



**NERC Polar Science Working Group Report  
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## 1. Summary and Principal Recommendations.

1. The polar regions occupy one fifth of the Earth's surface and contain the most pristine and extreme environments on Earth. With temperatures close to the freezing point of water, they are more threatened by rising temperatures than other environments on Earth, with potential consequences for the entire planet. Some polar regions are warming more rapidly than any other region on Earth and will continue to do so for the next century. Evidence of large-scale change at the poles has accumulated rapidly over the past decade. There is now a pressing need to understand processes of change in the polar regions and their wider implications.

2. The NERC Science Strategy (2007-2012) recognises the importance of the poles. This document identifies (§ 3), six issues of strategic importance: Ice sheets and their contribution to sea level rise (§ 3.1), the thermohaline circulation (§ 3.2); the role of polar processes in atmospheric composition (§ 3.3); the impact of change on biodiversity (§ 3.4); the importance of ice core and palaeo-oceanographic records (§ 3.5); and the developing resource potential of the Arctic (§ 3.6). These are central components of the NERC strategy themes, and issues that demand a cross-cutting approach across the themes (§ 3.7). The document also identifies (§ 4) the present international and national organisation of polar science, and the UK polar infrastructure.

3. The document (§ 5) identifies that while the balance of strategic scientific concerns lie equally in the northern and southern hemispheres, the weight of NERC investment in people and infrastructure lies in the Southern Hemisphere. This weighting is underlain by the UK's sovereignty of the British Antarctic Territory and commitment to the Antarctic Treaty. It results, *de facto*, in UK Antarctic science ranking among the world's best. Nonetheless, the UK, as a nation and as a member of the European Union, has pressing concerns in the Arctic. The Arctic is the nearer pole to the UK, and changes occurring there affect our climate and sea level. The retreat of the sea ice has energy, transport and fisheries implications for the UK. In the NERC Centre Surveys and the HEIs, the UK has world-class scientific strength in those areas – physical- and palaeo-oceanography, glaciology, and biosphere-atmosphere interactions – that bear on the UK's direct Arctic concerns, and are identified as key concerns in the NERC strategy. *We recommend that the NERC strategy and the UK national interest favour an increase in NERC Arctic science.*

4. In contrast to the Antarctic, the NERC approach to Arctic science has been and is non-strategic. However, long-term, international, co-ordinated programmes are the most effective approach to tackling polar challenges. *We recommend that NERC develop cross-theme elements to the theme action plans that maintain directed Arctic and Antarctic sub-themes, and whose mechanisms give weight to activities forming components of larger, international programmes.*

5. There is some scope for the increased use of NERC polar logistics in the Arctic. In particular, the BAS aircraft are available to support Arctic logistics in the summer. Increased deployment of BAS and NOC vessels in the sub polar oceans is possible, but tensioned with the demands of BAS base operations and on-going, often long-term, observations in Antarctica and elsewhere. In any event, the polar challenges will demand a collaborative approach to the provision of ice-strengthened and ice-

breaking vessels. *We recommend that NERC develop bi- and multi-lateral approaches to provide UK scientists access to and influence on ice strengthened and ice breaking vessels.*

6. There is broad satisfaction that Antarctic Funding Initiative (AFI) provides sufficient access to UK scientists in Antarctica. In the Arctic, access to bases, while usually welcomed, is more haphazard. *We recommend that NERC should pursue more formal arrangements that would simplify access negotiations and broaden access opportunities for NERC scientists.*

## 2. Introduction

7. The NERC primary Strategic Goal (2007 – 2012) is to deliver the scientific evidence needed for governments, business and society to respond urgently to the increasing pressures on natural resources and global climate. Within this context, the new NERC strategy identifies the Arctic and Antarctic as environments of particular importance. NERC Council requested the formation of a Polar Sciences Working Group to advise Council, within the context of the new NERC strategy, on the major scientific priorities in the polar regions, and to recommend national and international approaches to supplying the infrastructure required to support these polar science priorities, and those of the Arctic in particular. Annex 1 contains the Working Group's terms of reference.

8. The Working Group met on 11 May 2007 to discuss science priorities and on 19 June 2007 to discuss the infrastructure demands. From these meetings it derived a draft strategy that was the subject of a web-based community consultation in August and September 2007. A final meeting of the Working Group on 11 October 2007 considered the result of the consultation, generating a final draft for consideration by NERC SISB on 6/7 September 2007. This document, prepared for the NERC Council meeting of 28/29 November 2007, includes modifications requested by SISB.

9. This document does not aim to provide a comprehensive description of all aspects of polar science, nor replace detailed assessments of the state of the poles and their sensitivity to climate change, such as the Arctic Climate Impact Assessment or the reports of the Intergovernmental Panel on Climate Change. Its more narrow purpose is to identify subjects of strategic importance that may drive the provision of NERC polar infrastructure.

10. The Working Group considered that some definition of the term 'polar' was needed to define its remit. In the Northern Hemisphere, it took as a working definition the southern limit of terrestrial tundra, the Arctic Ocean and sub-Arctic seas and the atmosphere to the north of the region of the Polar Front; in the Southern Hemisphere it took the Antarctic continent and the Southern Ocean including the Antarctic Circumpolar Current, but excluding essentially mid-latitude processes such as Antarctic Intermediate Water formation and, for example, the Agulhas or Brazil Currents. It considered a more precise geographical definition would be too restrictive.

### 3. The Science Challenges.

11. In the Arctic and Antarctic changes are occurring as large and as rapidly as any on Earth. The future evolution of the poles, and their wider interaction with lower latitudes, introduce uncertainties in predicting 21<sup>st</sup> century sea level (§ 3.1) and climate (§ 3.2 and § 3.3) as large as those from any other source. Climate change will profoundly affect biodiversity (§ 3.4), particularly in the Arctic. Through, for example, ocean acidification, change will affect longer term biogeochemical cycling; that understanding of the Earth's longer-term climate is incomplete today is demonstrated in the records retrieved from ice cores (§ 3.5). The rate of change, particularly in the Arctic, is creating simultaneously new access to resources and new challenges to sustainability (§ 3.6). In this section, we identify the urgent challenges of polar sciences under these broad headings. In a final subsection (§ 3.7) these challenges are related to the science themes of the NERC Science Strategy.

#### 3.1 Ice Sheets and Sea Level Rise.

12. The IPCC Fourth Assessment Report 2007 identified the cryosphere as the largest uncertainty in contributions to future sea level rise. While work in the past decade has greatly reduced the uncertainty in the contributions of the Antarctic and Greenland ice sheets to present-day sea level rise, the present generation of numerical models are unable to reproduce the large-scale changes that have now been observed in the Greenland or Antarctic ice sheets. While this relates in part to deficiencies in the models themselves, it is at least as much a consequence of poorly known basal boundary conditions. As a result, we have very limited ability to predict the future contribution to sea level of the largest stores of fresh-water on Earth.

13. A wide variety of techniques have been used to demonstrate that the Greenland Ice Sheet is losing significant quantities of ice every year, but more importantly the rate of change has increased in recent years. This has been attributed to atmospheric warming, but the apparent sensitivity of the ice sheet to these changes has caused surprise, and there is also evidence of marked fluctuation in the ice flow to the ocean. There remains considerable uncertainty over the response of Greenland's ice-sheet to ongoing climate change.

14. Dramatic changes have occurred in the past two decades in the Antarctic Peninsula: northern sections of the Larsen ice shelf collapsed catastrophically, and grounded glacier flow to the oceans has accelerated, while strong snow-fall driven growth has occurred on the Dyer Plateau to the south. All these changes are associated with the largest regional warming trend observed on Earth today (para. 23). However, observations over the past decade have also shown that in the cold Pine Island and Thwaites drainage basins of the West Antarctic ice sheet (a sector long predicted to be unstable in the face of small changes in climate) ice, while remaining frozen, is flowing to the sea faster than snowfall can replenish it inland, and similar behaviour, albeit on a smaller scale, has now been observed in East Antarctica. These basins contain a water mass equivalent to several metres of sea level, and it is essential to establish the cause of the thinning. It has been linked to a recent trigger in the oceans, but it may equally be that we are witnessing an on-going and possibly accelerating retreat arising from the geometric instability of these marine-terminated

ice sheet basins. A detailed understanding of the thinning and the interaction of the grounded and floating ice flow with the surround shelf-seas is required.

