A conceptual framework for monitoring climate effects and feedback in arctic ecosystems

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This paper presents a conceptual framework for implementing the long-term ecosystem monitoring programme *Nuuk Basic* in low arctic Greenland. The overall purpose of *Nuuk Basic* is to collect long-term data quantifying seasonal and inter-annual variations and long-term changes in the biological and geophysical properties of the terrestrial, freshwater and marine ecosystem compartments in relation to local, regional and global climate variability and change. The overall aim of *Nuuk Basic* is to establish a data platform which enables (i) a thorough description and analysis of climatic effects on the structure, function and feedback dynamics of a low arctic ecosystem, (ii) together with its exiting high arctic counterpart, *Zackenberg Basic*, a more complete spatial coverage of the general climate–ecosystems interactions across the Arctic, and (iii) an understanding of the interactions between human utilization of natural resources and climate effects. The successful implementation and continued operation of *Nuuk Basic* will be secured by the internationally unique operational expertise Denmark/Greenland has gained through ten years operation of *Zackenberg Basic*.

Introduction

Background

The arctic climate displays dramatic changing. During the last 50 years temperature increases of 2-3°C have occurred throughout the Arctic (Chapmann and Walsh 2003), and projections for future arctic climate predict temperature increases of 5-7°C by the end of the 21st century (Kattsov et al. 2005). Indeed, pronounced climate changes are also expected for Greenland during the next 100 years with temperature increases of up to 6-8°C in Northeast Greenland following the expected retreat and reduction in the Polar Sea Ice (Storis) (Rysgaard et al. 2003). In contrast, temperatures are only expected to increase to 2-5°C in West Greenland. Similarly, precipitation in Greenland, in particular winter precipitation, has been predicted to increase 20-30% (minus evaporation) in the forthcoming 100 years (Kattsov et al. 2005).

It is also well-established that the Arctic during the past 3 decades has experienced considerable and rather dramatic changes in the Cryosphere and in ultraviolet (UV) radiation compared to previous time periods (Walsh et al. 2005, Weatherhead et al. 2005). For example, there has been an average reduction of up to 11%

of ozone over the last 25 years and since 1990 episodic reductions between 25-45% during spring. Future changes predict continuous low concentrations of ozone over the Arctic with concomitant high levels of UV radiation with increased negative impact on the arctic ecosystems which is most vulnerable for radiation in the spring (Weatherhead et al. 2005).

Similarly, the observed changes in the Cryosphere portray future dramatic changes. For example, associated with the behaviour of large-scale ocean-atmosphere fluctuations such as the Arctic Oscillation or the North Atlantic Oscillation, the thickness and the extent of arctic sea-ice have been reduced over the last 30 years, indicating 20% acceleration in the rate of the decrease of sea-ice in the Northern Hemisphere (Cavalieri et al. 2003). Concomitantly, the terrestrial snow-cover in the Northern Hemisphere has been reduced by 10% and with the expected temperature increase of 5-7°C further significant reduction in snow-cover is expected (Walsh et al. 2005). Coinciding with the measured increase in ground temperature in the Arctic, a significant degradation of permafrost has been observed. This is expected to continue with up to further 10-20% degradation during the 21st century resulting in a displacement of the southern range of permafrost hundreds of kilometres northward (Walsh et al. 2005). Notwithstanding the effects of increased temperature in the Arctic, the accumulation and thinning processes of the Greenland Ice Sheet are highly variable in time and space and are influenced by more than just atmospheric warming (Rignot & Thomas 2002). However, recent time series of maximum summer melt extent of the Greenland Ice Sheet do indicate a decadal trend of increased melt, in particular in West Greenland. Indeed dramatic melt rates such as those recently reported from the glaciers in the inner parts of the Godthåbsfjord (Rignot & Kanagaratnam 2006) – suggest potentials for not only increased sea-level rise by the 2100 (Walsh et al. 2005, Velicogna and Wahr 2006) but, equally important, an increased input of freshwater to the marine ecosystems in West Greenland.

Evidently, such changes in the climate, the Cryosphere and UV radiation will impose tremendous constraint on the terrestrial, limnic and marine environment of the Arctic with significant consequences for the structure, function and feedback of arctic ecosystems (Callaghan et al. 2005, Wrona et al. 2005, Weatherhead et al. 2005). Indeed, the consequences may be anything but simple. For example, following the projected increase in temperature considerably shifts in ecotypes are expected where the high arctic polar deserts will be replaced by low arctic tundra, which, in turn, will be invaded by forest like habitats (Callaghan et al. 2005). Such changes in the terrestrial vegetation will affect the feedback dynamics of gasses, where increased vegetation cover will increase net storage of carbon but increase the terrestrial flux of methane to the atmosphere (Callaghan et al. 2005). Similarly will the effects UV on individual metabolic rates perpetuate to ecosystem level and increased UV radiation is expected influence the entire cycle of nutrients.

