SOFI Workshop Report
WS 09 01

Priorities for future UK marine Arctic research

Report compiled by Ray Leakey from a workshop held 31 March – 1 April 2009 at the Scottish Association for Marine Science, Oban, Argyll PA37 1QA, UK

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Disclaimer

The views expressed in this report reflect those expressed by the report's contributors as interpreted by the report's compiler. They do not necessarily reflect official thinking or policy of NERC or the host higher education, government and research institutes of the report's contributors.

Acronyms

ACIA	Arctic Climate Impact Assessment
ACEX	Arctic Coring Expedition
APEX	Arctic Palaeoclimate and its EXtremes
ASBO	Arctic Synoptic Basin-wide Oceanography
AUV	Autonomous Underwater Vehicle
BAS	British Antarctic Survey
CCAMLR	Convention on the Conservation of the Antarctic Marine Living Resources
COBRA	Impact of Combined iodine and Bromine Release on the Arctic atmosphere program
CPR	Continuous Plankton Recorder
DAMOCLES	Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies
Defra	Department for Environment, Food and Rural Affairs
EPOCA	European Project on Ocean Acidification
EU	European Union
EUROCEANS	European Network of Excellence for Ocean Ecosystems Analysis
FCO	UK Foreign & Commonwealth Office
GISP	Greenland Ice Sheet Project
GOME	Global Ozone Monitoring Experiment
iAOOS	Integrated Arctic Ocean Observing System (Arctic Ocean Sciences Board)
ICES	International Council for the Exploration of the Sea
ICES	International Council for the Exploration of the Sea
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IODP	Integrated Ocean Drilling Program
IPCC	Intergovernmental Panel on Climate Change
ISAC	International Study of Arctic Change
LWEC	Living With Environmental Change
MARBEF	Marine Biodiversity and Ecosystem Functioning
NCEO	National Centre for Earth Observation
NERC	Natural Environment Research Council
NOCS	National Oceanography Centre, Southampton
NSERC	Natural Sciences and Engineering Research Council of Canada
OMI	Ozone Monitoring Instrument
QUEST	Quantifying and Understanding the Earth System
RAPID	Rapid Climate Change programme
RECARO	Understanding the impact of a reduced ice cover in the Arctic Ocean program
SAMS	Scottish Association for Marine Science
SCIAMACHY	Scanning Imaging Absorption Spectro-meter for Atmospheric Chartography
SMRU	Sea Mammal Research Unit
SOLAS	Surface Ocean-Lower Atmosphere Study
SOFI	Strategic Ocean Funding Initiative
THOR	Thermohaline Overturning–at Risk? programme

Contents

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Executive Summary

This report summarises the main discussions, conclusions and recommendations of a workshop on UK marine Arctic research held at the Scottish Association for Marine Science, 31 March – 1 April 2009. The aim of the workshop was for the research community to identify marine priorities for future funding and their match with NERC thematic science areas, in the context of other NERC and non-NERC initiatives.

The workshop recommended that UK support for multidisciplinary marine Arctic research should focus on the following over-arching research objective: *To improve our capability to predict the response of the Arctic marine system to current and future environmental change, and to predict the regional and global consequences of this response."*

The workshop identified the following high-level marine research priorities which would address aspects of the above objective in a strategic and efficient manner by exploiting current UK strengths and international collaborations:

- *To advance understanding of past variability in the Arctic environment through climate model hindcasts, in order to establish whether the current trajectory of Arctic climate change is unprecedented.*
- *To quantify variability in the ocean at space and time scales that are relevant to the effective development of predictive capability for the Arctic system.*
- *To advance and integrate the remote and* in situ *technologies necessary to observe the present condition and future evolution of Arctic sea-ice and its relationship to the oceanographic and atmospheric drivers.*
- *To improve our capability to predict the timing, trajectory and scales of variability of a reducing Arctic sea-ice cover.*
- *To determine the impact of sea-ice on air-sea fluxes of climatically active gases and aerosols.*
- *To improve understanding of the effects of climate change on ocean - Greenland ice-sheet interactions sufficiently to identify and quantify the implications and risks associated with feedbacks between the two systems.*
- *To assess the magnitude and stability of methane hydrates in Arctic shelf seas and the consequences of warming-induced methane release for sea-bed stability and atmospheric methane inputs.*
- *To improve our capability to predict the response of the Arctic marine primary productivity to current and future changes in sea-ice cover and water column properties, and to determine the probable consequences for ecosystem structure and function, and biogeochemical carbon flux.*
- *To determine the adaptive capabilities of Arctic marine organisms and their resilience and resistance to predicted environmental change.*
- *To promote research collaboration and knowledge exchange between the UK marine Arctic environmental research community and climate forecasters.*
- *To promote sustainable exploitation and management of Arctic natural resources by more effective knowledge transfer between the UK marine Arctic environmental research community and Arctic policy-makers and stakeholders.*

The workshop recommended that a long-term strategic approach is adopted towards the development and operation of UK-led observational capability in the marine Arctic and the subsequent analysis and dissemination of observational data.

The workshop recommended that any future research programmes are developed and executed in collaboration with international partners, and where possible utilising bilateral and multilateral agreements.

A research programme focused on a selection or all of the above research priorities would build on previous NERC and EU investments in UK research and contribute directly to several NERC thematic science areas and parallel initiatives. It would also inform and empower UK and EU government and industrial stakeholders (including the FCO, Defra, shipping, hydrocarbon, fisheries and conservation interests).

1. Introduction

This report summarises the main discussions, conclusions and recommendations of a workshop on UK marine Arctic research held at the Scottish Association for Marine Science on 31 March and 1 April 2009. The workshop was primarily supported through the Natural Environment Research Council Strategic Ocean Funding Initiative, administered through the Oceans 2025 programme.