15. For Greenland and Antarctica, the satellite record clearly identifies the ice streams and glaciers whose evolution is of greatest concern. A detailed knowledge of their bed geometry and mechanical properties, and an understanding of the hydraulic processes taking place at ice-sheet beds, and their spatial and temporal variability, is essential to predict the future of ice-sheets, ice-streams and ice-caps. Processes at work in Greenland, where surface melt-water can reach the bed, are distinct from those in most of Antarctica where temperatures are mostly too cold for this to occur. However, in Antarctica too there is increasing evidence of under-ice-sheet lake systems and rivers, and the role that they play in the dynamics of the ice sheet is not known. Studies of bed processes including sub-glacial hydrology both in Greenland and Antarctica are important.

### 3.2 The Global Ocean Thermohaline Circulation: Polar Forcing and Response

16. The oceanic overturning circulation (the “thermohaline circulation”, THC) plays a key regulatory function in the Earth’s climate over decadal and longer timescales. Paleoceanographic evidence shows that a vigorous THC delivers heat to the North Atlantic sector at the expense of the Southern Ocean on millennially-variable timescales, so that increases and decreases in THC strength should result in a climate “seesaw” between the northern and southern hemispheres. However, the potential threat of rapid climate change on much shorter – down to decadal – timescales due to changes in the THC is of great concern. Even allowing for the results emerging from the ‘RAPID’ programme, we are still unable to quantify its probability. It is therefore important to understand better what drives, and therefore what could disrupt, this circulation.

17. In the Arctic, the critical knowledge gaps devolve on to: (i) freshwater and its control on dense water formation, and (ii) THC forcing changes in a seasonally ice-free Arctic Ocean. In the north, freshwater input and dense water formation in the Arctic and sub-Arctic oceans are central components of the THC. We know little about the net consequences of secular variability in the sources and sinks of freshwater, including (i) the direct freshwater sources and sinks of river runoff, precipitation, evaporation, terrestrial glacial melt-water and sea ice transport, and (ii) the indirect sources and sinks of the oceanic exchanges both of freshened seawater and of very saline seawater input from low Atlantic latitudes. We do not know how the Arctic Ocean and communicating sub-basins respond dynamically to such changes, nor do we know the timescales of storage and (ultimately) export to the global ocean. Furthermore, as the Arctic sea ice declines, increased summer heat storage in the ocean will delay the onset and extent of the winter freeze-up, leading to further sea ice decline the following summer. Reduced ice cover will also increase the wind forcing of the ocean, and the extent to which freshwater will be retained within the Arctic halocline, or be transported out to the sub-polar oceans, is far from certain today. Present capability to model sea ice formation, deformation and decline is limited, and inadequate measurements of the surface and basal mass, momentum and heat fluxes hinder the testing and validation of new models.

18. While the northern high-latitude oceanic THC processing can be characterised as the intake of light surface waters and the output of dense deep waters, in the southern high-latitude oceans, the processing is very different: dense deep waters are drawn to the surface, and processed into lighter intermediate waters and even denser bottom waters. Our understanding of how this happens is very limited: the ACC is unique because the meso- and small-scale processes of eddies and mixing shape both along- and cross-ACC property fluxes to form the Southern Ocean THC. All related fluxes are very difficult to measure and are therefore only speculatively represented in models. As a result, the zeroth-order response of the Southern Ocean to projected climate variations is also, at best, speculative.

19. Understanding of Southern Ocean physics is questionable: in some cases the physics is understood but paucity of measurements results in unreliable quantification of effects (*e.g.* eddy-driven upwelling and related property fluxes); in other cases it is controversial (*e.g.* the link between the ACC and turbulent mixing, closing the deep overturning cell); or even unknown (*e.g.* how is the balance between winds, eddies, mixing and air-sea interaction set up?). The mean, the annual cycle, the interannual variability, and long-term trends in Southern Ocean surface wind or buoyancy forcing are poorly known; as is how these inputs translate into subsurface fluxes; and therefore, the processes by which subsurface oceanic inputs are transformed into different subsurface outputs. Fundamental exploration into cryospheric controls on the Southern Ocean THC is urgently required: in particular, measurements are lacking of the winter ocean under the sea ice, and the waters beneath ice shelves. Elucidation of the mechanisms controlling Southern Ocean/ACC variability is required, as are measurements to quantify many aspects of that variability.

### 3.3 The Coupling between Polar Processes, Atmospheric Composition and Regional and Global Change.

20. Changes in atmospheric composition cause climate change. Processes in polar latitudes exert an important influence on carbon uptake, and hence both the atmospheric concentration of CO<sub>2</sub> and polar acidification, and future changes there could also, for example, lead to massive releases of methane, another important greenhouse gas. Similarly, emissions from the polar cryosphere both of halogenated species and nitrogen oxides are implicated in changes in the tropospheric oxidizing capacity, with implications for atmospheric pollution and climate change. Furthermore, new research suggests that the poles are regions where recent changes in stratospheric composition are having an impact on surface climate. A research strategy aimed at climate change and air pollution demands a polar contribution to quantify these important coupling processes.

21. In the polar and subpolar oceans the supply of the nutrients nitrate and phosphate is high enough not to limit phytoplankton growth. This is because the oceanic thermocline outcrops at subpolar latitudes such that nutrient-rich and CO<sub>2</sub>-charged waters of the deep ocean are exposed to the atmosphere but are returned to the subsurface before biological utilization, therefore raising atmospheric CO<sub>2</sub>. The Southern Ocean contains the largest amount of unused surface nutrients but surface chlorophyll suggests it is the least productive of the polar oceans. Availability of light

and trace nutrients such as iron are known factors that limit productivity but ecosystem changes affecting nutrient/carbon "Redfield Ratios" and how vertical mixing occurs are poorly understood. Study of the physical and biogeochemical factors shaping the Southern Ocean carbon cycle will be important for assessing its role as a carbon sink in the past during fluctuating CO<sub>2</sub> levels and in the high CO<sub>2</sub> world of the future.

22. Natural gas hydrates exist both in the sea-bed and onshore in permafrost soils. 500-2500 GT carbon is estimated to be stored globally in gas hydrates and the underlying reservoirs of free gas: about half of the global total carbon burden, with the potential to affect climate. Hydrate stability depends on pressure and temperature, so changes in the hydrate system will be greatest in the Arctic, which is expected to see the greatest warming. We need to understand the mobility of the gas hydrate reservoir, and how much could escape to the atmosphere as bottom water temperatures increase or permafrost soils are flooded. However, there is little information about the distribution and quantity of hydrates in the Arctic. Large marine hydrate provinces are known to exist offshore Svalbard and in the Beaufort Sea, for example. Also, terrestrial (permafrost) hydrates are particularly climate-relevant as they are more dynamic, and methane from hydrate dissociation would directly enter the atmosphere.

23. Over the past 50 years surface temperatures over much of Antarctica have remained fairly stable. By contrast, large and statistically-significant warming trends are seen in the Antarctic Peninsula, the largest being in winter - approximately 10 times the mean rate of global warming. Recent studies have connected this warming to ozone changes in the lower stratosphere. Upper ocean temperatures to the west of the Peninsula have also increased by over 1°C in the same epoch. The east coast of the Peninsula has warmed more slowly and here the largest warming has taken place in summer and autumn. Subtle but important changes have occurred, the Southern Hemisphere Annular Mode (SAM) resulting in a strengthening of the westerly winds that blow over the Southern Ocean. Stronger westerlies are likely to impact on ocean currents, mixing and reduced CO<sub>2</sub> drawdown from the atmosphere into the ocean, but the full consequences of such changes, and the mechanisms connecting these changes with changes in the lower stratosphere, have yet to be fully understood, quantified and modelled successfully.