To what extent complex climatic effects may be equally important across the low and high arctic ecosystems is currently unknown and a multidisciplinary approach to ecosystem monitoring is required to illuminate this. Indeed, this is the lesson learned from over ten years of monitoring of a high arctic ecosystem at Zackenberg in Northeast

Greenland. Through the monitoring program *Zackenberg Basic*, we have come to acknowledge that although large-scale trends in climate changes in the Arctic display clear trends of, for example, increased temperature and retreating sea ice cover, such changes are not necessarily observed in local climate. In fact, what have been observed at Zackenberg over the last ten years are weather conditions varying tremendously from year to year. More importantly, the ecosystem at Zackenberg is highly responsive to this with significant consequences for the function of organisms as well as the annual dynamics of gas fluxes (Meltofte 2002). In addition to the high variability in local weather and ecosystem responses, the research and monitoring at Zackenberg has also demonstrated that similar climate changes perpetuate across physical barriers causing similar responses in physical separated and evolutionary distinct organisms. For example, long-lived organisms such as the willow on land and marine mussels display similar annual growth responses to changes in snow and ice cover, respectively, mediated by large-scale climatic systems like the North Atlantic Oscillation (Schmidt et al. 2006).

Central to the scientific establishment of *Nuuk Basic* is the multidisciplinary knowledge of climate-ecosystem interaction gained through *Zackenberg Basic* including the aforementioned presence of local spatiotemporal variability as well as the potential numerating effects of climate. However, it is equally important to realise that the establishment of *Nuuk Basic* in low arctic Greenland comprise unique and urgently needed additions (ACIA 2005) to our understanding of climate impacts in the Arctic, which cannot be achieved through *Zackenberg Basic* alone. First, *Nuuk Basic* will enable a thorough description and analysis of climatic effects in a low arctic ecosystem. Second, together with *Zackenberg Basic*, *Nuuk Basic* will provide a more complete spatial coverage of the general climate-ecosystem interactions across the Arctic and, third, *Nuuk Basic* will provide us with a far better understanding of the interactions between human utilization of natural resources and climate effects.

Recommendations by ACIA and beyond

As exemplified above, persistent climatic changes are likely to cause rather complex and in many cases unexpected indirect changes in the arctic ecosystems (Forchhammer 2002, Forchhammer & Post 2004). Indeed, our ability to understand, monitor, evaluate and model the consequences requires a comprehensive synthesis of current knowledge of all available information on the observed and projected climatic effects across the Arctic. Recently, this challenge was taken up by the Arctic Climate Impact Assessment (ACIA), which has provided us with an unparalleled and comprehensive assessment of climate impacts based on previous observed concomitant changes in climate, terrestrial, freshwater and marine systems in the Arctic (ACIA 2005). Founded upon the large amount of information provided by the assessment, ACIA has specified a range of recommendations pivotal for future climate change research in the Arctic (Table 1). These together with those proposed by the Arctic Monitoring Assessment Programme (AMAP) in their Climate Change Effects Monitoring Programme (AMAP 2000) and in their follow-up of ACIA (AMAP 2005) and by International Conference on Arctic Research Planning II (ICARP II), specifically Working Groups 7, 8 and 9 (Prowse et al. 2005, Callaghan et al. 2005, Bengtsson et al. 2005) inherently form the objective core of the monitoring in *Zackenberg Basic* and *Nuuk Basic*. Indeed, most of the monitoring actions taken by the basis monitoring programmes, ClimateBasis, GeoBasis, BioBasis and MarineBasis (Rasch et al. 2003), confine with the recommendation issued by ACIA embracing the long-term monitoring of Cryosphere and hydrology, arctic tundra systems, freshwater systems, marine systems and ultraviolet radiation (Table 1). In contrast to *Zackenberg* Basic, which monitors an untouched pristine high arctic ecosystem, *Nuuk Basic* monitors a low arctic ecosystem in which natural resources are utilized by the indigenous human population. Hence the implementation of *Nuuk Basic* are in accordance with a central issue addressed by ACIA, namely the role of resource utilization and climate change affecting arctic ecosystems (ACIA 2005).

The recommendations provided by ACIA are formulated in a general context, that is, actions to be taken in future climate change monitoring are not specifically addressed to be carried out within a single ecosystem. Indeed, inherent to ACIA's (2005) notion on the need for increased spatial coverage of climate impacts, actions to be taken may be performed at different locations on selected organisms or communities without specifically monitoring the entire system in which these are embedded. In contrast and indeed as a unique additional feature, *Zackenberg Basic* and *Nuuk Basic* address ACIA recommendations within a selected ecosystem in the high arctic and low arctic region, respectively. Specifically, both programmes perform monitoring on all physical and biological levels of the ecosystem so all observed changes can be functionally connected and, hence, summarized and conveyed as ecosystem response to climate changes. In this perspective, the monitoring in *Zackenberg Basic* and *Nuuk Basic* not only complies with most of the recommendations by ACIA but also move beyond by providing as recommended by ICARP II (Prowse et al. 2005, Callaghan et al. 2005) new pivotal knowledge of (i) how an entire arctic ecosystem respond to climate changes and (ii) how these are perpetuated through the system as direct and indirect impacts (Forchhammer & Post 2004). The knowledge gained from system monitoring at *Zackenberg Basic* and *Nuuk Basic* therefore constitute a major and unique contribution to forthcoming revisions of the ACIA recommendations.

