborg data (with its components from physical and chemical oceanography as well as the biological census (plankton9 data, though highly important as the only example from an East Greenland fjord system) will be limited because the station is closed during winter (as is Zackenberg).

The MarineBasis sub-programme calls for monitoring of the chemical parameters such as surface carbon dioxide and marine nutrients at a standard station, both at Zackenberg and Nuuk, which should lead to the deployment of automated buoy systems. This would not be so easy with the measurements taken at transects across and along the fjord systems. Extensive monitoring of pelagic species is carried out both in the Zackenberg as well in the Nuuk areas. The effects of the biological pump (vertical sinking particles of pelagic origin) and its effect on benthic dynamics are related to the occurrence of snow and ice cover. However, the monitoring sub-programmes require several decades to be able to successfully relate them to climate change.

The Panel also made the following observations that the MarineBasis sub-programme might like to consider:

- **Given the easy access to power at Daneborg/Zackenberg, Kobbefjord and Arktisk Station, it is surprising that there have not been more attempts to use automated monitoring systems like Ferry-Boxes (and others) which are cheap, widely deployed, *e.g.* in the North Sea, and which can also be installed on ships (like ferries such as the one running between Ilulissat and Qeqertarsuaq), as well as in other places.**

- **There appears to have been very few attempts to integrate marine data into terrestrial datasets or *vice versa* (For example: Gas flux measurements in the Young Sund (Daneborg/Zackenberg) area, or at Kobbefjord.**

2. The research platforms

Central to the GEM strategy is the contrast between sites within Greenland. For example, Zackenberg Basic, Northeast Greenland (74°28'N, 20°34'W), established in 1995, is a High Arctic site, relatively undisturbed by human activities. While Nuuk Basic, at Kobbefjord, Southwest Greenland (64°10'N, 51°31'W), established in 2007, is in the Low Arctic. Close to Nuuk, Greenland's largest town, Kobbefjord is exposed to a relatively greater human impact. Other elements of ecosystem research, particularly in the marine environment, have been undertaken since the 1980's at the Greenland Institute of Natural Resources (GINR), Nuuk, and its predecessors.

Recently, the GEM has been extended to incorporate research at Arktisk Station, on Qeqertarsuaq/Disko Island (69°15'N, 53°34'W), with a DiskoBasis monitoring manual developed in 2013/14. The DiskoBasis sub-programme links particularly strongly to monitoring at Zackenberg and Nuuk, through the CENPERM project, measuring the fluxes of carbon dioxide (CO_2) and methane (CH_4), as well as work using the International Tundra Experiment (ITEX) protocols. Ongoing ITEX monitoring of changes in plant species composition, undertaken just west of the town Qeqertarsuaq, dates back to 1989. ITEX is one of several ecosystem studies that links GEM to research programmes across circumpolar regions. Major syntheses of environmental changes in the Arctic, including ACIA (2005), AMAP and Arctic Biodiversity Assessment (2013), have drawn heavily upon data from all sites, but particularly Zackenberg, resulting in them having a high international profile.

The Panel is reluctant to recommend a further expansion of the number of monitoring sites because of the current limited resources and a concern that the efforts at the existing stations will be diluted at the expense of quality and depth of the ongoing research, as well as the further modernisation/improvement of existing infrastructure. A particular worry is 1) the finite GEM funding which, at present, comes mainly from two Danish ministries and a couple of private charitable trusts; and 2) the limited numbers of researchers and technicians.

Nonetheless, the Panel does support the necessary investment in the consolidation of all the Basis sub-programmes at Arktisk Station, where the logistics are in place and the programme largely requires more field assistants, and a review of the options for a GEM site in South Greenland (see RECOMMENDATION 3).

The Panel suggests the GEM Steering Committee should think about ways to attract young motivated Greenlanders into the sub-programmes (as has been done at ASIAQ) because most of the monitoring activities are conducted in Greenland.

Zackenberg (incl. Daneborg)

Zackenberg is located at the western part of Young Sund in Northeast Greenland, with very limited contributions to MarineBasis – some hydrology of Zackenberg River and some monitoring of coastal changes. The MarineBasis' main effort at Zackenberg is conducted from Daneborg, located 30 km east of the main station. Although Daneborg is much closer to the effects of the East Greenland Current, the ice cover often constrains

the monitoring work until mid-July. Also, these conditions compound the logistical problems of maintaining Zackenberg. Although ships re-provision Daneborg in August, everything is airlifted, at significant costs, into Zackenberg.

