Scientific Research in Polar Seas

ERICON

Science Perspective 2015-2030

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Foreword

Building up a new community-driven Science Perspective is always a major endeavour. This is especially so given the ambition to embrace the research and technological needs of many different research communities for the understanding of climate change processes in the polar regions. It means “taking a bet” on the future by foreseeing multilevel developments spanning diverse research fields in a specific world region.

Reaching the polar oceans is a major priority for scientists, but harsh weather conditions, remoteness, and logistical costs, as well as a lack of adequate tools and technological development, are constraining factors.

This Science Perspective with its key questions is structured around five main research topics in the polar realm (Chapters 1 to 5), and demonstrates the huge scientific interest and potential of a joint collaboration and international network around an internationally operated research icebreaker. A vessel such as the AURORA BOREALIS would offer new scientific potential exceeding the capabilities of individual nations. The time frame for the Science Perspective from the years 2015 to 2030 was chosen to allow for the planning and construction time of a novel research icebreaker, and the latest developments in polar research. On the international scene neither a technically comparable nor any joint internationally operated vessel is in sight in the medium-term. Meanwhile, the key questions identified by this Science Perspective will start to be addressed by existing less ambitious projects.

The ERICON AB Science Perspective is literally an expression of interest by the respective science communities, based on a foresight planning process that describes the high demand for such a novel platform and for research in both polar regions: the Arctic, high on the political agenda, and the Antarctic, which is an equally urgent research priority.

I would like to express my gratitude to all committed scientists from all nations who conveyed their strong interest in pursuing technological developments for the advancement of knowledge in the polar regions, making this Science Perspective not only a strategic plan for the future, but also a white paper to be read by decision makers in research and policy.

My very special thanks to Veronica Willmott for her dedication, persistence and humour, basic requisites for the successful finalization of this Science Perspective.

With best regards,

Bonnie Wolff-Boenisch,
ERICON-AB Project Coordinator

The ERICON Science Perspective Premises

Polar oceans and connected land areas have a high impact on the global environment, and they can be considered drivers of global climate change. This is particularly true for Europe and the Arctic Ocean because the interplay between the North Atlantic Ocean and the Arctic Ocean results in large anomalies in the climatic zones of the Northern Hemisphere. Henceforth, European nations have an eminent interest in understanding the Arctic region, its properties and natural variability, as well as its interaction with the adjacent temperate ocean basins. Many European nations therefore support polar research not only in the Arctic but in the Antarctica as well, and indeed many European polar research programs have a bipolar perspective.

The urgent need to form opinions and make decisions about the future of the global environment has resulted in large polar research efforts in many nations. At the present time the perspectives of polar research for the coming decades in the Northern and Southern Hemisphere high-latitude regions are being evaluated, defined, and strengthened in many ways.

This Science Perspective under the umbrella of the EU-funded European Research Icebreaker Consortium AURORA BOREALIS (ERICON AB) project (in short, AURORA) is one of these attempts. Advances in science are often preceded and enabled by advances in technology. In many cases, fundamentally new tools and techniques are needed to enable new missions. The AURORA project is built around the concept of constructing a research platform that can operate during all seasons of the year in the permanently sea-ice covered areas, and which is equipped with the latest technology, including the equipment to carry out deep-sea drilling in ice-infested waters with dynamic positioning technology. The project is aiming at a wide range of scientific communities that need a tool like the AURORA to conduct their research: namely the classical polar marine research disciplines requiring a research platform to conduct their research, and which are in dire need of data from the unfavourable seasons of the year; and the communities using deep-sea drilling techniques to study the properties, composition and history of the deep-sea floors in polar oceans.

The Science Perspective of the ERICON project presents a holistic strategy to provide the basis for an international integrated and interdisciplinary program to develop a more comprehensive understanding of the present and past evolution of the polar regions. The philosophy of this plan is to explicitly acknowledge **the importance of carrying out research in the Central Arctic Ocean and Antarctic ice-infested waters throughout the entire year**. Understanding the past and future changes of the polar regions is essential, as our present knowledge about these changes and their impacts on humans and natural resources is far smaller than in any other regions of the world. The Science Perspective is not intended to cover in detail all the research that can be carried out in polar regions, but to identify the outstanding scientific questions most relevant for understanding the processes underlying changes currently taking place. Many of these questions can only be identified and addressed through novel technology.

The AURORA concept aims to provide a unique research platform meeting the demands of several multidisciplinary scientific programmes in polar regions. The concept provides a pathway for the development of international cooperation in polar scientific research and operational capabilities. The implementation of a research platform with the AURORA concept will open up long-term perspectives for international programmes, and provide adequate knowledge for sound policy advice to governments on the status of changes to the global environment.

This Science Perspective will provide a basis for future scientific investigations of polar regions and define a ”decadal” strategy for European cooperation in Polar Science.

Development of this Science Perspective

The development of the current Science Perspective started in 2010 with the establishment of the ERICON AB Scientific Advisory Panel (ESAP). The ESAP comprises twenty-nine top-level polar scientists set up by members of the ERICON AB Stakeholder Council and the European Polar Board in late 2009, distributed into the five main core-themes that form the Science Perspective. A series of plenary meetings brought together the top-level scientists to discuss and select the key questions to be addressed in this volume. The Science Perspective was circulated among the ERICON members up until March 2012 for contributions and comments prior to its completion.

1st ESAP Meeting, 18-19th November 2010, ESF, Strasbourg, France

2nd ESAP Meeting, 9th April 2011, Vienna, Austria

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List of Acronyms

AABW, Antarctic Bottom Water;

AARI, Arctic and Antarctic Research Institute, St. Petersburg, Russia

ACC, Antarctic Circumpolar Current

ACCS, Antarctic Circumpolar Current System

ACEX, Arctic Coring EXpedition

ACIA, Arctic Climate Impact Association

AMAP, Arctic Monitoring and Assessment Programme

AMV, Atlantic Multi-decadal Variability

ANDRILL, ANtarctic geological DRILLing project

AO, Arctic Oscillation

ArcOD, Arctic Ocean Diversity project

ARGO, Array for Real-Time Geostrophic Oceanography

ASPeCt, Antarctic Sea-Ice Processes and Climate program

AUV, Autonomous Underwater Vehicle

AVO, Amplitude Versus Offset

BIW, Banda (Sea) Intermediate Water

BSR, Bottom Simulating Reflector

CAML, Census of Antarctic Marine Life project

CCGS, Canadian Coast Guard Ship

CDW, Circumpolar Deep Water

CoML, Census of Marine Life

CPOM, Centre for Polar Observation and Modelling (National Centre for Earth Observation; UK)

CPTU, cone penetrometer test

CRP, Cape Roberts Project

DP, Dynamic Positioning

DSDP, Deep-Sea Drilling Project

ERICON AB, European Research Icebreaker Consortium AURORA BOREALIS

ESA, European Space Agency

ESAP, ERICON AB Scientific Advisory Panel

ESO, European Science Operator

GAW, Global Atmosphere Watch

GCM(s), General Circulation Model(s)

GCOS, Global Climate Observing System

ICDP, International Continental Drilling Program

IODP, Integrated Ocean Drilling Program

IODW, Indian Ocean Deep Water

IOS, International Organization for Standardization

IPCC, Intergovernmental Panel on Climate Change

LIP(s), Large Igneous Province(s)

LLSVP(s), Large Low Shear Wave Velocity province(s)

LOIW, Lower Intermediate Water

Ma, unit of one million years."M" denotes mega- (10^6), and "a" denotes years (from the Latin *annum*)

MOC, Meridional Overturning Circulation

NADW, North Atlantic Deep Water

NAO, North Atlantic Oscillation

NASA, National Aeronautics and Space Administration

NERSC, Nansen Environmental Remote Sensing Centre, Norway

NIIW, North Indian Intermediate Water

NOAA, National Oceanic and Atmospheric Administration

NPDW, North Pacific Deep Water

NSIDC, National Snow and Ice Data Center

ODP, Ocean Drilling Program

ROV, Remotely Operated Vehicles

RSW, Red Sea Water

RV, Research Vessel

SAMW, Subantarctic Mode Water

SCAR, Scientific Committee on Antarctic Research

SDLS, Seismic Data Library System

SLW, Surface Layer Water

SST, Sea Surface Temperature

UCL, University College London

UPIW, Upper Intermediate Water

UPS, Uninterruptible Power Supply

WARS, West Antarctic Rift System

Executive Summary

Polar sciences are a modern branch of the natural sciences involving large groups of researchers, and sophisticated instrumentation contributing indispensable data for a better understanding of the polar regions and their impact on the global environment. The fact that a lot of the necessary data can only be collected by dedicated research vessels, from permanently manned stations, or during expeditions involving many different disciplines and substantial logistic efforts, has resulted in complex and expensive interdisciplinary experiments. These can only be effectively coordinated within the framework of close international cooperation.

The ERICON Science Perspective addresses the entire polar marine scientific community that requires a research vessel for carrying out their field and sea work throughout all seasons of the year. It also addresses the community that needs a deep-sea drilling facility, which would use the research platform, mainly during the summer months, to study the structure and properties of the oceanic crust and the history of the oceanic depositional environments in polar regions. Deep-sea drilling has only been done once in the ice-infested waters of the central Arctic during the Integrated Ocean Drilling Program (IODP) 302, aka, ACEX Coring Expedition. Around Antarctica substantial progress has been achieved by using the drilling platforms of the Deep-Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), and the IODP, during the ice-free seasons, and by using a drill rig from the land fast sea ice very close to shore on the Cape Roberts Project (CRP), and from the ice shelf in the ANtarctic geological DRILLing project (ANDRILL). However, in Antarctica, neither the CRP-tools nor the conventional drilling vessels, which cannot enter ice-infested waters, are able to cover all desirable drilling locations. So far, mainly due to the lack of a suitable ice-capable drilling platform, it has not been possible to investigate many of these locations. These scientific targets will now receive renewed attention in this report (cf. Chapters 3 and 4).

