NATURAL ENVIRONMENT RESEARCH COUNCIL

Arctic Research Programme
Science Plan

1. Summary

The Arctic is a region of very rapid change, driven by climate change in the form of rising temperatures, and other global pressures. This situation may lead to a step change within the Arctic system associated with rapidly declining summer sea ice and melting permafrost, resulting in major impacts both within the Arctic and more widely within the Earth System, via physical and biogeochemical feedbacks. Because of the importance of understanding this region and its interactions with the global Earth System, NERC is investing £15m over the period 2010-2016 in an *Arctic Research Programme*. The programme will be achieved through delivery of four linked scientific objectives.

2. The Research Programme's Objectives

The overarching aim of this programme is:

> To improve capability to predict changes in the Arctic, particularly over timescales of months to decades, including regional impacts and potential for feedbacks on the global Earth System

This will be achieved via four linked scientific objectives:

Objective 1	Understanding and attributing the current rapid changes in the Arctic
Objective 2	Quantifying processes leading to Arctic methane and carbon dioxide release
Objective 3	Reducing uncertainty in Arctic climate and associated regional biogeochemistry predictions
Objective 4	Assessing the likely risks of submarine hazards associated with rapid Arctic climate change

3. Scientific Background

The Arctic is a region of higher than average climate change and is predicted by IPCC AR4[1] to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that are not yet clear. The loss of sea ice and degradation of permafrost represent potential "tipping points" in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes may also initiate widespread destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK.

There is urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades. These changes reflect both natural variability and the response to anthropogenic radiative forcing, and there is a need to better

[1] http://www.ipcc.ch/ipccreports/ar4-wg1.htm

understand both. The radiative forcing arises from increasing levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents (e.g. anthropogenic aerosols, ozone). The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

Changes in the Arctic have the potential to affect global climate through albedo feedbacks (surface and/or cloud) as well as changes in atmosphere and ocean circulation. The removal of sea-ice enhances ocean to atmosphere heat fluxes, particularly in autumn, with the potential to cause substantial changes in atmospheric circulation. Increased fresh water inputs to the Arctic Ocean induced by global warming and changes in atmospheric forcing could increase freshwater export from the Arctic and disrupt the global thermohaline circulation. These global consequences need to be better understood and risks quantified. Although a related issue, research on the stability of the Greenland Ice Sheet will not form part of this programme.

Climate change (and other global change) pressures (e.g. nitrogen deposition), within the Arctic can lead to major changes in regional biogeochemistry and biodiversity. These can affect the whole Earth System, notably via changes in carbon storage and land/atmosphere and ocean/atmosphere greenhouse gas (particularly carbon dioxide and methane) exchange, as well as impacts on aerosol and ozone formation. We need research to understand the scale of present day and potential future changes in both marine, terrestrial and freshwater biogeochemistry and biodiversity, their impacts on the carbon and nitrogen cycle and feedbacks on the Earth System. We need to interrogate Arctic palaeo and archaeological records to describe post-glacial patterns of physical, biodiversity and biodiversity change and hazardous events associated with environmental change. We also need studies of the last interglacial (Eemian), a potential analogue of a future warmer Arctic.

Climate change will cause major changes in Arctic physical systems, largely as a consequence of permafrost and ice melt and gas-hydrate destabilization. These have implications for Natural Hazards risks, both within the Arctic (with fast growing population, infrastructure and economy) and beyond. Many individual processes and linkages between hydrological, cryospheric and geological systems are poorly understood, leading to inadequate predictive models. There are major challenges in determining system thresholds that may precipitate hazardous events, such as landslides and tsunamis, particularly under different rates of temperature and pressure (sea-level) change.

A variety of boundaries have been proposed to define the limits of the Arctic, including the tree-line, climatic boundaries (such as the atmospheric Arctic Polar Front), permafrost extent on land and maximum sea-ice extent on the Ocean. For the purposes of the Arctic Research Programme, the boundary will be more flexible, and will encompass sub-arctic land and ocean areas integral to the functioning of the Arctic system (ACIA, 2004[2]). A flexible height boundary will be applied, to encompass those regions of the atmosphere that demonstrably influence tropospheric and surface climate in the Arctic.

[2] http://www.acia.uaf.edu/

4. Strategic Context

The Arctic represents a critical region for global environmental change where the UK has significant strategic interests. Understanding the drivers and feedbacks of this change and predicting its scale and rate on timescales from months to decades represents a major and urgent global scientific challenge of great societal importance. It is timely to invest in this research programme now due to the rate and scale of change in this region, opportunities for collaborative research with international partners and the availability of new tools for remote sensing and direct measurements in this hostile environment.

Understanding current Arctic change is important in order that policymakers are well informed of its significance and Arctic communities are prepared to mitigate and adapt to its impacts. This research programme will enhance abilities to:

- forecast both regional and global weather and climate, over a wide range of timescales;
- forecast hazardous events, and develop mitigation strategies for these;
- plan for exploitation of resources such as minerals, methane hydrates and fisheries; and
- facilitate transport management and security issues related to polar sea-routes.

The programme has been developed as part of the NERC Earth System Science, Climate System, Natural Hazards and Biodiversity Themes[3]. Relevance to the Climate Theme is in understanding the recent changes in Arctic climate and improving predictions of the changes to be expected over the coming decades in aspects such as albedo or atmosphere/ocean circulation and their consequences for the global climate system. Earth System Science interests focus on the rate and scale of changes in the Arctic which impact the regional environment and global Earth System via a series of key physical, biological and biogeochemical feedbacks. The Natural Hazards investment relates to slope failures leading to submarine hazards, in particular submarine landslides associated with rapid climate change and the release of methane from geological sources. The primary focus of the Biodiversity Theme in the Arctic programme concerns improving understanding of major biogeochemical cycles (particularly Carbon and Nitrogen) in the Arctic, and the way these cycles may respond to environmental change. Biodiversity, particularly micro-organisms, plays an important functional role in these cycles but this role is rather poorly understood in terms of the ecological processes involved and the way these might respond to environmental change.