Zackenberg needs continued investment in infrastructure, particularly better labs and workspaces (offices), as well as internet access and winterised accommodation, if it is to operate year round. Monitoring the impact of the research and its infrastructure on the ecosystem should be enhanced.

GEM-efforts at Daneborg are logistically attached to a Sirius Sledge Patrol Station. Cooperation with Sirius, according to hearsay at Zackenberg, is not always free of friction. Limited lab facilities attached to storage shacks and some boats – separate from any Sirius installations. At GEM-Daneborg, we were met by an energetic and enthusiastic station manager; some active scientists analysing marine faunal and floral micro-organisms and CO_2 measurements. The marine investigations seemed to be poorly linked with what should be parallel work at Zackenberg (gas fluxes). The presentation at Daneborg was based mainly on data up to 2007 (perhaps another example for the fact that the GEM data bank problem remains unresolved, but we received a substantial updated publication list. Station personnel have access to various smaller boats, a prerequisite for station work in the fjord and for serving moored instruments. No attempts seem to exist to automate some of the measurements (Ferry-Boxes) which should be easy because of the availability of power all year round.

Kobbefjord, Nuuk

NuukBasic is modelled on the longer-term experience at Zackenberg. This Low Arctic site was established in 2007, as a contrast the High Arctic site at Zackenberg, and incorporated into the new Greenland Ecosystem Monitoring programme the following year. All but the GlacioBasis sub-programmes are active in Kobbefjord. However, ClimateBasis has recently instigated some monitoring of the mountain glaciers that feed the lakes and streams. The ClimateBasis, BioBasis and GeoBasis sub-programmes appear particularly well integrated with frequent interactions between staff in the both the field and office.

Since the site is less than a 30 minute boat ride from the town of Nuuk it tends to be manned on a daily basis by staff from GINR and ASIAQ. However, there is overnight accommodation for four people close to the shore at the head of the fjord.

Arktisk Station, Qeqertarsuaq/Disko Island

Arktisk Station is well established, with a long history and a cosy working atmosphere built up over more than 100 years. Compared to Zackenberg, it has a better infrastructure but is also lacking sufficient laboratory space. However, it is located below some prominent volcanic cliffs and many of the soils around the station and in the area with scientific installations are of volcanic origin. The soil heat balance is perturbed in many areas due to homeothermal (constant and above-freezing) springs, thus quite anomalous and, therefore, complicating the comparisons with other sites. Nonetheless, the Panel thought there was an interesting potential in conducting a regional, but small scale “heat flow” survey.

The mission of the Arktisk Station and its unique position among the Greenland research stations remained a bit fuzzy. In particular, the melange of the station's research targets, the impact of CENPERM and the level of contributions to GEM result in a portfolio and rationale, which was very difficult to unravel in the short time available to the Panel. Since Arktisk Station can be used during all seasons it should have huge potential, but would need a change of 'ethos' to give the station a firm working rhythm and purpose. It is not clear how the station's Steering Committee (mainly stakeholders from the University of Copenhagen) prioritises/selects projects (see annual reports). The publica-tion record (based on the 2012 report) seems to be either meagre or incomplete.

The potential role of the station has to be viewed as:

1) attracting a large number of foreign and Danish scientists to a remote, but spectacular place;

2) providing accommodation, logistics, equipment, local knowledge and gear (incl. a functional research vessel) to people who come poorly equipped;

3) offering limited and not very sophisticated lab facilities (incl. microscopes, wet and dry labs, electronic facilities – permanent internet;

4) access to experimental areas in the field;

5) having an unusual collection of older and more recent relevant publications.

Arktisk Station invites not only to short field campaigns ('blitz'), but also extended visits for researchers who bring enough money with their projects. The station leader revealed its importance for the village with good relations to the local community, where it is a major 'money bringer' to the town of Qeqertarsuaq and also maintains a dialogue with the local people about the role of science in managing environmental change. Is there any impact beyond this town?

When visiting the research installations in the field, we became aware of the fact that there is some human impact visible in the landscape. Power generation (applies to all other stations), waste water (applies to all other stations), and disposal of waste: The station should be developed into an exemplary 'green station'.

The GEM Climate Station seems to run well, though it does not have the backup of a duplicate mast and measurement system as installed and maintained by ASIAQ at Zackenberg and Kobbefjord. At Qeqertarsuaq, ASIAQ has a single mast system nearby. The duplicated weather / climate station on top of the station leader's house seems to be affected by its position on top of the chimney!