The concept of climate change and feedback

The interactions between climate and ecosystem can basically be regarded as a two-way process (Figure 1). First, any changes in climate such as increased variability in large-scale atmospheric-ocean systems will cause changes in the physical characteristics of ecosystems like snow and ice cover (Figure 1, arrow i). For example, the atmospheric fluctuations described by the Arctic Oscillation are closely associated with the last 35 years of inter-annual variability in snow onset, snowmelt, and number of snow-free days observed in the Northern Hemisphere (Bamzai 2003). Any climate-mediated changes in the physical characteristics will, in turn, affect the function of organisms and their interactions in the system. These effects may be divided into direct and indirect effects (Forchhammer & Post 2004). Direct climatic effects on the organisms themselves are easily observed with no time lags. For example, from the monitoring in *Zackenberg Basic*, we have learned that even small annual changes in the amount and extension of snow and sea ice have dramatic influence on for example seasonal growth, distribution and production of terrestrial vegetation as well as marine and freshwater plankton the following summer (Christoffersen & Jeppesen 2002, Mølgaard et al. 2002, Rysgaard et al. 1999, Tamstorf & Bay 2002). Indirect climatic effects, on the other hand, involve multi-organism interactions often between several trophic levels and are therefore more difficult to monitor using single-organism monitoring approach alone (Forchhammer & Post 2004). This has been recognised in several temporal ecosystem communities but also at Zackenberg. For example, we know that following winters with much snow and prolonged ice cover on lakes, the seasonal production of freshwater zooplankton decreases dramatically as a result of the low abundance of their food, phytoplankton, and not ice cover per se (Christoffersen & Jeppesen 2002).

The second aspect of the two-way interaction between climate and ecosystem is the reciprocal feedback from ecosystem to climate through changes in e.g. carbon, water and energy balances (Figure 1, arrows ii and iii). Documented from the work at Zackenberg and other studies, we know that changes in the physical characteristics of ecosystems are highly correlated with changes in for example the annual flux of carbon from system to atmosphere (e.g. Nordstrøm et al. 2001, Grøndahl et al. 2006). However, to what extent the climate-mediated changes in the biological diversity, function and structure of natural ecosystems affect the feedback induced exchange of carbon has not been described previously. In this context, the integration of Geo-, BioBasic and MarineBasis in *Zackenberg Basic* and *Nuuk Basic* offers a unique and unprecedented opportunity to bridge this gap of knowledge.

Specific integration of human resource utilization in the conceptual approach to monitoring climatic effects is rare although utilization of natural resources occurs throughout most arctic regions (Nuttall et al. 2005). In contrast to *Zackenberg Basic*, the monitoring of *Nuuk Basic* is performed in a system exposed to resource utilization (Figure 1, arrow iv) mainly through hunting and fisheries. Although *Nuuk Basic* is not planned to embrace specific monitoring of resource utilization, the programme is operated in a way that enables analytic comparisons with annual hunting statistics in West Greenland. The Institute of Greenland Resources and the National Environmental Research Institute has taken the first steps in establishing and maintaining databases to be used in context with *Nuuk Basic*. The difference between *Zackenberg Basic* and *Nuuk Basic* with respect to the influence of indigenous peoples presents a new and unique comparable aspect of climatic effects on arctic ecosystems.

The scientific structure

The ecosystem programmes *Zackenberg Basic* and *Nuuk Basic* each consist of four basis monitoring programmes related to the different physical and biological compartments representative of the ecosystem: ClimateBasis, GeoBasis, BioBasis and MarineBasis (Rasch et al. 2003), each focusing on providing long-term data within their compartments (Table 2). However, it must be emphasized that the four basis programmes are established and operated in a highly integrative manner (Table 1) to secure the overall goal of *Zackenberg Basic* and *Nuuk Basic*: collect long-term data quantifying seasonal and inter-annual variations and long-term changes in the biological and geophysical properties of the terrestrial, freshwater and marine ecosystem compartments in relation to local, regional and global climate variability.

The basis programmes of *Zackenberg Basic* and *Nuuk Basic* have been purposely constructed to be similar in order to enable a much more complete spatial coverage of the general climate–ecosystems interactions embracing both low- and high arctic regions. ClimateBasis, GeoBasis, BioBasis and MarineBasis have been described in detail elsewhere (Rasch et al. 2003) and will not be presented here. Instead, extending on these basis-specific descriptions, we present a thematic overview of their integrative associations across the major scientific physical and biological themes embraced by both *Zackenberg Basic* and *Nuuk Basic*. The scientific structure of the monitoring in *Zackenberg Basic* and *Nuuk Basic* embrace a total of 14 central themes covering the climatic (Climate), physical (Snow, Soil, Ice, Sea Ice, Lakes, Hydrology, Oceanography, UV radiation) and biological (Soil, Vegetation, UV radiation effects, Gas flux, Lakes, Arthropods, Mammals, Birds, marine pelagic- and benthic fauna and infauna) ecosystem compartments (Figure 2). What is obvious from Figure 2 is that both *Zackenberg Basic* and *Nuuk Basic* display highly integrated monitoring across the four basis programmes. A scientific summary of themes is given in Table 3.