The ERICON scientific program focuses on the research disciplines and activities that require a platform with the unique capability of **year-round operations** in the central Arctic and Antarctic ice infested waters. This document is organized in six chapters. **Chapters 1 to 5** are dedicated to five major **Scientific Core Topics**, each encompassing a number of high-priority key questions embracing the most important scientific challenges that should be targeted in the next fifteen years. **Chapter 6** focuses on the technological requirements needed to successfully answer these scientific questions.

The managerial, financial, and organizational structures for building and managing the vessel, as well as the technical designs of the research platform, are not included in the present document, but they have been elaborated on within the EU FP7 funded EUROPEAN ICEBREAKER CONSORTIUM "AURORA BOREALIS" (ERICON-AB) project, of which this Science Perspective is a component.

The five research topics, around which this Science Perspective is structured, provide an umbrella under which technological and scientific research needs and strategies can be identified. The key questions proposed in each of the chapters have been intentionally kept general and of a nature that will require a strong effort to fulfil, while allowing shorter-term studies to be undertaken on more specific issues. The research topics targeted in this Science Perspective are:

- **The Changing Polar Oceans, Ice and Atmosphere**
- **The Polar Marine Biosphere**
- **The Polar Ocean's Geological History**
- **Polar Paleoclimate and Marine Paleoenvironments**
- **Seafloor Processes and Natural Hazards**

A dedicated platform for polar research with drilling capacities will allow scientists of all polar disciplines to address the five research topics by establishing interdisciplinary campaigns with common goals.

Chapter 1: The Changing Polar Oceans, Ice and Atmosphere

Proposes key questions on the interaction of sea ice, ocean and atmosphere in times of climate change:

- ***How does polar climate change affect global climate? How does climate change affect the long-term trends and seasonal variability of sea ice and polar oceanic and atmospheric circulation patterns?***
- ***Which are the polar oceans sources and sinks of CO_2 and other gases?***
- ***How stable are ice-shelves, glaciers and ice-caps and what is their influence on sea level rise?***
- ***What are the real-time changes in water masses and where do they occur?***

The climate of the polar regions is rapidly shifting, as documented by the accelerated warming of their atmosphere, oceans and land. Such changes have been in turn paralleled by environmental modifications affecting the marine and terrestrial ecosystems, hydrosphere and cryosphere systems. The polar regions, in addition, play a fundamental role in modulating and driving the Earth's climate.

Understanding the interactions between the polar oceans, ice and atmosphere and the consequences of their climatic shift, requires an integrated approach, which includes all year round observations, laboratory and field studies, sample recovery and numerical modelling.

Chapter 2: The Polar Marine Biosphere

Addresses key questions on the threats and capacity of polar organisms to survive and adapt in times of changes.

- ***How did polar marine organisms adapt to past change and what does this tell us about the capacity to adapt to future change?***
- ***What are the threats to biodiversity and what are the wider implications of biodiversity changes in polar regions?***
- ***How changes in the biological systems of the polar regions will influence global biogeochemical cycles?***
- ***To what extent, in what direction, and on what time scales will polar organisms and ecosystems change?***

Polar marine ecosystems are intimately tied to sea ice extent and seawater temperatures, which together influence food sources, organism growth and reproduction, and biogeochemical cycles. Climate change will alter marine ecosystems; however, the complexity of the food webs, combined with chronic undersampling, constrains efforts to predict their future and to optimally manage and protect marine resources.

Chapter 3: The Polar Ocean's Geological History

Focuses on the geological history of the polar regions, formation of its basins, and opening of gateways.

- ***How and when were the Arctic Ocean Basins formed?***
- ***How and when did the supercontinent Gondwana break up?***
- ***What is the history of the polar gateways leading to the current oceanographic boundary conditions?***
- ***How is the spatial and temporal history of glaciation of the polar regions reflected in the stratigraphic framework of its shelves, slopes and basins?***

The geological history of the polar regions provides the context to understand polar paleoclimate and paleoceanography. How continents are distributed determines the pathways of the Meridional Overturning Circulation, a system of surface and deep ocean currents encompassing all basins, which is an important component in poleward energy transfer and climate control. The geological history at the same time provides the basis to evaluate the resource potential of the polar areas and the risk of geological hazards.

Chapter 4: Polar Paleoclimate and Marine Paleoenvironments

Approaches the paleoclimatic history of the polar regions through the following questions:

- ***What is the timing of the inception, variability (growth and collapse) of polar ice sheets and sea ice systems and what are the underlying forcing mechanisms?***
- ***How did varying paleo-atmospheric CO_2 affect polar regions (on different time scales)?***
- ***What was the role of the polar oceanic-ecosystems, including the deep biosphere, in terms of global carbon cycling, budgets and turnover rates?***
- ***What was the impact of past polar shallow- and deep oceanographic changes for global oceanic circulation?***

Understanding the dynamics and stability of the polar caps is of special relevance because a temperature rise of 2.9°C to 5.3°C (relative to the 1961-1990 baseline) is expected by the end of this century[1]. Paleoclimate records play a key role in our understanding of the Earth's past and on the forecast of future climate changes, by placing the instrumental record in a longer context, especially in times where the atmospheric CO_2 concentrations were higher than today.

Chapter 5: Seafloor Processes and Natural Hazards

Seeks to understand the potentially hazardous geological and geomorphological activity of the polar regions' seafloor when dynamically responding to changes in the cryosphere.

- ***What is the real extent of subsea permafrost on Arctic continental shelves?***
- ***How to quantify the role of gas hydrate systems in marine Arctic sediments?***
- ***Which is the glacial sedimentary model that best describes the polar depositional***

1. IPCC, 2007, Fourth Assessment Report (AR4). International Panel on Climate Change, Cambridge, Cambridge University Press.

environments, the sedimentary processes involved and the recurring pattern of sedimentation?

- ***Which are the sedimentary systems, within glacial depositional systems, that favour the accretion of unstable continental slopes?***

When the lithosphere adapts to new environmental conditions driving load-pressure changes (e.g., ice melt, rapid sea-level rise), it adjusts by modulating or triggering a broad range of surface and crustal phenomena, which include volcanic and seismic activity, submarine and subaerial landslides, tsunamis and landslide 'splash' waves, glacial outburst and rock-dam failure floods, debris flows and gas-hydrate destabilization.

Chapter 6:
Scientific-Technical Mission Requirements for an International Research Icebreaker

The key scientific questions outlined in the ERICON Science Perspective calls for a set of technical requirements that a European Research Icebreaker must fulfil.

- ***Naval Architecture – Design Requirements - Lifetime cycles***
- ***Operational Capacity and Endurance***
- ***Research Capabilities***

The ship has to be designed for year-round research operations in the entire Arctic Ocean and Polar Southern Ocean around Antarctica, including a partial wintering period during research missions, and ability to perform geotechnical-style scientific deep-sea drilling with a mobile rig added on a case-specific basis by third parties. Thus, the vessel must be able to autonomously break ice of 2.5 m thickness, including strong multi-year ice at a continuous speed of about 3 knots, while retaining a high seaworthiness in open waters. It must be equipped with a dynamic positioning system for open water, flow ice and light pack-ice conditions. In addition, the vessel design must incorporate a moon pool and sufficient scientific work space, and sheltered weather-poof hangars. The combination of such requirements in a compact and cost-effective vessel puts high challenges on naval architecture and maritime engineering.

AURORA Slim design. © Aker Arctic.

The Role of AURORA in Future Polar Research

Since the polar regions react more rapidly and intensively to global changes than other regions of the earth, they are currently a subject of intense scientific debate and investigations. News about shrinking of the Arctic sea ice cover, potentially leading to an opening of sea passages to the north of North America and Eurasia, leading to a “blue” Arctic Ocean, as well as about the calving of giant table icebergs from the ice shelves of Antarctica, are examples of these modern dynamics.

Global climate models demonstrate the sensitivity of the polar areas to changes in forcing of the ocean/climate system. The presence or absence of snow and ice influences global heat distribution through its effect on the albedo, and the polar oceans are the source of dense, cold bottom waters, which influence the Meridional Overturning Circulation. However, most of the processes occurring, today and in the past, in the deep-water source areas are still almost unknown, due to the fact that they lie in areas covered by thick sea ice, or infested by icebergs, and are as a result difficult to reach.

Modern research vessels capable of penetrating into the central Arctic are few. A new state-of-the-art research icebreaker is therefore urgently required to meet the needs of polar research and to document multinational presence in the Arctic. This new icebreaker would be conceived as an optimized science platform from the keel up, and will allow long, international and interdisciplinary expeditions into the central Arctic Ocean during all seasons of the year.

In spite of the critical role of the central Arctic Ocean in climate evolution, it has been sampled only once, during the ACEX expedition, in a difficult operation which involved the coordination of three ice-breakers. Its long-term environmental history and tectonic structure is hence poorly known. This lack of data represents one of the largest gaps of information in modern Earth Science, also relevant for the field of hydrocarbon exploration. Therefore, a new research icebreaker such as AURORA should be equipped with technical facilities to acquire long sedimentary sections to fulfil the needs of the IODP for an “Alternate Platform” to drill in deep, permanently ice-covered ocean basins. The drilling equipment will only be used during the summer months and could be removable, potentially to be used and adapted to International Continental Scientific Drilling Program (ICDP) projects. The icebreaker must also be powerful enough to keep station against the drifting sea ice cover and will have to be equipped with dynamic positioning.