24. The research focus on stratospheric polar ozone in recent years means that many of the important processes are reasonably understood. The focus of research has shifted to how ozone will recover in a changing climate and responses to regulation of ozone-depleting gas under the Montreal Protocol. The stratosphere is predicted to continue to cool as a result of increasing greenhouse gas concentrations and this cooling will favour polar ozone destruction, but will lead to ozone increases away from polar latitudes. The trajectory of global stratospheric ozone over the coming decades, and whether or not there will continue to be episodes of locally-extreme ozone depletion in the Arctic, are questions at the heart of studies of chemistry/climate interactions.

25. Snow and sea ice contribute important emissions to the atmosphere and mask emissions from the underlying surfaces. The discovery of a springtime depletion of tropospheric boundary-layer ozone, localized to polar coastal regions, has stimulated

enquiry about the importance of brominated species in tropospheric chemistry at a global scale. Other emissions, such as those from the snow pack, play a much more active role in a polar chemistry than hitherto considered, and could have a significant impact on future hemispheric, tropospheric ozone (and hence oxidizing capacity and air quality). Changes in the Arctic, induced by climate change, will change deposition and emission processes of a number of crucial atmospheric constituents, including halogens, the oxides of nitrogen, and methane. These components strongly affect the chemistry of the lowest layers of the atmosphere, and control important processes such as the transfer of pollutant mercury into the marine food-chain.

### 3.4 The Resilience and Response of Polar Organisms and Ecosystems to Environmental Change

26. Polar organisms and ecosystems are currently subject to rapid environmental change and the potential fragility of polar-adapted animals and plants to climate change may result, not only in the loss of globally-important biodiversity, but also in changes to ecosystems affecting climate feedbacks and commercially-important species. We know that such climate changes in the past (albeit possibly not as rapid) have resulted in massive changes in the distribution of organisms, with consequent changes to ecosystem composition and biogeochemical cycling. In addition, ocean acidification will impact significantly on polar organisms with resulting changes to biodiversity and ecosystem structure and function. Our relatively poor understanding of these climate-driven changes in polar ecosystems is, however, compounded by the past and present exploitation of marine species and, in the Arctic, by the effects of bioaccumulation of anthropogenic pollutants. The accurate prediction of the response of polar organisms and ecosystems to these environmental changes, including the effects of invasive species from warmer waters, is an important challenge.

27. There is great need to characterise biodiversity from genes to communities from the simplest ecosystems on Earth through to complex ecosystems. It is also imperative to assess the role of biodiversity in ecosystem processes and to evaluate the vulnerability of biodiversity to change. Wide-scale analyses of biodiversity levels and tolerances to change need integrating with, for example, regional organic flux resulting from a changing sea ice distribution, basin scale isolation, small-scale disturbances and historical factors. These levels in turn affect higher predators and human activity (such as krill, fish and shellfish harvesting), and the links need urgent evaluation. In the Antarctic, the fast changing environment of the Antarctic Peninsula is juxtaposed with areas that have exhibited very little or no change in the recent past, both geographically and with depth in the ocean. Because of these marked changes over small spatial scales it will be possible to identify effects of change on biodiversity compared to natural control areas in the same groups of animals. This is a natural marine laboratory for change effects that is unique on Earth. We need to compare and contrast similar communities inside and outside the west Antarctic Peninsula region to allow us to predict what will happen as other regions warm.

28. On land 'refugia', such as nunataks, islands and coastal regions, may be critical for the survival of polar diversity – indeed, it appears that many contemporary Antarctic biotas evolved millions of years ago and survived the Last Glacial Maximum in ice-free niches. Antarctic biodiversity studies have also shown that biological refugia have existed at low-level sites around the continent for millions of

years (a fact not reconcilable with current glacial maximum ice sheet models). These may be critical niches for the long-term preservation of polar biodiversity. We need to establish whether the identification and preservation of potential future refugia will allow the survival of unique polar biotas threatened by future habitat change?

29. The profound changes expected in the Arctic climate will result in a new regional ecosystem, through changes in climate, oceanography, sea-ice habitats, and in snow cover. The existing Arctic ecosystem and its populations face decline and possible extinction; new opportunities for a richer biodiversity and more productive ecosystems may emerge. In terrestrial Arctic ecosystems, higher summer temperatures will increase biogeochemical cycling in freely-drained soils, and in turn influence nutrient availability, with cascading effects on ecosystem function and productivity. Although winters may be warmer, stochastic icing events in the autumn before snow covers the land may produce more challenging conditions for plants and the animals dependent on them. Since these changes will influence the competitive interaction between species, both within and between trophic levels, the consequences for biodiversity are important.

30. In the Arctic marine environment, changes in sea-ice duration and extent, freshwater inputs and ocean currents will alter the timing and magnitude of phytoplankton production with consequent changes in pelagic and benthic ecosystem structure and function, and associated biogeochemical cycles. It is anticipated that Arctic marine ecosystem productivity will increase and this may lead to increased populations of some higher predators, including commercially important species; it may also lead to increased carbon flux to the deep sea. In addition, warmer seas will result in the introduction and northward migration of warmer water species, and associated decreases in the distribution of coldwater species with possible extinctions (including ice-dependent species such as polar bears and seals). The interactions within the Arctic marine ecosystem, and between organisms and their environment, are complex and poorly understood. We need improved prediction of the effect of such changes on the Arctic marine ecosystem achieved via the development and refinement of coupled biological-physical models applicable over a wide range of spatial and temporal scales.

31. With increasing solubility of CO<sub>2</sub> under lower water temperatures, the potential for ocean acidification to impact on calcareous organisms in polar waters is a significant issue. Recent studies indicate that cold-water coral ecosystems (primarily *Lophelia* reefs) may be most prone to such effects. Major coccolithophorid algal blooms, which help to draw down atmospheric CO<sub>2</sub> through photosynthesis and increased albedo, are showing physiological damage associated with lower pH ocean water. Other important taxa are vulnerable, such as pteropods and commercially exploited bivalve molluscs. A coordinated approach to the ecosystem effects of acidification in sub-polar and polar waters is required in both hemispheres.

### 3.5 The Unique Polar Environment

32. The polar regions host various archives, observation points and features that are unique on Earth. Polar ice cores offer information about how the Earth system operates that is not available anywhere else. When tied to other palaeo-records, they form our evidence base for testing models. The very presence of a persistent continent-sized ice sheet over Antarctica is unique, and offers further tests of understanding about the workings of the Earth on longer timescales. Other unique features of the polar regions, such as the long periods of darkness, the dry atmosphere, and the geomagnetic location offer unrivalled locations for observing the interaction of Sun and Earth, and for some astronomical studies. Previously unexplored environments, such as lakes beneath deep ice sheets, represent a technical challenge and an inspiring frontier for exploration.

33. Polar ice cores have made exceptional contributions to our understanding of processes in the entire Earth system, alerting us to the possibility of rapid climate change, and showing the close links and feedbacks between greenhouse gases and climate over glacial cycles. There remains huge potential for ice cores to teach us about interactions between elements of the Earth system. Extending the Antarctic ice core record to 1.5 Ma (the so-called "oldest ice" target) will give access to a period when glacial/interglacial cycles operated on a different period, 40 ka rather than 100 ka. This offers an opportunity to understand how the interaction between greenhouse gases, ice sheets and climate really works. In Greenland, drilling a core through the entire last interglacial, a period somewhat warmer than today, will provide quantitative constraints for models predicting the future demise of the Greenland ice sheet.

34. On shorter timescales, a bipolar network of ice cores reaching back 40 ka, through the rapid warmings (Dansgaard-Oeschger events) of the last glacial and glacial termination, will provide a pattern of spatial response that can be used to test our understanding of how changes in ocean heat transport affect climate. Networks of cores extending 2 ka would contribute important new quantitative information, in data-sparse regions, to IPCC-style climate reconstructions. On these (2 ka and 40 ka) timescales, supplementing the ice core data with polar lake and marine sediment cores and geomorphological ice sheet reconstructions covering similar time periods would add a valuable context about conditions on land and in the ocean, and the reaction of the ice sheets to climate change.