Before visiting the experimental installations in the field, scientists offered general presentations on GEM monitoring, with emphasis on ClimateBasis and GeoBasis, and CENPERM. Also, there was a summary of the current and historical marine work, but very little, if any was linked to MarineBasis. The DiskoBasis manual is still being written, but for GeoBasis and ClimateBasis measurements these seemed broadly consistent with those undertaken at Zackenberg and Kobbefjord.

In the field, the CENPERM installations in Blæsedalen were visited. These installations are of high standard, served by highly motivated young scientists. However, the excursion passed the hydrology monitoring point close to the bridge over the river Røde Elv, which was not very convincing.

At the moment, DiskoBasis activities can be compared with Zackenberg and Kobbefjord only in a limited number of areas, particularly GeoBasis. If it should become a major GEM site, it needs major investment and the installation of all the GEM Basis sub-programmes (this situation has recently been ameliorated by the additional grants: Disko Monitoring (1501/1097-0096) and Dancea (1097-0076). In particular, for MarineBasis the sea in front of the station is especially interesting because of the almost permanent and dramatic impact of icebergs coming from the Ilulissat glacier.

The Panel concluded that the Arktisk Station activities (both organisational structure, organisation of station life, mode of the allocation of accommodation, lab space and ship time), quality and possible extension of the lab space, etc., all need to be revisited. The entire station and its mode of operation should become subject of a major review of all aspects of performance, with no stakeholders involved in the group of referees. If upgraded to a major GEM site, the scientific programme of the station (incl. CENPERM) has to be fully adapted to GEM standards.

Appendix 4. SWOT analyses

During the workshop on September 8, the non-Panel participants took part in an analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT). The engagement across the PIs and wider stakeholders produced the following summary (Figure 2). Please note that some factors like 'Funding' and the 'Site-based' focus were viewed as falling in more than one category. For example, the diversity of funding can be viewed as a strength and, equally as a weakness, especially as much of it is agreed on an annual basis.

Figure 2. The collective workshop SWOT Analysis.

STRENGTHS	WEAKNESSES
Site-based • Long-term monitoring in collaboration with research • Multi-disciplinarity • Feedback from R&D on monitoring • Innovative monitoring (some of the 3500 parameters) • Agreed strategy for monitoring • Length of time-series FUNDING	Site-based • Multiple funding sources for research activities at field sites • Place-based view (lack of across-site integration) • "Part-time" PIs • 3500 parameters – a lot of technical details • Lack of communication tools at the sites prevent real-time data transfer FUNDING
OPPORTUNITIES FUNDING	**THREATS**
• Tune the new site selection • Remote sensing • Explorative studies/modelling • Closer link between monitoring and research • Strengthened scientific leadership • "Obsession" with GEM • Joined-up strategic planning • Better use of existing data (e.g. for site selection) • Use PROMICE tools/standards/protocols	• Lack of communication and transparency • Potential loss of funding for Greenland Climate Centre

Prior to the workshop, the Panel had conducted its own SWOT analysis, which was revealed only after the participants at the workshop had conducted the collective exercise

Figure 3. The Panel's SWOT Analysis prior to the workshop.

STRENGTHS	WEAKNESSES
OK discipline/interdisciplinary strategy. Diverse funding base - academic/charities/ govt. Enthusiastic field staff: good gender balance. Academic capital in Denmark /international . Well established and respected site(s).	Vague work plan/little accountability. Mis-match between field ops. & strategy. Culture of logistics led research. Comparatively little funding. Arguments justifying choice of sites. Despite aspiration limited interdisciplinarity. Concern about outcomes, despite impressive output of papers
OPPORTUNITIES	**THREATS**
Develop predictive holistic process models 50 year commitment for climate change Greenlandic capacity building of Ecosys. Sci. Widen network of sites relevant local policy and internationally. Set example in energy energy/waste manage Raise international profile of Kingdom's work in both academic and political circles	Insufficient long-term (decadal) funding. Lack of an accessible working database. Representativeness of sites. Lack of integration across all dimensions.

Appendix 5. GEM recommendations

RECOMMENDATION 1: The Panel views the GEM activities as producing much excellent science, published in leading international journals, and, as far as we can judge, comparatively good 'value-for-money'. In order that GEM can deliver its ambitious threefold mission, the Panel recommends it should be resourced for many decades to come. However, thought should be given to the GEM organisational structure, science focus and how the Work Plan maps onto the Strategic Plan to enable the programme to fully deliver its current objectives. Also, thought should be given to enhancing GEM's flexibility to meet future science policy needs.