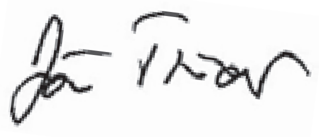
In the long run, AURORA could also have a major impact on research in the Southern Ocean, which is – in comparison with the central Arctic Ocean – better investigated, but which still needs urgently the deployment of a modern research platform dedicated to its seasonally ice covered deep-sea basins. Polar dedicated vessels must be available during all seasons of the year, and be able to endure particularly bad weather during the Southern Hemisphere fall, winter and spring seasons. Such vessels are presently not available.

Whereas great progress has been achieved over the past years in unraveling the plate tectonic history of the ocean crust under the Southern Ocean, there are major gaps in understanding the paleoceanographic history of the world´s biggest ocean current system, of the seasonal modes and patterns of sea ice formation, of the functionality of Southern Ocean benthic and pelagic ecosystems, and of their biodiversity.

The appearance of an innovative research icebreaker on the Southern Hemisphere scene would mean a revolution in the exploration of a region of the planet Earth, which is indispensable for understanding the mechanisms and causes of modern and future global environmental change. The qualities and research capacities would also result in major steps forward to establish internationally well-coordinated research programs directed towards virtually all aspects of marine polar research in the Southern Ocean.

An efficient use of a new research platform of this kind requires the formation of a consortium of several countries and their polar research institutions to ensure a high quality of science, and efficient employment of the research platform during all seasons of the year. Extensive and well-developed Arctic research programs exist in several countries, particularly in the Scandinavian countries, Russia and Germany. In each individual country, there exist different organizations or working groups, with rather diverse structures and impacts in their home countries. Other European countries, like Spain, Italy and France, have had quite extensive Antarctic programs for several decades. The construction of AURORA as a joint research icebreaker would result in a considerable commitment of the participating nations to co-ordinate and expand their polar research programs, in order to operate this research platform continuously and with the necessary efficiency.

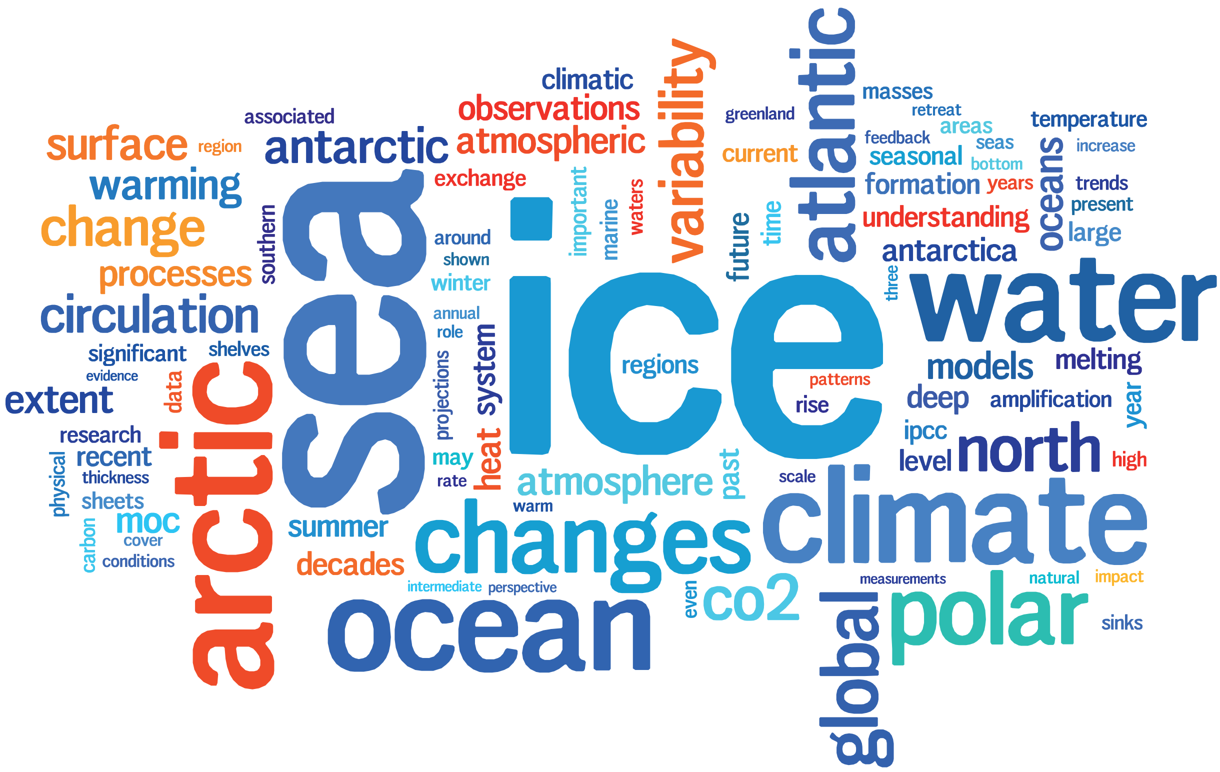
The establishment of AURORA as an international research icebreaker will have an extraordinary impact on our understanding of the **complexities of the polar regions**, on the **knowledge of the processes** that affect our planet as a whole, and on the improvement of the prediction ability of climate models, through an interdisciplinary approach.



Jöern Thiede,
President of the ERICON Council

Scientists drawing the electromagnetic sensor EM-Bird for ice thickness measurements in a canoe on the sea ice during the 26th Arctic expedition of the German RV Polarstern.

Chapter 1: The Changing Polar Oceans, Ice and Atmosphere



Introduction

The climate of the polar regions is rapidly shifting, as documented by the unprecedented warming of their atmosphere, oceans and land. Such changes have been paralleled by environmental modifications affecting the marine and terrestrial ecosystems, hydrosphere and cryosphere systems (ACIA, 2005; IPCC, 2007).

Despite the importance of high latitude changes for global climate, there is still a lack of understanding of how the system functions and what are the drivers of such changes (Bekryaev et al., 2010). In particular, there is a limited understanding of, and even controversy about the role of polar amplification in long-term surface air temperature variations and modern Arctic warming.

The instrumental data record shows that observed polar climate change is not symmetric. Except along the Antarctic Peninsula (Vaughan et al., 2003), most of the evidence of significant warming is from the Arctic. In addition, total sea ice extent in the Southern Ocean has shown no significant trend since satellites began recording data in 1979. Newer climate models generally also show little or no polar amplification over the Southern Ocean and Antarctica during the past century (IPCC, 2007). Climate models' projections indicate that Arctic amplification will be significant in one to two decades (Serreze and Francis, 2006), while significant Antarctic polar amplification will take much longer.

Numerical simulations forecast continued warming and accelerated decline in sea ice cover. However, there is a wide range in the exact projections of the future of the Arctic's climate, which in turn introduces significant uncertainties about how the Arctic may potentially shape climate around the globe (Budikova, 2009). Current climate models are limited by their ability to represent processes at scales smaller than the model grid resolution (now of the order of 100 km). Parameterizations of subgrid-scale processes should represent not only the present climate state, but also very different climates which may be expected in the future. Thus climate models must be validated through observations from both present and past climatic conditions.

Future scenarios of Arctic and Antarctic sea ice variation are needed, not only because of the importance of sea ice in global climate, but also to better guide the future commercial development of the Arctic, which could become much more intensive as sea routes through the Arctic open on a regular basis and for a longer portion of the year (AMSA, 2009). However, such future scenarios are currently not sufficiently reliable since the relative influence on climate sensitivity of complex feedbacks associated with the cryosphere (e.g., ice insulating feedback, MOC/SST-sea ice feedback, ice thickness/ice growth feedback) has not been quantified (Randall et al., 2007)

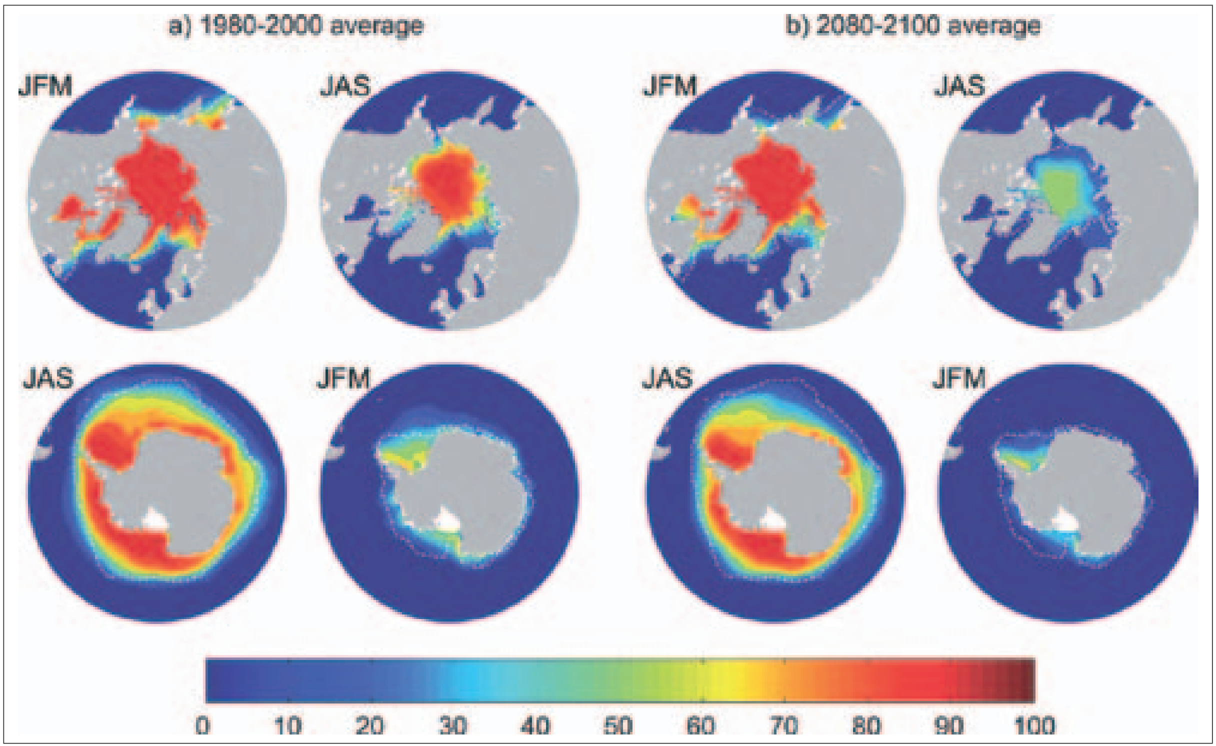


Figure 1.1. Multi-model mean sea ice concentration (%) for January to March (JFM) and June to September (JAS), in the Arctic (top) and Antarctic (bottom) for the periods (a) 1980 to 2000 and b) 2080 to 2100 for the SRES A1B scenario. The dashed white line indicates the present-day 15% average sea ice concentration limit. Modified from Flato et al. (2004) (IPCC, 2007).