35. The ice cores have revealed the natural variability in atmospheric CO<sub>2</sub> over glacial-interglacial cycles and there is a great challenge to understand such cycles. One view is that the initial forcing is by insolation changes in the North Atlantic but that the Southern Ocean is somehow responsible for the positive feedback reflected in the records of Antarctic air temperature. The Southern Ocean's carbon cycle (para. 21) is probably implicated. Changes in the transfer of heat to the Arctic Ocean by the THC produce a "bipolar seasaw" seen in marine records. Linking together research on climate records in the atmosphere and the oceans (§ 3.3) is a clear way forward to understand these climatic cycles prior to anthropogenic change.

36. Well beyond the ice core timeframe, the conditions that allowed Antarctica to be warm and the changes that led to the greenhouse-icehouse transition in the early

Cenozoic era offer further challenges to our understanding of the Earth system. Field and modelling studies can explore the relative roles and timing of events, such as the opening of Drake Passage and reductions in CO<sub>2</sub> towards present levels, in ice sheet development. The Arctic Basin is largely unexplored but stored within its sediments is evidence of, for example, the impact of the sudden release of freshwater into the Arctic basin (as seen during the Eocene 55Ma in drill cores), past sea ice distribution, and the impact of methane hydrate release. Marine and glacial sediments on the ocean floor provide an archive running beyond the timeframe of the ice cores that can for example show how the critical West Antarctic ice sheet has behaved in previous warm and cold periods.

37. As yet unexplored, sub-glacial lakes beneath the Antarctic ice sheet are the subject of intense recent interest. Well over 150 lakes have now been identified, and their isolation from the atmosphere for hundreds of thousands, and possibly even millions of years, introduces the possibility of a unique pattern of evolution and adaptation to the particular environment. The recent discoveries that hydraulic connection between the lakes occurs through large, unsteady floods, and that some lakes coincide with the onset of ice streams, is changing the view that the sub-glacial lakes have little relation to the ice flow. That large lakes, such as Lake Vostok, the 4<sup>th</sup> largest lake in the world, may abruptly discharge to the ocean, is now a distinct possibility. Geophysical exploration of the lake environment, and eventually sterile penetration of the lakes, is a challenging technological task, but of huge public interest, and opening a new frontier of exploration.

38. The poles offer a vantage point to remotely sense Earth's space environment (also called geospace), using the properties of the geomagnetic field that focus the effects of this environment into the polar regions, as illustrated by the phenomenon of the aurora. Differences between such effects in the Arctic and Antarctic also provide strong constraints on models of geospace. Improving such models is necessary to understand and predict the possible connections between geospace and the lower atmosphere (such as the effects of energetic charged particles on stratospheric chemistry and cloud formation), as well as the effects of geospace on radio communications and satellite operations, and on the radiation hazard to airline crew and astronauts.

39. The polar regions are home to biotas with unique evolutionary characters and special adaptations, including adaptations to the seasonal light regime, high levels of ultra-violet light, the production of antifreeze compounds, the lack of an otherwise globally ubiquitous heat shock response in higher animals, and extreme difficulty in making useful protein. There are biotas specifically adapted to the extreme environments. The polar regions are also home to iconic species of public interest including great whales, albatrosses, penguins and polar bears. Antarctica has the largest areas of unexplored biodiversity on Earth in terrestrial and marine ecosystems, and marine Antarctic biodiversity has recently been shown to be much greater than expected and of global significance; areas like the Amundsen Sea have almost no observations of what species live there, or their characteristics. In addition, the extremes of the polar regions are of importance in addressing the current debate concerning the two opposing forces of dispersal (which promotes a cosmopolitan distribution) and the physiology and evolutionary history (which promotes site-specific species) that govern the global microbial distribution. Fundamental studies of

the diversity, evolution, physiology and ecological function of polar organisms will significantly advance our understanding of living systems.

### 3.6 Resources and Sustainability of the Polar Regions

40. Many aspects of the geology, biology and oceanography of the polar regions are still unknown. These regions are, however, one of the last frontiers for the exploitation of natural resources. The Antarctic Treaty's Protocol on Environmental Protection provides an indefinite prohibition on all minerals related activity, except for scientific research. In contrast, the melting sea-ice in the Arctic has prompted an expansion of hydrocarbon and minerals exploration. The right to delimit an extended continental shelf under the UN Convention on the Law of the Sea, has prompted significant recent focus on the polar regions, further underlining that these regions are of major global political interest.

41. Whilst the Arctic continental shelves are now a major target for hydrocarbon exploration, many geological terrains that are potential major hydrocarbon provinces, such as the East Greenland and the Siberian continental shelves, are as yet unexplored. In the absence of a moratorium on extractive industries in the Arctic, as in the Antarctic, and indeed any other supra-national institutions or agreements on the governance of natural resources in the Arctic, the consequences of the race to extract these resources could be immense. Mapping and prediction of the occurrence and availability, under different scenarios of the technologies and economics of extraction, of oil, gas and minerals in the Arctic are key to understanding the effect on the environment of their exploitation and the impact of the waste products that they produce. NERC has a key role to play in developing new tools and techniques to assess the resources, and determine the full range of environmental impacts from use of various resources.

42. An ecosystem-based approach for the management of exploitation of marine resources in the Southern Ocean has been operating since the 1980s through the Convention for Conservation of Antarctic Marine Living Resources, CCAMLR. Delivery of the underpinning science remains a requirement, and is important, as there will be a step-change in the scale of the fishery during the coming decade. This fishery will affect not just the species that depend on krill for food, but has the potential to change the operation of the whole ecosystem. Developing models of the operation of Southern Ocean ecosystems that include realistic representations of life-cycles of key species and food web processes are essential for both resource management and predicting the impact of change. The techniques and approaches for the scientific basis for an ecosystem approach to management can be applied to the Arctic.

43. The opportunities for sustainable economic development in the Arctic region are increasing rapidly and will continue to do so. Opportunities relate particularly to the opening of new shipping lanes linking the Pacific and Atlantic across the Arctic (particularly the North-West Passage and the Russian "Northern Sea Route"), minerals extraction, fisheries, forestry and tourism. There are major questions surrounding the impacts that these activities might have and are already having on the Arctic environment – and whether this may have future consequences for the Antarctic. Inter-disciplinary science, ranging from basic to applied science and from

the natural and social sciences, is needed to build a much fuller understanding of the potential risks and impacts that are associated with economic development and the ways they are managed. The impact of Arctic change may be mitigated, to some degree, through a fuller scientific understanding that better informs new forms of environmental policy and management. There is also a need to evaluate the links between researchers and user groups to understand how the wide range of scientific research conducted on the Arctic environment feeds the diversity of stakeholders and institutions that are involved in the management of the Arctic.

44. Human adaptation to the Arctic involved major biological and cultural adaptation. Although there are suggestions that humans had reached the edge of the Arctic before the last glacial maximum, most of the expansion followed the last deglaciation. The Arctic provides a unique opportunity to trace the speed and direction of human settlement, and its impact on these environments, over the last 13,000 years. In the southern hemisphere, the Tierra-del-Fuego peoples established viable, long lasting communities by the beginning of the mid-Holocene and probably even reached the Falklands. Comparison between extreme adaptations at either end of the world, and investigation of just when and why people were there, will offer insights into earlier relationships between humans and cold climates.

### 3.7 Multiplexing Polar Science Challenges into NERC Science Strategy Themes.

45. The primary Science Goal of NERC (2007 – 2012) is for the UK to lead the world in the prediction of the regional and local impacts of environmental change from days to decades. To address this science goal, the science priorities have been gathered within seven science themes, namely, The Climate System; Biodiversity; The Sustainable Use of Natural Resources; Earth System Science; Forecasting and Mitigation of Natural Hazards; Environment, Pollution and Human Health; and Technologies.