The programme will directly address many NERC strategy challenges including; cryospheric change and its interaction with the Earth System, destabilisation of methane hydrate stores under global warming, submarine hazards associated with rapid climate change, improving understanding of biodiversity's role in ecosystems: processes, resilience and environmental change and increasing knowledge of the role of the polar and tundra regions in the global climate system.

By working in partnerships with organisations such as the Met Office and Department for Energy and Climate Change (DECC) the programme will contribute to Living With Environmental Change (LWEC)[4], in particular addressing LWEC objectives on predicting the impacts of climate change, promoting sustainable solutions through mitigation and adaptation, and managing ecosystem services for human well-being and protecting the natural environment in a changing world.

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[3] http://www.nerc.ac.uk/research/themes/

[4] http://www.lwec.org.uk/

A number of recent activities have set the context and priorities for UK science in the Arctic:

- NERC Polar Science Working Group Report[5]
- Priorities for future UK marine Arctic research[6]
- UK Arctic terrestrial research: achievements and priorities[7]

These reports form an important basis for the development of the Arctic programme, have influenced the science topics included and have informed prioritisation decisions within the programme. This Science Plan defines the science priorities of the programme; however, these documents provide additional information which may be relevant when preparing proposals.

5. The Research Programme Science Deliverables

In order to achieve the *Objectives* set out above the programme will produce *Deliverables* via research projects that focus on the specific topics below. These *Science Topics* have been selected to address scientific uncertainties within the Arctic region that are strategically important, associated with rapid change and where the UK can make a significant contribution. Activities will include a mixture of fieldwork, laboratory studies, remote sensing and modelling. Observational and modelling activities will be coordinated within and between projects from the outset, to ensure the modelling informs observations and vice versa. This will ultimately allow the programme to improve, test and validate models and prediction systems for the Arctic and the wider Earth System.

Programme research projects will be linked and will operate to form an integrated programme, enabling the identified aims and objectives to be effectively addressed. Integration will be achieved via a range of pre- and post-award activities, including programme events and workshops, that will allow researchers to come together to find synergies and align their work programmes.

All programme research projects will be required to produce *Deliverables* of one or more of the following types:

- new or improved models for process studies;
- improved parameterization of Arctic processes;
- improved capabilities for predicting changes in the Arctic; or
- interpretation of current Arctic climate change and its implications for policy makers and Arctic communities.

All programme research projects will be required to address one or more of the four programme *Objectives* by focusing on one or more of the following *Science Topics*:

[5] http://www.nerc.ac.uk/research/areas/polar/documents/polar_science_working_group_report.pdf
[6] http://www.oceans2025.org/PDFs/SOFI%20Workshop%20Reports/SOFI_Workshop_Report_7_Marine_Arctic_09.pdf
[7] http://www.shef.ac.uk/aps/uk-terrestrial-arctic/index.html

Objective 1 Topics: contributing to understanding and attributing the current rapid changes in the Arctic

1.1 Large scale variations in the energy and water budgets of the Arctic region

The Arctic is changing, with clear shifts in energy and water budgets over recent years, although distinct regional and temporal patterns are evident. A reduction in sea ice cover and duration of snow cover has also occurred. Freshwater discharge into the Arctic Ocean has been increasing, with changes in the peak timing of this runoff and the relative quantities from different sources. Freshwater storage in the Arctic Ocean and glacial runoff have increased significantly in recent decades. Vegetation composition and coverage has shown regional changes that influence albedo and snow cover.

These Arctic changes are caused by a complex set of interacting factors that are not fully understood. For instance, the extent and speed of sea ice loss exceeds many model predictions. There is still uncertainty over whether warming has been driven internally or externally – for instance, through reduced snow cover or by advection of warmer air from lower latitudes. The Arctic is not a closed system; for instance, several of the main river basins feeding the Arctic Ocean extend far south into other biomes. The clear increase in freshwater inputs to the Arctic Ocean may have two responses: increased output to the Atlantic, and increased storage. Relative magnitudes and mechanisms are poorly known.

There is a need therefore for further analytical, modelling and remote sensing studies to quantify and diagnose trends in the energy and water budgets of the Arctic. New research should focus on the spatial and temporal variation in patterns of atmospheric circulation, sea ice, ocean circulation, river discharge, snow cover, and energy budgets, and their feedback linkages. For instance, it is critical to explain the observed trends and annual variability in sea ice cover, the links between snow cover, vegetation change and river discharge over recent decades, and the role of changing land surface characteristics on energy balance and warming over past decades.

1.2 Understanding and addressing uncertainties in radiative forcing effects in the Arctic

Radiative forcing due to increased CO_2 levels is generally well understood. However, the radiative forcing associated with e.g. changes in tropospheric and stratospheric ozone, water vapour and due to volcanic forcing and solar variations are much more uncertain, if indeed represented at all. For example, the majority of climate models simply impose linear, monthly and zonally-averaged ozone trends in the stratosphere which are not fully coupled (chemically or dynamically) and do not represent natural variability. There is uncertainty in the modelling of current and future ozone depletion. For example, while there is general consensus among coupled chemistry models that reductions in CFC emissions will result in the recovery of stratospheric polar ozone during the coming decades, there is a large variation of ~20 years in the predicted time at which the turnaround from depletion to recovery will occur. Increases in stratospheric water vapour, partly due to increased methane, may have influenced recent surface temperature trends. However, these effects are not currently included in climate models and there are considerable uncertainties both in observations of stratospheric water vapour and in our understanding of the forcing and feedback mechanisms involved. Solar variations are included in climate models via changes to the total solar irradiance and hence its direct influence on surface temperatures, but its indirect impact through increased stratospheric heating and ozone production is not currently included. A further source of radiative forcing uncertainty in the future may come from increased emissions of short-lived species due to re-routing of shipping and aviation routes.

Understanding the relative contributions of these various factors to surface temperature trends is required for improved attribution of current Arctic changes and predictions for the future. Most current climate models include the coupled ocean and atmosphere system but only extend to ~10 hPa and are unable to fully represent radiative, chemical or transport processes in the stratosphere. On the other hand, coupled chemistry models that fully resolve stratospheric processes are not generally coupled to the ocean. Recent model developments that include the fully coupled ocean-troposphere-stratosphere climate and Earth System will enable an estimation of the relative influence of these stratospheric influences on predictions of e.g. surface Arctic temperatures, precipitation and sea ice extent.