The Arctic is currently the most rapidly warming region of the planet with a projected annual warming of $5^{O}C$ by the end of the 21st century, which is twice the global mean (IPCC 2007). The consequences of this rapid environmental change are already apparent within the Arctic and especially within the cryosphere, the most dramatic example of which has been the recent reduction in summer sea-ice extent which is unprecedented in the human record. These changes will have wide ranging environmental, political and economic impacts on both the Arctic region itself and rest of the planet, including the UK and EU (ACIA 2004). The changes underway in the Arctic are also a prelude to changes which may take place in other areas of the globe and offer a unique scientific opportunity to gain insights into regional environmental response to climate change. There is therefore a clear scientific need to improve our understanding of the Arctic system, including the Arctic Ocean and sub-Arctic seas.

The UK has considerable Arctic research expertise, and also has world-leading expertise in many areas of environmental science which can be directly applied to the Arctic. To date, however, UK Arctic research has tended to be uncoordinated and fragmented relative to that conducted in the Antarctic (House of Commons Science & Technology Committee 2007, FCO 2008). A more strategic approach to the funding and delivery of Arctic research is also consistent with:

- the NERC Polar Science Working Group recommendation *"that the NERC strategy and the UK national interest favour an increase in NERC Arctic science"* (NERC 2007)
- the recently signed Canadian-UK Memorandum of Understanding Concerning Cooperation in Polar Research (NSERC 2009)
- the current NERC Science Strategy (2007-2012) and the NERC Theme Leaders' interests in this area, taken forward by an Arctic Programme Meeting (13 May 2009, Birmingham; www.nerc.ac.uk/research/themes/news/090513).

The Marine Arctic Workshop was initiated in response to this background. Its overall aim was to assist the development of UK marine strategic research in the Arctic by enabling the relevant research community to identify scientific priorities in the context of NERC thematic science areas and parallel activities. Note that the Birmingham meeting covers the full range of Arctic environmental issues (terrestrial, atmospheric and geological, as well as marine); thus the SOFI-supported workshop was intended to provide preparatory marine input to those wider discussions.

The workshop was attended by 34 invited scientists from UK universities, research centres and governmental organisations to represent the range of UK marine environmental science currently undertaken in Arctic (see Annex 1). Professor David Barber of the University of Manitoba, Canada, was also invited to represent Canadian Arctic research interests and help provide an international context to the discussions.

2. Over-arching objective for UK marine Arctic research

The workshop identified the following over-arching research objective:

"To improve our capability to predict the response of the Arctic marine system to current and future environmental change, and to predict the regional and global consequences of this response."

This objective encompasses the need to understand the recent past and present day functioning of the Arctic marine system, and the ways in which the system will continue to change as the Arctic Ocean evolves, over subsequent decades, towards a state that is likely to be warmer, summer ice-free, and subject to greater freshwater influence. This understanding is necessary to improve global and regional climate and ecosystem models which currently fail to simulate the prevailing environmental conditions. It is also necessary to understand the direct and indirect effects of Arctic change on the UK environment.

There are many important fundamental challenges that must be met by the scientific community to address this over-arching objective:

- Historical observational data are rare and temporally limited, and palaeo-records are poorly represented spatially. A comprehensive understanding of how the Arctic marine system functioned under pre-anthropogenic “baseline” conditions is therefore currently not possible.
- Current Arctic marine observations are of limited temporal and spatial scope.
- The Arctic Ocean and sub-Arctic seas are already experiencing rapid environmental change and anthropogenic impacts (including resource exploitation) which preclude observation of a system that is in a steady state (or, more accurately, is statistically stationary).
- The Arctic marine system responds to some environmental drivers in a non-linear way.
- The Arctic Ocean and sub-Arctic seas are dynamic open-systems with boundaries that are open to influence from the atmosphere and surrounding continents and oceans.

Addressing this objective therefore requires a multidisciplinary approach, encompassing extensive observational, experimental and modelling activities which can only be comprehensively resourced at an international level.

The above broad scientific goal is already the focus of international attention and the case for the UK to enhance its current support in this area is compelling on strategic, political and economic, as well as scientific, grounds. Any continued or enhanced UK contribution should be undertaken in a strategic manner which complements and enhances concurrent international research activities, thereby adding value to both the UK and international efforts.

The UK already has world-leading expertise and resources pertinent to this over-arching objective (as summarised in NERC 2007, FCO 2008). Leading areas of research expertise include: physical oceanography, palaeoceanography, sea-ice processes, marine ecology and biogeochemistry, ocean-atmosphere interactions, instrumentation, climate modelling, and marine geological and geophysical investigations of ice sheet behaviour. This expertise is supported by UK owned or supported Arctic related infrastructure including: the *RRS James Clark Ross*; Royal Navy submarines; Autosub; CPR surveys, NERC Dornier 228 and BAE 146 remote sensing aircraft; BAS aircraft; European Space Agency satellites; and the Kings Bay Marine and NERC Harland laboratories on Svalbard. Application of this expertise and resources towards targeted and tractable research priorities will enable the UK to play an internationally leading role in addressing this global challenge, and place the UK in a stronger position to meet the challenges to society bought about by Arctic climate change.

The workshop therefore recommended that NERC support a directed programme of focused multidisciplinary research to significantly advance, in collaboration with international efforts, our ability to predict future marine arctic environmental change and understand its regional and global consequences.

3. Identification and selection of research priorities

The workshop identified high-level research priorities which would enable the UK community to address aspects of the above over-arching research objective in a strategic and efficient manner by exploiting current UK strengths and international collaborations. The selected priorities inevitably reflect, to some degree, the interests and experience of the workshop participants so the list is not definitive or exhaustive; however, it does encompass the range and scope of current UK marine Arctic research.

Research priorities were selected according to three criteria:

- Science merit, including match to UK research expertise and timeliness and relevance to UK national interest

- Feasibility, including match to operational realities and realistic resource expectations (funding and research platforms)
- Added value (scientific, political and financial) gained by international collaboration, adoption of a multidisciplinary approach, and focus on research where the UK offers strength and international lead in terms of expertise, technology or logistical infrastructure.

4. Specific priorities for UK marine Arctic research

The eleven research priorities outlined below were identified by the Workshop participants and represent the distillation of discipline-specific and cross-discipline round table discussions.

