

Greenland Ecosystem Monitoring

Strategy and Working Programme 2011-15



AARHUS
UNIVERSITY

DCE - DANISH CENTRE FOR ENVIRONMENT AND ENERGY



GEM: Greenland Ecosystem Monitoring (GEM) is an integrated monitoring and long-term research programme on ecosystems and climate change effects and feedbacks in the Arctic. Since 1994 the programme has established a coherent and integrated understanding of the functioning of ecosystems in a highly variable climate, which is based upon a comprehensive, long-term inter-disciplinary data collection carried out by Danish and Greenlandic monitoring and research institutions, primarily at the two main field stations: Nuuk in low arctic West Greenland and Zackenberg in high arctic Northeast Greenland.

The vision of GEM: Focusing on Greenland, GEM will contribute substantially to the basic scientific understanding of arctic ecosystems and their responses to climatic changes and variability as well as the potential local, regional and global implications of changes in arctic ecosystems. GEM will maintain and strengthen its position as an internationally leading integrated long-term monitoring and research programme.

Scientific coordination: Scientific coordination between GEM partners and external partners is carried out by the GEM Coordination Group. Overall priority setting in the GEM programme is resolved in the GEM Steering Committee.

GEM Coordination Group:

- Aarhus University, Denmark
- Asiaq – Greenland Survey, Greenland
- Central Institute for Meteorology and Geodynamics, Austria
- Greenland Institute of Natural Resources, Greenland
- National Geological Survey of Denmark and Greenland, Denmark
- University of Copenhagen, Denmark
- University of Southern Denmark, Denmark

GEM Steering Committee:

- Energy Agency/Ministry of Climate, Energy and Buildings, Denmark
- Agency for Science, Technology and Innovation/Ministry of Science, Innovation and Higher Education, Denmark
- Environmental Protection Agency/Ministry of the Environment, Denmark
- Ministry of Domestic Affairs, Nature and Environment/Government of Greenland, Greenland
- Aarhus University, Denmark
- Asiaq – Greenland Survey, Greenland
- Greenland Institute of Natural Resources, Greenland
- National Geological Survey of Denmark and Greenland, Denmark
- University of Copenhagen, Denmark

Zackenberg (GEM) secretariat: Scientific leader and executive secretary: Morten Rasch
Coordinator and academic secretary: Lillian Magelund Jensen

Zackenberg secretariat
c/o Department of Bioscience
Aarhus University
Box 358
Frederiksborgvej 399
DK-4000 Roskilde
Denmark

Phone: +45 87 15 87 34
E-mail: zackenberg@dmu.dk

More information about GEM can be found on the websites:

- www.g-e-m.dk
- www.zackenberg.dk
- www.nuuk-basic.dk

GREENLAND ECOSYSTEM MONITORING STRATEGY AND WORKING PROGRAMME 2011-15



AARHUS
UNIVERSITY

DCE - DANISH CENTRE FOR ENVIRONMENT AND ENERGY

GEM



Greenland Ecosystem Monitoring

Data sheet

- Title: Greenland Ecosystem Monitoring Strategy and Working Programme 2011-15
- Editors: Morten Rasch¹, Niels Martin Schmidt¹ and Thomas Juul-Pedersen²
- Contributors: Birger Ulf Hansen³, Kirsten Christoffersen⁴, Kisser Thorsøe⁵, Mads C. Forchhammer¹, Mark Andrew Pernosky⁵, Michele Citterio⁶, Mikael Kristian Sejr¹, Mikkel Peter Tamstorf¹, Morten Rasch¹, Niels Martin Schmidt¹, Peter Aastrup¹ and Thomas Juul-Pedersen²
- ¹Department of Bioscience, Aarhus University
²Greenland Climate Research Centre c/o Greenland Institute of Natural Resources
³Department of Geography and Geology, University of Copenhagen
⁴Department of Biology, University of Copenhagen
⁵Asiaq – Greenland Survey
⁶Geological Survey of Denmark and Greenland (GEUS)
- Publisher: Aarhus University, DCE – Danish Centre for Environment and Energy
URL: <http://dce.au.dk>
- Year of publication: 2012
- Please cite as: Rasch, M., Schmidt, N.M. and Juul-Pedersen, T. (eds.) (2012). Greenland Ecosystem Monitoring Strategy and Working Programme 2011-15. DCE – Danish Centre for Environment and Energy, Aarhus University. 82 pp.
- Reproduction permitted provided the source is explicitly acknowledged
- Layout and drawings: Tinna Christensen, Department of Bioscience, Aarhus University
Front cover photos: Lars Holst Hansen (landscape), Henning Thing (field work) and Morten Rasch (water samples)
Back cover photos: Thomas Juul-Pedersen (walrus), Henning Thing (*papaver*) and Niels Martin Schmidt (musk ox)
- ISBN: 978-87-92825-33-9
ISSN: 1904-0407
- Paper quality: Paper 80 g Cyclus offset
Printed by: Rosendahl – Schultz Grafisk
- Number of pages: 82
Circulation: 200
- Internet version: The report is available in electronic format (pdf) on www.g-e-m.dk, www.zackenbergs.dk, www.nuuk-basic.dk and on www.dce.au.dk
- Supplementary notes: The publication may be ordered free-of-charge from:
The Greenland Ecosystem Monitoring secretariat
c/o Department of Bioscience
Aarhus University
P.O. Box 358
Frederiksborgvej 399
DK-4000 Roskilde
Denmark
- E-mail: zackenbergs@dmu.dk
Phone: +45 871 58 734

Content

Executive summary	5
1 Introduction	7
1.1 Background	8
1.2 Process	9
1.3 Structure of this report	11
2 Greenland Ecosystem Monitoring Strategy 2011-15	12
2.1 Rationale of GEM	15
2.2 Scientific questions to be addressed during 2011-15	18
2.3 Adaptive monitoring	18
2.4 Research cooperation	20
3 Scientific questions to be addressed during 2011-15	22
3.1 Greenhouse gas exchange with the atmosphere and nutrients balance	23
3.2 Ecosystem function and resilience	24
3.3 Water balance, including glaciology and water circulation in the marine environment	26
3.4 Snow and ice, including effects on phenology, energy and carbon balance	29
3.5 Up-scaling, modelling and prediction	30
4 Milestones, deliverables and timetables	36
4.1 Milestones	37
4.2 Deliverables	38
4.3 Timetables	40
5 Basis programmes after implementation of strategy	42
5.1 The ClimateBasis programme	43
5.2 The GeoBasis programme	43
5.3 The BioBasis programme	44
5.4 The MarineBasis programme	45
5.5 The GlacioBasis programme	47
6 Budgets	48
6.1 Budget prior to 2011	49
6.2 Budget for 2011	49
6.3 Budgets for 2012-15	51
6.4 Expected external financing	52
7 References	54
Annex A	56
Annex B	62



Photo: Torbern Tagesson.

Executive summary

This report describes how the Greenland Ecosystem Monitoring Programme (GEM) will implement the Greenland Ecosystem Monitoring Strategy, 2011-15 during the period 2012-15. The report has been produced by the GEM Coordination Group on request from the GEM Steering Committee. The working programme was endorsed by the GEM Steering Committee on 25 November 2011.

Chapter 2 contains the Greenland Ecosystem Monitoring Strategy, 2011-15. The vision of GEM is:

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

GEM will maintain and strengthen its position as an internationally leading integrated long-term monitoring and research program.

The mission of GEM is:

1. 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 feedbacks processes.
2. 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.
3. To provide a platform for cutting-edge inter-disciplinary research on the structure and function of arctic ecosystem.

For 2011-15, GEM has defined the following objectives:

1. GEM will strengthen the scientific understanding of arctic ecosystem function and structure in relation to climate variability and change by (i) introducing an analytical component to the program, (ii) elaborating the concept of adaptive monitoring currently built into the program, (iii) focusing data collection to optimally address central scientific questions/objectives of local, regional and global relevance,
2. GEM will facilitate new externally funded projects that improve the program's capacity for up-scaling and prediction on Greenlandic ecosystems (for instance, by inclusion of a network of less extensively investigated sites in Greenland supplementing the existing sites at Zackenberg and Nuuk, and by strengthened cooperation with marine and oceanographic research efforts).
3. In cooperation with its international partners, GEM will extend its analytical approach to enhance the process-related understanding of Greenlandic/arctic ecosystems and the development of methods and equipment necessary to procure the process-related understanding for other arctic ecosystems.
4. GEM will actively participate in the processes aimed at establishing a better coordinated and integrated data collection, storage and analysis on climate change effects across the Arctic. This will be done by cooperation with and participating in relevant international activities, and by taking initiative to establish new international networks and research programmes focusing on the effects of climate changes on arctic ecosystems.
5. GEM will maintain – and develop further – its role as a leading international expertise on methods/techniques/instrumentation used for ecosystem monitoring and data management in the Arctic. This will be achieved by proactively attracting relevant international research projects on development of field

equipment, methods and data management systems for ecosystem monitoring and research across the Arctic, and by testing the relevant instrumentation and data management systems at the GEM sites.

To fulfil the strategy, GEM has defined the following 13 questions to be addressed during 2011-15:

1. How does climate change and variability control the annual and seasonal exchange of greenhouse gasses (H_2O , CO_2 , CH_4 and N_2O) between arctic terrestrial ecosystems and the atmosphere?
2. How does climate change and variability affect the CO_2 exchange between arctic marine ecosystems and the atmosphere?
3. How does global change, including stronger climatic variability and change, affect the species composition and function of arctic ecosystems?
4. Are there important thresholds in arctic ecosystems that might lead to sudden and significant shifts of their overall biodiversity and function?
5. How does climate variability and change affect the water balance (including availability of water in terrestrial ecosystems, glacier mass balance and extreme run-off events) of arctic ecosystem?
6. 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?
7. How does river water discharge affect the water circulation in arctic fjord systems?
8. How does 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?
9. How does the energy balance of arctic ecosystems (marine, terrestrial and limnic) change with climate change and variability?
10. How does 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?
11. To what extent can results from GEM be used for up-scaling and prediction to address the questions above on a regional scale covering Greenland and the sea around Greenland (now and for the future) and what are the constraints for such up-scaling and prediction efforts?
12. What models shall be developed in to address the questions above on a regional scale (Greenland and surrounding sea)?
13. How can current monitoring and long-term research efforts in GEM most effectively be adjusted to meet current and future scientific needs and policy-related demands?

Chapter 3 gives an overview of how GEM will address these questions during 2011-15. Some adjustments of the programme have been necessary reallocate the means necessary to address the questions above. For that purpose, the GEM Working Group has defined 18 so-called Strategic Projects and ten so called Analytical projects to be accomplished during 2011-15. A description of each of these projects is given in Annex B.

GEM cooperates and/or is formally involved in a number of projects and initiatives. Among these, the larger projects have a total budget of approximately 500 mill. DKK du-ring 2011-15. These projects will in different ways all contribute to the fulfilment of the Greenland Ecosystem Monitoring Strategy 2011-15. Besides, GEM will also benefit from and cooperate with a number of existing or planned projects that will contribute to the fulfilment of the strategy. A comprehensive list of 93 currently identified projects is given in Annex A.