1.3 Production of aerosols and clouds and their radiative effects in the Arctic

Absorption and scattering of radiation by aerosols directly affects the radiation balance of the Arctic. This region is especially vulnerable to changes in radiative fluxes because of the small amount of solar energy normally absorbed in the polar regions and the highly reflecting surface, enhancing aerosol-radiative interactions due to multiple scattering of short wave radiation. The Arctic is also sensitive to the indirect effect of aerosol particles acting as cloud condensation nuclei (CCN) and ice nuclei (IN). Hence, changes in aerosol properties are likely to have a significant impact on microphysical and optical cloud properties.

Each winter through spring, long-range transport from northern Eurasia results in a persistent Arctic Haze, rich in sulphate and with a particle size range that is very efficient at scattering solar radiation. The haze also is weakly absorbing due to the presence of black carbon. Arctic climate is particularly sensitive to black carbon deposition on highly reflecting snow and sea ice. The sulphate-containing aerosol within Arctic Haze is also thought to impact ice nucleation. The changing composition of the Haze has been proposed to have substantially contributed to Arctic warming.

The production of local nucleation and Aitken mode particles, particularly in the summer, may be influenced dramatically through the impact of changing sea-ice cover and ocean productivity on fluxes of DMS, sea-spray and sea surface microlayer-derived organic particles which may act as both CCN and IN. Estimates of the impact of increases in DMS emissions suggest significant changes to summer aerosol concentrations and the radiative balance in the Arctic region.

Current understanding of the changing trends in aerosol in the Arctic and associated radiative effects, due to complex interactions between aerosols, clouds and radiation, is poor. This topic offers the opportunity to improve the understanding of such processes with coordinated observations using aircraft, ship, satellite platforms, and research stations as well as laboratory measurements and model experiments.

This topic should complement but not duplicate the £3m NERC research programme Aerosols and Clouds, likely to commence in 2011.

1.4 Role of physical oceanic processes in recent Arctic change

Many large-scale quasi-permanent features of the Arctic Ocean are well-recognised, such as the seasonally-varying sea ice cover, the halocline, Atlantic and Pacific inflows, the various freshwater inputs; and we are beginning to detect long-term (multi-decadal) changes in these features. However, the Arctic Ocean and sea ice system is extremely difficult both to measure accurately and to model accurately, by reason of (i) inaccessibility, and (ii) small scales. Firstly, inaccessibility. For the ocean, this is a direct result of the sea ice cover. Making in situ measurements from ships is challenging, as is the deployment and recovery of fixed (moored) installations. Also, while some sea ice and ocean surface properties can be measured remotely, the interior of the sea ice itself and the immediately underlying ocean are also hard to measure. Secondly, small scales. The deformation radius of the deep ocean is ~10 km, while in the shallow shelf seas it is ~1 km. Furthermore, sea ice is highly heterogeneous at and below the scale of the sea ice floes (ca. 100 m –5 km) due to processes that control the large-scale heat, mass and momentum balances of the ice cover, the heterogeneity being caused by processes such as sea ice deformation due to pressure ridging and lead formation, melt pond formation, snow redistribution, and new sea ice formation from frazil ice.

Properly representative measurements are hard to achieve when important processes may be small or narrow; similarly, the ocean and sea ice system may not be modelled with confidence when the desired spatial resolution may be at the limit of, or even beyond, the capabilities of the present generation of computers. From the perspective of regional and global climate impacts, we need to determine the nature and causes of variations in import, storage and export of heat, freshwater, salinity and greenhouse gases. Many physical processes are directly implicated. Few of them are adequately described, quantified or understood, either temporally, both in terms of seasonal and interannual variability and long-term trends, or spatially, in terms of wide geographical distribution or of critical locations. There are convincing indications that some may yet be quite unrecognised. This topic aims to correct these deficiencies.

1.5 Understanding modes of atmospheric circulation variability and their Arctic ice/ocean system interactions

Changes in modes of circulation such as the Arctic Oscillation (AO), North Atlantic Oscillation (NAO) and Pacific North American (PNA) modes could lead to changes in Arctic climate through changes in heat and moisture transport, winds and the subsequent effects on ocean circulation, transport of pollutants and land surface warming and runoff. For example, the winter time polar dome currently presents a barrier to pollution transport from lower latitudes, but the fast warming of the Arctic may lead to more efficient pollution transport from industrialised regions at lower latitudes. The major factors and mechanisms that influence these modes of circulation and how they might change in the future, e.g. the changes in location and strength of the mid-latitude jet and frequency of blocking events, are not well understood.

There may also be important feedbacks between Arctic warming and Northern Hemisphere circulation patterns, for example through sea ice loss. Additional heat can be stored in the Arctic Ocean after summers with below-normal ice extent, and if the fluxes of heat and moisture from the surface to the atmosphere in autumn are anomalously large, this can lead to a deeper and less stably stratified boundary layer and a more negative NAO index during the subsequent autumn. Continued Arctic warming will lead to increases in summer meltwater inputs from land to ocean, which could, through ocean freshening, make winter sea ice formation easier. Verification of the exact nature of the changing climatology and its impacts, using data from satellites and long term research stations, as well as improved model simulations, will be vital.

1.6 Identifying long term biogeochemical and biodiversity changes from Arctic palaeo records

Palaeorecords from terrestrial and marine sediments detail long-term changes not available at the annual or decadal scales of modern observations. In particular, palaeorecords provide (1) a baseline for evaluating current trends and variability, (2) proxy data for validating process, climate, and Earth System models, and (3) insights on future environmental conditions. For example, records from the previous interglaciation (Eemian) document the last time when Arctic sea ice was significantly less extensive than today, and records of early-Holocene summers in the Arctic indicate conditions generally warmer than present; both periods thus provide insights into ecosystem diversity and function in a future warmer Arctic. Over the past 1000–2000 years, climate means approximate modern conditions but include, on decadal-to-century scales, the fluctuations of the Little Ice Age and Medieval Optimum; this period provides a fuller context for observed 20th Century changes. Temporal patterns of Arctic and sub-Arctic carbon sequestration inform Earth System model simulations of past carbon dynamics.