It should be noted that the research priorities differ in breadth and focus so the level of resources required to address each priority varies. It should also be noted that the priorities have not been ranked in order of importance.

Research priorities 1 to 6 are primarily concerned with understanding the response of the Arctic marine environment to climate change. Research priorities 5 to 9 focus on the consequences of Arctic environmental change for air-sea exchange, marine biota, biogeochemical cycles and geological processes including methane hydrate stability. Research priorities 10 and 11 enable knowledge exchange with climate modellers and Arctic policy-makers and stakeholders.

Research priority 1: *To advance understanding of past variability in the Arctic environment through climate model hindcasts, in order to establish whether the current trajectory of Arctic climate change is unprecedented.*

The Arctic region has undergone significant changes in the recent geological past. We know that climate has fluctuated from warm to cool periods, characterised by changes in sea-ice and ice-sheet extent, over a range of temporal and spatial scales. Recent ocean drilling results (ACEX IODP, 2006) show that the Arctic Ocean Basin was essentially a temperate, freshwater lake 49 Ma ago with the first indications of glacial ice by 43 Ma, in step with the onset of Antarctic glaciation. However the timing and influence of climate oscillations at time scales less than 100 ky in the Arctic remains enigmatic.

Current changes appear to be unprecedented in terms of the rates and magnitudes (i.e. the trajectory) of the changes. Better understanding of the spatial and temporal variability of the Arctic marine palaeo-record is needed in order to establish the significance of current changes and to enable climate model hindcasting. Of particular interest is the last interglacial period (stage 5, Eemian, 125ky), which poses significant palaeoclimate questions because it is climatically different (more stable and warmer) than the present Holocene. At shorter timescales, Holocene Rapid Climate Change events such as the Little Ice Age and the Medieval Warm Period allow insights into the processes and timing of abrupt climate change in polar regions. Also of interest are the processes influencing and the potential impacts of decreases in the Greenland Ice sheet. Whilst modern glaciological studies can provide much data towards this goal it is only through high resolution, multi-proxy marine geological and geophysical studies that the ancestral behaviour of this climatically-significant ice sheet can be revealed; particularly that of the most recent step change from the last glacial maximum (18 ka BP) to Holocene. Application of a multiple-proxy approach is critical to reduce uncertainties in the interpretation of such palaeo-records.

The UK has world-leading expertise in glaciomarine sedimentology, Quaternary palae-oceanography, geochemistry and the application of marine geophysical tools relevant to this research priority. It also has access to the infrastructure and platforms required to maintain and develop research in this area (i.e. to recover cores and develop and test new proxies). These include UK research vessels and access to international vessels via collaborations with Canadian, Norwegian and German researchers.

Multidisciplinary links to other marine Arctic research priorities:

- Oceanography (Research priority 2)

- Sea-ice predictions (Research priority 4)
- Ocean ice-sheet interactions (Research priority 6)
- Ecosystems and biogeochemistry (Research priority 8)
- Climate forecasts (Research priority 10)

Delivery to NERC Themes and related initiatives:

- Climate Change
- Earth System Science
- Natural Hazards
- Ice-sheet Mass Balance and Sea-level Rise programme scoping study

Links to other NERC, UK and international research programmes:

- Oceans 2025
- ACEX
- APEX

Research Priority 2: *To quantify variability in the ocean at space and time scales that are relevant to the effective development of predictive capability for the Arctic system.*

The Arctic Ocean occupies a unique position as a mediterranean sea at one endpoint of the global ocean thermohaline circulation system. The well known recent significant decline in summer sea-ice concentration indicates an important change in one of the Arctic Ocean's boundary conditions and illustrates the importance of the ocean's interaction with the atmosphere. The change in sea-ice concentration is visible and apparent. By contrast, the interior of the Arctic Ocean and the other boundary conditions (fresh water input from land, fluxes through straits), which are also important, are not so easily observed.

Variability in the Arctic Ocean takes place through processes that operate over a vast range of space and time scales and that are related through non-linear interactions and feedbacks. The past decade and a half have brought to light modes of variability of the oceanic component of the Arctic system which will require sustained, as well as focused, observations in order to understand both the dynamics and the space/time scales of variability. Some of this variability is internal to the Arctic Ocean, and some is an expression of variability in fluxes across boundaries at lower latitudes, however much is likely to result from the interaction between internal Arctic Ocean dynamics and external forcing.

Better predictability of the Arctic system is dependent upon improved knowledge of fluxes across the Arctic Ocean's boundaries. It is also dependent on improved knowledge of internal oceanographic processes within the Arctic Ocean and quantification of their effects. The UK has world-leading expertise in Arctic oceanography which can be harnessed to observational and modelling tasks that will better quantify the variability in the system. Key tasks are:

(i) Sustained observations of boundary fluxes to understand and quantify overall budgets for the Arctic Ocean. In particular, this should include measurements of fluxes (heat, salt, and mass) through the major gateways (such as Fram Strait) to the global ocean, as well as fluxes (heat, freshwater, radiative and momentum) across the surface of the ocean, whether this is ice-covered or ice-free, and freshwater inputs from the major river systems.