46. There is a natural relationship between the broad challenges of polar sciences and the NERC themes. Ice sheets (§ 3.1), the thermohaline circulation (§ 3.2) and the role of polar processes in atmospheric composition (§ 3.3) are central components of the Climate System theme; polar ecosystems (§ 3.4) of the Biodiversity theme; ice core and palaeo-oceanographic records (§ 3.5) of the Earth System Science theme; and the developing resource potential of the Arctic (§ 3.6) of the Sustainable Use of Natural Resources theme.

47. Equally, polar challenges extend across themes. Many concerns of polar biodiversity (§ 3.4) relate to its robustness in the face of climate change. Sea level rise (§ 3.1), itself a natural hazard, depends on the waxing and waning of ice sheets, which bears directly on the concerns of Earth system science, but whose prediction depends on the integration of ice dynamic models with coupled climate models. Similar remarks apply to methane hydrate release (paras. 22 & 36). Antarctic sub-glacial lakes (para. 37) bear on ice dynamics, a climate concern, flood-water release to the ocean, an Earth system science concern, and microbial biodiversity in extreme environments. Heavy metals entering the Arctic food chain (para. 25) are a concern of environmental health and sustainability. We have regarded human evolution (para. 44) as bearing on sustainability, but it is equally a matter of biodiversity. A combined

approach between themes is needed to address polar challenges.

#### 4. People, Science Infrastructure and Delivery.

48. The difficulty of access to and operations in the polar regions makes essential international coordination of national scientific endeavor. This is provided in the Antarctic by the Scientific Council on Antarctic Research (SCAR, est. 1958), an Interdisciplinary Committee of the International Council for Science (ICSU). The Royal Society UK National Committee of Antarctic Research, hosted by British Antarctic Survey represents the UK. SCAR also provides scientific advice to the Consultative Meetings of the Antarctic Treaty. The internationalisation of the Antarctic under the Antarctic Treaty and consensus as to its scientific importance makes SCAR a substantial, influential and effective coordinating body. A second important body for logistic coordination is the Council of Managers of National Antarctic Programs (COMNAP) of which BAS is a member.

49. International relations in the Arctic are distinct from those of the Antarctic. The Arctic Council provides a forum for Arctic-rim countries, but it does not have the status in international law, or the overarching role of the Antarctic Treaty System. The Arctic Council does not, for example, discuss fisheries matters. The UK, as a non-Arctic country, is a State Observer to the Council. The International Arctic Science Committee (IASC), an Associate Member of ICSU, provides scientific coordination in the Arctic, although it does not have the scale, scope or authority of SCAR. An NERC nominated individual represents the UK. It was established in 1990 in recognition of the need for an Arctic science coordinating body. It is also an Observer to the Arctic Council.

50. Of particular importance in polar science are large-scale, long term, international projects arising through from coordinating bodies and initiatives such as the International Polar Year (IPY), the Study of Environmental Change (SEARCH), the Arctic Ocean Science Board (AOSB) or International Study of Arctic Change (ISAC). This is particularly true of the Arctic and Southern Ocean. The European Union is also an important funding body, particularly for Arctic programmes, in which UK scientists are leading participants, and has been active in developing polar scientific networks. Illustrative examples are the EU-funded 'DAMOCLES' project, aimed at monitoring Arctic atmosphere – sea-ice – ocean interactions, which involves 45 research institutions in 12 European countries, and is coordinated with Canada, Japan, the Russian Federation and the US-NSF; and the SCAR and SCOR sponsored circumpolar initiative, 'Integrating Climate and Ecosystem Dynamics' (ICED) for the Southern Ocean, part of a wider IGBP programme; and the project to drill the sub-glacial Lake Ellsworth, West Antarctica, involving 14 UK HEI institutions, under the auspices of the SCAR 'SALE' programme.

51. Within the UK, the FCO takes the lead on all Antarctic governance and administration of the British Antarctic Territory (BAS provide support and presence within the BAT). Conversely, a number of Government Departments lead on issues relating to the Arctic, including climate change, energy security, fisheries, marine transport and strategic defence matters, which concern to varying degrees Defra, BERR, DfT, FCO and MOD. Individual Departments lead on the various Arctic policy issues. Overall, however, there is less coordination of Arctic science than that

of Antarctica. The UK Meteorological Office, the European Centre for Medium Range Weather Forecasting, the Hadley Centre and the Centre for Environment, Fisheries & Aquaculture Science (CEFAS) all make direct contributions to polar scientific research.

52. Polar science is supported at NERC Centre Surveys to varying degrees. BAS researches the entire spectrum of Antarctic and Southern Ocean science. BAS operates an extensive Antarctic infrastructure (para. 53 and Annex 3). BAS coordinates the Antarctic Funding Initiative (AFI), providing responsive mode funding to NERC Centre Survey and HEI investigators that require access to the Antarctic. The Scottish Association for Marine Science (SAMS) has NERC and externally supported programs focused on the Arctic, Northern Seas and marginal ice zone (MIZ). NOC, BGS and CEH all have Arctic focused research (for example, BGS coordinated the Arctic coring operation (ACEX) of IODP; NOC and POL have modelling and observational projects connected with Arctic and North Atlantic circulations). The bi-polar NERC Collaborative Centre for Polar Observation and Modeling (CPOM) specialises in the combination of satellite observations and models.

53. UK polar logistics (see Annex 2 for a more detailed description) are principally those of the BAS Antarctic logistics. It operates three year-round research stations: Rothera, on the western Peninsula; Halley, on the Brunt Ice Shelf in Coates Land, and Bird Island, South Georgia. It maintains a summer station at Signy, on the South Orkney Islands, and two summer field stations, Fossil Bluff, on the Peninsula, and Sky-Blu. BAS operates two ice-strengthened ships: the RRS *James Clark Ross* and RRS *Ernest Shackleton*. Typically, these vessels are in the Southern Hemisphere for some 6 months each year and are available for scientific study respectively for 4.5 months and 1 month. The Royal Navy HMS *Endurance* supports BAS operations in Antarctica and can provide Lynx helicopters for supporting field parties. BAS operates a 'Dash-7' and four 'Twin Otters' equipped with wheels and skis, which operate in Antarctica for six months (October to March) each year. NERC maintains a small summer base at Ny-Ålesund in the Svalbard Archipelago, north of Norway. Other important UK polar infrastructure is Drake Passage bottom pressure recorders, and tide gauge recorders at Port Stanley, Vernadsky and Rothera, maintained by POL, as part of the GLOSS network; the NOC-developed *Autosub* AUV platform, for which operation beneath sea ice and ice shelves has been an important design driver; the use as permitted by operational constraints of Royal Navy submarines for Arctic sea ice monitoring; and the availability of satellite observations from polar-orbiting satellites, from the NERC-supported ESA programmes, NASA, and other agencies.

54. Some 30 countries maintain logistic capability in the Antarctic to some degree. Of these, the United States and Germany maintain capability equal to or larger than that of BAS, and many other countries (*e.g.*, Australia, Russia, Italy, Japan, France, Norway and China) have significant assets; in all, there are 40 research stations on the continent. While national programs tend to be focussed geographically according to the location of stations and political interest, there is a good record of bilateral (*e.g.*, the UK-US survey of the bed of the Pine Island/Thwaites drainage basins) and multi-lateral (*e.g.*, the EPICA ice core project) international collaboration, often coordinated through SCAR or COMNAP. Other countries provide logistic support to individual HEI investigators working outside the UK Antarctic Territory, such as the Dry

## Valleys of East Antarctica.

55. The Arctic Rim countries operate bases (see Annex 3 for a summary) of varying size. The logistic support for some of these bases are provided by contractors on behalf of a research or survey organisation (*e.g.*, VECO runs the US NSF logistics in Greenland), while others (*e.g.*, Station Nord in Greenland and Station Alert in Ellesmere Island) are supported by military logistics. Access to these bases for UK researchers depends on case-by-case negotiations, but long-standing, if informal, contacts have proved effective in the past.