At timescales of millennia and longer, the marine geological record of the Arctic informs our understanding of Arctic palaeoclimates and hence contemporary studies of high-latitude cryospheric, atmospheric and oceanic processes. Variations in ice-ocean-climate interactions on the Polar North Atlantic margins have produced a distinctive sedimentary record containing multi-proxy archives that indicate changes in biogeochemistry, biodiversity, and palaeoceanography. The timing and structure of glacial-deglacial cycles in the Arctic (especially the warmer than the present-day Eemian deglacial) and the initial inflow of Atlantic water into the Arctic Ocean are not well constrained. A significant unknown is the response of the central Arctic Ocean to the loss of sea-ice. New techniques provide proxy records of key biogeochemical parameters (e.g., pH, redox state), and study of the Eemian sediment record beneath present-day sea-ice to establish a multi-proxy record of biogeochemical processes could provide an important validation test of predictive ecosystem modelling.

On land, Arctic lakes are bellwethers of environmental change and valuable model systems with which to evaluate terrestrial and freshwater community and ecosystem dynamics. The past century has seen considerable change in aquatic ecosystems and current conditions may be unique within the past 200 kyr. Over recent decades there have been marked structural and compositional changes in vegetation at the forest-tundra boundary and within tundra communities; these are expected to generate functional changes in biogeochemical cycles and the surface energy balance. While it has been assumed that such changes in terrestrial and aquatic communities are primarily driven by climate, factors such as increased nitrogen fertilization may also play a role.

Long-term growth of peat-dominated systems is recognized as a major carbon sink, and interest is also growing in the role of numerous Arctic lakes in the carbon balance. A major challenge is to understand and quantify long-term patterns of carbon fluxes both from land to ocean via hydrological pathways and to the atmosphere from the land surface and from lakes. New insights may be gained using innovative proxies (particularly a range of molecular approaches) and by dating, reconstruction and modelling of lake initiation and growth in carbon-rich permafrost terrain.

Key areas for future research include contributions towards i) understanding past patterns of regional climate and environmental variability; ii) expanding records of past biodiversity to new taxa, particularly those critical to biogeochemical cycling; iii) understanding ecosystem function and resilience under unusually warm conditions and the transition to such conditions. Several other Science Topics can usefully incorporate the long-term perspective, for example, tracing regional variability through time in elements of the energy and water budget (Topic 1.1); identifying key processes driving marine biogeochemistry, biodiversity and carbon cycle change (Topic 1.7); quantifying carbon stocks in lake and peat land systems (Topic 2.1); estimating patterns of past biodiversity and relative rates of past carbon cycling (Topic 2.2); linking climate change, changes in vegetation cover, and geomorphic processes such as thermokarst to carbon dynamics (Topic 2.3).

1.7 Identifying key processes driving Arctic marine biogeochemistry, biodiversity and carbon cycle change

This topic will employ observational and experimental approaches, in combination with ecosystem/biogeochemical modelling addressing feedbacks between biology, biogeochemical cycling and environmental forcing, to improve understanding of key biogeochemical processes under the current and future Arctic Ocean. It offers the opportunity to study both coastal and oceanic systems using UK or international research station, ship and satellite platforms.

The overall productivity of Arctic waters is predicted to increase as sea ice becomes thinner and less extensive leading to a longer growing season for phytoplankton. Changing currents and terrestrial-derived inorganic and organic inputs will also influence water column optical properties and nutrient supply. Changes in the timing and magnitude of primary production, in turn, influence C and N remineralisation, and flux to and from the atmosphere and sediments. Biodiversity, particularly microbial biodiversity, plays an important functional role in biogeochemical cycles but this role is poorly understood in terms of the ecological processes involved and the way these might respond to environmental change. Ecosystem/biogeochemical models need to be developed, and embedded within high resolution physics, that address the complex interplay between physics, ice dynamics, chemistry, ecosystem structure and carbon cycling in the Arctic, and how these are mediated by environmental forcing.

Changes in sea ice, coupled with changes in marine productivity, influences the fluxes of climatically active species including CO_2, N_2O, CH_4, DMS, halogenated species and inorganic and organic particulates from the sea and sea ice surfaces, thereby changing atmospheric composition, cloud cover and vertical mixing. The process of sea ice formation and melt also acts as a major CO_2 pump to deep waters.

The focus of this topic will therefore be on microbial processes (including primary and secondary production), coupled C, N and P cycles, carbon export to depth, and the production of climatically relevant gases including CO_2, N_2O, CH_4, DMS and halocarbons. The information gained will be used to improve biogeochemical models which then interface with physical oceanographic models to predict changes in primary production and biogeochemical cycles (Objective 3). It may also link to Topics 1.3 and 1.6, and to activities related to methane emissions funded under Objective 2.

Objective 2 Topics: contributing to quantifying processes leading to Arctic methane and carbon dioxide release

2.1 Estimating large scale Arctic inventories of terrestrial and shelf organic carbon and methane and their vulnerability to climate change

The carbon stocks of Arctic tundra and sub-Arctic and boreal soils within the Arctic have escaped robust quantification. Improvements in the SOC (soil organic carbon) inventory (including its quality and lability) for the Arctic region are needed to underpin assessments of the contemporary and future C balance and net fluxes of CO_2 and CH_4 (Topics 2.2, 2.3 & 3.2) Likewise, the storage of methane clathrate hydrates beneath both terrestrial and subsea (continental shelf) permafrost of the Arctic is extremely poorly quantified (global inventories of methane hydrate range from 700 to 10,000 Pg of C), as is the stability of these hydrates in response to thawing or to release from sub-marine landslides (Topics 2.4 & 3.1).