The operational structure of Nuuk Basic is outlined in Figure 3. *Nuuk Basic* is the low arctic equivalent to *Zackenberg Basic*, and the different sub-programmes (Climate Basic, GeoBasic, BioBasic and MarineBasic) involved in *Zackenberg Basic* will also be responsible for the run of *Nuuk Basic*. As previously with *Zackenberg Basic*, the *Nuuk Basic* Working Group will be established with representatives from the different sub-programmes, logistics and relevant scientific key-supervisors with Danish Polar Centre as the secretariat. *Nuuk Basic* will be the monitoring component of the research programme Ecogreen in the same way as Zackenberg Basic is the research component of Zackenberg Ecological research Operations (ZERO).

It is the ambition to coordinate *Nuuk Basic* and *Zackenberg Basic* with other climate related monitoring activities in Greenland in a centre without walls, tentatively called the Greenland Climate Change Effects Monitoring Programme (Figure 3). One such example could be integration with the glaciological monitoring in Greenland funded by the Danish Environmental Protection Agency and operated by Geological Survey of Denmark and Greenland.

The geographic and logistic settings of *Nuuk Basic*

The study area of *Nuuk Basic* embrace two localities: the main locality is Kobbefjord and the satellite locality in Nordlandet (Figure 4). Whereas Nordlandet focus on climate-related interactions between reindeer and their forage and how these influence the flux of carbon between land and atmosphere, Kobbefjord embrace an entire drainage basin (Figure 4). Specifically, the Kobbefjord study area consists of: (i) A well-confined fjord without branches and with a surface area of c. 25 km^2, a maximum depth of c. 145 m and a sill at the mouth at a depth of c. 40 m, and (ii) a drainage basin with an area of 32 km^2 situated at the head of the fjord.

The local climate is low arctic with a mean annual temperature of -1.4 °C and a mean annual precipitation of 752 mm (1961-90). The drainage basin is situated in an alpine landscape with mountains rising up to 1.400 m a.s.l. and with glacier coverage of c. 2 km^2. Geologically, the area is homogenous with Precambrium gneisses as basement throughout the drainage basin. A well defined cross profile near the mouth of the local river enables easy measurements of drainage basin output, while the high mountains in the area allows for easy installation of digital cameras for snow cover monitoring. The terrestrial setting is diverse and includes the most typical vegetation types of a low arctic ecosystem within a very confined area. The area is well suited for monitoring the seasonal and inter-annual dynamics, carbon balance, biodiversity, zonal migration and structural and functional changes of terrestrial and freshwater communities.

In the fjord, the upper c. 15 m of the water masses is affected by freshwater input from the local rivers during spring and summer. In the photic zone, the sea-bottom is characterised by a high diversity of fauna. Well oxygenated bottom waters are present in the fjord but, low oxic conditions can occur locally in bays with low water exchange. In the deeper parts of the fjord oxygen penetrates c. 1 cm into the sea bottom during winter, but only a few mm during summer.

A small field station with accommodation facilities for four persons will be established in the drainage basin at Kobbefjord. Nordlandet will have two cabins, one for the accommodation of two persons and one for storage. These facilities will be used only for piecewise intensive field campaigns through out the entire annual season. The Greenland Institute of Natural Resources will accommodate Danish scientists during longer campaigns, and will provide office and laboratory facilities for programme staff and visiting scientists.

Outreach and public foundation

Due to the proximity of the *Nuuk Basic* field site to Nuuk, the Capital of Greenland, the programme has an excellent opportunity to involve the local population in the monitoring activities and as such in climate change related issues. Several perspectives are important. First, there is generally a very high level of interest in environmental research, and especially climate change research, among the Greenland population due to their high dependence on natural resources. With *Nuuk Basic*, it will be possible eventually to involve a nature interpretation and management services focussing on knowledge transfer and interactive education for local school and high school pupils. In practise, it will be possible to invite school classes on 1-day educational trips to the field stations at either Kobbefjord or Nordlandet introducing new generations in Greenland for the important aspects of climate effect monitoring. This is an excellent opportunity for Nuuk Basic which has not been possible with *Zackenberg Basic* due to its remote and isolated location in the heart of Northeast Greenland. Secondly, it is the clear intention of *Nuuk Basic* that as much of the work as possible shall be carried out by local staff. Specifically, the programme aims at employing local staff for operating the programmes under the supervision of Danish specialists. The logistics (i.e. maintenance of field stations at Kobbefjord/Nordlandet, transportation of scientists to and from field localities etc.) will be carried out by local labour employed at The Greenland Institute of Natural Resources.

As with *Zackenberg Basic*, the reporting of *Nuuk Basic* will be by annual reports with basic coverage of the annual results from the monitoring programmes and in popular journals and newspapers. However, in order to maintain the highest quality of the monitoring programmes, the publication in peer reviewed international journals is of highest priority to *Nuuk Basic*. Annual workshops will secure the optimal integration between the four basic programmes as well as the between *Zackenberg Basic* and *Nuuk Basic*.

Finally, a website for *Nuuk Basic* will be established. This website will contain information about the programme, a bibliography of programme publications, a database with free access to data from the monitoring a collection of the most recent popular articles stored as PDF-files. This website will be hosted by Danish Polar Centre, and attempts will be made to visualise on the internet the close link between *Zackenberg Basic* and *Nuuk Basic*.