(ii) Quantitative studies of internal processes in order to understand and better model the mechanisms leading to variability. Aspects include

- Atlantic Water variability, especially along the periphery of the Eurasian Basin
- Freshwater variability, especially in the halocline, through excess of precipitation over evaporation, river inputs, and terrestrial glaciological inputs
- Eddies and small scale processes responsible for the horizontal dispersion, as well as vertical and horizontal mixing, of heat, salt, and other properties
- Shelf-basin interactions, especially the processes leading to halocline formation and deep water renewal

These tasks can be best achieved via:

- contributions of autonomous sensor platforms to nodes of a growing Arctic Ocean Observing System with deployment through international partnerships
- contributions to sustained mooring observations of fluxes at the Arctic-Atlantic gateways with deployment through UK and international collaborations
- contributions to logistical support of manned ice-camps in the Arctic, including logistical support using the BAS aircraft fleet
- intensive campaign-oriented observations in the Greenland, Iceland and Norwegian seas, and adjacent Arctic Ocean/Barents Sea region using the UK research fleet
- basin-wide observations independent of sea-ice conditions by making better use of Royal Navy submarines on Arctic deployment
- satellite geodetic techniques including altimetry and gravity
- continued investment in the development and implementation of technology for observation of the polar oceans including development of new observational approaches
- development of an eddy-resolving model of the Arctic Ocean for targeted improvement of understanding of important physical processes in key regions
- contributions to international pan-Arctic marine surveys and process studies

Multidisciplinary links to other marine Arctic research priorities:

- Palaeoceanography (Research priority 1)
- Sea-ice observations (Research priority 3)
- Sea-ice predictions (Research priority 4)
- Ocean ice-sheet interactions (Research priority 6)
- Ecosystems and biogeochemistry (Research priority 8)
- Climate forecasts (Research priority 10)

Delivery to NERC Themes:

- Climate Change
- Earth System Science
- Technologies

Links to other NERC, UK and international research programmes:

- Oceans 2025
- ASBO
- RAPID
- DAMOCLES
- ISAC
- iAOOS
- NCEO Cryosphere programme
- THOR

Research Priority 3: *To advance and integrate the remote and* in situ *technologies necessary to observe the present condition and future evolution of Arctic sea-ice and its relationship to the oceanographic and atmospheric drivers.*

The Arctic sea-ice cover is undergoing unprecedented change in its thickness, extent and seasonal durability. The sea-ice is a keystone of the Arctic environment and the global climate system so the impacts of the changes are far reaching; however they are poorly understood. Central to the challenge of understanding sea-ice change are the essential technologies to observe the present condition of the sea-ice at a variety of spatial and temporal scales.

Ice thickness is a key parameter for the validation of models and assimilation of the data into models. There are critical questions relating to ice thickness, such as where in the Arctic the sea-ice is thinning, and the relative contribution of dynamic or thermodynamic ice loss mechanisms. The UK has world-leading expertise in the remote sensing of sea ice thickness yet there remains an urgent need to reduce the uncertainties in these techniques. Allied to this is the development of methodologies for ice classification and ice age determination to interpret the annual evolution of the sea ice cover.

Remote techniques are dependent upon *in situ* observations and there are a range of mature and emerging technologies that can be brought to bear in this area. Ice-deployed systems, fixed monitoring systems and under-ice surveying techniques all have a role. There is a will and community expectation to draw together the collective experience in submarine-based measurements through both UK and US operations. A vital step in the development of this research area is the inter-comparison of the observational methods and the effective and timely linkage of these data to the remote sensing and modelling communities.

Having the means to obtain the right observations at the right scales permits a clearer analysis of the drivers and impacts of changes in sea-ice. This includes both the oceanographic processes (such as vertical heat fluxes and buoyancy fluxes) and the atmospheric processes (such as wind driven circulation, heat and momentum fluxes).

The next decade is likely to bring about big changes in Arctic sea-ice as the region moves from one that is dominated by multi-year ice to one that is predominantly first-year ice. This presents the research community with an unrivalled opportunity to prepare an observational programme that would galvanise UK sea ice expertise and contribute to international community programmes.

Multidisciplinary links to other marine Arctic research priorities:
- Oceanography (Research priority 2)
- Sea-ice predictions (Research priority 4)
- Air-sea fluxes (Research priority 5)
- Ocean ice-sheet interactions (Research priority 6)
- Climate forecasts (Research priority 10)
- Sustainable exploitation and management (Research priority 11)

Delivery to NERC Themes:
- Climate Change
- Earth System Science
- Natural Hazards
- Technologies

Links to other NERC, UK and international research programmes:
- Oceans 2025
- DAMOCLES
- RECARO
- ISAC
- iAOOS
- NCEO Cryosphere programme

Research Priority 4: *To improve our capability to predict the timing, trajectory and scales of variability of a reducing Arctic sea-ice cover.*

One of the greatest challenges in Arctic science is to accurately predict future states of the sea-ice cover. In terms of the economic impacts, the concept of a seasonally ice free Arctic opens up considerable opportunities for resource exploitation and associated social and environmental impacts. However, the timeline leading to this anticipated ice-free state is far from clear with the summer sea-ice minimum in 2007 being far outside the range of modelled values. After such exceptional conditions, it is vital to know if the sea-ice is capable of recovery or if it represents a tipping point of the system. If recovery is possible, to what extent will the system exhibit hysteresis?

In addition to the modelled projections, there is a critical requirement to predict the variation in the summer thickness, concentration and timing of the sea-ice cover at spatial and temporal scales relevant to marine operations. At smaller spatial and temporal scales, ecosystem function is highly tuned to the timing of change in the ice cover.

Accurate representation of processes in models is a high priority, particularly with respect to the melt cycle and the pack dynamics. This must occur in the framework of both development of the theory, *in situ* observations and simulations/experiments in tanks.

The framework for this research priority must be one of sea-ice within the Earth System, such that it focuses on the links and feedbacks in the ice/ocean/atmosphere system. The UK has world-leading expertise sea-ice research which can be applied to this research priority using UK and international infrastructure including satellites, submarines, ice camps and icebreakers.