The most widely-cited estimate of the carbon content in soils of the Arctic tundra (21.8 kg m^{-2}) is based on sampling from only 48 data points over an area of 8.8 x 10^{12} m^2 as part of a broader study (published in 1982) of soil carbon pools across the world's life zones. More recent work has, however, emphasized (a) the very limited sampling density for the Arctic (including North America), (b) the role of cryoturbation in redistributing soil organic carbon (SOC) both laterally and vertically through soil profiles, and (c) the importance of sampling deep enough to ensure that SOC within permafrost and entrained to substantial depth is incorporated into SOC inventories for this region (Topic 2.3). Indeed, more recent sampling in North America and Russia, taking these factors into account, indicates that stocks of SOC in the Arctic region have been seriously underestimated. Apart from the substantial uncertainties remaining concerning the quantity of SOC in the Arctic region, and its spatial distribution, there is also limited information on the quality of SOC by depth, even though this has significant bearing on its potential lability in response to changes in soil thermal and moisture status, including permafrost thaw and increases in the depth of the active layer (Topic 2.3). Furthermore, shifts in plant functional types (PFTs) or plant-soil interactions (for example, root priming) will also have cascading effects on decomposition processes and SOM that are supplemental to the direct effects of global change drivers on vegetation and soils. Palaeoenvironmental records linking biodiversity and community change with biogeochemical processes (Topic 1.6) have potential to improve understanding of the links between ecosystem processes and the climate system. These issues might robustly be addressed by integrating process studies in the field with modelling and earth observation.

In the marine realm, any advancement in modelling potential methane emissions from Arctic shelf sediments requires better understanding of the physical state, distribution, and volume of hydrate susceptible to melting under differing warming scenarios. Research is required to document better both the proportion of gas within the hydrate – sediment column, and the limits and processes of gas release to the seafloor (Topic 2.4).

2.2 Identifying key biological and physical drivers in the Arctic in the release of carbon dioxide methane within a global radiative forcing context.

The aims are to identify and determine the relative importance of key biological and physical drivers in the Arctic in the release of carbon dioxide/methane, in a global radiative forcing context.

(i) Carbon cycling in soils and rivers

This section focuses on the cycling of carbon in soils and/or rivers, with possible links to the N cycle, and/or possible links to the water cycle (e.g. transfer of DOC and its fate, including fluxes as CO_2 or CH_4, from soils to surface waters, and transfer of DOC to oceans). Key issues are rates of production and respiration of organic carbon and associated production of CO_2 and CH_4. This part of the topic is more about fluxes of C to and from soil C reservoirs than storage in above-ground biomass, although it is recognized that changes in plant communities are likely to have cascading effects on soil processes and C stocks. Two further objectives are to scale-up from fieldwork data to the landscape/regional scales and to use such data for improved representation of GHG fluxes in global models. Key biological drivers include: biodiversity, particularly microbial diversity. Key physical drivers include: realistic increases in soil/water temperature, changed timing and scale of water fluxes and flows (e.g. as a result of glacial, snow and permafrost thaw) and changes in soil moisture. Studies are likely to involve fieldwork in catchments in tundra regions.

(ii) Terrestrial and continental shelf methane

This section concerns the key biological (e.g. particularly microbial biodiversity, including marine microbial biodiversity) and physical drivers (e.g. thawing of the active layer) in soils and continental shelves in the Arctic in the release of methane within a global radiative forcing context. In soils, this is likely to involve field and laboratory work on processes involved in methane production and consumption and hydrate stability. Target catchments could be similar to those in part (i) above. For methane in continental shelves, this is likely to involve laboratory studies, fieldwork concerning methane vents, and measurements of methane consumption rates in sediments and water columns. The output of the activities in part (ii) should be an improved description of methane fluxes in regional and global models. This part of the topic links closely to Topic 1.7 and Objective 4.

2.3 Improving understanding and modelling of terrestrial permafrost and its impact on methane and carbon dioxide emissions

Permafrost underlies ~15% of the exposed land in the Northern Hemisphere and is a globally significant store of organic carbon. The carbon is stored, often for thousands of years, in organic soils (peatlands), mineral soils, ice-rich silts (Yedoma) and deltaic deposits. Significantly, much of the carbon resides in the upper metres of permafrost, which are particularly sensitive to climate warming and permafrost thaw. Current warming and thaw of near-surface permafrost result in increased rates of microbial decomposition of carbon and subsequent release of CO_2 and CH_4 into the atmosphere and hydrosphere.

Improved numerical models of permafrost temperature and distribution are needed to incorporate the complex interactions between changing physical and biogeochemical properties e.g. snow, shrub and cryptogam cover, ground-ice distribution and organic soil depth, that are already affecting the warming terrestrial Arctic. Models are essential to predict how much of the carbon frozen in continuous and discontinuous permafrost would be susceptible to thaw and GHG release. Field or large-scale laboratory studies of the impacts of thawing ice-rich permafrost (thermokarst) on geomorphic processes (e.g. cryoturbation and active-layer deepening), vegetation communities, soil properties (Topic 2.1) and landscape evolution (Topic 1.6) are needed to parameterize the numerical models. As thaw of permafrost during the next 100 years is likely to spread and intensify across the Arctic and sub-Arctic, field and modelling studies are needed that transect the whole permafrost zone.

The strength of the feedback between permafrost carbon and climate change depends on the amount of carbon stored in permafrost and the rate of carbon release to the atmosphere. At present, quantitative data on the distribution and rates of Arctic carbon release are sparse, short-term and site-specific. There is a pressing need to estimate inventories of Arctic terrestrial carbon and evaluate their vulnerability to permafrost thaw (Topics 2.1, 2.2). Also needed are monitoring and modelling rates of production and respiration of carbon and the associated production of CO_2 and CH_4. Upscaling is essential from individual field sites to the large areas of the boreal fringe and low Arctic that are likely to experience significant permafrost change and which have a larger carbon budget than mid- and high Arctic regions.