This core theme targets four focus areas, each of which addresses one or more key questions:

Variability Trends

- *How does polar climate change affect global climate? How does climate change affect the long-term trends and seasonal variability of sea ice and polar oceanic and atmospheric circulation patterns?*

CO_2 Sources and Sinks

- *What are the polar oceans sources and sinks of CO_2 and other gases?*

Stability of Ice Sheets

- *How stable are ice shelves, glaciers and ice caps and what is their influence on sea level rise?*

Changes in Water Masses

- *What are the real-time changes in water masses and where do they occur?*

Understanding the interactions between the polar oceans, ice and atmosphere, and the consequences of their climatic shift, requires an integrated approach, which includes year-round observations, laboratory and field studies, sample recovery and numerical modelling. The results of this field of research are key components of the other topics addressed by this Science Perspective, since they provide the basis for understanding the dynamics of ice, water and atmospheric masses and their synergies with the climatic system and surrounding organisms. The four focus areas targeted in this chapter interlink with the other chapters through a paradigm of forcing, response and variability changes (Table 1.1.).

Table 1.1. Links and interrelationships between the focus areas of Chapter 1 and the other scientific chapters of this Science Perspective.

● Forcing ● Response ● Variability

Chapter 1: Sea Ice, Ocean, Atmosphere	Chapter 2: Polar Marine Biosphere	Chapter 3: Polar Palaeoclimate and Marine Palaeo-Environments	Chapter 4: Geological History	Chapter 5: Natural Hazards
Variability Trends	Forcing, Variability	Forcing, Response	Response	Forcing, Response
CO_2 Sources and Sinks	Forcing, Response, Variability	Response, Variability	Response	Response
Stability of Ice-Sheets	Forcing	Forcing, Response, Variability	Response	Forcing, Response
Changes in Water Masses	Forcing, Variability	Response, Variability	Response	Forcing

For example, changes in variability trends of sea ice, ocean and atmosphere:
– will force changes and produce variability of the polar marine biosphere;
– have responded to changes in palaeoclimate, and at the same time forced changes in palaeoenvironments;
– are conditioned by geological history;
– will force and simultaneously respond to natural hazards (i.e., changes in trends can trigger natural hazards, and natural hazards can also be responsible for changes in sea -ice trends).

KEY QUESTION 1

How does polar climate change affect global climate? How does climate change affect the long-term trends and seasonal variability of sea ice and polar oceanic and atmospheric circulation patterns?

What are the ocean-atmosphere-ice interactions?

The capacity of Arctic sea ice to influence global climate through atmosphere and oceanic circulation is broadly recognized. But the recent loss of summer sea ice in the Arctic is directly linked to changes in northern wind patterns in the following autumn, producing alterations of the heat balance at the cold end of the climate machinery (Liu et al., 2012). With a continued decrease in summer sea ice over the coming decades, scientists anticipate, among other impacts, further changes in the atmospheric circulation patterns (Overland and Wang, 2010). The sensitivity of Arctic sea ice to climate warming depends strongly on the thickness of the ice (Wadhams, 2012), but observations of sea ice thickness variations are far less robust than those of its areal extent. Nevertheless, the available information shows that Arctic multiyear sea ice volume has declined dramatically over the past decades (Laxon et al., 2003; Haas et al., 2008; Kwok et al., 2009).

The natural climatic variability of the Arctic and North Atlantic climate system displays large amplitude multidecadal variability, controlled by the interaction of several oscillatory modes: the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Variability (AMV). Because the AMV has considerable strength and a timescale in the same range as that projected for the anthropogenic signal, the AMV may partially mask the latter. In order to differentiate natural from human-induced climate variability, it is important to understand the genesis and predictability of those variability modes (Ou, 2012). The evidence supports the notion that ocean-ice-air interactions play a key role in shaping Arctic and North Atlantic variability (Polyakov et al., 2005).

Around Antarctica, sea ice has increased by about 1% per decade since the start of the satellite record (Cavalieri and Parkinson, 2008). However, it is still unknown whether this small increase in sea ice extent is a sign of significant change, because ice extents in the Southern Hemisphere vary considerably from year to year and from place to place around the continent. If we consider different Antarctic regions individually, only the Ross Sea sector had a significant positive trend in sea ice extent, whereas in the Bellingshausen and Amundsen seas sector sea ice extent has actually decreased (Cavalieri and Parkinson, 2008). These large scale variations make it difficult to detect a trend in Antarctic sea-ice extent.

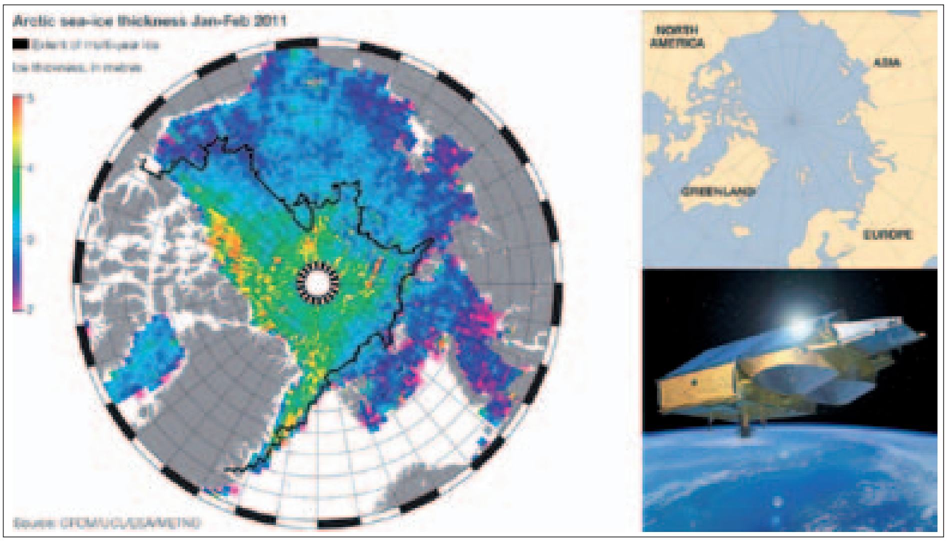


Figure 1.2. CryoSat's sea ice thickness map from the Arctic Ocean. Data from January and February 2011, approaching the annual maximum. The European Space Agency (ESA) recently launched the CryoSat-2, a satellite equipped with a sophisticated radar altimeter to acquire accurate measurements of the thickness of floating sea ice. © CPOM/UCL/ESA.

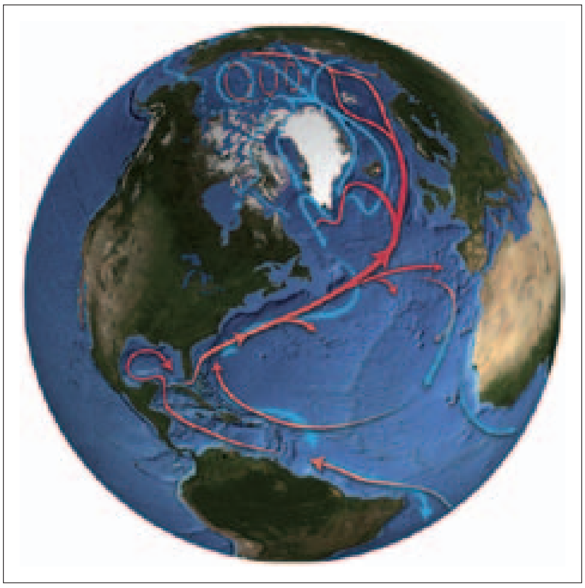


Figure 1.3. Oceanic circulation of the North Atlantic and Arctic oceans. The North Atlantic and Arctic Oceans are critical components of the ocean-climate system. Warm tropical waters flow northward, releasing heat to the North Atlantic region, and eventually flow into the depths of the Arctic Ocean. Cold waters sink in the North Atlantic and flow southward to drive the Ocean Conveyor. © E. Paul Oberlander, Woods Hole Oceanographic Institution. Reprinted with permission.