RECOMMENDATION 2: The Panel recommends that GEM builds upon the upscaling workshop held in November 2013 and prioritises efforts in ecosystem modelling, in order to both achieve a meaningful regional synthesis, and contribute more fully to the Kingdom's policy objective.

RECOMMENDATION 3: The Panel recommends that, given the Government of Greenland / Kingdom of Denmark's expectations that the current monitoring and research do underpin sustainable development, GEM should explore the opportunity of establishing a GEM site in South Greenland, where climate warming is permitting agriculture to diversify its crops, increase local production and expand northwards. Without this information predictive models of the impact of ecosystem change farther north are likely to be of less policy relevance.

RECOMMENDATION 4: The Panel recommends, that GEM reviews the opportunity to increase its policy relevance by monitoring how climate change, and its interaction with other drivers, impacts ecosystem functioning and, thereby, influences the resilience of natural capital assets, the delivery of ecosystem services and, through wider collaboration, the consequences for human well-being.

RECOMMENDATION 5: In order to maximize the impact of the planned synthesis in 2015/2016 of the GEM research, the Panel recommends that the synthesis focus primarily on cutting-edge, interdisciplinary research to address the mechanisms driving change in the structure and function of Arctic ecosystems, rather than what was done in each Basis sub-programme, or at a particular site. To do this will also require a major effort in synthesis of the existing data, subject to the database being complete, and rectifying the generally slow progress on upscaling models.

RECOMMENDATION 6: The Panel recommends a deliberate effort to better integrate collaborative projects into the long-term observational monitoring, so that the new knowledge becomes a direct influence on planning of the continued long-term measurements. The Panel suggests that this could be achieved by a review of the current 13 questions and a more systematic implementation of the adaptive monitoring concept. This approach may involve the active encouragement of projects at Kobbefjord, and elsewhere.

RECOMMENDATION 7: The Panel recommends that there needs to be more strategic thoughts about a SMART set of the over-arching questions. The refinement of the central questions needs to be an on-going process and integral to the implementation of the GEM strategy through the concept of adaptive monitoring.

RECOMMENDATION 8: The Panel recommends that the adaptive monitoring approach is implemented more systematically and involves, where possible, the field staff responsible for the on-going data collection, several of whom told us they didn't feel connected to the outcomes.

RECOMMENDATION 9: The Panel recommends that GEM explores the scope for more specific experiments, as well as expending more effort on process modelling, in order to investigate the likelihood of thresholds in Arctic ecosystems and exploring their potential consequences.

RECOMMENDATION 10: The Panel recommends that GEM develops a collaborative (institutional) modelling and prediction 'group' where there is continuous interaction of fundamental thinking and curiosity to interrogate the incoming data, enhancing understanding and refining approaches to both the ongoing monitoring and research.

RECOMMENDATION 11: The Panel recommends that, as soon as possible, GEM establishes an independent (of the ministries and other stakeholders), international advisory board to provide the high-level overview and support to both the Science Leader and the stakeholders.

RECOMMENDATION 12: The Panel recommends that there is an options review and feasibility assessment of green energy generation and utilisation efficiency, as well as dealing with all forms of human waste management, at all sites.

RECOMMENDATION 13: The Panel recommends the development of a 'corporate' GEM-brand, facilitated through a single GEM annual report and a unified website. Both the GEM annual report and the website should be structured by the five themes of GEM, disaggregated to the level of the re-evaluated set of the 13 questions. Also, the monitoring and the relevant science projects should be integrated accordingly under the relevant theme/question.

RECOMMENDATION 14: The Panel recommends a much stronger explicit link between the coastal marine work and the terrestrial/limnic research, through a stronger strand/theme of integrated conceptual thinking, observation and process models.

RECOMMENDATION 15: The Panel recommends a wider review of the potential institutional structures to meet the Kingdom of Denmark's future needs for high-profile excellent and relevant research in the Arctic, recognising the considerable financial and political implications. Although it is not within the remit of the Panel's mandate to define specific proposals, one of several possible models is a 'centre' with two 'hubs'. One 'hub' would involve growing the capacity to implement the integrated monitoring, research and logistics from a base in Greenland. The other 'hub' involves creating a dedicated, process modelling group which can draw on the expertise of Danish research institutes and universities in Denmark and more widely. This second 'hub' would co-locate the relevant researchers in a single site. The two hubs can be linked by the two original GEM concepts: i) a holistic study of the Greenland ecosystem, but expanded to include other drivers in addition to climate change, and ii) the principles of adaptive monitoring, which integrates both science questions, data collection, analytical approaches (incl. modelling), and interpretation, in an iterative way, as mentioned previously.