2.4 Improve understanding and modelling of methane emissions from sediments of shelf and upper continental slope.

Advances in modelling potential methane emissions from sediments of Arctic shelf and upper continental slope require better understanding of the physical state, distribution, and volume of hydrate susceptible to melting under different warming scenarios. Global inventories of methane hydrate place the amount of methane carbon in marine sediment in the range 500 to 10,000 Pg. This uncertainty in the amount of hydrate, which reflects incomplete knowledge its distribution and concentration, is very high for the Arctic region. Furthermore, the type of sediment that hydrate occupies, its stratigraphy and structures and whether hydrate is in pores or fractures, control how rapidly the methane released from hydrate migrates to the seabed. Research is required to better determine where hydrate exists, its quantity and distribution in the sediments, and the processes of gas release and migration to the seafloor under different environmental drivers.

The fate of methane efflux from hydrate dissociation beneath the seabed is an important facet of understanding potential changes in the global carbon cycle attributable to hydrate decomposition. Understanding the transport processes and flux (both as dissolved and gaseous phases), of methane gas from decomposed hydrate to the atmosphere is a fundamental question. It is known that methane oxidizes, within the water-column and surficial seafloor sediments, by both aerobic and anaerobic processes to which microbial and macro biological activity contribute. These processes together with sediment type, pore-water chemistry and the rates of advection in the sub-seabed system affect the solubility and oxidation of methane, but their relative contributions and variability are not well understood. Coupled ocean–climate modelling of the effect of the release of methane from hydrate underlines the importance of establishing how much methane vents to the atmosphere (as a 25 x more potent greenhouse gas than CO_2) and how much is oxidised in the ocean to CO_2. Similarly, the fate of CO_2 (including its phase state) within the water column, and the controls on its flux rate to the atmosphere in the Arctic region need to be understood. This latter research should complement but not duplicate the Ocean Acidification programme, and could link to the existing NERC Methane Network. This Topic links with Topics 2.1 and 2.2.

Objective 3 Topics: contributing to reducing uncertainty in Arctic climate and associated regional biogeochemistry predictions

3.1 Identifying and quantifying key physical ocean, atmosphere and sea ice processes for improving models for large scale Arctic prediction

Model predictions indicate rapid warming over the Arctic, with a so-called 'polar amplification' of around a factor two compared with the global average, but with substantial spread between the various models. Changes in the Arctic over the next few decades will reflect the response to anthropogenic radiative forcing due to greenhouse gas, aerosol and ozone changes and also natural variability. However there is consensus between climate models that the present trajectory of Arctic climate will eventually lead to a seasonally ice-free ocean.

The present generation of climate models represents aspects of the Arctic atmosphere, ocean and sea ice system with reasonable fidelity. However, there is a large model spread in the relative influence of factors that determine the surface temperature and precipitation response. For the atmosphere, this includes the direct radiative forcing, net surface fluxes, atmospheric heat and moisture transport and atmospheric feedbacks such as clouds. Most of these factors are subject to substantial uncertainties, which are addressed specifically in Objective 1. This topic aims to identify and quantify the key processes that control the rate of large-scale Arctic surface temperature and precipitation changes. It also includes consideration of processes that may not be currently included in climate models. For example, coarse spatial resolution can mean that sub-grid-scale processes are either poorly reproduced, inadequately parameterised, or simply absent. Such processes might relate to transport and mixing of heat, salinity, freshwater and dissolved gases in shelf seas, narrow boundary currents and small-scale eddies. Many sea ice processes have a leading-order impact on the mass balance of the sea ice and hence on the entire Arctic climate, so accurate parameterisations are required.

It is anticipated that combined analysis of both new and historical observations and of different kinds of models will be translated into new understanding which will lead to improvements in climate models.

3.2 Build in and quantify impact of further model improvements, based on outputs from Objectives 1 and 2

The overarching aim of this programme is to improve capability to predict changes in the Arctic and it is therefore high priority to ensure that model improvements proposed in Objectives 1 and 2 are pulled through into models which are used for climate and biogeochemical prediction. In particular it is anticipated that model improvements may arise from a number of areas including the following:

- Modelling links between surface runoff and ocean circulation (link to Topics 1.1 and 1.4)
- Modelling aerosols and clouds (link to Topic 1.3)
- Modelling atmosphere-ocean-cryosphere interactions (link to Topic 1.5)
- Palaeo-modelling of long term changes in the Arctic (link to Topic 1.6)
- Modelling coupling between marine biogeochemistry, physical oceanography and climate (link to Topic 1.7)

- Modelling coupling between vegetation, soils and climate (link to Topics 2.1-3)
- Modelling coupling between shelf sediments and climate (link to Topics 2.1-4)

The intention of the programme is that model improvements should feed into models described in the emerging NERC Earth System Modelling Strategy.

3.3 Quantifying the impacts of Arctic change on the wider climate system and Earth System on timescales from months to decades

Observations reveal recent changes in sea ice extent, snow extent and vegetation cover in the Arctic. The global impact of these changes and the associated mechanisms are not well understood or quantified. There are a number of areas which could be focussed on including quantifying the response of the Atlantic thermohaline circulation to changes in heat and freshwater fluxes across the Arctic boundaries (links to Topics 1.1, 1.4, RAPID) and quantifying the extent to which regional weather patterns are influenced by the interannual variations in Arctic sea ice extent and related sea surface temperatures (links to Topic 1.5). It is also of interest to develop understanding of the feedbacks between climate-driven land and marine changes and associated changes in biogeochemical cycling, including fluxes of radiatively active gases such as methane, and the larger climate system (links to Topics 1.6, 1.7, QUEST). It is anticipated that this topic would be addressed using Earth System models which model the interactions between the components of the climate and Earth System.