1 Introduction

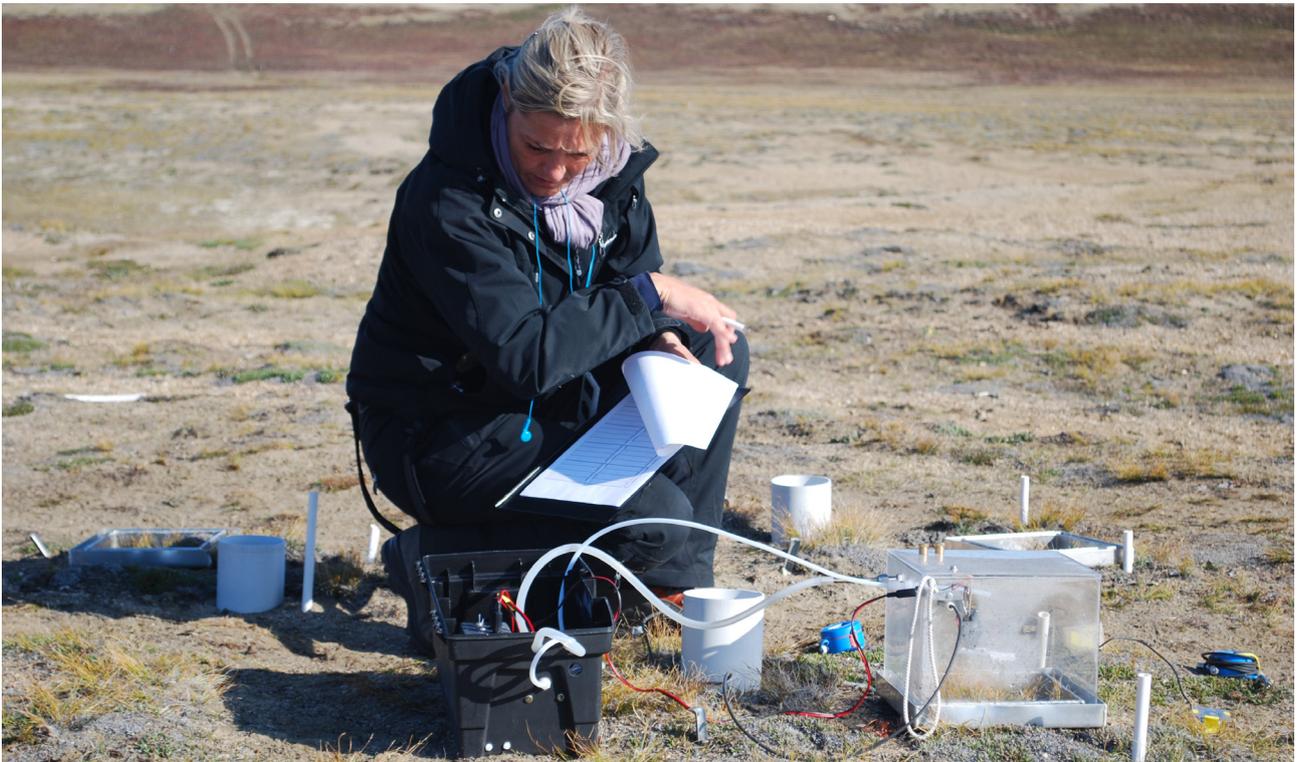


Photo: Morten Rasch.

This working programme describes in detail how the Greenland Ecosystem Monitoring Programme will implement the Greenland Ecosystem Monitoring Strategy, 2011-15 (see Chapter 2) during the period 2012-15. The working programme has been produced by the Greenland Ecosystem Coordination Group on request from the Greenland Ecosystem Monitoring Steering Committee. The working programme was endorsed by the Greenland Ecosystem Monitoring Steering Committee 25 November 2011.

1.1 Background

The current monitoring by Greenland Ecosystem Monitoring (i.e. until 2010) is reflected in the manuals for the different monitoring sub-programmes at respectively Zackenberg (ClimateBasis, GeoBasis, BioBasis, MarineBasis and GlacioBasis) and Nuuk (ClimateBasis, GeoBasis, BioBasis and MarineBasis) which are available on the homepages for Zackenberg Basic (i.e. www.zackenberg.dk) and Nuuk Basic (i.e. www.nuuk-basic.dk).

A Greenland Ecosystem Monitoring (GEM) Strategy for the period 2011-15 (see Chapter 2) was endorsed by the GEM Steering Committee in early 2011. This new strategy implies adjustments of the investigations and analyses currently carried out within GEM, especially focusing on addressing the following thirteen scientific questions:

1. How does climate change and variability control the annual and seasonal exchange of greenhouse gasses (H₂O, CO₂, CH₄ and N₂O) between arctic terrestrial ecosystems and the atmosphere?
2. How does climate change and variability affect the CO₂ exchange between arctic marine ecosystems and the atmosphere?
3. How does global change, including stronger climatic variability and change, affect the species composition and function of arctic ecosystems?
4. Are there important thresholds in arctic ecosystems that might lead to sudden and significant shifts of their overall biodiversity and function?
5. How does climate variability and change affect the water balance (including availability of water in terrestrial ecosystems, glacier mass balance and extreme run-off events) of arctic ecosystem?
6. 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?
7. How does river water discharge affect the water circulation in arctic fjord systems?
8. How does 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?
9. How does the energy balance of arctic ecosystems (marine, terrestrial and limnic) change with climate change and variability?
10. How does 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?
11. To what extent can results from GEM be used for up-scaling and prediction to address the questions above on a regional scale covering Greenland and the sea around Greenland (now and for the future) and what are the constraints for such up-scaling and prediction efforts?
12. What models shall be developed in to address the questions above on a regional scale (Greenland and surrounding sea)?
13. How can current monitoring and long-term research efforts in GEM most effectively be adjusted to meet current and future scientific needs and policy-related demands?

The GEM Steering Committee has subsequently asked the GEM Coordination Group to produce a detailed working programme for the period 2012-15 describing the adjustments to the programme necessary to reach the goals set in the strategy. To allow for immediate implementation of obvious necessary adjustments of the program, the GEM Coordination Group proactively decided already in autumn 2010 to suggest a number of strategic initiatives necessary to achieve parts of the goals set in the strategy (see Annex B). These initiatives were budgeted in the GEM application submitted to the Danish Energy Agency and the Environmental Protection Agency late in 2010.

During 2011, The GEM Coordination Group has continued the work on adjusting the programme in relation to the new strategy. This working programme describes the plan for the continued monitoring and new initiatives that will be implemented in the GEM programme during 2012-15.

1.2 Process

At the GEM meeting in the autumn 2010, the GEM Coordination Group held a workshop to identify immediate actions necessary to reach some of the goals set in the GEM Strategy 2011-15. It was decided to prioritise the following eight strategic projects as a first adjustment of the programme to the GEM Strategy:

1. Airborne lidar survey of the A.P. Olsen Land ice cap by DTU Space, led by GlacioBasis, Zackenberg (GEM SI 1)
2. Land-ocean coupling in Young Sund, led by MarineBasis, Zackenberg (GEM SI 2)
3. Freshwater runoff to Young Sund / Tyrolerfjord, led by ClimateBasis, Zackenberg (GEM SI 3)
4. Establishment of a snow model for the Zackenberg area, led by GeoBasis, Zackenberg (GEM SI 4)
5. Establishment of eddy covariance measurements on heath in Kobbefjord, led by GeoBasis, Nuuk (GEM SI 5)
6. Caribou dynamics in Akia: integrating the herbivore component in Nuuk Basic, led by BioBasis, Nuuk (GEM SI 6)
7. Establishment of a vegetation up-scaling and prediction model for Zackenberg, led by BioBasis, Zackenberg (GEM SI 7)
8. Editing of interdisciplinary synthesis of GEM results 1996-2015, led by the GEM Secretariat (GEM SI 8)

These eight projects are described in detail in Annex B. Each of the strategic initiatives has been given an identification code starting with 'GEM SI' followed by a serial number. The identification codes for each initiative/project are used in the timetable (table 4.1) in Section 4.3.

To allow for the implementation of the eight strategic projects, each monitoring sub-programme agreed to support a so-called 'GEM Strategic Fund' with approximately 3% of their normal budget by reductions in the current monitoring (according to the 2010 funding situation) equalling 2.5 mill. DKK for the period 2011-15.

Also in 2011, an Analytical Synthesis Fund was supported with 1 mill. DKK for 2011 by the Danish Energy Agency and the Environmental Protection Agency to allow for synthesizing, with an inter-disciplinary approach and across monitoring sub-programmes, issues of relevance to the questions asked in the GEM Strategy. Ten analytical synthesis projects of relevance were defined by the GEM Coordination Group, each with the purpose of start producing at least one international and peer-reviewed paper in 2012. The ten analytical projects are:

1. Influence of local climate and geophysical conditions on lake ecosystem dynamics at Zackenberg during the last 15 years (GEM A 1)
2. Revisiting factors controlling methane emissions: a paradigm shift in the high arctic? (GEM A 2)
3. Tempo-spatial trends in soil water chemistry: plant-soil interactions and controls by permafrost thawing (GEM A 3)
4. Timing, magnitude and source of a glacial lake outburst floods from A.P. Olsen Land ice cap (Zackenberg, NE Greenland) (GEM A 4)
5. Snow conditions controlling muskoxen distribution at Zackenberg (GEM A 5)
6. High arctic marine production: quantifying controls by terrestrial melt-water (GEM A 6)

7. Introducing the Normalized Difference Greenness Index (NDGI) as a predictor of Gross Primary Production in an arctic ecosystem (GEM A 7)
8. Water, energy and radiation feedback changes in the Arctic (GEM A 8)
9. Arctic CO₂ fluxes across marine and terrestrial environments in a changing climate (GEM A 9)
10. 15 years of climate monitoring in a high arctic catchment (Zackenberg, NE Greenland): observed changes and trends (GEM A 10).

These ten projects are described in detail in Annex B. Each of the analytical synthesis projects has been given an identification code starting with 'GEM A' followed by a serial number. The identification codes for each initiative/project are used in the timetable in Section 4.2.

In 2011, two additional workshops have been held with the purpose of further adjusting the GEM programme and thereby allowing for the preparation of this working programme.

In spring 2011, a workshop was held with the purpose of identifying unaddressed topics in the current GEM Working Programme. At this workshop, it was concluded that substantial changes of the existing working programme were needed, especially to allow for addressing the questions 11-13 in the GEM Strategy 2011-15. It was therefore decided, that each of the monitoring sub-programmes should be evaluated internally (together with the scientific experts associated with each of the sub-programmes) to allow for reallocation of means to new strategic projects to fulfil the strategy. This work was carried out internally within the monitoring sub-programmes during May-September 2011.

In September 2011, a follow-up workshop was held in the GEM Working Group with the purpose of defining the new projects necessary to fulfil the GEM Strategy 2011-15. The ten new strategic projects proposed are as follows:

1. Surface energy budget at two sites in West Greenland (GEM SI 9)
2. Monitoring of alpine glaciers in Kobbefjord (GEM SI 10)
3. Up-scaling climate change effects to the Greenland scale (GEM SI 11)
4. Increased field investigation capacity of GeoBasis, Nuuk (GEM SI 12)
5. Establishment of a snow model for the Zackenberg and Nuuk areas (GEM SI 13)
6. A seasonal marine study at Zackenberg (GEM SI 14)
7. A marine climate gradient study (GEM SI 15)
8. Monitoring radiative energy fluxes in the mass balance of A.P. Olsen Land Ice Cap (GEM SI 16)
9. Quantifying melt-water retention in the upper glacier ablation area (GEM SI 17)
10. International workshop on up-scaling of ecosystem function data to a Greenland scale (GEM SI 18)

These ten new strategic projects are described in details in Annex B. Each of the strategic initiatives has been given an identification code starting with 'GEM SI' followed by a serial number. The identification codes for each initiative/project are used in the timetable (table 4.1) in Section 4.3.

The new strategic projects were budgeted, and adjustments of the existing monitoring programmes were made to reallocate the necessary internal means for these new strategic projects. The projects are being partly financed by reallocation of internal means, partly financed by existing external means and partly funded by means to be applied for from external sources.

To allow for the implementation of the ten new strategic projects, each monitoring sub-programme agreed to further support the 'GEM Strategic Fund' with approximately 7% of their normal budget by reductions in the current monitoring (according to the 2011 funding situation) equalling approximately 4 mill. DKK for the period 2012-15.