International framework

In recent years, several attempts have been made to internationally coordinate monitoring in the Arctic by either establishing umbrella organisations, as for example Circumarctic Environmental Observatories Network (CEON) and Coordination of Observation and Monitoring of the Arctic for Assessment and Research (COMAAR), to encompass and coordinate existing international monitoring networks, projects and programmes, or by establishing, in different climate settings, a limited number of 'Flagship Observatories' or

'Supersites' such as those at Abisko Scientific Research Station, Svalbard, Toolik Research Station, Point Barrow, Cheerskii and Zackenberg Research Station, all with extensive, long-term, integrated and cross-disciplinary monitoring (Prowse et al. 2005, Callaghan et al. 2005, Study of Environmental Arctic Change 2005, Committee on Designing an Arctic Observatory Network 2006). The Zackenberg Research Station and *Zackenberg Basic* have been intensively involved in these international networks, as will *Nuuk Basic*. As flagship observatories, both *Zackenberg Basic* and *Nuuk Basic* will be at the forefront of already existing projects, programmes and networks (Table 4)

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Table 1. ACIA recommendations of relevance to Nuuk Basic

Recommendations	Programme	Action
Cryosphere and hydrology		
Sea ice: Fine resolution studies of sea ice cover in coastal waters	M	Satellite and photo surveillance
Sea ice: Seasonal, inter-annual and interdecadal measurements of sea surface albedo	M	Satellite surveillance (optional)
Snow cover: In situ measurements of snow water equivalents in high latitude areas	CG	Manual snow depth and density measurements
Snow cover: Measurements of snow albedo over northern terrestrial regions	CG	Point measurements, satellite surveillance (optional)
Snow cover: Establishment of models to simulate snow melt process	CG	Point and spatial through camera and satellite surveillance
Glaciers and ice sheets: Mass balance studies from regions where data are sparse	M/GEUS	None in programmes. Link to GEUS ice margin monitoring
Permafrost: Long-term field data on permafrost-climate interactions and on permafrost-hydrology interactions	G	CALM
River and lake ice: Improve understanding of hydrological and meteorological control of freeze-up and break-up	CBG	Hydrological monitoring, camera surveillance
Freshwater discharge: Increase the network of gauge stations for monitoring discharge rates	C	Hydrological monitoring
Freshwater discharge: Better estimation of subsurface flow		None
Arctic Tundra and Polar Desert ecosystems		
Biodiversity changes: Monitor currently widespread species that are likely to decline under climate change	B	Systematic monitoring of species
Relocation of species: Measure and project rates of species migration	B	Systematic transect monitoring (local/regional)
Vegetation zone redistribution: Improve information about current boundaries of vegetation zones	BG	NDVI monitoring (cameras, satellite)
Carbon sinks and sources: Long-term, annual C monitoring throughout the Arctic	G	Not whole year but summer and 'shoulder' periods (CO2 and CH4)
Carbon sinks and sources: Models capable of scaling ecosystem processes from plot experiments to landscape scale	BG	Spatial modelling
Carbon sinks and sources: Develop observatories to relate disturbance to C dynamics	BCG	Monitoring platform and database
Carbon sinks and sources: Combine ecosystem carbon flux estimates with C flux from thawing permafrost	G	Irrelevant to Nuuk Basic. No permafrost
Ultraviolet-B radiation and CO2 impacts: Long-term impact on ecosystem of increased CO2 concentrations and UV-B radiation	BCG	UV-B and CO2 monitoring
Increasing and extending the use of indigenous knowledge: Expand use of indigenous knowledge	G	None
Monitoring: More networks of standardised, long-term monitoring are required	BCG	It is the ambition that Nuuk Basic participate in all such networks
Monitoring: Integrated cross-disciplinary monitoring of co-varying environmental variables	BCG	The concept for this is developed in Zackenberg- and NuukBasic
Monitoring: Long-term and year-round eddy covariance sites and other long-term flux sites for C flux measurements	G	Seasonal, CO2 by eddy correlation, CH4 by chamber measurements
Long-term and year-round approach: Long-term observations are required	BCG	ClimateBasic year round, Bio- and GeoBasic seasonal
Long-term and year-round approach: Year-round observations are necessary to understand importance of winter processes	BCG	ClimateBasic year round, Bio- and GeoBasic seasonal