56. Many countries have ice strengthened and ice-breaking fleets that may be used for scientific survey in the Arctic and Southern Oceans (see Annex 4). As with bases, access for UK researchers to them, the facilities they offer, and ice thickness in which they may operate all vary on a case-by-case basis. At one extreme are Russian, heavy breakers available to anyone (including tourists) on a commercial basis, which have no specific science laboratories, but can operate in any ice conditions; at the other is the specifically designed, scientific platform of the German *Polarstern* to which NERC investigators are welcome as 'minority partners'. Presently there are no bilateral or multilateral arrangements to facilitate UK access to ice breakers, which is a matter for individual PIs to negotiate.

## 5. Conclusions & Recommendations

57. As § 3 shows, the NERC ambition to lead the world in the prediction of the regional impacts of climate change demands a particular attention to polar change. At present, NERC polar strategic science is weighted, in terms of people and particularly logistics, to the Southern Hemisphere. This weighting is underlain by the UK's sovereignty of the British Antarctic Territory and commitment to maintaining its high profile and influence within the Antarctic Treaty. It results, *de facto*, in UK Antarctic science ranking among the world's best, and UK scientists playing leadership or partnership roles in large international, experimental initiatives.

58. The Arctic Rim countries face the problems of Arctic climate change directly and have immediate environment and strategic concerns. The US, Canada and Scandinavian countries have strategic scientific programs underlain by national strategies (for example, NSF chairs the US Interagency Arctic Research Policy Committee that implements by Act of Congress a US Arctic Policy). These nations naturally have scientific leadership of large terrestrial and marine initiatives, and in some areas (for example, Arctic terrestrial ecology) are world leaders.

59. Nonetheless, the UK, as a nation and as a member of the European Union, has important concerns in the Arctic. The Arctic is the nearer pole to the UK, and changes occurring there may directly affect our climate and sea level. The retreat of the sea ice has energy, transport and fisheries implications that may benefit from enhanced regional strategic co-ordination. In addition, in NERC Centre Surveys and HEIs, the UK has world class, scientific strength in those areas – physical- and palaeo-oceanography, glaciology, and biosphere-atmosphere interactions – that bear on its most direct Arctic concerns, and which relate most directly to NERC and UK leadership of, and ambition in, climate modelling at lower latitudes. *We recommend that the NERC strategy and the UK national interest favour an increase in NERC Arctic science.*

60. In contrast to the Antarctic, the NERC approach to Arctic science has been and is non-strategic. Projects and programmes, and the use of existing logistics (for example, access to *James Clark Ross*) result from response mode grants, or at the largest, one-off thematic programmes (for example, the ARCICE programme). In our view, an increase in NERC Arctic science using its historical mechanisms will result in limited scientific reward. Many of the climate and biodiversity challenges (§§ 3.1, 3.2 & 3.3) reside in the oceans and ice sheets and relate to distinguishing secular change from decadal variability over large regions presenting special problems of access and operations. Long-term, international, co-ordinated programmes (para. 50) are the most effective approach to tackling these challenges. Long-term support requires a directed approach; international partnerships may be encouraged by, for example, the successful NERC approach to its support of the UK participation in the IPY projects. *We recommend that NERC develop cross-theme elements to the theme action plans (paras. 46 and 47) that maintain directed Arctic and Antarctic sub-themes, and whose mechanisms give weight to activities forming components of larger, international programs.*

61. NERC has airborne and marine polar capabilities with which it might support increased Arctic programmes. BAS aircraft are located in Canada (for servicing) in

the Arctic summer, coinciding roughly with the period (late April to early September) in which Arctic fieldwork may be pursued. They are unused for approximately 10 weeks of this period. The Twin Otters, in their logistic and survey roles, may be particularly useful: to provide logistics to UK field parties on the Greenland Ice Sheet, or for surveys of ice sheet thickness, for example. *We recommend NERC makes effective use of the BAS aircraft in the Arctic summer.*

62. Increased use in the Arctic and the Southern Ocean of the *James Clark Ross*, *Discovery* and *James Cook* is in principle possible, but doing so would have implications on the present programmes of BAS, NOC and others. BAS ship provision is determined by the requirement to operate two permanent, year-round bases at the limits of the British Antarctic Territory. Within the schedule this demands, there is perhaps some room (of the order of two weeks) to increase *James Clark Ross* commitment in the sub-polar oceans, but this is tensioned against a reduction of scientific activity at, for example, an Antarctic island base. Deployments of the *Discovery* and *James Cook* are not so constrained and increased deployment in the sub-polar oceans is possible, but the Working Group considered that the scientific impact of this change would need a careful consideration beyond its competence<sup>1</sup>.

63. In any event, the UK alone cannot supply the marine infrastructure demanded by polar challenges. A collaborative approach to the provision of ice-strengthened and ice-breaking vessels is required. Prospects for access to ice strengthened and icebreaker capability lie in the Canadian, Russian, Swedish and other fleets (see para. 56 and Annex 3). It is also essential that collaborative arrangements permit UK scientists a significant partnership role (for example, in the planning of the cruise) and that NERC supported scientists may avoid the ‘double jeopardy’ of separated funding decisions. Canada is a potential partner. Russia offers ships on a straightforward commercial basis with high icebreaking capability and limited scientific infrastructure (for example, hydrographic winches *etc.*). Sweden has at least one fine vessel (the *Oden*) and a willingness to enter into bilateral arrangements. *We recommend that NERC develop bi- and multi-lateral approaches to provide UK scientists access to and influence on ice strengthened and ice breaking vessels.*

64. The EU scientific infrastructure roadmap includes a proposal for a European scientific ice breaker, *Aurora Borealis*, whose ambition is in keeping with the strategic concerns identified in this document, NERC must evaluate carefully the costs and risks of involvement. As far as it is possible to determine today, the capital costs are high. In addition, the operating costs are uncertain, and these, as noted in the recent UK National Audit Office (NAO) report on ‘Big Science’, need to be identified at the outset so as to also identify the downstream implications of the capital investment. It is also unclear that the scientific goals cannot be met at less cost by the combined use of breakers and other marine platforms (as was done, for example, for the ‘ACEX’ experiment, para. 52).

65. UK polar scientists have welcomed the Antarctic Funding Initiative (AFI) managed by BAS. It is regarded as providing sufficient access to UK bases in Antarctica for investigators pursuing research that lies outside the BAS core

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<sup>1</sup> For the same reason, the Working Group has not responded to consultation requests to comment on the decision not to ice strengthen the *Discovery* replacement.

programme. In the Arctic, access to Arctic Rim bases (Annex 2), while usually welcomed, is a matter for individual researchers, differs from country to country, and depends to an extent on individual contacts. *We recommend that NERC should pursue more formal arrangements that would simplify access negotiations and broaden access opportunities for NERC scientists.* Access to Svalbard, which lies on the Arctic Rim and contains the largest Eurasian icecap, is important, providing access to the some of the Arctic environments that research requires. It is not clear, however, that the present NERC base at Ny Ålesund is optimal<sup>2</sup>. *We recommend that NERC review use of the base in Ny Ålesund, and explores the best options for maintaining a British base in Svalbard, possibly with location of some activity in Longyearbyen and with it the potential for a collaborative partnership with the University and the Svalbard Science Centre.*

66. The UK's ability to forecast change in polar regions is underpinned by the development of advanced coupled numerical models of the ocean, ice and atmosphere. The evidently poor understanding of ice sheet response to continued warming, and the attendant effect on sea level, and the limited capability of sea ice components of global coupled models, demands a heightened investment of effort in ice sheet and sea ice models. There is a considerable capability in the UK in the theory and modeling of stand-alone ice sheets and sea ice models, and of their coupling with the ocean and atmosphere; however, the coordination of this community could be improved. We encourage a more strategic approach to model interfacing, reuse, and benchmarking among this community.