During the process of preparing first a new strategy for GEM and later the working programme for GEM, a number of new research projects affiliated with or cooperating with GEM have been funded by external sources. Among the more substantial are:

1. The EU project INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic) with co-leadership by a member of the GEM Coordination Group (7.6 mill. EURO for 2011-14)
2. The EU ESFRI (European Strategy Forum on Research Infrastructures) project SIOS (Svalbard Integrated Arctic Earth Observing System) with a member of the GEM Coordination Group as task leader (4.5 mill. EURO for 2011-13)
3. The EU project PAGE21 (Changing Permafrost in the Arctic and its Global Effects in the 21st Century) with several members of the GEM Coordination Group involved (8.7 mill. EURO for 2011-15)
4. The EU project Ice2sea (Estimating the Future Contribution of Continental Ice to Sea-Level Rise) with a member of the GEM Coordination Group participating (10 mill. EURO for 2009-13)
5. The Danish Research Centre of Excellence CENPERM (Centre for Permafrost Dynamics in Greenland) led by a member of the GEM Coordination Group (has started contract negotiations with Danish National Research Foundation, planned to launch in beginning of 2012, 73 mill. DKK for 2012-17)
6. The Nordic Centre of Excellence DEFROST led by a member of the GEM Coordination Group (25 mill. NOK for 2010-2013)
7. The Canada Excellence Research Chair in Geomicrobiology and Climate Change led by a member of the GEM Coordination Group (50 mill. CAD for 2010-17)
8. The Greenland Climate Research Centre led by a member of the GEM Coordination Group (75 mill. DKK for 2009-14)
9. The Arctic Research Centre at Aarhus University led by a member of the GEM Coordination Group (to be launched early in 2012).

These projects will all make use of monitoring data from GEM and collaborate with GEM on a number of different scientific topics all supporting the GEM Strategy 2011-15. The fulfilment of the GEM Strategy 2011-15 will therefore be based on a combination of inputs from the existing GEM monitoring, from the different strategic projects funded by reallocation of means within GEM, and by all the externally funded projects with a total budget being almost seven times as high as the total budget of GEM. A complete list of 93 existing and planned projects that will contribute to the fulfilment of the GEM Strategy 2011-15 is given in Annex A.

1.3 Structure of this report

The intention of this report is to give an overview of the work to be carried out in GEM during 2012-15 to allow for the implementation of the 2011-15 strategy.

Chapter 2 outlines the Greenland Ecosystem Monitoring Strategy 2011-15 that was sanctioned by the GEM Steering Committee in early 2011. In chapter 3, we describe how the thirteen scientific questions stated in the strategy will be addressed during 2012-15. Chapter 4 presents a timetable for the implementation of the strategy, including important milestones and deliverables. In chapter 5, we describe the continuing monitoring efforts of the individual sub-programmes. Budgets are presented in chapter 6.

2 Greenland Ecosystem Monitoring, Strategy 2011-15



Photo: Henrik Spanggård Munch.

Greenland Ecosystem Monitoring (GEM) is an integrated monitoring and long-term research programme on ecosystems and climate change effects and feedbacks in the Arctic. The programme has established a coherent and integrated understanding of the functioning of ecosystems in a highly variable climate, which is based upon a comprehensive, long-term inter-disciplinary data collection currently carried out at two sites. These are located at Nuuk in low arctic West Greenland and at Zackenberg in high arctic Northeast Greenland.

The major strategic strength of GEM is its scientifically integrated approach to the study of ecosystems based on concurrent long-term collection of data on climate, landscape processes, geophysics, biology and biogeochemistry in the marine, the terrestrial, the limnic and the glaciological compartments of two well-confined ecosystems in high and low arctic regions of Greenland, respectively. This provides a unique foundation to analysing and describing ecosystem responses to temporary and more permanent climate changes within specific and different climatic regimes (one high arctic and one low arctic). This approach also improves the understanding of feedbacks between arctic ecosystems and the total climate system.

In the period 2011-2015, GEM intends to (i) strengthen the adaptive monitoring 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 up-scaling and predictions, and (vi) strengthen the visibility and outreach of the GEM.

A scientific synthesis of the results from the programme will be published in 2016.

Vision

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

GEM will maintain and strengthen its position as an internationally leading integrated long-term monitoring and research program.

Mission

The threefold mission of GEM embraces the following actions:

1. 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 feedbacks processes.
2. 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 (see Section 2.1).
3. To provide a platform for cutting-edge inter-disciplinary research on the structure and function of arctic ecosystem.

Objectives, 2011-2015

1. GEM will strengthen the scientific understanding of arctic ecosystem function and structure in relation to climate variability and change by (i) introducing an analytical component to the programme (see Section 2.2), (ii) elaborating the concept of adaptive monitoring (see Section 2.3) currently built into the program, (iii) focusing data collection to optimally address central scientific questions/objectives of local, regional and global relevance (see Section 2.2),
2. GEM will facilitate new externally funded projects that improve the program's capacity for up-scaling and prediction on Greenlandic ecosystems (for instance, by inclusion of a network of less extensively investigated sites in Greenland supplementing the existing sites at Zackenberg and Nuuk, and by strengthened cooperation with marine and oceanographic research efforts).

3. In cooperation with its international partners, GEM will extend its analytical approach to enhance the process-related understanding of Greenlandic/arctic ecosystems and the development of methods and equipment necessary to procure the process-related understanding for other arctic ecosystems.
4. GEM will actively participate in the processes aimed at establishing a better coordinated and integrated data collection, storage and analysis on climate change effects across the Arctic. This will be done by cooperation with and participating in relevant international activities (see Section 2.1), and by taking initiative to establish new international networks and research programmes focusing on the effects of climate changes on arctic ecosystems.
5. GEM will maintain – and develop further – its role as a leading international expertise on methods/techniques/instrumentation used for ecosystem monitoring and data management in the Arctic. This will be achieved by proactively attracting relevant international research projects on development of field equipment, methods and data management systems for ecosystem monitoring and research across the Arctic, and by testing the relevant instrumentation and data management systems at the GEM sites.

Strategic alliances

GEM has already established comprehensive national and international strategic alliances/cooperation with a range of other research and monitoring groups, networks, sites, programmes and projects across the Arctic. So far, this has been done mainly to increase the analytical capacity involved in the synthesis of the data produced by GEM and to allow for up-scaling of the detailed process studies from the GEM sites (see Section 2.4). During 2011-15, the interaction with the international science community will be developed further by (i) establishing cooperation with relevant leading international research groups to supplement, especially in the fields of permafrost, spatial and structural ecology, biodiversity, hydrology and remote sensing, the scientific competences already involved in GEM and among its existing strategic partners, and (ii) by facilitating/participating in initiatives towards the establishment of observatories networks across the Arctic (e.g. SAON and INTERACT).

Milestones

1. **2011:** GEM shall attain a leading role in at least one extensive circum-arctic network of ecosystem field sites to coordinate data collection, storage and analysis on climate changes' effects and feedbacks in arctic ecosystems.
2. **2012:** GEM will publish a comprehensive analysis of monitoring and research needs based on current and previous results of the GEM programme.
3. **2013:** GEM will publish an extensive report on best practises of monitoring, data storage, management and administration at arctic research sites.
4. **2014:** GEM will publish a catalogue of field sites applicable for environmental research in the Arctic.
5. **2014:** GEM will publish a comprehensive synthesis on existing ecosystem research and monitoring present at field sites throughout the Arctic.
6. **2015:** GEM will host an international workshop on climate change effects and feedbacks in arctic ecosystems to initiate the scientific synthesis of the 20 years of data collection at Zackenberg and the 10 years of data collection at Nuuk. Further, a strategy and work plan for GEM activities beyond 2016 will be established.

Publication, education and outreach

The GEM programme will produce annual reports in English providing a comprehensive overview and account of activities at the GEM sites. The annual reports will include a summary for policy makers.

The scientific results produced by GEM will be disseminated through relevant high ranking international peer reviewed scientific journals and in relevant international assessments. GEM intends to provide data for at least 30 peer-reviewed scientific papers per year and the programme will further aim at providing large visibility in all relevant international assessments. In 2015, an international GEM workshop will be held to initiate the production of a comprehensive assessment of the GEM results based on the objectives stated in this strategy and to be published in 2017 as a monograph in a leading peer reviewed international journal.

GEM will strengthen its educational component by (i) taking initiative to and implement cross-disciplinary university courses in arctic ecology and system sciences based on the scientific expertise and literature produced by GEM, (ii) strengthen the involvement of PhD-students in the programme, and (iii) prioritising involvement of Danish and Greenlandic university students as field assistants in the field work at Zackenberg and Nuuk.

GEM will secure high visibility and understanding of its results among the general public by (i) prioritising dissemination through popular science articles and public lectures with focus on especially the pre-university education system, (ii) proactively promoting cooperation with media (written and broadcasting), and (iii) establishing cooperation with relevant museums and zoological gardens on dissemination of GEM results.

Financing

As a programme being highly dependent on external financing for its operation and further development, GEM will continuously seek funding for its activities and infrastructure needs through national and international public and private funds.

2.1 Rationale of GEM

The climate in the Arctic is changing rapidly and this has already resulted in significant changes of the ecosystems (Post et al. 2009) with further ramifications for:

1. The global climate – through a number of feedback mechanisms
2. The biodiversity in the Arctic
3. The living resources in the Arctic



Photo: Thomas Juul-Pedersen.

Accordingly, there has been an extensive international focus on arctic areas over the recent years. The publication of the report Arctic Climate Impact Assessment in 2005 (ACIA 2005), later followed by many evidences of a very extensive melting back of The Greenland Ice Sheet and the more than 2,000 local glaciers in Greenland (AMAP 2009a), gained considerable attention from the international policy makers, not only in the Arctic, but in the entire world. As a result, a number of initiatives have been taken to monitor and predict the climate changes and the effects of these changes in the Arctic.

Zackenbergl Basic in high arctic Northeast Greenland was implemented in 1995 as a long-term monitoring of the arctic ecosystem effects and feedback processes induced by climate changes. After a few years, the programme became a Danish/Greenlandic national contribution to AMAP's Climate Change Effects Program.

In 2007, a similar monitoring programme, Nuuk Basic, was established in low arctic West Greenland (Forchhammer et al. 2008), and, in 2008, the two programmes were collectively organised under Greenland Ecosystem Monitoring (GEM). Today, GEM has a status of being an internationally recognized and well-established monitoring and research programme of effects of climate variability and change and resulting feedback from arctic ecosystems. GEM is unique in an international context due to its comprehensive inter-disciplinary monitoring. Taking the same approach to monitoring at two climatically contrasting locations, furthers our understanding of climatic effects on ecosystems and its living resources, biodiversity and feedbacks processes. This provides a unique opportunity to compare, and to some extent also up-scale ecosystem responses to climate changes. It could also support efforts in establishing predictive scenarios for Greenlandic ecosystems.

However, the efforts of up-scaling and making future predictions at the Greenlandic scale need supplementary monitoring and research efforts at a broader geographic scale than currently existing in GEM. In particular, a strengthened organisation of sites providing supplementary monitoring and research data is needed, as is an enhanced cooperation between GEM and relevant research efforts, as for instance marine and oceanographic studies.

Arctic-wide up-scaling and predictions requires development of reliable methods and methodologies for measurements, and the strengthening of a coherent network of monitoring and research sites across the Arctic.

In recent years, a range of international initiatives has been taken to extend, coordinate and harmonise the data collection and the management of data concerning climate change in the Arctic. As an example, Arctic Council has decided in cooperation with the International Arctic Science Committee and the World Meteorological Organisation to take leadership of a process which eventually shall lead to the establishment of a '*Sustaining Arctic Observing Network*' (SAON) (SAON IG 2008). In relation to SAON, Arctic Council recommends among other things that the member states shall '*sustain and increase the current level of observing activities and data and information services*'.

Arctic Monitoring and Assessment Programme (AMAP), a working group under Arctic Council, has in several publications increased its focus on climate change (ACIA 2005, AMAP 2009a,b), and in the report '*Update on Selected Climate Issues of Concern*' (AMAP 2009b) AMAP recommends among other things '*to initiate and maintain circumpolar measurements of carbon fluxes within the Arctic*' and '*to integrate and expand monitoring efforts to enhance understanding of cause-effect relationships and temporal and spatial variability driving regional scale climate*'.