Objective 4 Topics: contributing to assessing the likely risks of submarine hazards associated with rapid Arctic climate change

4.1 Improving understanding and geotechnical modelling of Arctic slope stability and hydrate stability.

Causal relationships between climate change and hydrate-primed slope instability have been proposed for many continental slopes during the Pleistocene where glacial maxima with lowered eustatic sea-level induce methane decomposition, increased pore pressure and sediment instability, and consequent slope failure. The reverse, with climate and oceanic warming inducing a rise in subsurface slope sediment temperatures with concomitant hydrate melting is also now recognized. Within the Arctic region, hydrate deposits located at upper slope and shelf sea depths are particularly susceptible to melting as the upper waters of the Arctic water warm. Processes of increasing sediment pore pressure and volume expansion as hydrate melts are broadly established from very limited observations and numerical modelling where melting rate, water depth, depth to failure surface, hydrate content, varying slope angle, lithology, and void ratio can constrain simple hydrate melting models. However, many of these factors are poorly parameterized with field observations, including importantly the spatial variability of these parameters along Arctic continental slopes. Additionally, relationships between such parameters and in in-situ stress state, and geotechnical properties of the sediment-hosting hydrate are poorly known. Further, the phase state of pore spaces, particularly hydrate formation from free-gas and soluble phases, and either in pore spaces or on grain surfaces are important controls on hydrate cementation (and conversely melting) and hence sediment permeability and slope stability. The relative rates of excess pore pressure release and hydrate melting are also crucial. Advancements in understanding and geotechnical modelling of hydrate and slope stability will need both to better parameterize existing models with more extensive and spatially variable field observations, and advance experimental analysis / numerical modelling of hydrate stability at pore space scales. Both approaches will support improved and integrated geotechnical modelling of slope stability and hydrate stability, that includes time-scales unique to the Arctic region with oceanic warming and heat transfer to underlying shelf and upper slope sediments. This latter research could link to the existing NERC Methane Network. This Topic links with Topics 2.1 and 2.4.

4.2 Improving understanding and prediction of future trends in seismicity and implications for Arctic slope failure.

Seismicity associated with active Arctic region plate boundaries can be largely modelled stochastically as a seismic risk with modest moment magnitude. In contrast, intra-plate seismicity associated with post-glacial rebound, as ice-unloading creates crustal strain, can be a time variable trend and of higher seismic magnitude. For the sub-Arctic region, deglaciation of the Fennoscandian ice-sheet during the early Holocene resulted in the development of large post-glacial faults of extensive strike length, both onshore and offshore, that coincide with regions of highest post-glacial rebound. Similar structures are known from the Canadian margin. Modern intra-plate seismicity for the Arctic region comprises zones of significant seismicity around the non- to thinly glaciated passive margins of Greenland including events of < M_L (local Richter magnitude) 5.5 in the 1990's that are interpreted as flexural stress due to ice load removal. Recent seismic hazard assessments for Greenland yield maximum expected magnitudes of $M_L = 5.9$ and peak ground accelerations of 0.051 g. Large magnitude earthquakes have included the $M_L = 7.3$ event beneath Baffin Bay (Canada) in 1993, and $M_L = 6.2$ event at Svalbard in 2008. Future trends of Arctic warming, ice-sheet loss, and potentially increasing seismicity is unknown. The seismic hazard from post-glacial earthquakes tends to be the greatest immediately after deglaciation. Understanding and predicting future seismicity (due to existing and increasing ice-loss) as triggering events for slope failure are required. Research that takes existing ice-sheet loss models that incorporate Arctic climate warming, and sequentially develops crustal relaxation and predictive seismicity models is important, especially for the Greenland and Svalbard continental margins as sites of potential slope failure facing the northern Atlantic.

Research that validates and tests such predictive studies of future seismicity as triggers for slope failure is also important. The Greenland, Svalbard, and Norwegian margins, but particularly the latter, are extensively embayed by submarine landsliding < 15,000 years in age including the large Storrega slide. Except for Storegga, the dating of these landsliding events is not well constrained, but available data can be interpreted as showing northward younging of failure events in step with the northward progression of deglaciation. Research that documents the temporal relationship between slope failure, hydrate instability, and post-glacial earthquake seismicity for the Holocene in Arctic and sub-Arctic regions, as validation (or otherwise) of predictive seismicity studies will advance the programme. This Topic links with Topic 4.1.

4.3 Developing modelling of tsunamis generated by Arctic slope failure and quantifying the probability and economic impact of tsunamis of Arctic origin with variable magnitude

Empirical and numerical modelling have developed to establish the broad parameters of tsunami waves, though the latter have developed to include site effects of generation, near and far-field propagation, and run-up. Progressively more complex numerical models using Navier-Stokes equations have included finite element spatial approximation, semi-

Lagrangian advection, and full pressure Poisson solutions. Arguably the greatest uncertainty in such tsunami modelling is now applying sufficiently appropriate parameters of submarine landslide initiation and subsequent temporal evolution as initiating conditions for numerical modelling. For the ~8,100 year old Storrega slide, initiated on the lower slope, possibly primed by hydrate instability on the upper slope and possibly initiated by post-glacial crustal strain seismicity, numerical modelling, validated by the observation of onshore tsunami deposits in Norway, Shetland Islands, and mainland Scotland, indicates wide dispersal of a large tsunami into the northern Atlantic. A significant aspect of the Storrega modelling is the interpretation of a staged, retrogressive landslide failure that initiated the tsunami. Interpretations of initiation of the Storegga failure need not hold for older or future submarine landslides for the Arctic region. Recent tsunami modelling of a hypothetical landslide failure from the Svalbard slope, suggests propagation into the northernmost Atlantic.

Further development of tsunami modelling of Arctic – sub-Arctic submarine landsliding needs to assimilate both new improvements in geotechnical modelling of slope stability and hydrate stability, and prediction of future trends in seismicity and implications for slope failure proposed in other sections of Objective 4, to develop new generation tsunami modelling that better incorporate the variability of initiating landslide failure. This work will lead to better understanding of the spatial and mechanical variability of landslide failure, where sediment overloading pore pressure, hydrate instability, glacial sediment distributions, and post-glacial earthquake release as new parameters for tsunami modelling and risk for the Arctic margins. An aspect of this work is to better integrate the submarine geotechnical and geohazards communities.

The underlying rationale of Objective 4 is to quantify the probability and impact of tsunamis potentially generated in the Arctic region, and whether this probability will increase due to climate warming. All the research proposed above will underpin this hazard risk assessment. The crucial aspect of this work is to quantify probabilities of tsunami generation of varying magnitude from Arctic continental margins that incorporates new understanding of spatial and mechanical variability of landslide failure, sediment overloading pore pressures, hydrate instability, glacial sediment distributions, and post-glacial earthquake seismicity. Each of these factors will have either different spatial variability or response times, but the integrated probabilities of tsunami generation, and hence hazard risk, should be on a time-scale of the next 100-200 years.