Table 1, continued. ACIA recommendations of relevance to Nuuk Basic

Recommendations	Programme	Action
Freshwater Ecosystems and fisheries		
Freshwater ecosystems: Increase knowledge on long-term changes in physical, chemical and biological attributes	BCG	Physical, chemical, biological monitoring
Freshwater ecosystems: Establish integrated, comprehensive monitoring programs at regional, national and circumpolar scales	BCG	It is the ambition that Nuuk Basic shall participate in all such networks
Freshwater ecosystems: Standardise internationally approach for monitoring	BCG	Standardised procedures developed for Nuuk Basic
Freshwater ecosystems: Improve knowledge of synergistic impacts of climate on aquatic organisms	BCG	Possible with existing data
Freshwater ecosystems: Increase understanding of cumulative impacts of multiple environmental stressors on fresh water ecosystems	B	Nuuk Basic mainly addresses undisturbed ecosystems in relation to climate
Freshwater ecosystems: Increase knowledge of effects of UV radiation - temperature interactions on aquatic biota	B	None
Freshwater ecosystems: Increase knowledge of linkages between structure and function of aquatic biota	BCG	Included in existing programmes
Freshwater ecosystems: Increase knowledge on coupling among physical/chemical and biotic processes	BCG	Included in existing programmes
Marine Systems		
Observational techniques: Increase application of recently developed techniques	M	Yes, state-of-the-art equipment and techniques in use
Surveying and monitoring: Undertake surveys that are poorly mapped and whose resident biota has not been surveyed	M	No investigations like this before the Zackenberg and Nuuk Basic
Surveying and monitoring: Continue and expand existing monitoring programs	M	It is the ambition that Nuuk Basic shall participate in international cooperation
Surveying and monitoring: Evaluate monitoring data through data analysis and modelling	M	Included
Data analysis and reconstruction: Reconstruct twentieth century forcing field		None
Data analysis and reconstruction: Establish database with all available physical and biological data	M	Included - data can easily be provided to other databases
Data analysis and reconstruction: Recover past physical and biological data	M	Included
Data analysis and reconstruction: Past climate events to understand physical and biological responses to climate forcing	M	Included
Field programs: Undertake field studies to quantify climate-related processes	M	Major purpose
Modelling: Develop reliable regional models	MB	Included
Approaches: Prioritize ecosystem based research by integrating multiple ecosystem components in models concerning climate effects	MB	The concept in both Nuuk and Zackenberg Basic
Ozone and Ultraviolet Radiation		
Ultraviolet radiation: Address the impact of increased UV irradiance	BCG	Included

B: *BioBasic,* ***G:*** *GeoBasic,* ***C:*** *ClimateBasic,* ***M:*** *MarineBasic,* ***GEUS:*** *Geological Survey of Denmark and Greenland*

Table 2. The specific aims of the four basis monitoring of *Zackenberg Basic* and *Nuuk Basic*: ClimateBasis, GeoBasis, BioBasis and MarineBasis. Adopted from Rasch et al. (2003).

Basis Programme	**Aim**
ClimateBasis and GeoBasis	Provide long-term data that are: • Necessary for describing all aspects of the regional climate at Zackenberg and Nuuk. • To be used to quantify and model the variation in snow cover at Zackenberg and Nuuk. • To quantify the freshwater, sediment and nutrient transport from the terrestrial system to the marine system. • To quantify, together with BioBasis and MarineBasis, the carbon balance of the terrestrial part of low and high arctic ecosystems. • To improve current understanding of the effect of climate variability on the physical landscape dynamics.
BioBasis	Provide long-term data: • To establish ecological base-line data for evaluating and modelling how climatic changes, directly and indirectly, sum up and affect an entire low and high arctic ecosystem, respectively. • For the fundamental knowledge of the spatio-temporal dynamics of a low and high arctic ecosystem in a changing climate. • To describe and quantify intra- and intertrophic processes. • To describe and quantify short- and long-term changes in UV radiation effects, species composition and the communities in which they are embedded. • To describe and quantify short- and long-term changes in individual life history of central floral and faunal species.
MarineBasis	Provide long-term data: • Necessary for modelling the coupling between physical oceanography and biological production and consumption. • For use in modelling the regulation of pelagic-benthic coupling (vertical flux). • To quantify and improve understanding of the lateral coupling (land/fiord/sea). • To quantify the effect of changing freshwater input, sea ice cover and deepwater formation on biological production and consumption. • To improve current understanding of the effect of climatic changes on selected species composition and adaptation in the arctic marine environment.

Table 3. Summary of the central scientific themes embraced by the four basis programmes in *Zackenberg Basic* and *Nuuk Basic*.

Scientific theme	Description
Climate	Temperature (air, surface and soil), wind, humidity, precipitation
Snow	Cover, thickness, distribution
Hydrology	Water balance, nutrient cycling
Glacier ice	Iceberg export to Godthåbsfjord
Sea ice	Cover, thickness, distribution
UV radiation	Strength, seasonal, inter-annual variations and ecosystem effects
Soil	Water balance, chemistry, soil arthropods, decomposition
Vegetation	Species diversity, growth, reproduction, phenology, parasitism, distribution of vegetation types, UV radiation effects
Gas flux	Carbon dioxide, methane, interactions with structure and function of herbivore-plant interactions
Lakes	Chemistry, Carbon balance, abundance and production of plankton and fish
Arthropods	Insect abundance, reproduction and phenology
Mammals & Birds	Selected terrestrial, freshwater and marine species, species diversity, Abundance, distribution, reproduction, phenology
Water phase	Temperature, salinity, currents, chemistry, carbon balance, plankton, crustacean, fish.
Sea bottom	Chemistry, carbon balance, growth, abundance and distribution of benthic animals

Table 4. Projects, programmes and networks in which *Zackenberg Basic* is and *Nuuk Basic* will be involved. More information is given by the attached reference or web site.