In relation to biodiversity, Conservation of Arctic Flora and Fauna (CAFF – another working group under Arctic Council), established in 2005 the programme Circumpolar Biodiversity Monitoring Programme (CBMP). This program was endorsed by Arctic Council in 2004 and 2006. The programme shall among other things *'facilitate the conservation of biological diversity in the Arctic and the sustainable use of the region's natural resources by harmonizing and enhancing arctic monitoring efforts, thereby improving our ability to detect and understand significant trends'*.

Similarly, the EU is funding initiatives related to implementation of a more extensive and coordinated/harmonised monitoring of the Arctic through different larger infrastructure initiatives as for example INTERACT (International Network of Terrestrial Research and Monitoring in the Arctic), ICOS (Integrated Carbon Observation System), LifeWatch and SIOS (Svalbard Integrated Arctic Earth Observation System) which all except INTERACT are being supported by EU through the programme ESFRI (European Strategy Forum on Research Infrastructures) (ESFRI 2008).

Through the history of Zackenberg Basic and Nuuk Basic, comprehensive methodologies, inter-disciplinary monitoring activities and data storage and retrieval capacities have been developed, all of which has great potential for the arctic monitoring and science community. GEM can therefore contribute to the further the development of the above mentioned.

The predicted climate changes will have a major impact on the Greenland society, mainly due to the dependence on living resources. In 2009, the Danish Ministry of Science, Technology and Innovation therefore took initiative to the establishment of a Greenland Climate Research Centre (GCRC) to *'procure, integrate and communicate scientific, technological and societal knowledge on climate change effects to Greenland'*. According to the terms of reference for GCRC, it is the intention that a strong cooperation shall continue between GCRC and GEM, and GEM is currently involved in several terrestrial, limnic and marine projects under GCRC.

GEM is already involved in a number of international programmes and projects, and it is the goal of the present strategy that GEM shall strengthen its involvement by (i) active participation in circumpolar networks, (ii) provision of significant Danish and Greenlandic contributions to international assessments on climate changes and their effects in the Arctic, and (iii) regularly contribute relevant information to the Danish and Greenlandic administrations for evaluation of arctic climate change effects.

Denmark and Greenland already have a strong position in the international work related to arctic climate change effects. The challenge for the GEM programme will be (i) to maintain the high scientific/technical level of the monitoring and continuously adjust the programme to secure a continued relevance of the monitoring, (ii) to contribute further to and actively participate in the international processes towards a more internationally coordinated effort in ecosystem and climate change effects research which according to the sections above already is ongoing or about to start in a number of areas, (iii) constantly improve the quality of the monitoring and long-term research effort and maximise the efficiency of the program, (iv) improve the connection between monitoring and research in order to address focus scientific key questions, and (v) enhance international research efforts at GEM stations.

2.2 Scientific questions to be addressed during 2011-15

The comprehensive long-term inter-disciplinary data collection carried out by GEM allows the programme to provide data to address the following 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:

Greenhouse gas exchange with the atmosphere and nutrients balance

1. How does climate change and variability control the annual and seasonal exchange of greenhouse gasses (H_2O , CO_2 , CH_4 and N_2O) between arctic terrestrial ecosystems and the atmosphere?
2. How does climate change and variability affect the CO_2 exchange between arctic marine ecosystems and the atmosphere?

Ecosystem function and resilience

3. How does global change, including stronger climatic variability and change, affect the species composition and function of arctic ecosystems?
4. Are there important thresholds in arctic ecosystems that might lead to sudden and significant shifts of their overall biodiversity and function?

Water balance, including glaciology and water circulation in the marine environment

5. How does climate variability and change affect the water balance (including availability of water in terrestrial ecosystems, glacier mass balance and extreme run-off events) of arctic ecosystem?
6. 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?
7. How does river water discharge affect the water circulation in arctic fjord systems?

Snow and ice, including effects on phenology, energy and carbon balance

8. How does 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?
9. How does the energy balance of arctic ecosystems (marine, terrestrial and limnic) change with climate change and variability?
10. How does 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?

Up-scaling, modelling and prediction

11. To what extent can results from GEM be used for up-scaling and prediction to address the questions above on a regional scale covering Greenland and the sea around Greenland (now and for the future) and what are the constraints for such up-scaling and prediction efforts?
12. What models shall be developed to address the questions above on a regional scale (Greenland and surrounding sea)?
13. How can current monitoring and long-term research efforts in GEM most effectively be adjusted to meet current and future scientific needs and policy-related demands?

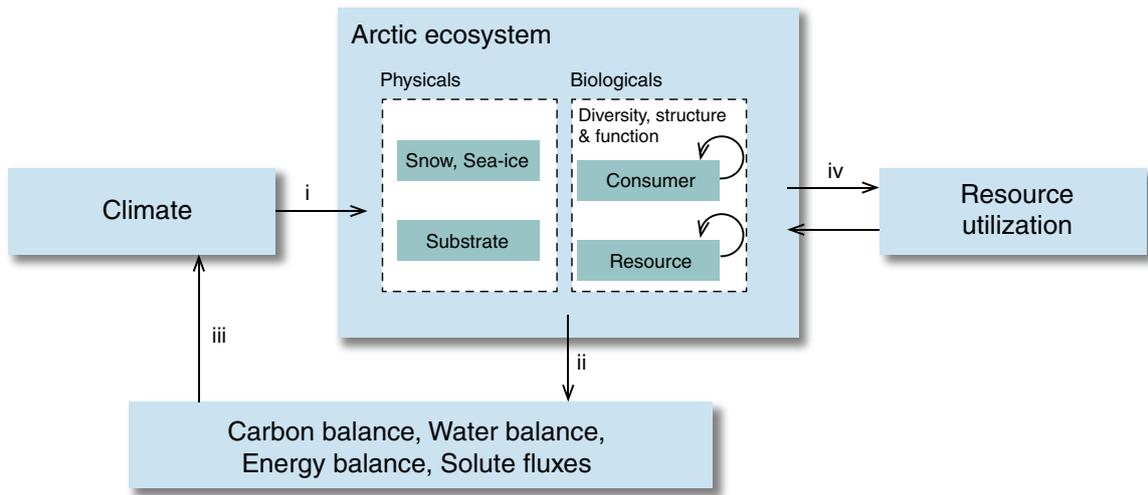


Figure 2.1 The concept behind the GEM project. From Forchhammer et al. 2008

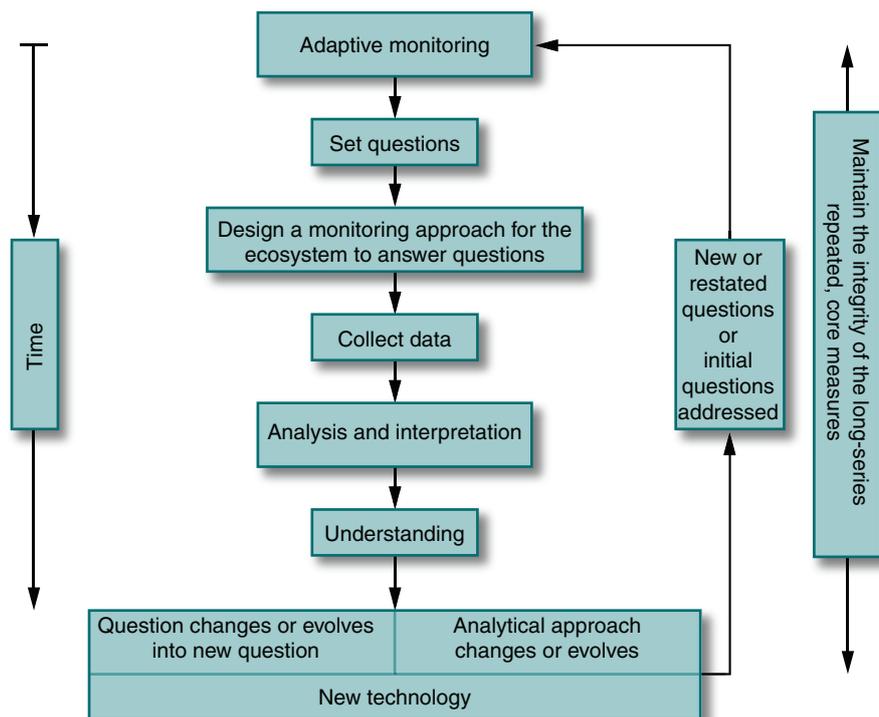
2.3 Adaptive monitoring

The overall conceptual framework for GEM (figure 2.1) is described in details by Rasch et al. 2003 and Forchhammer et al. 2008. The concept is based on a system approach to include the entire ecosystem, i.e. the terrestrial, the limnic and the marine component of the ecosystem. It comprises an integrated model for the study of (i) direct effects to the ecosystem, (ii) indirect/cascading effects within the ecosystem, (iii) the feedbacks from the ecosystem and the effects of resource utilisation.

In 2011-15 GEM will strengthen its analytical component and do this by following the paradigm of adaptive monitoring (figure 2.2) as suggested by Lindemayer and Likens (2009) in the question setting, the experimental design, the data collection, the analysis, the interpretation and the evaluation of its monitoring and long-term research results. Adaptive monitoring secures:

1. That the monitoring is based on a scientific conceptual basis.

Figure 2.2 The concept of adaptive monitoring. From Lindemayer and Likens 2009.



2. That it addresses relevant scientific and political/administrative questions (according to relevant international assessments and the Danish/Greenlandic policy in relation to arctic monitoring under the auspices of Arctic Council).
3. That it is evaluated and adjusted at regular intervals to secure a continued relevance of the questions to be addressed.

The development of the strategy has, as recommended by Lindemayer and Likens 2009, occurred through a partnership between scientists and policymakers. This is considered important because scientists on one hand will often not fully comprehend the kinds of problem faced by policymakers and be fully aware of the policy options, while policy makers on the other hand will often not know how to frame questions in ways that can be resolved by well-executed, long-term research and monitoring.

Throughout the period 2012-2015, the managers of the GEM sub-programmes will continuously consider the need of adjustments in the monitoring efforts of the over-all GEM programme.

2.4 Research cooperation

GEM has developed strategic alliances with other sites, research groups, networks, programmes and projects to increase the analytical capacity involved in the synthesise of the data produced by GEM and to allow for up-scaling of the detailed process studies from the GEM sites

GEM has established the following alliances with other international research groups to supplement the research capacity involved in analyses of data from the programme:

1. Greenland Climate Research Centre led by Professor at Greenland Institute of Natural Resources and Canada Excellence Research Chair Søren Rysgaard
2. The Climate Modelling Group at Danish Meteorological Institute led by Professor Jens Hesselbjerg Christensen
3. The Carbon Group at Lund University led by Professor Torben Røjle Christensen
4. The Snow Modelling Group at Colorado State University led by Professor Glen Liston
5. The Population Dynamics Group at Pennsylvanian State University led by Professor Eric Post
6. The Ecology Group at Sheffield University led by Professor Terry Callaghan
7. The Ice Group at Niels Bohr Institute at University of Copenhagen led by Professor Dorthe Dahl-Jensen
8. The Marine Sediment Group at University of Southern Denmark led by Professor Ronnie Glud
9. The Remote Sensing Group at DTU Space led by Leader of Department Rene Forsberg

GEM has established the following alliances with other sites in Greenland and the Arctic to allow for up-scaling of the detailed process studies at Zackenberg:

1. Greenland Institute of Natural Resources in low arctic West Greenland
2. Arctic Station in low arctic West Greenland
3. Sermilik Station in low arctic East Greenland
4. Abisko Scientific Research Station in sub arctic Sweden
5. Toolik Field Station in high arctic Alaska

GEM is involved in the following international networks/programmes:

1. SIOS – Svalbard Integrated Arctic Earth Observing System (ESFRI initiative)
2. ICOS (ESFRI initiative)
3. SCANNET (circum-arctic network of field sites)
4. INTERACT (EU project to coordinate research and monitoring at arctic field sites)

GEM is involved as vice-chair of the project and leader of two work packages in the EU-funded programme/network 'INTERACT 2010-14' with a total budget 7.6 mill. EURO. The network includes 32 terrestrial field sites across the arctic (in Europe, USA, Canada and Russia). The aim of INTERACT is to build capacity for identifying, understanding, predicting and responding to diverse environmental changes throughout the wide environmental and land-use envelopes of the Arctic.