67. It is hard to overstate the contribution to our knowledge of change in the polar regions provided by long-term, ongoing satellite and ground observations. We emphasise the need for NERC to maintain these observations via the NERC Earth Observation programme of the ESA Earth Explorer and GMES programmes, the NERC *Autosub* programme, and to exploit to the full the potential of UK Navy submarines for sea ice monitoring. The practical difficulty of providing spatially and temporally continuous measurements in the polar regions places a special importance on the further development of autonomous platforms such as profiling floats, sensors attached to marine mammals and birds, drifters, long-range airborne and marine gliders, terrestrial rovers, and intelligent moorings, which are having a growing impact by providing unprecedented spatial and temporal resolution for process studies and sustained observations. Critical to their operability in cold environments is the development of enabling technologies in the fields of power, telemetry, navigation and sensors. *We recommend that the technology theme places an emphasis on the development of autonomous platforms.*

68. The Working Group considered whether polar science introduced special training requirements. While it recognised that performing field experiments in hazardous environments did introduce the need for particular practical training, such as that presently provided by BAS for field parties to Antarctica and Svalbard, it did not consider that there was a need for special scientific training particular to the polar sciences.

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<sup>2</sup> This statement in the consultation draft generated a number of responses, which, taken together, demonstrated its truth.

## **Annex 1: The Terms of Reference for the Polar Science Working Group**

### Introduction

NERC Council has asked that a working group (the Polar Science Working Group or 'PSWG') be established to identify NERC's polar science priorities, within the context of the new NERC strategy.

### Methodology

The PSWG will be co-chaired by Prof Chris Rapley and Prof Duncan Wingham. Membership of the Group will be recommended by the co-Chairs and agreed with NERC Director, Science and Innovation. A representative from NERC Swindon Office will attend the meetings.

The PSWG will produce an interim report for SISB in May 07 and produce a final report for Council in June 07.

### Remit

1. To advise Council of the NERC strategic scientific priorities in the Arctic and Antarctic within the context of NERC's new science strategy;
2. To advise Council of the access and infrastructure needed to achieve these priorities. In particular, the group will assess the infrastructure needs for Arctic science, including how these could be met using existing NERC infrastructure;
3. To identify the associated skills & training requirements;
4. To advise Council of the potential for collaboration with international partners to provide access and infrastructure to facilitate NERC's scientific objectives in the Arctic and Antarctic, where appropriate;

Resourcing issues are not within the remit of this group.

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## **Annex 2: UK Polar Logistics.**

A2.1. BAS operates a considerable Antarctic infrastructure consisting of bases, ships and aircraft. It maintains three year-round research stations: Rothera, on the western Peninsula; Halley, on the Brunt Ice Shelf in Coates Land, and Bird Island, South Georgia. (It also maintains a station on King Edward Point, South Georgia on behalf of the South Georgia and South Sandwich Government). It maintains a summer-only station at Signy, on the South Orkney Islands; and two summer field stations, Fossil Bluff, on the Peninsula, and Sky-Blu, at the Ellsworth Mountains. BAS also supports network of more-or-less temporary fuel depots throughout the Territory that permit, for example, drilling of ice cores. The bases have distinct scientific roles. Rothera, the largest of the bases, supports biosciences, glaciology, geosciences and meteorology; Halley's location supports atmospheric physics from the surface to the thermosphere boundary layer meteorology, chemistry studies from the snow pack to the mesosphere, ozone depletion studies and geospace research – solar-wind-magnetosphere-ionosphere physics; Bird Island (a site designated one of Special Scientific interest) has some 1,000,000 pairs of penguins, albatrosses and petrels), while Signy specialises in terrestrial ecology and microbiology. Fossil Bluff and Sky-Blu are essential staging posts to studies of the deep interior. Taken as a whole, the bases allow the entire range of Antarctic field sciences.

A2.2. BAS operates two ice-strengthened ships; the RRS *James Clark Ross* and RRS *Ernest Shackleton*. These vessels perform two roles, as supply ships to the BAS Antarctic bases, and as scientific survey platforms. The *James Clark Ross* is fully equipped for all aspects of biological, chemical and physical oceanography and marine geophysics. It is available in the Southern Hemisphere for some 6 months each year (excluding the approximately 2 months per year for passage). It supplies Bird Island and Rothera, leaving 75% of its time is available for scientific survey. The *Ernest Shackleton* has 'wet' and 'dry' laboratories and cranes for package deployment. It is principally used to supply Halley and Signy; typically one month per year is available for scientific survey. The *James Clark Ross* and *Ernest Shackleton* can cruise at 12 knots in open water. They can operate in up to 1 metre of sea ice at 2 knots, although some of this capability is reserved for operational margin. The Royal Navy's ice patrol vessel, HMS *Endurance* provides support to operations in Antarctica, by agreement with the FCO and BAS. In particular, it provides access to two Lynx helicopters for supporting field parties in remote locations and has facilities for multi-beam echo sounding.

A2.3. BAS operates five aircraft. The 'Dash-7' provides an 'air-bridge' for up to 16 passengers or some 2000 kg of cargo from the Falkland Islands to Rothera; from Rothera it can carry fuel and supplies to Sky-Blu. It has some capability for airborne remote sensing, but its principal purpose is logistics. Its introduction in 1991 greatly increased BAS's capability to mount campaigns in the deep interior of the ice sheet. Four 'Twin Otters', equipped with wheels and skis, provide survey and logistic and capability. One is equipped for aero-geophysics ice sheet survey (ice penetrating radar, gravimetry and magnetics, *etc.*), a second for meteorological remote and in situ sensing. The remaining two aircraft are solely used for logistic support. The aircraft operate in Antarctica for six months (October to March) each year. The Dash 7 and Twin Otters are serviced in Canada during the Austral winter. During this period,

these aircraft are available for some 10 weeks for Arctic surveys or logistics, although they are not presently used for this purpose.

A2.4. In the Arctic, NERC maintain a small summer (April to September) base, located at Ny-Ålesund, Spitsbergen (79°N 11°E). The island is part of the Svalbard Archipelago, north of Norway. The King's Bay Company (KBC) provides the service infrastructure for the base, which is managed for NERC by BAS. It comprises a 400m<sup>2</sup> laboratory, a workshop and storage space plus single bedrooms. It is accessed by plane from the commercial airport at Longyearbyen. SAMS sponsors, under a 10-year commitment to KBC, the Marine Laboratory at Ny-Ålesund (a separate facility) to permit experimental studies on marine organisms and biogeochemistry.

A2.5. In the north, the *RRS James Clark Ross* is available for up to 60 days per year. In addition, *RRS Discovery* and *RRS James Cook* (operated by the National Marine Facilities Division at NOC) are usually available for deployment in the sub-Arctic (mainly ice free) oceans; typically in any one year one or two months of ship time is there. In contrast to the Antarctic, however, the deployments are not constrained by the need to supply the Antarctic bases, but are planned on a case-by-case basis according to the demands of Centre Survey and HEI investigators.

A2.6. NERC has two aircraft remote sensing, a Dornier 228 equipped for terrestrial remote sensing, and, jointly with the Meteorological Office, a BAE 146 for meteorological and atmospheric chemistry measurements. Both aircraft are available to investigators on a case-by-case basis, and have been used for sub-Arctic operations (*e.g.*, in Alaska and Svalbard) from airports with sufficient runway lengths. Neither aircraft is equipped with skis for 'bush' polar operations permitting landings on land and marine ice. BGS has a Twin Otter that is used for terrestrial and coastal studies.

A2.7. Royal Navy submarines have made measurements of Arctic sea ice thickness since 1971 using upward looking sonar, and recently these have been extended to three-dimensional mapping using multibeam sonar. The submarines have also carried out along-track measurements of upper ocean structure and collected water samples. These measurements provide a long-term, if spatially sparse record of sea ice thickness and its changes, and large-scale measurements of the shape of the ice underside including pressure ridges, vital for the development of sea ice mechanics models. The constraint is that the scientific work must be done as part of a military operation, although much scope is given for modification of tracks for scientific purposes; also UK submarines, through agreements with Denmark and Canada, are able to cover a larger part of the waters of the Arctic Ocean than US submarines, although UK cruises are of course less numerous.