Appendix 6. Background, history and organisation of the GEM programme

Systematic observations have been made in Greenland since the beginning of the 18th century. Whaling ships and colonial outposts took care of the readings in the early days. Over the years, scientific observations have grown exponentially. Currently, several thousand parameters are being observed on a routine basis in and around Greenland every day. The current Greenland Ecosystem Monitoring programme is focusing on Greenland with surrounding air and sea space. The vision of the programme is to contribute substantially to the basic scientific understanding of Arctic ecosystems and their responses to climatic changes and variability as well as the potential local, regional and global implications of changes in Arctic ecosystems.

The mission of GEM is:

- To contribute to a coherent and scientifically sound description of the state of the environment, incl. its biodiversity in Greenland and the Arctic in relation to climatic changes with focus on ecosystem responses and on global impacts related to the feedback processes.
- 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 administration.
- To provide a platform for cutting-edge inter-disciplinary research on the structure and function of Arctic ecosystem.

The GEM programme is based on a systems approach and more than 3500 parameters are monitored at the two main stations at Zackenberg (www.zackenberg.dk) and Kobbefjord (www.nuuk-basic.dk). These stations were established in 1995 and 2007, respectively.

The programmes at the two sites are subdivided into the following five components: ClimateBasis (monitoring of primary climatological and hydrological data); GlacioBasis (local glacier extent, mass balance and contribution to water balance); GeoBasis (landscape processes, terrestrial biogeochemistry, climatic feedbacks form changes in snow cover, energy balance and carbon cycling); BioBasis (terrestrial ecology and limnic ecosystems); MarinBasis (coastal water ecology, incl. carbon cycling, hydrography).

Annual basic operating costs are approximately 4 mill. USD. Substantial contributions to the infrastructure of the stations have been received from private funds over the years.

During the past few years, GEM efforts have been complemented by similar, but less comprehensive, long-term monitoring efforts at Arktisk Station (arktiskstation.ku.dk/english), established in 1906 on Qeqertarsuaq/Disko Island in West Greenland (terrestrial climate and biogeochemistry measurements) and at the Sermilik Station in Southeast Greenland (geo.ku.dk/english/research/field_station), established in 1959 (glacier change, hydrology and sediment transport).

A new monitoring station (www.au.dk/villumresearchstation) is about to be built at Station Nord (en.wikipedia.org/wiki/Nord,_Greenland), established in 1953, in the ultimate Northeast corner of Greenland (satellite and drone-based techniques). Several other research and

monitoring stations have been operating in Greenland over the years, but have not been listed here.

The monitoring programme is implemented through a cooperation between Danish and Greenlandic scientific institutions and universities, and the operation is funded primarily by DANCEA (Danish Cooperation for Environment in the Arctic) administered by the Danish Energy Agency and the Danish Environmental Protection Agency. The Danish Ministry of Science and Higher Education and the Greenland Government also contribute to the operations. The monitoring and research activities are part of a wider international network of similar programmes funded by various national and multi-lateral sources.

A GEM Steering Committee leads the programme. Sub-programmes of GEM are coordinated by a coordination forum (Coordination Committee) consisting of project managers of the sub-programmes. The Coordination Committee advises the Steering Committee on scientific and administrative issues. The GEM secretariat and the scientific leader of the GEM programme provide support to the Steering Committee and the Coordination Committee and manage the overall programme on a day-to-day basis.

Activities and timeline

		2013							2014						
Activities	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Aug	Sep	Okt	Nov	Dec
Draft terms to GEM SC															
Identification of evaluators															
Revised terms approved by sc															
Selection of evaluators															
Telelphone conference with evaluators															
Written material to evaluators															
1. meeting of evaluators (Cph) and meetings with key scientist															
preliminary draft evaluation report															
2. meeting of evaluators (GL) and visits of GEM stations															
Draft evaluation report															
3. meeting of evaluators and meetings with key scientists															
Final evaluation report															

Budget

The cost of the evaluation will be covered by the Danish Energy Agency and the Danish Environmental Protection Agency, incl. expenses of travel and *per diem*.

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