GEM delivers data to the following circum-arctic networks:

1. International Tundra Experiment (ITEX)
2. The Global Observation Research Initiative in Alpine Environments (GLORIA)
3. Circumpolar Active Layer Monitoring (CALM)
4. Arctic Coastal Dynamics (ACD)
5. Hydrology Data and Information Services Centre (HDISC)
6. Different working groups under Arctic Council including Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF)

During 2011-15, GEM will supplement its strategic alliances to strengthen its analytical competence by establishing cooperation with leading international research groups in the fields of permafrost, spatial ecology, hydrology and remote sensing.



Photo: Lars Holst-Hansen.

3 Scientific questions to be addressed during 2011-15



Photo: Henning Thing.

In this chapter, we describe in detail how we will address each of the thirteen questions given in the Greenland Ecosystem Monitoring Strategy 2011-15.

For each question we describe (i) the current monitoring already contributing to addressing the question in the strategy, and we describe (ii) how new initiatives will be implemented to further allow us to address the question. Furthermore, for each question, we list the different existing or planned projects (according to the complete project list given in Annex A) which will contribute to addressing the question, and we describe the expected outcome in terms of expected publications addressing the question and possible scientific positions (e.g. PhD and PostDoc).

Each of the project numbers listed in the fields '*Relevant projects*' refer to a project number in the matrix in Annex A. For each of these projects, Annex A gives: '*Project title*', '*Principal Investigator*', '*Budget*', '*GEM funding*', '*External Funding*', '*Status*' (i.e. '*Funded*', '*Partly funded*', '*Already applied for*' or '*To be applied for*'), and the name of the '*External source*' for funding outside GEM.

3.1 Greenhouse gas exchange with the atmosphere and nutrients balance

The carbon pool in the arctic permafrost regions represents close to 50% of the estimated global soil organic carbon pools and more than twice of the current atmospheric carbon pool. Further, the arctic seas are on a global scale an important sink for atmospheric carbon, and combined with reduced sea ice cover, melting of the permafrost will influence arctic greenhouse gas exchange with the atmosphere to a degree that will significantly influence global climate. Increased release of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) due to permafrost melting may be compensated partly by increased uptake of CO₂ by an ice free Arctic Ocean, but we are still far from being able to quantify this important balance. Therefore, improved knowledge of the nature of the physical and biological feedback mechanisms in the Arctic is needed.

Question 1	How does climate change and variability control the annual and seasonal exchange of greenhouse gases (H ₂ O, CO ₂ , CH ₄ and N ₂ O) between arctic terrestrial ecosystems and the atmosphere?
Existing monitoring	This question is being addressed by GEM at both the present monitoring sites and at the new site on Disko Island (Arctic Station). Further, GEM delivers data directly to several large research projects working primarily at the Zackenberg, Nuuk and Disko sites. Several of the GEM Coordination Group members are either leading or key members on these projects.
New initiatives	<p>The seven largest of the relevant research projects listed above are the Nordic Centre of Excellence DEFROST, the Danish Centre of Excellence CENPERM, the Greenland Climate Research Centre, the Canada Excellence Research Chair in Geomicrobiology and Climate Change, the Arctic Research Centre at Aarhus University, the EU project PAGE21 and the EU project INTERACT. Among these projects, several will, over the next 4-6 years, address the question above with use of data from GEM, e.g.:</p> <ul style="list-style-type: none"> • CENPERM: improve quantification of element cycling and predictions of future changes in carbon and nitrogen pools and greenhouse gas fluxes from fragile arctic ecosystems • DEFROST: focus on key terrestrial, lacustrine and marine cryospheric systems that have the potential for giving rise to substantial changes in climate feedback mechanisms both in terms of surface-atmosphere energy exchange and exchanges of greenhouse gases • PAGE 21: improve the understanding of ecosystem-atmosphere and hydrological fluxes of C and N and relate these fluxes to ecosystem, soil, climate, and permafrost characteristics and processes • INTERACT: use the site infrastructures to improve monitoring and facilitate research into key feedback mechanisms from northern terrestrial ecosystems in a changing climate <p>There will be a number of PhD's and Postdoc's enrolled within the GEM groups at University of Copenhagen and Aarhus University working on these topics, while other PhD students will be enrolled at other Nordic universities (e.g. Lund, Stockholm) which are close collaborators of GEM.</p> <p>Both the Zackenberg and Nuuk sites have been upgraded in 2011 with ICOS level instrumentation for greenhouse gas exchange measurements of dry and wet sites, and the Disko site will follow in 2012 with instrumentation for year-round measurements of CO₂ fluxes. N₂O measurements have been used in a pilot project in 2010 at Zackenberg, but automatic N₂O measurements are still missing and will be sought implemented through external funding (INTERACT, FNU or others).</p> <p>Recent literature has shown water pathways to be more important than earlier believed in relation to the carbon balance of ecosystems. GEM will therefore seek external funding (existing leading projects, FNU etc.) to further investigate the carbon balance of this ecosystem element. GEM has also reallocated internal means to cover the full spring, summer and autumn seasons in Nuuk. Additionally, a kick-off terrestrial winter field campaign financed by the Arctic Research Centre at Aarhus University will facilitate a joint effort by five universities (Stockholm, Lund, Copenhagen, Manitoba and Aarhus) in which this question is central.</p>
Relevant projects	1, 4-12, 17, 19, 25, 30-43, 49, 50
Expected outputs by 2015	The projects mentioned above will over the next 4-6 years fund more than 30 PhD and PostDoc positions, all focusing on topics related to Question 1. Most of the results from these projects will be published in peer-reviewed journals but will also be used in assessments, presentations etc. We expect more than 30 research papers addressing this question to be published before 2015.

Question 2	How does climate change and variability affect the CO ₂ exchange between arctic marine ecosystems and the atmosphere?
Existing monitoring	Currently, CO ₂ fluxes are not measured directly. We measure the concentration of CO ₂ (the partial pressure, $p\text{CO}_2$) in the surface water and the atmosphere. We can then estimate the flux of CO ₂ using measured wind speeds, but this estimate is typically associated with 20-25 % uncertainty. In Nuuk, $p\text{CO}_2$ is measured at one position each month and an annual flux estimate is calculated. In Young Sund, measurements are conducted once in August throughout the fjord. Annual flux cannot be calculated for Young Sund, and as a result neither the influence of ice conditions can be assessed there.
New initiatives	The primary aim of our new initiatives is to measure CO ₂ fluxes directly, using the eddy-covariance technique and to focus on the effect of sea ice on air-sea exchange of CO ₂ . Two other important data gaps are the very limited seasonal coverage in Young Sund and the lack of measurements from other fjord systems in Greenland and from the shelf. A seasonal marine study in Young Sund is planned and so are additional measurements of CO ₂ along the Greenland coasts (i.e. 'A marine gradient study'). Direct measurements of CO ₂ flux have been initiated in Nuuk in 2011 and plans are to conduct measurements in Young Sund also. A PhD student has recently started a on a project addressing the influence of sea ice on air-sea gas exchange (part of DEFROST).
Relevant projects	49, 50, 61, 62, 64-66
Expected outputs by 2015	The research and monitoring efforts on this topic is expected to produce six scientific papers and a PhD thesis before 2015.

3.2 Ecosystem function and resilience

The on-going and future changes in the arctic climate, both in terms of directional change and altered variability, are likely to assert major impacts onto the marine, the terrestrial and the limnic ecosystems. The impacts are expected to be both directly on the various compartments of the ecosystems, but also on their interactions, and, hence, on the feedbacks inherent to the systems. Understanding how the different biotic and abiotic elements and interactions embedded in the ecosystems respond to climatic variability and change is therefore vital for the understanding of the short-term and long-term impacts on the ecosystem as a whole, including the degree of resilience as well as the presence of important thresholds in the systems.



Photo: Lars Holst Hansen.

Question 3	How does global change, including stronger climatic variability and change, affect the species composition, and function of arctic ecosystems?
Existing monitoring	<p>GEM will continue to monitor the core elements of the high and low arctic ecosystems, and thereby provide the long-term data series essential for answering these questions. GEM monitors the biological compartments of the terrestrial and limnic ecosystems with emphasis on biodiversity, abundance, reproduction and phenology across trophic levels, and how these biological entities respond to climatic variability and change. In the marine environment, GEM focuses on the diversity and abundance of phyto- and zooplankton communities, and the abundance of planktonic larvae stages of larger organisms, macroalgae, seabirds, sea-bottom fauna and whales.</p> <p>GEM continuously monitors climatic and hydrological parameters, which form the basis for explaining many of the changes and patterns observed in species composition and ecosystem functions in both locations.</p> <p>The existing glaciological monitoring provides a field record of the interactions between glacier mass balance and climate. All processes are accounted for, except for melt-water refreezing in the snow cover that is known to occur on the A.P. Olsen Land Ice Cap with effects expected to change due to climate change.</p>
New initiatives	<p>Projects outside GEM but with involvement of GEM scientists such as 'Arctic climate change: Species interactions and ecological response time', 'Plant-Soil-Herbivore interactions in the Arctic – Feedbacks to the carbon cycle' and 'Circumpolar Biodiversity Monitoring Program' focus specifically on unravelling the impacts of climate change on the resilience and stability of the terrestrial ecosystem.</p> <p>The present limnic monitoring focuses mainly on the most important biotic and abiotic compartments of the freshwater lake system. GEM will in the coming years however seek to address the freshwater river system in more detail through external funding for a research project on this topic. GEM will continue to work closely with the other programmes to deliver knowledge and data on both feedback mechanism studies focusing on the energy balance and the carbon balance as well as the snow modelling and continued focus on nutrient transport both in the soil and in the streams and rivers. Several of the projects mentioned under Question 1 (e.g. DEFROST and CENPERM) will also work with this question during the coming years.</p> <p>In the marine environment, special attention has been given to the biodiversity and species composition of the sea floor fauna on the West Greenland shelf (projects 73, 74, 75 and 84 which provide baseline information on current status and knowledge of factors influencing marine diversity and structure). In addition, several new projects have been initiated to improve our knowledge of the factors that structure marine ecosystems and how climate change could affect them in the future (projects 77, 86, 87 and 90). Finally, the proposed 'Seasonal marine study' in Young Sund/Tyrolerfjord will provide valuable information on seasonal patterns in the plankton community structure and function outside current monitoring period. Plankton species distribution is also a central part of a climate gradient research cruise along the east coast of Greenland planned for 2012. The northernmost transect has purposely been established as an extension of the fjord-sea transect monitored annually in Young Sund/Tyrolerfjord. Key marine topics of research projects collaborating with GEM keep improving our knowledge on function and community structure, thus providing a broad insight into arctic pelagic and benthic ecosystem compartments in a changing climate. While some projects focus on climatic physiological adaptations of key species, others study species distribution and food web interactions.</p> <p>The proposed update to the glaciological monitoring will assess the magnitude and impact of melt-water retention processes on glacier mass balance and its evolution in a changing climate requires field observation of the spatial and temporal patterns of melt-water refreezing in the snow and firn layers. This will be obtained through logging of temperature profiles, drilling of firn cores and optimisation of the current snow radar surveys.</p>
Relevant projects	1-32, 34, 35, 37-42, 44-46, 49, 50, 54, 56-65, 67-75, 84, 86, 87, 90-92
Expected outputs by 2015	Based on the current monitoring efforts and the collaboration with external projects, at least five scientific papers within the fields of climate change and terrestrial biodiversity and ecosystem functioning is expected together with ten scientific papers on species composition and/or ecosystem functions for the marine ecosystems before the end of 2015. The planned glacier monitoring will provide data for four further papers relevant to the geophysical effects of climate variability and change on the glaciers.