Multidisciplinary links to other marine Arctic research priorities:

- Palaeoceanography (Research priority 1)
- Oceanography (Research priority 2)
- Sea-ice observations (Research priority 3)
- Air-sea fluxes (Research priority 5)
- Ocean ice-sheet interactions (Research priority 6)
- Ecosystems and biogeochemistry (Research priority 8)
- Climate forecasts (Research priority 10)
- Sustainable exploitation and management (Research Priority 11)

Delivery to NERC Themes:

- Climate Change
- Earth System Science
- Natural Hazards
- Technologies

Links to other NERC, UK and international research programmes:

- Oceans 2025
- DAMOCLES
- RECARDO
- NCEO Cryosphere programme

Research Priority 5: *To determine the impact of sea-ice on air-sea fluxes of climatically active gases and aerosols.*

Arctic sea-ice and snow play an important role in polar chemistry and climate. In addition to determining the albedo, the extent and nature of ice/snow cover influences the fluxes of heat, water, carbon dioxide and climatically active trace gases (e.g. methane, dimethyl sulphide, halogenated species, nitrous oxide) from the sea surface, thereby changing atmospheric composition, cloud cover and vertical mixing. Sea-ice itself has been proposed as the main source of reactive bromine in polar regions, which in turn has a major influence on surface atmospheric O_3 and on mercury sea-air fluxes, both of which impact on Arctic biota. The process of sea-ice formation and melt acts as a major CO_2 gas pump to deep waters. Sea-ice also influences the microbial activity of pelagic and sea-ice microbial communities thereby indirectly influencing biogenic gas production and air-sea exchange.

Current overarching questions include: (1) how gas exchange between the Arctic Ocean/sea-ice/snow and atmosphere changes as a function of climate and, in particular, as a function of changing ice/snow cover, temperature and pelagic and sea-ice microbial communities; (2) how this will in turn affect regional and global atmospheric composition and climate. Currently, there is insufficient knowledge of the physical, photochemical and biological processes which govern these exchanges to allow for predictions of the future state of the Arctic atmosphere. For example, although it is widely accepted that reactive bromine in this region originates from sea-ice, many aspects remain under debate, including whether aerosol, frost flowers, or blown snow are the main source, whether reactive iodine is available to stimulate halogen activation from such reservoirs, how efficiently the bromine is recycled on ice and snow surfaces, and whether satellite data (GOME, SCIAMACHY, OMI) of BrO are consistent with tropospheric *in situ* measurements. Other questions include: (i) Feedbacks between air-surface interactions and Arctic cloud cover through production of cloud condensation nuclei from halogen and organic compounds; (ii) The role of Arctic haze in deposition of Hg; (iii) The biological and/or chemical transformations of Hg deposited to the snow/sea-ice surface during halogen-mediated “mercury depletion events”; and (iv) The importance of brine-formation and brine sinking for producing gas depleted surface waters during sea-ice formation and melt.

The UK currently has world-leading expertise in the study of air-sea exchange including the influence of sea-ice processes. It also has access via the international community to the infrastructure and platforms required to maintain and develop research in this area including ice camps and icebreakers.

Multidisciplinary links to other marine Arctic research priorities:

- Oceanography (Research priority 2)
- Sea-ice observations (Research priority 3)
- Methane hydrates (Research priority 7)
- Ecosystems and biogeochemistry (Research priority 8)
- Climate forecasts (Research priority 10)

Delivery to NERC Themes:

- Climate Change
- Earth System Science
- Environment, Pollution and Human Health

Links to other NERC, UK and international research programmes:

- Oceans 2025
- COBRA
- SOLAS
- IMBER

Research Priority 6: *To improve understanding of the effects of climate change on ocean - Greenland ice-sheet interactions sufficiently to identify and quantify the implications and risks associated with feedbacks between the two systems.*

There is currently much concern over the stability of the Greenland ice-sheet. Oceanographic processes exert potential impacts on the ice-sheet. Warmer ocean currents and loss of sea-ice are known to enhance calving of glacial outflows and, in some areas this may lead to ice sheet instability. Loss of sea-ice may also lead to increased evaporation with consequences for regional precipitation (increased snowfall on the ice-sheet).

Changes to the Greenland ice-sheet can, in turn, influence Arctic and global ocean processes including sea-level rise and thermohaline circulation. Ice-sheet unloading can lead to a decrease in crustal stress, reactivating dormant faults and increasing earthquake occurrence with the associated risk of submarine landslides and tsunami. Increased melt-water input to coastal and offshore waters alters water column stability and increases nutrient concentrations; the degree to which these changes influence North Atlantic thermohaline circulation and coastal biological productivity are unknown.

We therefore need a coordinated marine programme of research to provide the data required by glaciologists seeking to model past, present and future behaviour of the Greenland Ice Sheet. This will involve observation of palaeo-glaciological features on the continental shelf (e.g. by swath bathymetry and coring), oceanographic measurements focused around ice shelves and glaciers to establish the variability of currents reaching marine–terminating ice fronts, and improvements in ocean climate models so that future ocean warming scenarios can be produced. Ice sheet models will provide estimates of melt-water input in the Arctic, which need to be translated into predictions of local sea level rise and possible circulation changes.

The UK currently has world-leading expertise in the study of glaciomarine sedimentation and marine-based investigations of Greenland ice sheet history, crustal response to deglaciation and ice sheet modelling. These have provided invaluable insights into past sea levels and ice extent. It also has access to the infrastructure and platforms required to maintain and develop research in this area (including sea-bed mapping and seismics) via UK and international research vessels, and the unique capability to study close to marine-terminating ice using Autosub.

Multidisciplinary links to other marine Arctic research priorities:

- Palaeoceanography (Research priority 1)
- Oceanography (Research priority 2)
- Sea-ice observations (Research priority 3)
- Ecosystems and biogeochemistry (Research priority 8)

Delivery to NERC Themes and related initiatives:

- Climate Change
- Earth System Science
- Natural Hazards
- Ice-sheet Mass Balance and Sea-level Rise programme scoping study

Links to other NERC, UK and international research programmes:

- Oceans 2025
- GISP & GISP2

Research Priority 7: *To assess the magnitude and stability of methane hydrates in Arctic shelf seas and the consequences of warming-induced methane release for sea-bed stability and atmospheric methane inputs.*

Arctic shelf sea sediments are characterised by extensive methane hydrate deposits containing approximately 1,400 Gt of carbon with 0.5 Mt released each year. Methane hydrates are sensitive to temperate and are predicted to become increasingly unstable as Arctic waters warm.

Recent work has recorded dissociation of methane hydrate deposits in the Western Svalbard shelf. Methane is being released into the water column but the subsequent fate of the released gas, and whether it is being transported and released to the atmosphere, has yet to be established. Importantly, the flux of gas release at this representative site, and general distribution and quantity of hydrate deposits around the Arctic Ocean margin that could be perturbed by warming are unknown.