A2.8. NOC has also led the development of *Autosub*, an autonomous underwater vehicle. While limited in range, and subject to deployment constraints in heavy sea ice that makes retrieval problematic, *Autosub* provides a unique platform for investigating physical and biological processes under marine ice and ice shelves. *Autosub* is available to individual PIs on a case-by-case basis through thematic funding ('*Autosub* Under Ice'). Recent experience with the use of small hand-deployable AUVs under ice suggests that, as guidance and retrieval systems improve, small AUVs can have a valuable role to play in local surveys from ice camps or icebreakers, matched with surface and airborne measurements.

A2.9. Satellite observations, particularly the low Earth orbiting, high inclination satellites with microwave payloads (*e.g.*, ERS, ENVISAT and Radarsat) are now the most important source of knowledge of the land and marine ice sheet change at large scales, and meteorological satellites crucial in forecasting the state of the atmosphere in these otherwise data sparse regions. Data are freely available to NERC investigators from NASA and ESA, and the increase in the internet bandwidth, and management of data archives, has made this relatively easy in practice in recent years. NERC funds, and provides the UK delegates to, the ESA 'Earth Explorer' programme, that develops new Earth-observing satellite missions; one of these, *CryoSat-2*, is UK-led and aimed specifically at determining the thinning rate of the Arctic sea ice. NERC is also a partner, with DEFRA and DTI, to the ESA 'GMES' programme, that will provide a long-term climate monitoring capability. Among these missions are high-inclination satellites whose payloads will continue the time-series initiated with the ERA and ENVISAT missions.

### **Annex 3: Summary of Arctic Rim Bases**

The Canadian Polar Continental Shelf Project (Geological Survey of Canada) maintains a station at Resolute Bay (Cornwallis Island) and has forward facilities at Eureka (Ellesmere Island). PCSP provides accommodation, field equipment, air support and a radio communications system that maintains contact with remote field camps and aircraft. These facilities are available to UK scientists working with Canadian collaborators. A Canadian military base at Alert (Ellesmere Island) provides landing facilities and restricted logistic support, and is also an important atmospheric monitoring station

The Barrow Arctic Science Consortium (a private non-profit organisation) has bases in Alaska (Barrow Environmental Observatory and Atqasuk Research Center) and provides logistic support for work in Chukotka. A further station in northern Alaska, Toolik Field Station, is operated by the University of Alaska, Fairbanks.

VECO Polar Resources provide logistic support for NSF-funded projects throughout the Arctic. In Greenland they maintain a research station at Summit and have facilities at Kangerdlussuaq, Thule Air Base and Raven Forward Facility. VPR support is available to UK scientists with the agreement of NSF.

The Danish Polar Centre also provides logistic support in Greenland, and operates a field station at Zackenberg. Locally-run science logistics facilities include the Kangerdlussuaq International Science Support, Sermilik Field Station, the Arctic Station at Qeqertarsuaq and the Greenland Institute of Natural Resources in Nuuk. Station Nord, operated by the Danish Armed Forces, provides landing facilities and some logistic support to researchers. Danish and Greenlandic logistic support is available to UK scientists via the DPC, who act on behalf of the Greenlandic Home Rule government.

In Svalbard the Norwegian Polar Institute has facilities in Longyearbyen and Ny Ålesund. Several other countries, including the UK, have facilities at Ny Ålesund. Other stations in the European Arctic include the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR, Norway), Abisko Science Research Station and Kiruna Institute for Space Physics (Sweden) and Arctic Research Center (Finland). Facilities at European stations are often available to UK researchers as part of EU exchange and coordination schemes.

## Annex 4: Notes on the Global Icebreaker Fleet

### Introduction

Icebreaking research-capable vessels are broadly classified as *light*, *medium* and *heavy*. These terms approximately translate into an ability to navigate through marginal, seasonal and multi-year ice respectively. Ice classes do not translate directly into vessel size. While heavy icebreakers are large, light icebreakers are not necessarily small. There are some very large research and logistics vessels with a light ice classification (*e.g.* the Chinese *Xue Long*). Most heavy icebreakers have the capacity to operate helicopters.

### Overview by Country

- USA: One medium-heavy icebreaker for Arctic research (*Healy*) and a new light-medium build to be commissioned. Two medium-heavy icebreakers for Antarctic science (*Laurence M. Gould* and *Nathaniel B. Palmer*) and two Antarctic logistics vessels (*Polar Sea*, *Polar Star*). One of the latter is laid up, being too expensive to refit to operability. The American fleet is stretched to the limit (see ref [1]) and has operated recently in collaboration with Russian, German and Swedish icebreakers (amongst others; ref [2]) to fulfil its scientific and logistical commitments.
- Canada: A large fleet with many vessels of all classes, the larger ones mainly 1960s–1980s builds but in good condition, operating mainly in Canadian territorial waters. The 2 largest vessels (Canadian “Heavy Gulf” class) are *Louis St. Laurent* and *Terry Fox*. The four “Medium Gulf” vessels are *Des Groseilliers*, *Henry Larsen*, *Pierre Radisson* and *Amundsen*.
- Russia: A large fleet with many vessels of all classes, including a sizeable fleet of nuclear-powered vessels. Through the Murmansk Shipping Co. (ref [3]), two large diesel (*Kapitan Dranitsyn* and *Kapitan Nikolaev*) and nine nuclear (including the newest, *Yamal*, 1992) icebreakers are commercially available for charter. Current usage includes tourism as well as science. The nuclear vessels are practically unlimited by endurance or ice thickness. Other Russian ports (*e.g.*, Archangelsk and Vladivostok) also support fleets of icebreakers of various sizes.
- Japan: One light-medium icebreaker.
- China: One very large light icebreaker.
- Norway: Several light-medium icebreakers; good value charter vessels (*e.g.*, the *Jan Mayen*, light icebreaker, £5K/day in 2000).
- Sweden: A fleet including 3 heavy icebreakers (*Oden*, *Frej* and *Ymer*). *Oden* is the newest (1987) and is a fine ship. The Swedes have recently appeared amenable to bilateral agreements on vessel disposition and use.
- Finland: A fleet of powerful Baltic icebreakers which find summer employment on, for example, cable- and pipe-laying, anchor-handling, oil supply/support.
- Germany: *Polarstern* is a prime heavy icebreaker. It is accessible to UK scientists via the multinational charter/barter agreement to which NERC is a signatory.

However, it appears to allow only conditional access to *Polarstern*, as a “minority stakeholder” or junior partner.

EU: *Aurora Borealis* is a proposed European multi-role heavy icebreaker, which has been included in the ESFRI (European Strategy Forum on Research Infrastructures) ‘road map’ for large-scale scientific infrastructure.

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**Annex 5. Membership of the Polar Science Working Group**

<i>Co-Chairs</i>	
Prof. Chris Rapley	BAS
Prof. Duncan Wingham	UCL

<i>Science Group</i>	
Prof. Steve Albon	Macaulay Institute
Dr. Sheldon Bacon	NOCS
Prof. Julian Dowdeswell	SPRI/ University of Cambridge
Prof. Jane Francis	University of Leeds
Prof. David Macdonald	University of Aberdeen
Prof. Lloyd Peck	BAS
Prof. John Pyle	University of Cambridge
Prof. Graham Shimmield	SAMS
Prof. Bob Spicer	Open University
Prof. Eric Wolff	BAS

<i>Infrastructure Group</i>	
Prof. Steve Albon	Macaulay Institute
Dr. Sheldon Bacon	NOCS
Prof. Jane Francis	University of Leeds
Prof. Dwayne Heard	University of Leeds
Dr. Pete Nienow	University of Edinburgh
Mr John Pye	BAS
Prof. Graham Shimmield (and Dr Ray Leakey)	SAMS
Prof. Bob Spicer	Open University
Prof. Eric Wolff (Deputy: Dr Rob Mulvaney)	BAS

\* Prof Alan Rodger (BAS) attended the PSWG meeting on 11th October