Question 4	Are there important thresholds in arctic ecosystems that might lead to sudden and significant shifts of their overall biodiversity and function ?
Existing monitoring	GEM focuses on the short- and long-term effects of extreme events and potential thresholds, such as plant water stress following reduced snow precipitation, and the collapse of the lemming population at Zackenberg. GEM has increased its focus on the extreme run-off events from the glacier and is collaborating with the Austrian project GlacioBurst to understand the dynamics controlling these extreme events. GEM also monitors the plankton community structure along with abundance of biomass and growth/condition indices of key species of benthic fauna and macroalgae at both sites. Physical and chemical drivers for the marine ecosystem structure and function, such as temperature, salinity and nutrients, are also monitored. GEM monitors the glacier surface energy and mass to relate climate and glacier mass balance. In a warming scenario, a higher equilibrium line will trigger a positive albedo feedback.
New initiatives	Several external projects will help to address these questions (e.g. 'Impacts of extreme warming events on high arctic ecosystems' and 'Arctic climate change: Species interactions and ecological response time'). New initiatives include a planned study along the east coast of Greenland that aims at describing the plankton community structure and function along the climate gradient, thus providing better insights into possible future scenarios with changing climate. This research cruise will be spatially linked to increased marine research efforts at the Zackenberg monitoring site. A proposed seasonal marine study in Zackenberg will form a platform for marine research and monitoring efforts aimed at expanding knowledge on seasonal ecosystem structure and function at the site. On-going marine research projects collaborating with GEM are studying the physiological adaptations and possible threshold values of key plankton species to factors subject to climatic forcing, such as temperature and salinity. The work of several research projects along with a joint winter campaign at the Zackenberg site are relevant for understanding the effects of abrupt changes in physical conditions, such as sea ice cover and salinity, on marine ecosystems. On the glacier, upgrading of an existing automatic weather station will enable us to provide ground truth data to quantify the magnitude and impact of the albedo feedback.
Relevant projects	1-34, 37-42, 46, 48-50, 56-65, 67-75, 77-81, 84, 86, 87, 90-92
Expected outputs by 2015	Based on the current monitoring effort and the collaboration with external projects, GEM expects to produce before the end of 2015 three scientific papers within the fields of resilience, extreme events and thresholds in terrestrial ecosystems and six scientific papers specifically on the marine systems. Two more papers will deal with the observed surface energy flux and mass balance changes on the glaciers.

3.3 Water balance, including glaciology and water circulation in the marine environment

The Greenland Ice Sheet, the second largest ice body in the world, poses a strong influence on the surrounding ecosystem compartments and the local climate. A continuing warming trend is expected to increase ice melt along with glacial activity, introducing more freshwater through the terrestrial compartment into the surrounding fjord and coastal systems. The increased freshwater discharge will likely also lead to higher export of particulate material and solutes from the catchment area to the marine environments. In addition to a freshening of the fjords and coastal systems, transference of material and solutes, such as organic material and nutrients, from the terrestrial to the marine compartments may also lead to changes in productivity and function of the different ecosystems. Also, the content of dissolved organic carbon (DOC) and colored dissolved organic matter (CDOM) in freshwaters are heavily affected by climate variability. Thus, in a warmer and wetter climate it is known that more erosion and thawing of permafrost will take place. This leads to an increased amount of DOC and CDOM in aquatic ecosystems, which enhances the nutrient availability for planktonic and benthic production as well as export of organic compounds to the marine environment. In contrast, erosion of sediments can have significant impact on the terrestrial environment and topography, while increasing sediment discharge may deteriorate light conditions and thus productivity in the receiving marine environments. The

dynamic processes and feed-back mechanisms affecting ice melt and glacial activity remain the focus of intense research efforts in Greenland and other polar glacial regions. Among these avenues of research, local ice masses surrounding the ice sheet are significantly underinvestigated. A.P. Olsen Land Ice Cap and Freya Glacier in the Zackenberg region are together with the Mittivakkat Glacier in the Sermilik area, the only sites from where field measurements are available for the glacier surface mass balance to be calculated. However, this does provide an ideal N-S transect along the east coast to analyse the wide area spatial trends, from the high precipitation climate of Mittivakkat to the dry high arctic climate of A.P. Olsen Land.

Question 5	How does climate variability and change affect the water balance (including availability of water in terrestrial ecosystems, glacier mass balance and extreme run-off events) of arctic ecosystem?
Existing monitoring	<p>GEM is continuously monitoring climatic and hydrological parameters at both Zackenberg and Nuuk. The current monitoring of climate at Zackenberg shows that there have been significant increases in temperatures during selected months as well as a significant increase in annual mean temperatures during the past 15 years.</p> <p>In Zackenberg, GEM is monitoring glacier mass balance and climatic parameters and gradients on the glacier. This enables mass balance modelling to quantify the input of freshwater from the glacier into the Zackenberg river system. In Zackenberg, GEM monitors the variability and trends, both in space and time, of the glaciological and climatic factors controlling the hydrological contribution of a typical local ice mass detached from the ice sheet. Through this activity, GEM is the leading producer of field observations linking climate, glacier mass balance and melt-water runoff.</p> <p>GEM has in recent years, increased the focus on the extreme run-off events from glaciers with a monitoring camera at the lake. Furthermore, GEM is collaborating with an Austrian project, GlacioBurst, which during 2011-2014 will focus on understanding the dynamics controlling extreme flood events.</p> <p>GEM's monitoring efforts at both the Zackenberg and the Nuuk sites include measurements of seasonal patterns in salinity in the fjords, which are greatly affected by seasonal terrestrial run-off as well as sea ice and glacial ice melt.</p> <p>Ongoing research efforts, funded by the GEM Strategic Fund, focuses on tracing and quantifying terrestrial freshwater input to the fjord system in Zackenberg by hydrological conditions and the signature of solutes from land. An externally funded parallel study on tracing freshwater has also been conducted at the Nuuk site. Moreover, extensive research efforts by several Greenland Climate Research Centre related projects on the influence of the Greenland Ice Sheet on fjord systems and fjord-sea interactions are providing novel and essential knowledge relating to the water balance. The GEM Strategic Fund is also funding a project in which the terrestrial freshwater input to the fjord system is Zackenberg is quantified</p>
New initiatives	<p>In Zackenberg, new field observations will monitor the magnitude, spatial patterns and seasonal trends of glacier melt-water retention. This work will include a field component to carry out specific snow radar surveys and firn coring, and a laboratory component to analyse the retrieved samples and quantify the amount of snow melt-water refrozen into the firn.</p> <p>For a number of local glaciers at the Nuuk site monitoring will be initiated. The monitoring of the small glaciers in Kobbefjord will provide valuable knowledge for understanding the entire ecosystem and as input to the planned establishment of a hydrological model for Kobbefjord.</p>
Relevant projects	35-39, 43, 44, 46, 49-53, 55-65, 67-75, 77-81, 84, 86, 87, 90-92
Expected outputs by 2015	A paper on climate trends at Zackenberg during the first 15 years and a paper on glacial outburst floods will be published in 2012. Furthermore the results of the monitoring of the local glaciers in Kobbefjord are expected to be published in at least one paper before 2015. Relating to water balance (i.e. freshwater input to fjords) and fjord hydrography, GEM expects to produce seven scientific papers.

Question 6	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?
Existing monitoring	GEM is monitoring the freshwater, solutes and suspended material discharge of selected rivers at the two sites. GEM also quantifies the annual vertical sinking export of sediments and organic material (including carbon) in the marine environment at both sites, this material is in part supplied by the river discharge.
New initiatives	On top of research efforts on extreme flood events, GEM has also increased its focus on dissolved organic carbon (DOC) from the river Zackenbergelven through collaboration with research projects at the Greenland Climate Research Centre. Automatic water sampling in Zackenbergelven will be tested during 2012 and 2013 based on planned external funding. To supplement the existing measurements of suspended sediment discharge from three rivers to Young Sund/Tyrolerfjord a number of water samples will be collected to quantify the entire sediment output to Young Sund/Tyrolerfjord from these rivers. A joint research effort in 2011, funded primarily by the GEM Strategic Fund, focused on tracing and quantifying the terrestrial signal in Young Sund/Tyrolerfjord based on optical properties and spatial differences in sinking export in the fjord system. These findings together with a year-round mooring and a proposed prolonged marine field campaign in Zackenberg, outside the regular monitoring period (i.e. July/August), aim at delivering seasonal data on terrestrial input throughout the open-water season. This topic is also in focus for three research projects at Greenland Climate Research Centre specifically studying Ice Sheet/glacier-fjord interactions and freshwater input to fjords, along with two research cruises linked directly to the marine monitoring studying spatial influence of terrestrial derived freshwater and material in fjords. The role of glacial lake outburst floods on the transport of sediments and solutes will be further investigated through the existing GEM monitoring activities and in collaboration with the Austrian research group led by Dr. Wolfgang Schöner.
Relevant projects	49-59, 61-64, 67, 71, 72, 81-83, 85, 88, 89
Expected outputs by 2015	The existing and planned initiatives relating to terrestrial discharge and input to the fjord systems of solutes, particulate material and sediments are expected to produce approximately seven scientific papers before the end of 2015.

Question 7	How does river water discharge affect the water circulation in arctic fjord systems?
Existing monitoring	GEM is continuously monitoring climatic and hydrological parameters at both the Zackenberg and Nuuk sites. The discharge measurements from the main rivers at both sites are part of the monitoring efforts quantifying the freshwater input to the marine environment. Subsequently, hydrographical measurements, i.e. operated profilers and continuous moorings, provide relevant information on salinity and temperature in the receiving fjords. Continuous measurements at selected stations show seasonal patterns and variability, while length and cross sections at both sites (i.e. Zackenberg and Nuuk) depict spatial patterns at times.
New initiatives	Two projects funded by the GEM Strategic Fund work on quantifying the terrestrial freshwater discharge from three rivers in Zackenberg, and tracing and quantifying the freshwater entering the Young Sund system, respectively. Funding for continuing the monitoring of Lake Tasersuaq in the inner part of the Godthåbsfjord will be sought from external sources. The lake is the single largest contributor of terrestrial freshwater to the fjord system, and has been monitored from 1974-1983 and 2008-2011. Moreover, hydrological modelling of Kobbefjord will enable calculations of the total freshwater input to Kobbefjord and the source and timing of the freshwater to the marine environment, which will affect the circulation in the water. Seasonal trends in hydrological conditions are studied closely throughout the year in Godthåbsfjord as part of three Greenland Climate Research Centre projects linked with the marine monitoring programme. Two scientific cruises at the Nuuk site also incorporated hydrological measurements to evaluate the influence of freshwater on fjord circulation. A joint research effort in 2011 along with a seasonal marine study in Zackenberg in conjunction with year-round oceanographic moorings will provide essential seasonal knowledge on water circulation and the effects of river discharge. Moreover, a planned winter campaign at Zackenberg will in coordination with the marine monitoring programme study under-ice hydrography when no river water input is present.
Relevant projects	49-53, 55, 61-64, 71, 72, 82, 83, 85, 88, 89, 92
Expected outputs by 2015	GEM is working on a paper that focuses on glacial outburst floods at Zackenberg. GEM is also contributing directly to approximately six papers addressing tracing and quantifying of terrestrial freshwater in the fjord systems, hydrography and fjord circulation. Furthermore, GEM is involved in a paper about the freshwater input to Godthåbsfjord, which is expected to be published during 2012-13.