Hydrate dissociation also affects sediment pore-pressure and slope stability. There is evidence to suggest previous hydrate-related submarine landslides along the Norwegian margin, and similar events may be possible on the Svalbard and Barents Sea margins. Additionally, methane gas emissions from hydrate are anaerobically oxidised to CO_2 in Arctic seas that enhance the effects of ocean acidification.

The UK currently has world-leading expertise in marine geophysics, thermodynamic hydrate modelling, and sediment-pore and water-column biogeochemistry, and sustained observing programmes that are applicable to Arctic Ocean hydrate research. It also has access to the infrastructure and platforms required to maintain and develop research in this area (including sea-bed mapping using AUV's, combined seismic–electrical exploration geophysics, and seafloor observatory systems) via UK and international research vessels.

Multidisciplinary links to other marine Arctic research priorities:

- Oceanography (Research priority 2)
- Air-sea fluxes (Research priority 5)
- Climate forecasts (Research priority 10)

Delivery to NERC Themes and related initiatives:

- Climate Change
- Earth System Science
- Natural Hazards
- Methane Network capacity building and start-up initiative

Links to other NERC, UK and international research programmes:

- Oceans 2025
- COBRA
- Dynamics of gas hydrates in polar marine environments NERC IPY Consortium

Research Priority 8: *To improve our capability to predict the response of the Arctic marine primary productivity to current and future changes in sea-ice cover and water column properties, and to determine the probable consequences for ecosystem structure and function, and biogeochemical carbon flux.*

The biological productivity of Arctic coastal and oceanic waters is predicted to increase as Arctic sea-ice becomes thinner and less extensive, allowing more light and a longer growing season for marine phytoplankton. Changes in sea-ice thickness and extent also influence sea-ice algal production, while changing ocean currents and increased freshwater inputs will influence water column optical properties and nutrient supply. Predicting the magnitude of future changes in Arctic productivity is complex and current ecosystem models currently lack understanding of key parameters controlling phytoplankton growth (especially light and nutrients) and baseline data on spatial and temporal variability of primary production for model parameterisation and validation.

Changes in the timing and magnitude of Arctic primary production, in turn, influence the structure, function and productivity of the pelagic food web, biogenic carbon flux to sediments, benthic ecosystem productivity and carbon burial and export. The sea-ice, pelagic and benthic systems are closely coupled, especially across the extensive Arctic shelf-seas, and feedbacks within and between systems are complex. A model-led systems approach is therefore required to understand and predict the response of Arctic marine food webs and biogeochemical cycles to climate change, and to ensure the health of fisheries and charismatic species of high conversation interest.

The impact of Arctic climate change and anthropogenic impacts (including fisheries) may lead to ecological regime shifts, as already observed in the Bering Sea. This further challenge requires access to long-term observational data, at appropriate temporal and spatial resolutions, to detect such non-linear changes. Strategic long-term monitoring platforms, historical records and palaeo-oceanographic data are required to provide such “baseline” data and detect future changes.

The UK currently has world-leading expertise in modelling pelagic and benthic ecosystems, including the development of physical-biological coupled Arctic ecosystem models (incorporating sea-ice physics) and the Southern Ocean food-web modelling. The UK also leads in several areas of observational and experimental research underpinning current modelling efforts including: remote-sensing of optical properties and phytoplankton in CASE II (coastal) waters; long-term plankton monitoring; sea-ice biogeochemistry, microbial biogeochemistry and genomics; sediment trap and benthic-lander technology; fish behaviour and distribution; and higher-predator monitoring.

The community is therefore well placed to undertake a model-led programme of targeted observational and experimental research to address the above research priority. Such research is already supported by UK research vessels, the Kings Bay marine laboratory on Svalbard, and CPR surveys; however, it would benefit from access to international research icebreakers to enable access to full ice-covered waters.

Multidisciplinary links to other marine Arctic research priorities:

- Palaeoceanography (Research priority 1)
- Oceanography (Research priority 2)

- Sea-ice observations (Research priority 3)
- Sea-ice predictions (Research priority 4)
- Air-sea fluxes (Research priority 5)
- Adaptation of marine organisms (Research priority 9).
- Sustainable exploitation and management (Research Priority 11)

Delivery to NERC Themes and related initiatives:
- Biodiversity
- Earth System Science
- Sustainable Use of Natural Resources themes goals
- Ocean Acidification large scale programme

Links to other NERC, UK and international research programmes:
- Oceans 2025
- SOLAS
- IMBER

Research Priority 9: *To determine the adaptive capabilities of Arctic marine organisms and their resilience and resistance to predicted environmental change.*

There is urgent need to understand the factors which create, maintain and protect global biodiversity and how this diversity relates to ecosystem function and the provision of ecosystem goods and services. The study of the adaptive capabilities of Arctic marine organisms offers unique insights into our understanding of global biodiversity: (i) The response of Arctic organisms (which are used to living in a stable environment) to rapid environmental change guides understanding of the response of organisms from climatically stable lower latitude environments to future change; (ii) Comparison of Arctic organisms with populations within the same species from warmer (but less thermally stable) boreal environments, and with highly endemic Antarctic species, guides understanding of short versus long-term adaptation to environmental conditions; (iii) Arctic environments subject to natural disturbances (e.g. iceberg impacts) act as natural experimental systems with which to study anthropogenic-induced impacts on ecosystems and their recovery.

The Arctic marine environment is a significant component of the global ocean so quantifying its biological diversity, the ability of existing species to survive change, and the impact of invasive species (some of which may cross from the Pacific to Atlantic oceans) is important. Refinement of Arctic marine ecosystem models, which currently categorise organisms into functional groups, will also eventually require an understanding of how the diversity within functional groups react to changes in the physical and biological environment, and how these influence ecosystem structure, function and productivity. Micro-organisms and higher trophic groups are of particular interest: the former because of their potential for pollutant (oil) remediation and biotechnological exploitation; the latter because of their important stabilising and integrating function, their use in acquiring relevant data, and their inherent commercial and conservation value.