This work should also enable interaction with the re-insurance industry to assess the economic impacts of tsunamis of variable magnitude to existing population centres and to marine and coastal infrastructure bordering the Arctic, but with particular emphasis for the northern Atlantic. Such impact modelling should be also forward-looking incorporating assessments of future hydrocarbon infrastructure development of Arctic shelf seas (e.g., Beaufort and Barent seas) for the next 100 years.

6. Partnerships & Collaboration

Research collaborations and stakeholder and international partnerships all have an important role to play in the programme. These will be explored and facilitated by the Programme Management Team, but should also be developed by and form part of individual projects.

The programme will work with relevant NERC programmes such as Oceans 2025[8], RAPID-WATCH[9] which is evaluating the impact of Arctic fresh water fluxes on the global thermohaline circulation, Ocean Acidification[10] which includes the Arctic as one of its areas of focus, Changing Water Cycle[11], NERC Methane Network[12] and Macronutrient Cycles[13]. Collaboration at both the programme and project level will be encouraged.

The programme will work with and integrate into the programme relevant NERC National Capability activities such as in the NCEO cryosphere programme and strategic modelling activities such as those undertaken in NERC Marine Centres. Model development will be delivered in the context of the NERC Earth System Modelling Strategy[14] (currently under development) and in collaboration with the Met Office through JWCRP.

The programme will work with a range of stakeholders with interests in the Arctic; these will include public and private sector organisations and the general public. Involvement of project partners in research activities will be encouraged. The focus of the programme on improving capabilities to predict future Arctic weather and climate means that it will be essential for the programme to work in partnership with the Met Office. The ability to better predict local conditions in the Arctic, both long and short term are important to many stakeholders planning to operate in the High North. There is a growing interest in Government in the Arctic and central Government is now increasingly coordinated in its efforts in the region. The Foreign and Commonwealth Office is seeking to promote UK presence and link the programme into the Working Groups of the Arctic Council[15]. Equally a number of other Government departments e.g. the Department for Energy and Climate Change (DECC), Department for Transport (DfT) and Department for Environment, Food and Rural Affairs (Defra) all have interests in the region and require access to data, modelling and monitoring.

Partnerships with industry may also be of potential mutual benefit. There are a number of UK and international companies working or planning to work in the Arctic. These include hydrocarbons companies and the tourist industry which is steadily increasing in the region. The shipping and maritime insurance industries are increasingly interested in the potential opening up of the North-East and North-West passages. The fishing industry must also respond to changes in sea ice extent, and effects on the biodiversity of the region and its impacts further to the south. Policymakers in the UK and EU will also need such information for the development of Fishery management programmes.

The programme is likely to be of interest to the general public and provides an important opportunity for engaging young people in science. In particular the programme will encourage appropriate interaction with local indigenous peoples via recognised channels.

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[8] http://www.oceans2025.org/
[9] http://www.nerc.ac.uk/research/programmes/rapidwatch/
[10] http://www.nerc.ac.uk/research/programmes/oceanacidification/
[11] http://www.nerc.ac.uk/research/programmes/cwc/
[12] http://methanenet.org/news/about-methanenet
[13] http://www.nerc.ac.uk/research/programmes/macronutrient/
[14] http://www.nerc.ac.uk/research/news/esmstrategy.asp
[15] http://arctic-council.org/section/working_groups

Due to the scale of the scientific and logistical challenges and the international nature of the Arctic region, the programme will need to be developed in collaboration with other nations. Individual UK researchers have valuable links to individuals and institutions in various Arctic nations including Russia, but until now there has been very limited coordination of our Arctic links. The NERC Arctic Office will therefore play a key role in facilitating collaborations and access to facilities of mutual benefit and has already begun work on identifying potentially useful assets and building international relationships with polar operators.

One example is the memorandum of understanding signed by the governments of UK and Canada on closer cooperation in polar science and logistics. The NERC Arctic Office has overseen an agreement under this MOU with the Canadian Polar Continental Shelf Program (PCSP) to give UK researchers improved access to logistic assets at its Resolute Station on Cornwallis Island and thus most of the Canadian Arctic Archipelago. An improved permitting system for UK researchers to work in the Canadian archipelago is also in place and additional agreements on accessing field huts/stations operated by various Canadian institutions across the Canadian Arctic will make these assets available for participants in the new Arctic programme.

Discussions with US research agencies (NSF, NOAA and NASA e.g. Carbon in Arctic Reservoirs Vulnerability Experiment) have indicated enthusiasm for US researchers to potentially run parallel research projects alongside the UK Arctic Programme and provide access to relevant US Arctic field programmes. Collaborative agreements already exist between UK and European polar organisations and further agreements to cooperate in research and polar logistics are planned. These European and North American partners offer further potential conduits to the Eurasian Arctic alongside existing direct UK-Russian agreements that facilitate UK research in the Siberian Arctic. The Arctic Office is also looking to opportunities to utilise links with Asian nations involved in Arctic research and polar logistics.

7. Capacity Development

To assist the development and effective targeting of the programme research NERC and the Met Office will co-fund an initial study to identify key uncertainties in Arctic climate predictions. The outputs will be used by the programme, to inform the development of research proposals addressing its objective to reduce uncertainty in Arctic climate predictions.

The programme aims to involve researchers who have not previously worked in the Arctic, to bring in new ideas and techniques. This will be facilitated through the application process for programme awards that will encourage the formation of new research teams. The integrated programme design will also support inter-disciplinary working and increased interaction across sectors such as marine, terrestrial, atmospheric. To develop the UK Arctic research community and leave a legacy the programme will support PhD studentships, both linked to research grants and as stand-alone projects.

8. Implementation Plan

The *Implementation Plan* for the *Arctic Research Programme* outlines how this *Science Plan* will be delivered. It is available as a separate document on the NERC website and should be read prior to submitting proposals to the programme.