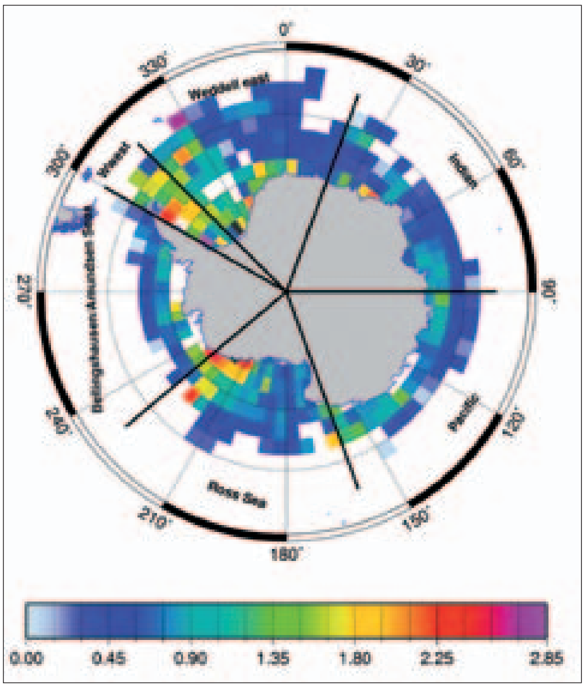


Figure 1.4. Circumpolar map of mean annual sea ice thickness (including ridges). The data set comprises 23,373 observations collected over more than two decades of activity and has been compiled as part of the Scientific Committee on Antarctic Research (SCAR) Antarctic Sea ice Processes and Climate (ASPeCt) programme. From Worby et al. (2008).

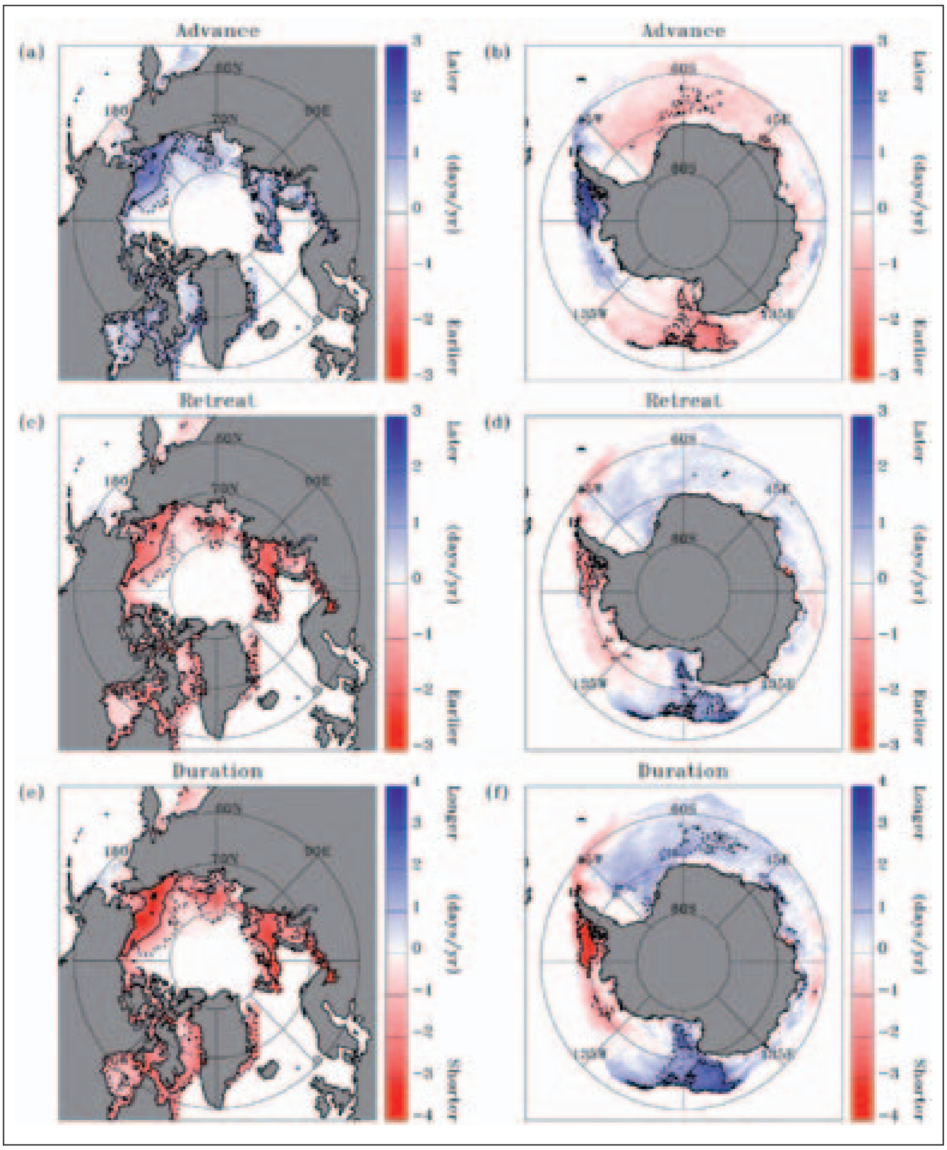


Figure 1.5. Trends (days/year) from 1979/80 to 2010/11 in (a, b) sea ice advance, (c, d) sea ice retreat, (e, f) ice season duration, for (left) the Arctic, and (right) the Antarctic.
From Stammerjohn et al. (2012).

The timing of annual sea ice retreat and advance in both polar regions has also changed since the start of the satellite record. In the Arctic region, Antarctic Peninsula and Bellinghausen Sea region sea ice retreat is now consistently more than one month earlier and advance is more than one month later, making the summer ice-free season almost three months longer. In contrast, in the western Ross Sea (Antarctica) sea ice retreat now occurs one month later and advance one month earlier, making the summer ice-free season two months shorter (Stammerjohn et al., 2012).

When trying to understand the role of sea ice in the earth's climatic system, scientists and modellers face enormous complexities: processes at micro scale (like sea-ice formation) have far reaching implications at regional and global scale. Accordingly it is vital to examine the main processes and feedbacks at every scale from an integrated perspective.

KEY QUESTION 2

Which are the polar oceans sources and sinks of CO_2 and other gases?

Understanding the processes of carbon dioxide (CO_2) exchange between atmosphere, ocean and land is especially important since global marine and terrestrial systems currently absorb about half of the CO_2 emitted by fossil-fuel combustion (Sabine et al., 2004). But, even though the monitoring of seasonal and geographical CO_2 exchange rates has been increasing in recent years, the ice-covered polar oceans have been largely ignored, not only because of the difficulty of access, but also because a continuous sea ice cover is believed to block the outgassing of CO_2 rich waters to the atmosphere very efficiently, and global models do not include CO_2 exchange over sea ice (Rysgaard et al., 2011). The relative importance of high and low latitudes for the transport of CO_2 by physical processes is not well known, and may be poorly represented in most ocean carbon models (IPCC, 2007).

The ocean carbon cycle is mainly controlled by three pumps: the physical, the biological and the alkalinity or anion pump (Sundquist and Broecker, 1985). The physical pump is driven by physical and chemical processes, which affect the solubility of CO_2 and the transport of water from the surface mixed layer to depth. The biological pump is driven by primary production, consuming dissolved CO_2 through photosynthesis, and producing particulate and dissolved organic carbon (POC and DOC). The alkalinity pump concerns the removal of carbon by calcification in the upper waters, and the release of carbon when calcium carbonate is dissolved at depth (Sundquist and Broecker, 1985). Since the solubility of CO_2 increases with decreasing temperature, high latitude oceans are potentially large sinks of atmospheric CO_2.

In polar oceans, the formation and melting of sea ice is an important CO_2 flux mechanism. As sea ice forms, the brine rejection into the water column causes formation of high saline dense water in the polar and subpolar seas, strengthening and ventilating the deep thermohaline circulation in the world ocean. Besides the physical impact of sea ice on ocean circulation, brine rejection also influences the release of dissolved gases and solutes into the water column (Rysgaard et al., 2011). In the Arctic Ocean, the large decrease in summer sea ice extent has been shown to significantly alter the fluxes of carbon through its impact on the primary productivity of the region (Wang et al., 2005) and the air-CO_2 flux (Bates, 2006). At present, even though seasonal sea ice cover reduces the gas exchange between the atmosphere and the ocean, the Arctic Ocean takes up CO_2 in the order of 66 to 199 Tg C year–1, contributing 5–14% to the global balance of CO_2 sinks and sources (Bates and Mathis, 2009). Biological amplification of ocean acidification, due to the remineralisation of organic matter transported downwards, will probably reduce the ability of many species to produce CaCO3 shells or tests, which would have profound implications for the Arctic marine ecosystem. However, whether sea ice facilitates the uptake or release of CO_2 by the ocean, and the season-dependent processes by which sea ice controls air–sea CO_2 exchange, are areas of active research with no definite answer (Bates and Mathis, 2009; Rysgaard et al., 2011).

In the Southern Ocean, recent observations have shown that between 1981 and 2004 the CO_2 sink weakened by 0.08 Pg C year^{-1} relative to the trend expected given the large increase in atmospheric CO_2 (Le Quéré et al., 2007). As a consequence, the efficiency of the Antarctic CO_2 pump is expected to decrease in the coming decades.

In order to understand and evaluate the processes and effects of CO_2 exchange between sea, ice and atmosphere, it is necessary to produce measurements of air-sea gas exchange processes in polar regions all year round (specially in winter). In addition, in situ atmospheric and marine chemistry measurements are necessary to evaluate the importance of seasonal cycles in sea ice biology and biogeochemistry.

A detailed understanding of many of the physical properties of sea ice is still lacking, and is much needed if we are to obtain better projections from climate models and global circulation models (Dieckmann and Hellmer, 2003).

KEY QUESTION 3

How stable are ice shelves, glaciers and ice caps and what is their influence on sea level rise? How do changes in polar ice reflect real-time climate change?