Current theoretical understanding is insufficiently advanced to deliver accurate predictive numerical models of Arctic community resilience and resistance. The immediate challenge is therefore to quantify existing biological diversity (at genetic, organism and community levels) and to develop a conceptual understanding of the physiological mechanisms and genetic constraints which enable organisms to adapt to their cold and highly seasonal environment. The latter requires experimental studies on response to multiple environmental stressors (such as temperature, pH and pathogens).

The UK currently has world-leading expertise in the physiology, phylogenetics, functional genomics and biodiversity of marine organisms, including Arctic and Antarctic species and cold-adapted deepwater species. It also has access to some of the research platforms required to maintain and develop observational and experimental research in this area including the Kings Bay Marine Laboratory on Svalbard, UK low-temperature aquaria, and CPR surveys. Access to experimental facilities in colder, ice covered waters is possible via Canadian and Danish collaborations.

Multidisciplinary links to other marine Arctic research priorities:

- Ecosystems and biogeochemistry (Research priority 8)
- Sustainable exploitation and management (Research Priority 11)

Delivery to NERC Themes and related initiatives:

- Biodiversity
- Sustainable Use of Natural Resources
- Ocean Acidification large scale programme

Links to other NERC, UK and international research programmes:

- Oceans 2025
- ECOPA
- Census of Marine Life
- MARBEF
- EUR-OCEANS
- LWEC

Research Priority 10: *To promote research collaboration and knowledge exchange between the UK marine Arctic environmental research community and climate forecasters.*

Current global and regional climate models are limited in their ability to simulate Arctic environmental conditions by poor understanding of underlying processes. The disparity between the IPCC climate model predictions of Arctic sea-ice extent and recent observations is a striking demonstration of current model limitations. Model validation is also limited by uncertainties in observational data which are limited in spatial and temporal resolution (IPCC 2007). Climate models and coupled global climate models can be used to predict the time scale for a seasonally ice-free Arctic Ocean as well as for the purpose of understanding the dynamics of this complex, coupled system. In either case, the effort to close the gap between model results and observations will require accepted metrics of success (model skill), more observations of quantities that quantify model skill, and incorporation of testable dynamics into the models. The UK has world leading expertise in global and regional climate forecasting. It is therefore of mutual benefit for the UK marine Arctic environmental research community and climate modelling communities to work closely together. The objective of this research priority is to ensure that climate model outputs guide marine observational and process studies, and that outputs from such studies are transferred to the climate modelling community.

Multidisciplinary links to other marine Arctic research priorities:

- Palaeoceanography (Research priority 1)
- Oceanography (Research priority 2)
- Sea-ice observations (Research priority 3)
- Sea-ice predictions (Research priority 4)
- Air-sea fluxes (Research priority 5)
- Ocean ice-sheet interactions (Research priority 6)
- Methane hydrates (Research priority 7)
- Ecosystems and biogeochemistry (Research priority 8)

Delivery to NERC Themes:

- Climate Change
- Earth System Science

Links to other NERC, UK and international research programmes:

- NERC/Met Office Joint Climate Research Programme

Research Priority 11: *To promote sustainable exploitation and management of Arctic natural resources by more effective knowledge transfer between the UK marine Arctic environmental research community and Arctic policy-makers and stakeholders.*

The predicted reduction in summer sea-ice thickness and extent increases the opportunities and threats associated with marine transport and resource exploitation in the Arctic. The seasonal opening of the Northern Seas Route and Northwest Passage is likely to make trans-Arctic shipping during summer feasible within several decades bringing with it concerns over maritime safety, pollution and transport of invasive species. Increased access to Arctic living and non-living resources, including fisheries, oil, gas and heavy metals, are likely to have considerable strategic impact on the UK and EU economies, and on the international political and security environment. The Arctic marine environment is already subject to resource exploitation including major fisheries in the Bering and Barents Sea, and oil extraction off Alaska. It is important that pre-emptive measures are taken to ensure that resources are exploited in a sustainable manner with minimum environmental impact.

The UK environmental science community is not currently engaged in research on the sustainable exploitation and management of Arctic natural resources but has related expertise which can be applied to the Arctic. The latter includes expertise in environmental impact assessments and the conservation and management of marine living resources (particularly in North Atlantic and Southern Ocean fisheries). The UK also has expertise in Arctic social sciences, including the fields of public policy, human geography, governance and anthropology. The UK community is therefore well placed to ensure that outputs from the preceding research priorities are transferred to the policy-makers and stakeholders.

Multidisciplinary links to other marine Arctic research priorities:

- Sea-ice observations (Research priority 3)
- Sea-ice predictions (Research priority 4)
- Ecosystems and biogeochemistry (Research priority 8)
- Adaptation of marine organisms (Research priority 9).

Delivery to NERC Themes:

- Biodiversity
- Environment, Pollution and Human Health
- Natural Hazards
- Sustainable Use of Natural Resources

Links to other NERC, UK and international research programmes:

- LWEC
- CCAMLR
- Defra (R&D in support of marine fisheries management)
- ICES

5. Supporting UK marine Arctic observational capability

The limited temporal and spatial scope of current observational data available from the marine Arctic represents a serious barrier to the development of a more comprehensive understanding of how the Arctic marine system currently functions and how it will respond to change. Model parameterisation and validation is, in particular, difficult without suitably resolved observational data.

Satellites and autonomous *in-situ* platforms offer an efficient and cost effective means of obtaining high spatially and temporally resolved observational data from the Arctic, especially where such platforms encompass multidisciplinary observations. The UK has played a leading role in the development of remotely sensed and *in-situ* technologies for polar observation including ice-penetrating radar, sea-ice deformation measurements, ice-buoys and ice-tethered platforms, under-ice sampling from AUVs and submarines, use of animal platforms, benthic landers and CPRs. Many of these platforms and technologies are unique assets available to the UK marine science community (e.g. the large, long-range Autosub AUV; extensive access to Royal Navy submarines; Iridium data buoy technology; Cryosat altimetry expertise; the CPR survey). However, deployment of such platforms has often depended on third party logistical support and funding to support the long-term observations and data analysis has been limited.