Acronym	Name	Reference / Web page
ABBCS	Arctic Birds Breeding Conditions Survey	http://www.arcticbirds.ru/
ACD	Arctic Coastal Dynamics	http://www.awi-potsdam.de/acd/
CALM	Circumpolar Active Layer Monitoring Programme	http://www.geography.uc.edu/~kenhinke/CALM/
CEON	Circumpolar Environmental Observatories Network	http://www.ceoninfo.org/
ENVINET	European Network of Arctic-Alpine Environmental Research	http://envinet.npolar.no/
GRDC	Global Runoff Data Centre	http://grdc.bafg.de/servlet/is/Entry.987.Display/
ITEX	International Tundra Experiment	http://www.geog.ubc.ca/itex/
SCANNET	Scandinavian / North European Network of Terrestrial Field Basses	http://www.scannet.nu
CHASM	The Committee for Holarctic Shorebird Monitoring	http://www.caff.is/sidur/uploads/Shorebirds.pdf

Figure 1. Conceptual visualization of the interactions between climate and ecosystem response (i, ii), ecosystem feedback (iii) and human resource utilization (iv).

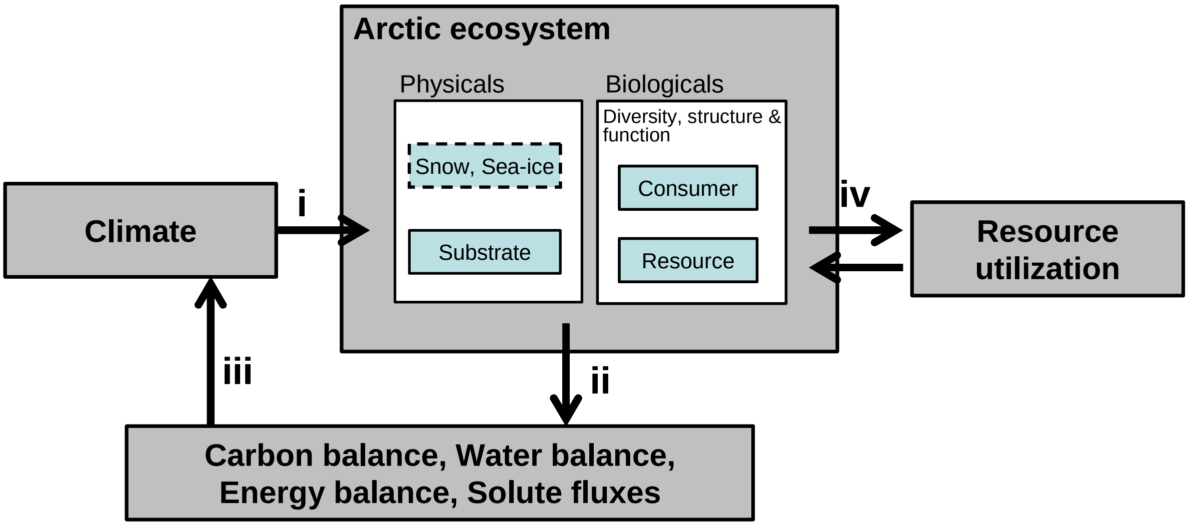

Figure 2. Schematic landscape representation of the major scientific themes in *Zackenberg Basic* and *Nuuk Basic* and how these are related to the four basis monitoring programmes: ClimateBasis (C), GeoBasis (G), BioBasis (B) and MarineBasis (M). Under each theme title is given the capital letters for the basis programmes involved.