The Antarctic and Greenland ice sheets carry about 33 million km^3 of ice, which is enough water to raise the global sea level by about 70 m (IPCC, 2007). The average annual snowfall on the ice sheets is equivalent to 6.5 mm of sea level, and therefore only a small imbalance between snow precipitation and meltwater discharge into the ocean could be a major contributor to present-day sea-level rise, at present ~3 mm/year (Nerem et al., 2006). During times of rapid deglaciation over the past million years, changes in the volume of the ice sheets have resulted in rates of sea-level rise at least one order of magnitude larger than at present. Recent evidence from observational and modelling studies of both Antarctica and Greenland suggests that profound changes in flow and mass balance are possible over time scales of a few years to decades (Bamber et al., 2007). Since the present condition of the ice sheets depends not only on this long-term trend, determined by past climate and dynamic history, but also on more recent changes in climate and ice-sheet dynamics, a detailed knowledge and understanding of the evolution of polar ice sheets is of considerable societal importance (Rignot and Thomas, 2002).

The balance between net accumulation and melting of ice is not the same on the two ice sheets, due to differences in their climatic regimes (for a review see Rignot and Thomas, 2002).

Greenland's climate is strongly influenced by nearby land masses and the North Atlantic, with the warm Gulf Stream to the south. The average accumulation rate is currently ~30 cm/year, which is twice that for Antarctica. Ice melting occurs during summer over half of the ice-sheet surface, with much of the water flowing into the sea. Ice is lost primarily by surface runoff and iceberg calving, except in the north where basal melting from small ice shelves is important (Rignot and Thomas, 2002).

Antarctica exhibits cold conditions even during the summer, so there is little surface melting, even near the coast, and this exerts a climatic influence not only on the continent but also the surrounding ocean. Massive floating ice shelves exist around much of the continental coastal areas, fed by outlet glaciers and ice streams from the ice sheet, some of which penetrate deep into the heart of Antarctica. Ice shelves from the Antarctic Peninsula have been in constant retreat over the past few decades (Skvarca et al., 1999), culminating in the total collapse of the Larsen B ice shelf in March 2002 (Scambos et al., 2003). Estimating the extent to which sea level may rise as a result of changes in the Greenland Ice Sheet and in Antarctica during the current century and beyond is a major source of uncertainty in projections of future sea level rise (IPCC, 2007). While most of the current models suggest that ice loss from Greenland will contribute about 5-10 cm to the rise in global sea level by 2100, recent projections for global sea level rise that include the contributions from thermal expansion of the oceans and the rest of the world's ice masses are as high as 1m (with an error of ± 0.5m) (AMSA, 2009).

Moving the time horizon much further into the future is very difficult and entails enormous uncertainties. However, the complete melting of the Greenland ice sheet would raise global sea levels by 7 m (IPCC, 2007), which is a devastating prospect for coastal populations around the world. But while most climate change models suggest that complete melting would take some thousand years, a threshold for destabilizing change will be approached on a much shorter time frame (AMAP, 2009).

Because the changes in polar ice mass have a considerable impact on people and ecosystems, as well as having global impacts through a variety of climate feedback mechanisms, it is important to know whether they will continue in the future.

KEY QUESTION 4

What are the real-time changes in water masses and where do they occur?

What are the changes in dense water formation and what are their climatic consequences?

One of the important new findings in oceanography is that the ocean, including its abyss, is warming at a rate of 0.5°C or more per century (Levitus et al., 2000). The major contributor of heat advection towards the Arctic arises from the northward-flowing Atlantic Water, the intermediate depth (150-200 m) temperature of which has increased in recent decades. The Atlantic Water warming, associated with the Eurasian basin water masses stratification, facilitates an upward spread of Atlantic Water heat through the Arctic which strongly affects the sea ice distribution in extent and thickness (Polyakov et al., 2010). Records of its natural variability have shown that those recent warm water masses entering the Arctic Ocean are unprecedented for the past 2000 years (Spielhagen et al., 2011).

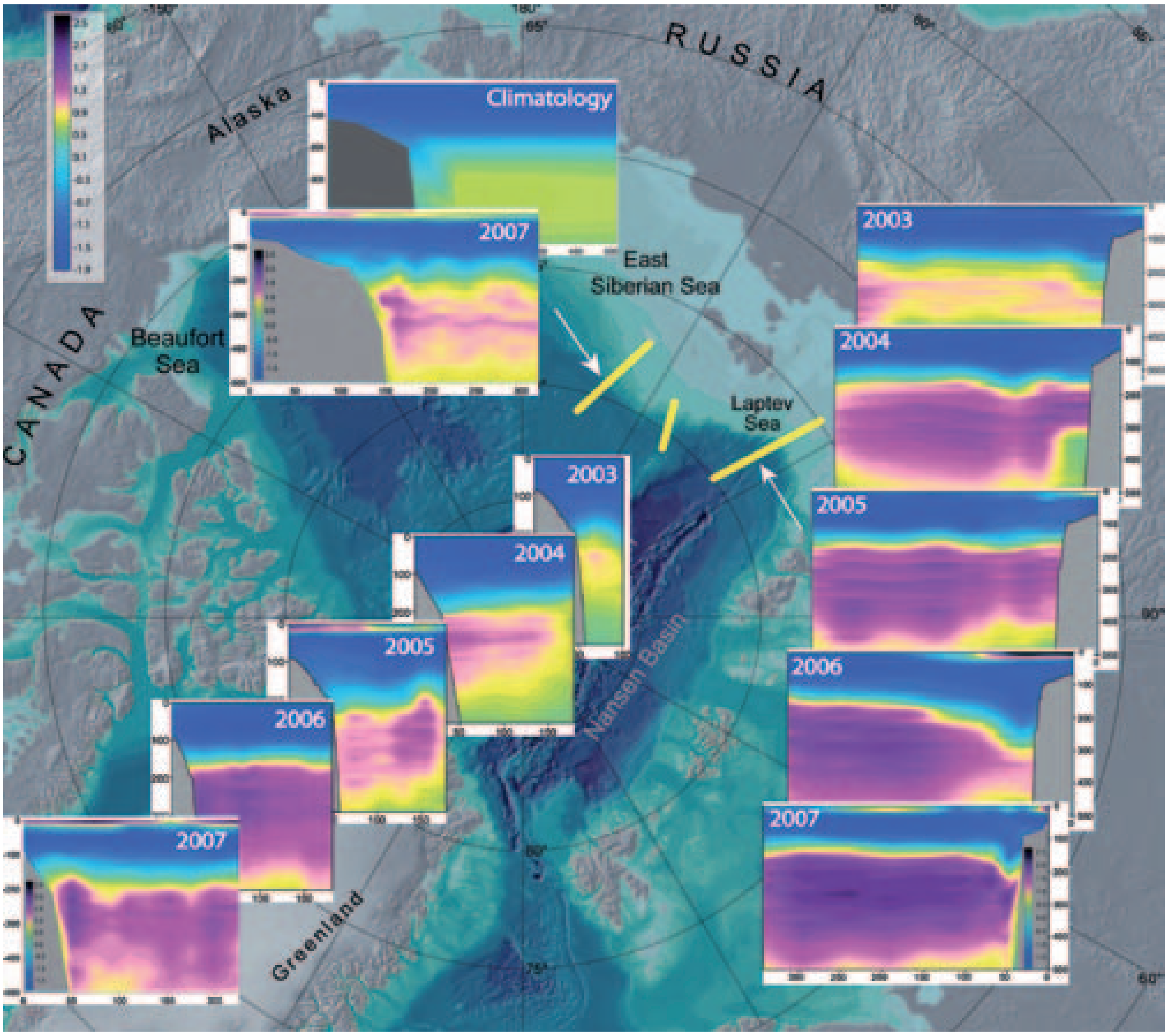


Figure 1.6. Vertical cross sections of water temperature (°C) from the Laptev Sea slope (see three series of cascaded plots relating to three locations shown by yellow lines on the map). These observations provide evidence of the rapid progression of warm water pulses in the Atlantic Water layer of the Arctic Ocean. From Polyakov et. al. (2010). © American Meteorological Society. Reprinted with permission.

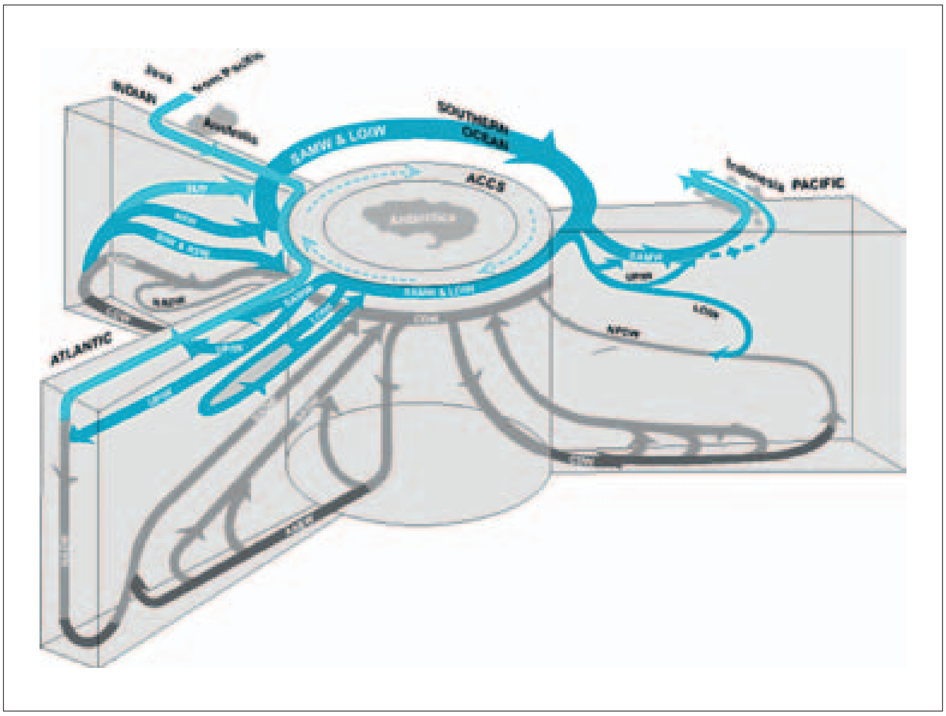


Figure 1.7. Three-dimensional circulation within the Atlantic, Indian, and Pacific oceans showing the vertical recirculation within each basin and the interchange between oceans within the Antarctic Circumpolar Current and via the Indonesian throughflow. AABW, Antarctic Bottom Water; ACCS, Antarctic Circumpolar Current System; BIW, Banda Sea Intermediate Water; CDW, Circumpolar Deep Water; IODW, Indian Ocean Deep Water; LOIW, Lower Intermediate Water; NADW, North Atlantic Deep Water; NIIW, North Indian Intermediate Water; NPDW, North Pacific Deep Water; RSW, Red Sea Water; SAMW, Subantarctic Mode Water; SLW, Surface Layer Water; UPIW, Upper Intermediate Water. From Schmitz (1996). © WHOI. Reprinted with permission.