3.4 Snow and ice, including effects on phenology, energy and carbon balance

During the last century, climate in the Arctic has undergone rapid change, with marked changes in temperature and precipitation patterns – especially during winter. These changes will induce further changes in the cover of snow, lake-ice and sea-ice distribution. Snow and ice play a vital role in shaping arctic ecosystems through direct and indirect influence on e.g. radiation patterns and insulation properties, as well as acting as barrier between biotic compartments. Consequences of changing snow and ice cover include melting of the upper permafrost layers and increased irradiation and heating of surface waters. Soil ecosystems with underlying permafrost cover approximately 25% of the land area in the Northern Hemisphere and store almost half of the global soil carbon. The most dramatic effect of permafrost thawing is the accelerated decomposition and potential mobilization of organic matter stored in the permafrost, affecting global climate through the mobilization of carbon and nitrogen accompanied by release of greenhouse gases such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). The net effects of these changes are controlled by coupled feedback mechanisms with different impacts depending upon climate, amount of carbon and nitrogen stored in the soil, ice content, temperature and active layer dynamics. In contrast, reduced sea ice cover in arctic waters is expected to elevate the ocean uptake of greenhouse gases along with overall increasing marine productivity. Changing sea ice cover will generally prolong the pelagic productive season, while at the same time decrease or eliminate sympagic (i.e. ice associated) productivity. Species composition and community structures are likely to change due to changing ice cover and subsequent changing physical conditions (e.g. temperature and salinity) and currents.

Hence, the alterations in the physical environment changes the dynamics of the entire ecosystem, and since the balance of competition between plants and animals is also altered we will therefore see changes in the biodiversity and function of marine, terrestrial and limnic ecosystems.



Photo: Henrik Spangård Munch.

Question 8	How does 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?
Existing monitoring	<p>GEM will continue to put emphasis on understanding the effects of climate-induced changes on biodiversity, abundance, reproduction and phenology of the central biological ecosystem compartments in the terrestrial and limnic ecosystems. GEM will thus examine not only biodiversity per se, but also aim at understanding how such changes affect the functioning of the individual compartments as well as the ecosystem as a whole through cascading effects. These examinations will be conducted on a number of scales, from plot (e.g. local plant species), landscape (e.g. plant communities) to regional scale (e.g. greening patterns in Greenland; see below).</p> <p>GEM also conducts sea ice monitoring in collaboration with the Sirius Patrol (Danish Defence), providing monthly ice thickness and snow depth measurements at the marine monitoring site in Zackenberg including timing of sea ice formation and break-up and hence length of the sea ice season. Pelagic and benthic species compositions and biomass measurements are conducted annually during the annual field campaign a few weeks after the sea ice break-up in Zackenberg. The low arctic fjord system (i.e. Nuuk) remains mostly ice free year-round. Satellite images within the fjord and the outside Baffin Bay are used to assess the extent of sea ice, along with providing information on glacial ice in the fjord. This sea ice information is combined with the monitoring efforts on pelagic species composition and biomass, along with distribution and conditions indices of selected species of benthic fauna and macroalgae.</p>
New initiatives	<p>GEM will over the next four years pay special attention to investigations of the snow and ice and its influence on the ecosystems. This includes enhanced focus on producing a snow model as well as investigating hard snow layers and temporal thermal trends in the snowpack at Zackenberg and Nuuk. GEM has reallocated means to ensure automatic full winter measurements of snow density and temperature profiles at both sites. Further, a newly initiated PhD position at University of Copenhagen focusing on remote sensing methodologies for snow and vegetation interactions will use both Nuuk and Zackenberg for development of new methods and models to scale up key parameters from plot to drainage basin scale. Finally, several of the leading projects mentioned above (e.g. DEFROST, CENPERM etc.) will focus on this question.</p> <p>A proposed seasonal marine study will include sampling following the ice break-up, with the same procedures as in regular monitoring years, along with additional sampling during mid-summer and autumn, thus elaborating on the seasonal succession of species composition and ecosystem function. Information gathered during this extensive spring-autumn campaign will be combined with a planned winter campaign providing valuable knowledge during different stages of the sea ice season.</p>
Relevant projects	1-34, 36-46, 48-50, 61-65, 67-75, 84, 86, 87, 90-92
Expected outputs by 2015	GEM expects to contribute to a number of peer-reviewed papers related to phenology, NDVI, gasflux-experiments and effects of UV-B. Moreover, marine efforts relating to sea ice distribution and the marine ecosystem function and biodiversity is expected to produce around five scientific papers before the end of 2015.



Photo: Henrik Spangård Munch.

Question 9	How does the energy balance of arctic ecosystems (marine, terrestrial and limnic) change with climate change and variability?
Existing monitoring	<p>Since 2003, GEM has continuously increased its efforts of investigating energy balance feedback mechanisms in the terrestrial systems both through direct point measurements of energy balance and through extensive studies of snow cover distribution (being the most important physical parameter controlling the energy balance).</p> <p>Since 2008, the addition of a glaciological component to GEM led to the extension of the network of automatic weather stations to include glaciated surfaces, on the glaciers, GEM continuously monitors all heat fluxes, enabling the complete surface energy balance to be computed.</p>
New initiatives	<p>In 2011 the efforts have further increased through collaboration with the INTERACT project. Hence, an upgrade of two stations at Zackenberg and two in Nuuk, both fully equipped for energy balance investigations, has been implemented. GEM members are key partners in several large research projects focusing on the energy balance feedbacks. Some of these include INTERACT and DEFROST that will:</p> <ul style="list-style-type: none"> • improve monitoring and facilitate research into key feedback mechanisms from northern terrestrial ecosystems in a changing climate (INTERACT) • will focus on key terrestrial, lacustrine and marine cryospheric systems that have the potential for giving rise to substantial changes in climate feedback mechanisms both in terms of surface-atmosphere energy exchange and exchanges of greenhouse gases (DEFROST) <p>Work on the marine energy balance has until now mainly relied on research initiatives and studies conducted in other arctic regions. However, research efforts on direct measurements of CO₂ fluxes in the coastal/marine environment involve deployment of measuring towers, which will, as a first step, include latent and sensible heat measurements. Later plans include radiation measurements as well. A proposed mobile tower able to measure radiation on less monitored areas, like barren land and sea water surfaces, have also been proposed by the GEM group to enhance knowledge on energy balance feedback mechanisms on the entire arctic ecosystem. These projects, along with process studies in the Canadian Arctic, in collaboration with the Greenland Climate Research Centre, will produce information and form the basis for addressing issues on marine energy balance. As described for Question 11, the GEM group also intends to upgrade two existing automatic weather stations along the west coast of Greenland to become fully equipped energy balance stations. They will, together with the already existing stations, provide an opportunity to describe the energy balance changes along a latitudinal gradient in Greenland. GEM will also during 2012-15 initiate a project aiming specifically at understanding biological impacts on the energy balance during winter.</p> <p>As further detailed under question 11, distributed modelling of the surface energy balance is a major avenue of research when attempting to upscale from local or point observations to wider areas. Work will be carried out to take advantage of existing science and knowledge on the modelling of surface energy fluxes over glaciated surface.</p>
Relevant projects	25, 30-39, 41-46, 49, 54, 56, 61, 62, 66
Expected outputs by 2015	<p>A research paper on the current knowledge on high arctic energy balance component dynamics and potential climate feedbacks, based on Zackenberg data, will be submitted during 2012. Additionally, several PhD students (funded by DEFROST and INTERACT) attached to the group in Lund, will work specifically on the terrestrial energy balance feedback during the coming three years. A paper examining biological impacts on the energy balance during winter will be produced before the end of 2015. Further, external research projects, collaborating with GEM, aim at producing one to two scientific papers focussing on marine/coastal heat and radiation budgets before 2015. Furthermore, a paper with results from a newly established surface energy balance mast over the glaciated surfaces will also be published before 2015.</p>

Question 10	How does 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 ?
Existing monitoring	For the last 15 years active layer thickness have been monitored at only three sites in Greenland – two at Zackenberg and one at Disko. GEM delivers data to the long-term CALM network, which was initiated in the late 1980s in collaboration with the International Tundra Experiment (ITEX). Nuuk is placed within the sporadic permafrost zone, and no large permafrost areas have yet been identified. However, in the last five years freezing/thawing processes in the upper part of the soil layers have been monitored. In the same periods soil characteristics and nutrient variability has been monitored at the main plant communities in both Zackenberg and Nuuk.
New initiatives	<p>GEM is involved in several leading research centres and projects (e.g. CENPERM, DEFROST, PAGE21) that are focusing on permafrost and carbon balance studies including landscape processes. One of the results of these projects will be the installation of several 10 m deep boreholes at several sites along the coast of Greenland (including Zackenberg and Nuuk during 2012-13). Further, GEM delivers data directly to several large projects, in which the Zackenberg, Nuuk and Disko sites are main sites. Several of the GEM Coordination Group members are either leading or key members in these projects. Four of these projects include the Nordic Centre of Excellence DEFROST, Danish Centre of Excellence CENPERM, EU project PAGE21 and EU project INTERACT during the coming 45 years. The projects aim to:</p> <ul style="list-style-type: none"> • first to quantify the thermal state of the Greenlandic permafrost by permafrost drilling across all climate zones and landscape types relevant to mapping global permafrost degradation and associated environmental impact [CENPERM]. • to investigate the relations between melt-water processes and increased nutrient mobility following thawing of the permafrost in order to quantify potential future changes in microbial activity and plant cover. This includes investigations of the thermal state of the permafrost and erosion following permafrost degradation [CENPERM] • critically important gaps in understanding of permafrost thermal state and terrestrial landform processes and how these affect surface hydrology, carbon cycling, energy and greenhouse gas exchange and impacts on infrastructure and future landscape management will be filled [DEFROST] • identify and evaluate the key processes and parameters influencing and controlling the vulnerability of the arctic permafrost carbon and nitrogen pools to future climate change [PAGE21] <p>There will be a number of PhD's and Postdoc's enrolled within the GEM groups at University of Copenhagen and Aarhus University working on these topics, while others will be enrolled at Lund University and UNIS, both being very close collaborators with GEM.</p> <p>Disko will in 2012 be updated and included as a moist site in GEM with the possibility of obtaining full year-round data series of all soil parameters needed for further permafrost modelling.</p>
Relevant projects	1, 2, 5, 7, 12, 21, 23, 25, 28-35, 37, 40-50
Expected outputs by 2015	These projects will lead to more than 20 PhD and PostDoc positions that all focus on areas related to Question 10. Most of the results from these projects will be published in peer-reviewed journals but will also be used in assessments, presentations etc. More than twenty papers addressing this question are expected to be published before the end of 2015.

3.5 Up-scaling, modelling and prediction

This theme covers two different aspects: a) prediction based on models of what could happen in the future (temporal aspect) and b) up-scaling, which is extrapolation (sometimes by models) of data from the GEM sites to a larger areal coverage (spatial aspect). Results from GEM are already used for predictions, and several simple models exist predicting how temperature, sea ice cover or snow cover could look during different climate scenarios in the future. However, most of these models are geographically constrained to the study sites or close surroundings. To expand these models geographically we need better knowledge of how representative results from the GEM sites are on various scales (i.e. local scale (drainage basin), regional scale (i.e. Greenland) and large scale (i.e. the Arctic)). In particular the two latter require data from other sites in Greenland or across the Arctic. Several large projects are focusing on regional up-scaling (e.g. DEFROST and CENPERM), and GEM members participate or lead many of these projects with an important task to ensure that other Greenland studies are conducted to allow for direct comparison with existing GEM data where possible. Two principally different approaches to up-scaling are normally used: a) gradient studies, and b) remote sensing studies. The first relies on examinations along relevant gradients, and is often site-based,

Question 11 To what extent can results from GEM be used for up-scaling and prediction to address the questions above on a regional scale covering Greenland and the sea around Greenland (now and for the future) and what are the constraints for such up-scaling and prediction efforts?