The workshop therefore recommended that a long-term strategic approach is adopted towards for the development and operation of UK observational capability in the marine Arctic and the subsequent analysis of observational data. This approach should be science led, cross-disciplinary to encompass multi-functionality, and closely integrated with international observation programmes. It would contribute directly to the delivery of the NERC Technology strategic science theme goals.

6. Interactions with boundary systems

The Arctic marine environment is an open-system influenced by surrounding continents and the global atmosphere-ocean system. The response of this system to current and future environmental change cannot be understood without consideration of the interactions and feedbacks with boundary systems.

The above research priorities encompass interactions and feedbacks with the Pacific and Atlantic Oceans (priorities 1, 2 and 3), the atmosphere (priorities 2, 3 and 5), continental ice-sheets (priorities 1 and 6) and continental freshwater inputs (priorities 1, 2, 3, 6 and 8). There is clearly considerable potential to enhance UK marine Arctic research efforts by working with the wider UK and international atmospheric, terrestrial, and oceanographic research communities. The workshop recommended that any directed programme of marine Arctic research interfaces with these communities.

7. Geographic focus of UK marine Arctic research interests

The above research priorities require observations and data synthesis across differing spatial scales. Workshop participants identified several geographic areas of interest with respect to delivering the above research priorities. In some cases a pan-Arctic approach is required which can only be delivered via international collaboration. In other cases more localised geographic study areas were identified, some of which are accessible using UK research platforms alone.

The workshop concluded that it was premature to identify specific study areas to address the above research priorities as these depend on future operational considerations including funding, logistics and international collaborations. However, some prospective areas were identified based on a combination of scientific requirements and likely operational opportunity:

- Basin-wide observations (via satellites, autonomous platforms, submarines)
- The Arctic-Atlantic gateways (especially the Fram and Nares Straits)
- The Barents, Greenland, Iceland and Norwegian Seas.
- Greenland and Svalbard fjords.
- Baffin Bay and North Water region.

8. International collaboration and added value

The UK marine Arctic research community has established international links with researchers from the Arctic rim nations (Canada, Denmark, Norway, Russia and the USA) and the European Union. UK researchers have also made significant contributions to the International Polar Year (IPY) as partners in 37 IPY endorsed research clusters. For example, UK researchers have made significant contributions to many EU Arctic research programmes, participated in Norwegian, German and Danish research cruises and ice camps, utilised the Russian ice-breaker fleet, and undertaken collaborative studies at Norwegian (Svalbard) and Danish (Greenland) coastal research stations.

Links with North American Arctic researchers are historically not as strong as those with Europe; however, the recently signed Canadian-UK Memorandum of Understanding Concerning Cooperation in Polar Research offers considerable opportunities for UK researchers to access

Canadian Arctic and sub-Arctic infrastructure, including the research icebreaker CCGS *Amundsen*. Several areas of common research interest with Canadian marine researchers have also been identified at a recent UK-Canadian Polar Research Workshop sponsored by the British and Canadian High Commissions. These include studies of the sea-ice, oceanography, palae-oceanography and biogeochemistry of the Labrador, Lincoln and Beaufort seas (NSERC 2009).

The above international links and collaborations offer substantial opportunities to add scientific, logistical and financial value to future UK research efforts. They also enhance the scientific and political impact of UK Arctic research.

The workshop therefore recommended that any future research programme is developed in close collaboration with international partners, and in particular the Canadian, Danish and Norwegian Arctic research communities.

9. Delivery to NERC Strategy and stakeholders

A directed research programme focused on a selection or all of the above research priorities would contribute directly to several NERC thematic science areas, and especially Biodiversity, Climate Change, Earth System Science, Natural Hazards, Sustainable Use of Natural Resources, and Technologies.

Several research priorities also complement more specific NERC initiatives and activities, including the Ice-sheet Mass Balance and Sea-level Rise programme scoping study (priority 6), Methane Network capacity building and start-up initiative (priority 7), Ocean Acidification large scale programme (priority 9), Joint Climate Research Programme strategic partnership (priority 10) and LWEC programme (priority 11)

Such future investment would build on previous NERC and EU investments in UK Arctic research (including previous NERC IPY consortia, SOLAS, RAPID and EU research programmes such as DAMOCLES and EPOCA) enhancing the legacy of these programmes by maintaining expertise in critical areas of environmental science.

Finally, a directed marine Arctic research programme would also (via priorities 10 and 11) help inform and empower UK and EU government and industrial stakeholders (including the FCO, Defra, shipping, hydrocarbon, fisheries and conservation interests).

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Annex 2: Workshop Agenda and Timetable

Tuesday 31 March

13:00: Welcome & introduction (Ray Leakey)

13:20: Talk on international Arctic science (David Barber)

14:00: Breakout discussion groups (disciplinary) to prioritise key Arctic science questions:
- Sea-Ice (Chair: David Barber)
- Oceanography (Chair: Mark Brandon)
- Geology (Chair: Ian Wright)
- Chemistry (Chair: Ronnie Glud)
- Biology (Chair: Ray Leakey)

15:00: Coffee break

15:30: Continue in groups followed by feedback from group chairs (plenary)

17:30: Close of session

19:30: Workshop dinner

Wednesday 1 April

09.00: Talks on international opportunities & logistics
(David Barber, Cynan Ellis-Evans and Sheldon Bacon)

10:00: Breakout discussion groups (interdisciplinary) to discuss multi-disciplinary research opportunities and geographic focus:
- Group 1 (Chair: David Barber)
- Group 2 (Chair: Liz Morris)
- Group 3 (Chair: Lloyd Peck)

11:00 Coffee break

11:30 Continue in groups

13:00: Lunch

14:00: Feedback from discussion group chairs (plenary)

14:30 Discussion and synthesis (plenary)

15:30 Workshop ends