While many factors contribute to the historical observations and palaeoclimatic variability, a number of model studies identify the North Atlantic and its associated deepwater formation as a focal point of decadal and centennial time scale variability (e.g.,Manabe and Stouffer, 1993). These model studies, combined with observations, provide evidence that changes in freshwater influx into the Northern Atlantic Ocean can substantially modify the deep ocean circulation, and in turn, dramatically influence the climate state and drive rapid climate change. The freshwater surplus in the Arctic Ocean due to ice melt, and its influx into the global ocean, needs to be quantified with the aim of evaluating its possible consequences (Wadhams, 2012).

The role of the southern source of deepwater, the Antarctic Bottom Water (AABW), in modulating variability, has received very little attention, and this has limited the development of a complete understanding of multi-decadal to millennial time scale climate change. Whether the North Atlantic Deep Water (NADW) is the ultimate driver of the Meridional Overturning Circulation (MOC), and whether substantial additional variability is generated by freshwater impacts in the Southern Ocean, remain unresolved issues (Seidov et al., 2001).

Ice core data from both Greenland and Antarctica have shown that abrupt climatic changes associated with large amounts of sea ice in the North Atlantic, and rapid changes in thermohaline circulation, may have occurred repeatedly in the past (Weaver, 1995; Knorr and Lohmann, 2007). For example, mathematical modelling suggests that a continuous freshwater source as a result of ice melting could prevent deep-water formation in the North Atlantic and slow down or even totally shut down the MOC (Manabe and Stouffer, 1997). Switching off the ocean's main global circulation system would have profound effects on global marine life and fisheries. Moreover, shutting down deep-water formation in the North Atlantic would eliminate important sinks for greenhouse gases, increasing their level in the atmosphere and speeding up the rate of climate change. Even though the total shutdown of the MOC is considered a high impact, low probability event (Wood et al., 2006), the increasing perception of the vulnerability of MOC to climate change has stimulated a large amount of scientific research over the past few decades.

BOX 1.1. Polar Amplification of Current Global Climate Change

An analysis of observational records shows that global surface air temperatures have increased by 0.6 °C since 1861, with a greater rate of warming in the 20th century (Jones et al., 1999). During that period, the 1990s was the warmest decade in the Northern Hemisphere. The global warming has been associated with an increase in the land-surface precipitation rate, a decrease in snow cover and sea ice extent, sea level rises and changes in atmospheric and oceanic circulation patterns (IPCC, 2007).

The term “polar amplification” describes the amplified rate of surface warming at the poles compared to the rest of the globe. Near-surface warming in the Arctic has been almost twice as large as the global average over recent decades (Johannessen et al., 2004; ACIA, 2005), a phenomenon that is known as “Arctic amplification”. Although the underlying causes of this temperature amplification are still uncertain, it is broadly accepted that changes in the surface albedo associated with melting snow and ice enhance warming in the Arctic (e.g., Serreze and Francis, 2006). Other processes such as changes in cloud cover and atmospheric water vapour content, the increase in the atmospheric poleward transport of heat and moisture and changes in Arctic storm behaviour (Graversen et al., 2008) also contribute to enhanced Arctic warming. However, intrinsic Arctic variability obscures long-term changes and limits our ability to identify complex feedbacks in the Arctic climate system (Polyakov et al., 2002). Nevertheless, model projections show that we are probably close to the point where absorption of solar radiation during summer limits ice growth in the following autumn and winter, which will initiate a feedback leading to a substantial increase in Arctic Ocean temperatures (Serreze and Francis, 2006).

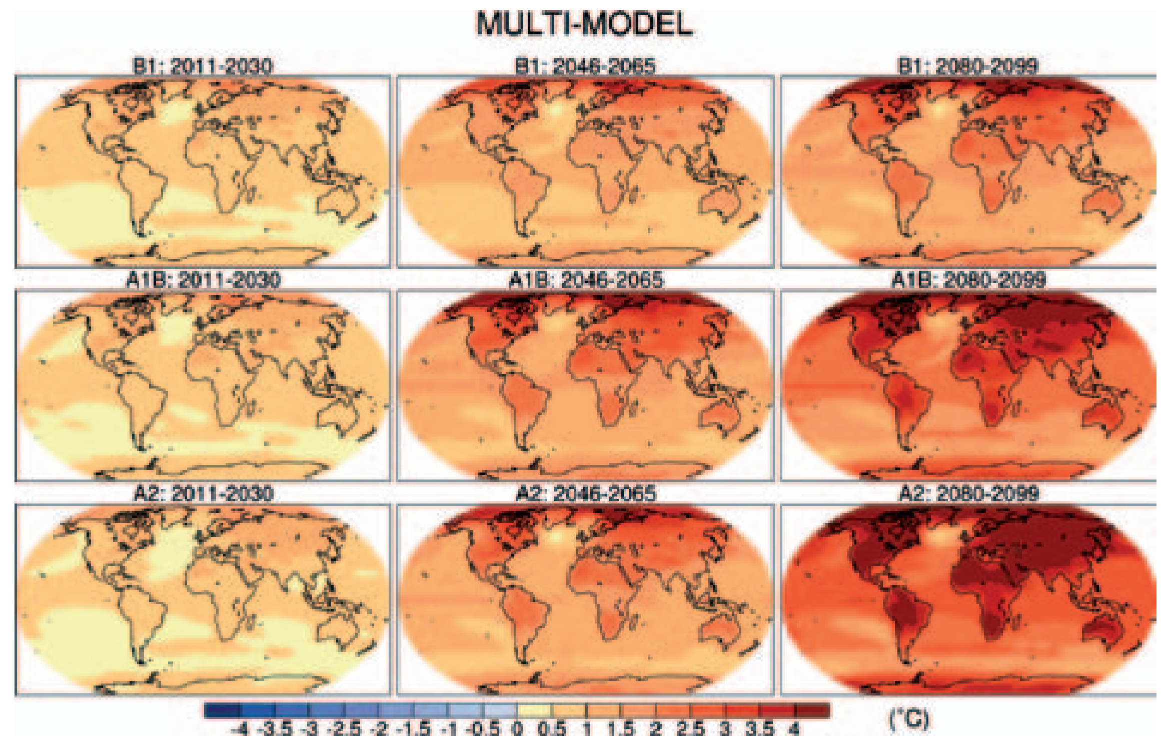


Figure BOX 1.1. Multi-model mean of annual mean surface warming (surface air temperature change, °C) for the scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011 to 2030 (left), 2046 to 2065 (middle) and 2080 to 2099 (right). Anomalies are relative to the average of the period 1980 to 1999. © IPCC (2007).

BOX 1.2. The Meridional Overturning Circulation

It is at the polar regions where the process of convection takes place, as cold and salty water sinks to great depths and is replaced by warmer waters from the upper ocean layers, in a process which moves millions of cubic meters of ocean water. This is the engine of the Meridional Overturning Circulation (MOC). The MOC is a global-scale overturning in the ocean that transports significant amounts of heat towards the poles through warm and highly saline water, and at depth returns cold, less saline waters towards the equator (Wüst, 1935). The MOC is sustained by two major deepwater sources, the North Atlantic and the Southern Ocean surrounding Antarctica (primarily the Weddell and Ross seas and the Adelie Land-George V margin). In the North Atlantic, it is between the Greenland-Norwegian and the Labrador seas, where the warm salty water from the North Atlantic is cooled by Arctic waters and by intense heat loss to the atmosphere, becoming denser and sinking to deeper layers of the ocean. The salt which is rejected as sea ice forms further increases the density, thus contributing to the process. Although this process of sinking water is slow, it takes place over a wide area and each winter several million km^3 of water are brought down and begin moving slowly south along the bottom of the Atlantic Ocean. The dense, cooled water thus formed, called North Atlantic Deep Water (NADW), becomes part of the MOC, eventually returning to the surface in the Southern, Indian and Pacific oceans, coming back to the Atlantic and moving polewards as the Gulf Stream and North Atlantic Drift, which warms north-western Europe substantially (Fanning and Weaver, 1997; Clark et al., 2002). The MOC also has a strong impact on nutrient circulation, and hence on biogeochemical cycles. Since the MOC is driven by both temperature and salinity differences, critical salinity values of the polar regions' thermohaline structure, as a consequence of ice melt, could have a strong impact both on the deep-water formation and on the global circulation.