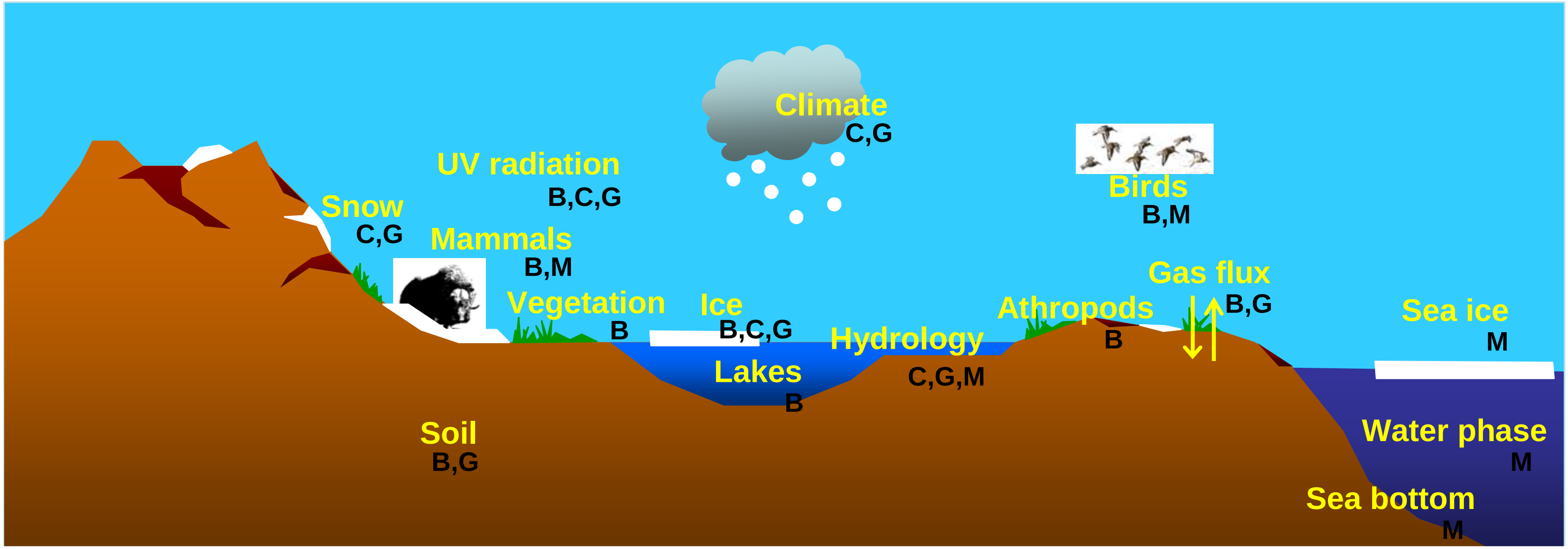

Figure 3. Operational structure for *Nuuk Basic*. **GCCEM**: Greenland Climate Change Effects Monitoring. **ZERO**: Zackenberg Ecological Research Operations. **UofC**: University of Copenhagen. **NERI**: National Environmental Research Institute. **GINR**: Greenland Institute of Natural Resources. **DPC**: Danish Polar Centre.

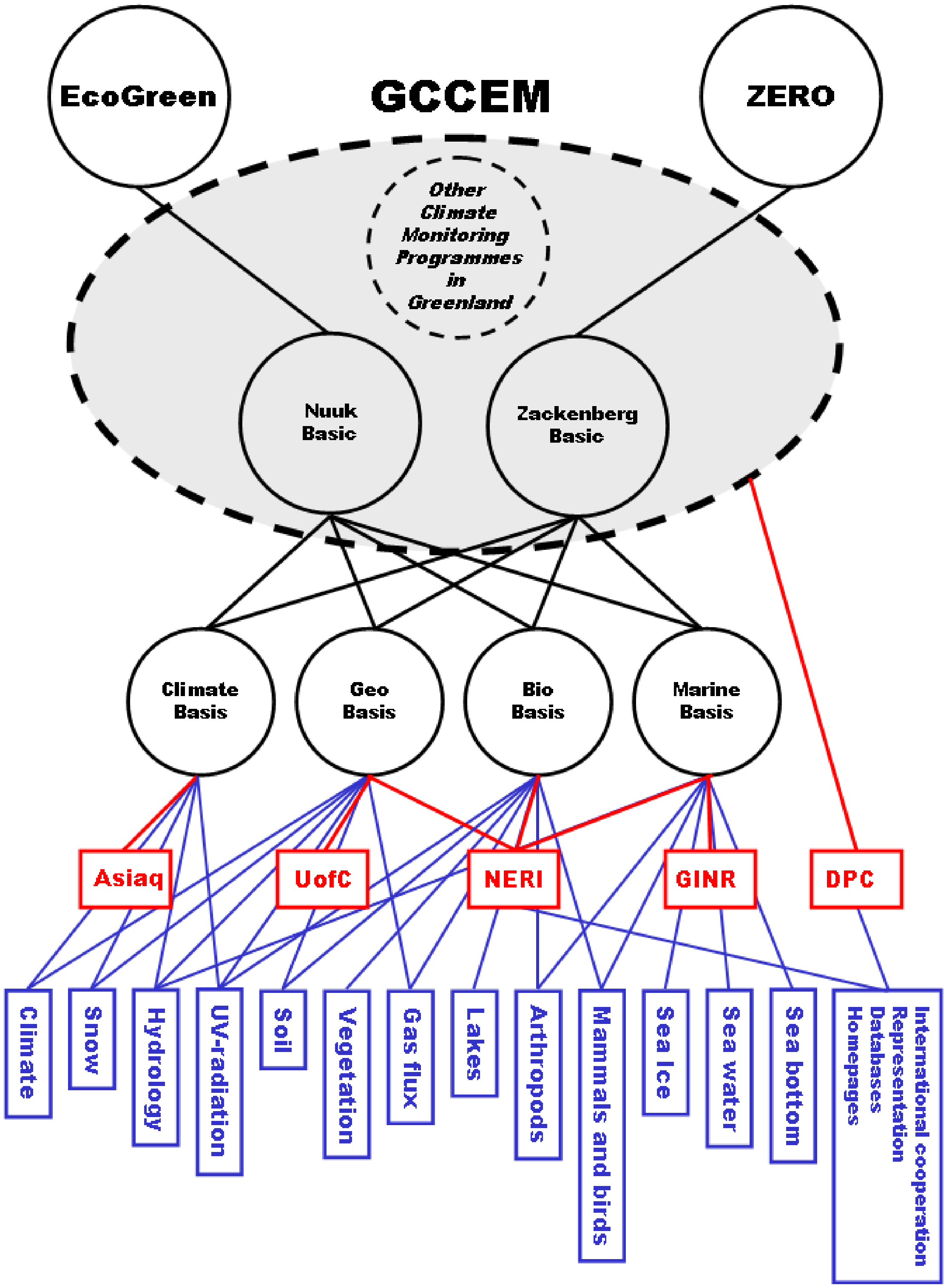

Figure 4. (a) Locations of *Zackenberg Basic* and *Nuuk Basic*. (b) The entire Godthåbsfjord system in which *Nuuk Basic* with the fieldstations at Kobbefjord and Nordlandet is located. (c) The entire drainage bassin and associated terrestrial, freshwater and marine environments at Kobbefjord.