Existing monitoring	<p>GEM serves two purposes with respect to up-scaling or prediction on Greenland ecosystems: 1) the knowledge and practical expertise that has been accumulated through GEM allows us to put forward well-founded hypotheses and to pin-point, which parameters would be relevant and possible to up-scale. 2) The time series available through the GEM monitoring will always be the back-bone of any regional up-scaling in Greenland. GEM constitutes a unique combination of ecosystem data from contrasting geographical locations and offers thus the possibility of addressing a variety of questions and comparing these across sites, and in time and space. This is unique for the Arctic.</p> <p>The primary constraints for up-scaling and modelling are funding and modelling expertise. However, as can be seen from the list of already initiated projects, GEM staff has succeeded in securing substantial funding for especially up-scaling outside GEM, and comparable field work is already being conducted at sites outside the GEM sites. Several papers have already been produced in which GEM data are used in regional or large scale studies covering important aspects such as biodiversity, population dynamics, and CO₂ dynamics. In addition, as mentioned above, the arctic centres in Nuuk and at Aarhus University have allowed more modellers into GEM related projects.</p> <p>On the glacier, current GEM work allows up-scaling of point surface energy and mass balance at the weather station sites to the entire glaciated surface of the glacier, based on observed seasonal and spatial trends.</p>
New initiatives	<p>Within GEM, a number of specific plans and projects for up-scaling already exist. These include up-scaling in relation to biodiversity, species composition, population dynamics, vegetation greening, and greenhouse gas exchange. In addition to these, a number of terrestrial, limnic and marine projects are focusing on studying differences in biological structure (species composition and diversity) and the processes that influence it along the existing climate gradients in Greenland. These studies are expected to produce knowledge of how climate in a broad term influences ecosystems, as well as providing up-scaling data that allow us to put the GEM sites into a regional context for several central parameters. Additionally, GEM will continue to support and contribute to external projects and international syntheses, such as the ITEX, ICOS) by a) providing central data and b) through scaling knowledge of local parameters and processes. Examples of major up-scaling initiatives are:</p> <ul style="list-style-type: none"> • Quantify and up-scale the importance of permafrost thawing, C and N cycling dynamics, shifts in vegetation types and root dynamics on ecosystem functions as well as greenhouse gas emissions on a regional scale in the coming decades and centuries [CENPERM] • Link pedon data to new land-cover classification products that have a much higher resolution (1 × 1 km and even 250 × 250 m), allowing for a second, independent and potentially more accurate up-scaling of existing soil carbon dataset. This new up-scaling approach will also provide a much better connection to the Earth System Modelling through the utilisation of common and consistent global land-cover classification schemes [PAGE21] • Large scale patterns in marine benthic biodiversity with focus on the climate gradient on the West Greenland coast (Marin 13, 14, 15, 25) • The importance of climate as regulator of near-shore marine ecosystem structure, function and biodiversity (Marin 17, 27, 28, 32) • Large-scale patterns in terrestrial biodiversity and ecosystem functioning with focus on the climate gradient in West Greenland (BIO23) <p>Additionally, several new PhD projects within GEM-related projects will be working on up-scaling of important parameters from plot to drainage-basin scale. Further, GEM will reallocate means to fund a PhD focusing specifically on further scaling of the GEM results (e.g. snow dynamics, greening of Greenland, carbon flux emissions etc.).</p> <p>GEM will also in 2012 host a workshop with focus on up-scaling of feedback dynamics and arctic ecosystem dynamics to higher spatial scales. The workshop will invite key principal investigators from not only CENPERM, DEFROST, PAGE21 and INTER-ACT but also other arctic groups (e.g. groups involved in Alaska, Canada and Svalbard). The purpose of the workshop is (i) to increase the knowledge within GEM on issues relating to up-scaling of ecosystem data, (ii) to increase our network with modelling and remote sensing community, (iii) to increase the interest in these communities to use our data for ground truthing and model calibration, (iv) to adjust the programme in relation to demands for up-scaling defined by relevant stakeholders and policymakers, and (v) to establish a coherent plan for up-scaling to a Greenland scale of relevant parameters from GEM.</p> <p>Taking advantage of established scientific results and knowledge on the up-scaling and modelling of surface glacier mass balance, it is planned already in 2012 to start up-scaling the mass balance modelling to other glaciers and ice caps surrounding the A.P. Olsen Land ice cap. This work will be done in cooperation between GEM and ice2sea members, based on input data from a regional climate model (RCM) from DMI and RCM with perfect boundary conditions from reanalysis climate data. Beyond this, external funding will be sought to setup a focused research project that will use additional field calibration and validation sites to upscale the modelling of glacier mass balance at the whole Greenland scale.</p> <p>GEM is already involved in up-scaling climate data from Zackenberg through investigating climate gradients along the coast of East Greenland. In addition, it is planned that full surface energy stations will be added to two existing automatic weather stations along the west coast of Greenland during the period of 2012-2013. Together with the instrumentation at Nuuk and Disko, these surface energy balance sites will allow GEM to calculate important N-S climate gradients along the west coast.</p>
Relevant projects	1-35, 37-42, 46-62, 65, 66, 68-70, 73-75, 77, 86, 87
Expected outputs by 2015	GEM will through data, collaborating projects and funding already available produce approximately thirteen scientific papers on up-scaling during the next 3-4 years. A coherent plan for our up-scaling efforts will be produced by the end of 2012 as an outcome of the planned workshop on up-scaling.

whereas the latter relies on modelling of data acquired via remote sensing. Gradient studies may be particularly relevant for scaling up highly complex parameters, or parameters with poorly known relationships to drivers. Remote sensing on the other hand can be an excellent way to do large scale studies of more parameters with well-known drivers. Typical data that can be extracted from satellites are information on sea ice cover, snow cover, ocean surface temperature, and plant greenness (land and sea). Generally, up-scaling beyond local scale has not played a big role in GEM so far, neither by gradient studies nor by remote sensing. However, during the next four years GEM will, where relevant and at the relevant scale, increase the implementation of up-scaling in general and remote sensing in particular. In addition, both local and regional patterns as well as remote sensing in general are focal areas in the Greenland Climate Research Centre and the new Arctic Research Centre at Aarhus University. Marine modelling efforts are in progress, in collaboration with the Greenland Climate Research Centre, on hydrography for both monitoring sites, and modelling of marine biological aspects are planned.

A prerequisite for the development of models is collaboration between modelers and ecologists, who have the data and the understanding of the dynamics of

Question 12	What models shall be developed to address the above questions on a regional scale (Greenland and surrounding sea)?
Existing monitoring and new initiatives	<p>A large number of relevant statistical models already exist, and currently the main task is therefore to ensure the essential data input to these models. While GEM data form the core for many modelling initiatives, both within and outside GEM, the biggest challenge is to ensure that data, through standardisation and harmonisation, can be cross-walked across projects, programmes and sites. In addition, in order to increase the up-scaling capacities of the GEM data, data collection and modelling must go hand-in-hand, and field protocols should be based on a sound statistical set-up, thus maximising the use of the data.</p> <p>A number of models are currently being applied within GEM (e.g. the SnowModel (Colorado State University, USA, in collaboration with GeoBasis); Species Distributions Models (BioBasis); Energetically based population models (BioBasis)). GEM members are also involved in a project aiming specifically at harmonising modelling efforts across platforms ('Pilot Centre for Predictive Socio-Ecological Modelling'). Further, as part of several of the mentioned external projects (DEFROST, PAGE21, CENPERM) there will be many resources put into the modelling of carbon dynamics of the arctic ecosystems:</p> <ul style="list-style-type: none"> • DEFROST will identify limitations of current Nordic climate models in terms of their capability to simulate the processes of observed changes in permafrost, snow and ice • PAGE21 will gather the three major modelling groups dealing with coupled climate models <p>On a regional scale, the GIPL-2.1 model driven by HIRHAM5, will be used to link a physical permafrost degradation numerical model to a GHG dynamic model. Permafrost temperatures and active layer depth have been simulated with GIPL 2.1, a nonlinear transient heat conduction model, for the glacier free surface of Greenland using the results of HIRHAM climate simulations as input data. The proposed modelling will be linked to other models, e.g. SnowModel, for integrating complex and high-resolution snow redistributions, latitudinal climate gradients and energy and moisture budgets.</p> <p>Modelling in general and how to incorporate modelling early in the development of the individual projects will also be addressed at the workshop mentioned under Question 11.</p> <p>The up-scaling of surface glacier mass balance will build on the existing code currently being used and developed at GEUS and at the University of Zurich. We anticipate that new parameterisation, especially for surface melt-water retention and snow and ice albedo will be necessary. GEM will be involved into this model development work, primarily by supplying the ground observations needed for assessing their performance of different parameterizations.</p> <p>For the marine compartment of the ecosystem, models are currently being developed for GEM sites on a valley/fjord scale. Currently no specific projects addresses regional models for the marine compartment of the ecosystem.</p>
Relevant projects	1-32, 34, 35, 37, 40-42, 45, 46, 48-55, 61-63, 65,93
Expected outputs by 2015	One paper will discuss parameterisations for glacier mass balance modelling and their performance in the context of up-scaling. A coherent plan for our up-scaling efforts will be produced by the end of 2012 as an outcome of the planned workshop on up-scaling.

Question 13	How can current monitoring and long-term research efforts in GEM most effectively be adjusted to meet current and future scientific needs and policy-related demands ?
Existing monitoring	<p>Since the implementation of Zackenberg Basic in 1996 and of Nuuk Basic between 2005 and 2007, the integrated ecosystem monitoring programme within GEM has continuously adjusted the individual sub-programmes and implemented changes to meet the always changing needs from both the scientific community (both within and outside GEM) and the decision-makers. This adaptive approach has enabled GEM to supply relevant data and knowledge on key questions regarding the arctic ecosystems and their role in global climate change.</p> <p>The present strategy and the associated working programme are results of this dialog and the continuous adjustments of the GEM programme based on a number of international reviews as well as the numerous results and experiences obtained through the long-term monitoring effort.</p>
New initiatives	<p>During the next four years, GEM will maintain and broaden its dialog with the relevant scientific communities and the decision-makers, thereby ensuring that GEM maintain its position as one of the most comprehensive and solid research and monitoring programmes in the Arctic. GEM is involved in a number of international projects and programmes also addressing the involvement of relevant stakeholders and policy-makers. Among these can be mentioned the CBMP (in which Denmark holds co-chairmanship with USA on the terrestrial component) and INTERACT (in which GEM takes lead on international cooperation with relevant organisations (e.g. IASC, AMAP, CAFF, SAON etc.) and projects (e.g. ICOS, GEOSS, LIFEWATCH, SIOS etc.).</p> <p>The workshop mentioned under Question 11 will also invite relevant stakeholders and policymakers to give a saying on societal needs in relation to future developments of GEM.</p>
Relevant projects	1-35, 40-42, 48, 49-55
Expected outputs by 2015	A coherent plan for our up-scaling efforts will be produced by the end of 2012 as an outcome of the planned workshop on up-scaling.

the ecosystem that is being modelled. Whilst most of the GEM members do not have sufficient modelling experience, they hold first-hand knowledge of the arctic ecosystems. Current and future modelling efforts will hence rely on collaboration with external projects. The international collaboration, evident from the extensive list of projects that GEM scientists are involved in, has led to more external funding and modellers being introduced to the GEM data and problems. This development will continue, and during the next four years, modelling will be a more integrated component of how GEM data are used and result in models that can assist in extrapolating data in time and space.

Most of the modelling takes place outside the GEM framework and can thus only partly be influenced by the GEM strategy. However, three general areas are in focus from a GEM point of view: permafrost, snow and sea ice cover. For each of these three parameters central questions are how seasonal dynamics and geographic coverage will change in the future and what the consequences will be on greenhouse gas exchange, element cycling (nutrients and carbon) and ecosystem structure (species composition and diversity). Projects exist that address these questions on local scale (fjord or valley) and most of the processes oriented research will take place within GEM whereas modelling will be done in associated centres. Currently ongoing modelling efforts (funded outside GEM) include 3D physical models of ocean circulation of the two fjords in GEM with plans to include modelling of primary production. When this model is in place scenarios with changes in melt-water input or sea ice cover can be run.

As part of a new up-scaling initiative GEM will supplement the existing climate stations at Zackenberg and Nuuk with full surface energy budget stations, will install new stations for surface energy balance at Disko, Narsaq and Qaanaaq. These stations will give important inputs to the state of the climate along the west coast of Greenland and will give valuable input when comparing climate trends in Greenland to global climate trends.