Although most of the future scenarios of the MOC in warmer climatic conditions with extensive melting of sea ice forecast a weakened current, there are some models that do not show a significant reduction of its strength under such conditions (Schmittner et al., 2005), indicating either a large uncertainty in the response to forcing or the models' inability to accurately simulate the current climate of the high-latitude North Atlantic, mainly because of the lack of field data, particularly during winter.

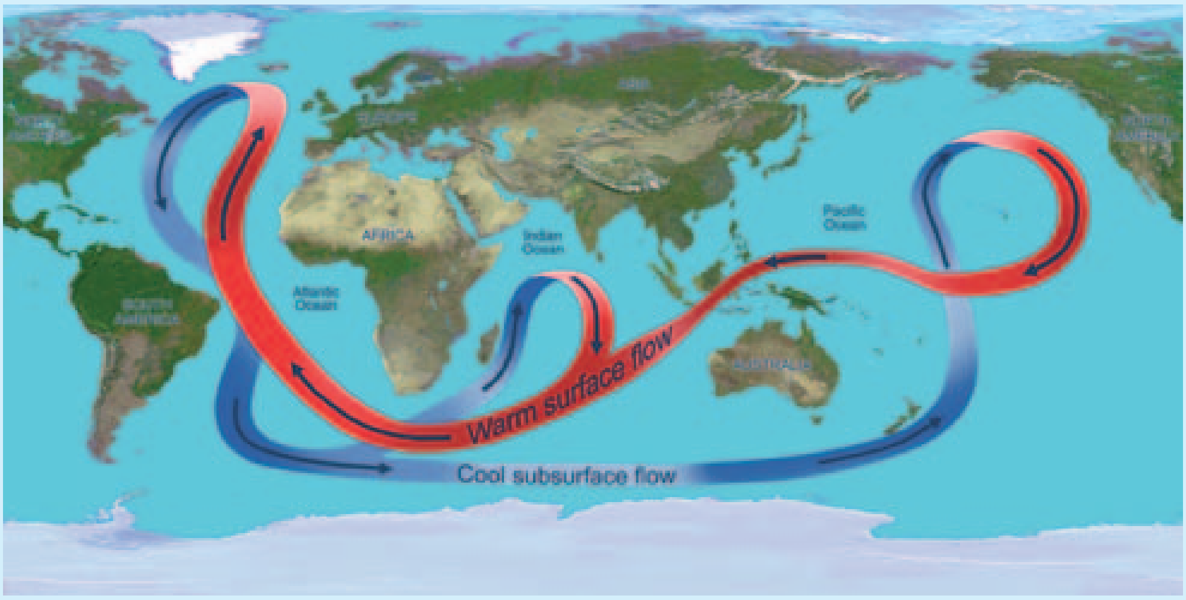


Figure BOX 1.2. Simplified map of the world's MOC. This current system transports vast amounts of heat and salt around the planet via warmer surface currents (red) and colder deep currents (blue). It plays a central role in determining Earth's climate. © NASA/JPL.

BOX 1.3. New Minima in Arctic Sea Ice

Sea ice is one of the critical components of the polar ocean's marine system that has suffered a substantial change over the past decades. Sea ice is an integral player in the global climate system because it mediates the exchange of radiation and sensible heat between the atmosphere and the ocean, impacting the climate through the ice-albedo feedback mechanism* (Curry et al., 1994). In addition, sea ice plays an important role in the processes of deep water formation in polar areas, which is the motor driving the MOC.

The maximum seasonal sea ice extent in high-latitude seas corresponds to about 7% of the Earth's surface area. Around Antarctica the seasonal sea-ice cover changes by about 80%, whereas the seasonal changes in the Arctic Ocean are less pronounced because a significantly higher fraction of sea ice is multiyear ice (Gloersen and Campbell, 1991), i.e., more than 1 year old.

Since the late 1970s, Arctic sea ice extent has consistently declined, and since the early 1990s the retreat has been accelerating, with only 50% of the sea ice present in 1972 still remaining (1972 was when satellite observations started). A new minima in sea ice extent was reached on 8 of September 2011, with 27,000 million km^2, exceeding the previous minima of 2007 by 0.6%, most probably the smallest extent since the last climate optimum about 8,000 years ago (Heygster, 2011).

* Areas of reduced sea ice produce a change in surface albedo that promotes the absorption of more solar energy. When coupled with anthropogenic influences the conditions may be providing persistence to a new regime of reduced sea ice.

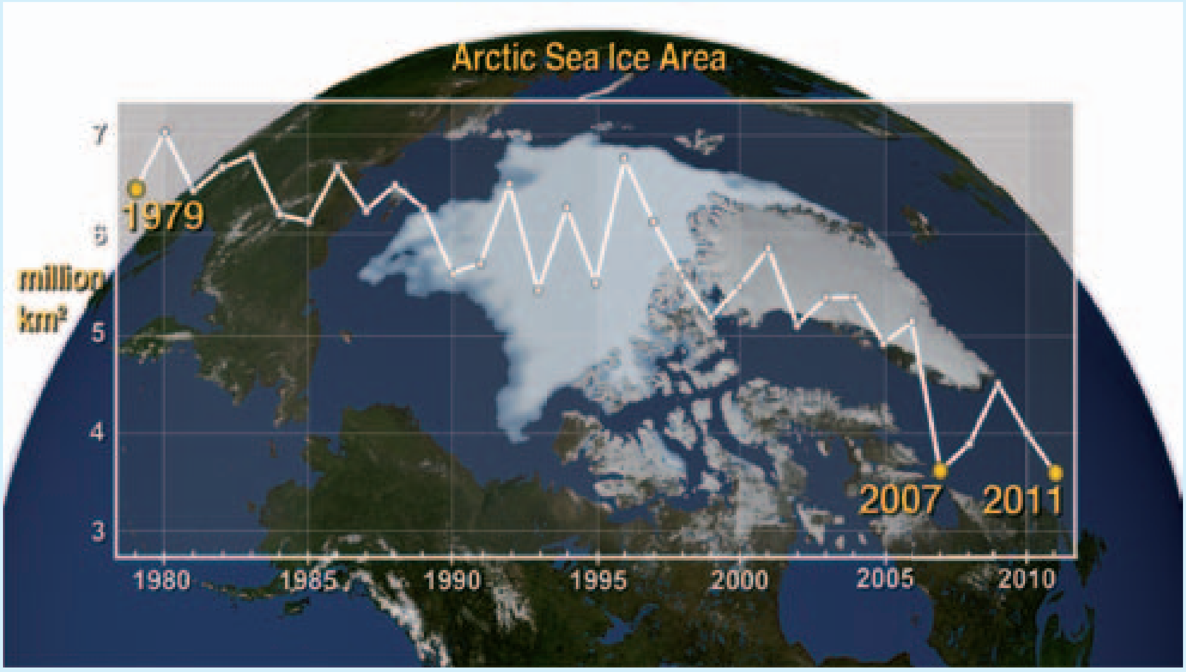


Figure BOX 1.3. Image of the Arctic sea ice minimum from 2011 overlaid by a graph with the annual Arctic sea ice minimum (in millions of square kilometres) from 1979 to 2011. The '1979', '2007', and '2011' data points are highlighted on the graph.

BOX 1.4. Improving Weather and Sea Ice Forecasts

As one of the six NOAA Arctic Vision Priority Goals, improving sea ice forecasts reflects the urgent need for monitoring in polar regions. Projections of a nearly sea ice-free Arctic summer by the end of the century, made just three years ago, have been revised recently to the effect that ice-free summers may occur before mid-century. Arctic change is accelerated by the unique physical properties associated with sea ice loss, which acts to accelerate warming of the Arctic, driven by increasing greenhouse gases in the global atmosphere. Reduction in summer sea ice diminishes reflection of solar energy and creates additional ocean heat storage in newly formed sea ice-free areas. Furthermore, the additional heat stored in the ocean during summer is given back to the atmosphere the following autumn, causing changes in normal patterns of weather and climate variability which have global consequences. The ability to quantitatively forecast Arctic sea ice over different time scales requires regular observation of Arctic atmospheric and ocean states, circulation, and sea ice characteristics, and it also requires an understanding of the interactions between clouds, radiation, and aerosols together with the development of coupled atmosphere-ice-ocean models. In the Arctic region an array of adverse weather phenomena expose both expanding human activities, such as oil and gas exploration and marine transport, and the region's vulnerable environment to high risks. There is a need to improve the understanding and forecasting of adverse weather in the region.

A polar-dedicated platform, such as AURORA, would be able to deploy and maintain automatic weather stations and meteorological ice camps all year round and provide real-time, highly accurate observations, analysis and tests, including in winter and in regions permanently covered in sea ice.

Research Needs

To investigate recent changes in the volume of ice sheets, the seasonal and interannual variability of polar ocean ice, ocean and atmospheric conditions, and to project future climate change with confidence, there is an urgent need for a polar research dedicated platform. The platform must make it possible to:

- Increase year-round observations in the polar regions (especially during winter and including the winter ocean mixed layer).
- Generate long-term ocean and atmospheric time series, repeated hydrographic surveys and underway shipboard surface observations.
- Deploy and support ice camps and automatic stations, extending the range and capability of aircraft surveys.
- Study, monitor, and observe the ocean in continental shelves where dense water forms, where winter measurements are crucial (in situ chemistry, observation of the ocean beneath the ice).
- Deploy and recover AUVs and ROVs (able to navigate under ice shelves or close to glaciers) to collect valuable year-round measurements such as temperature, in situ chemistry, ice formation, freshwater flux, heat flux and bottom melt.

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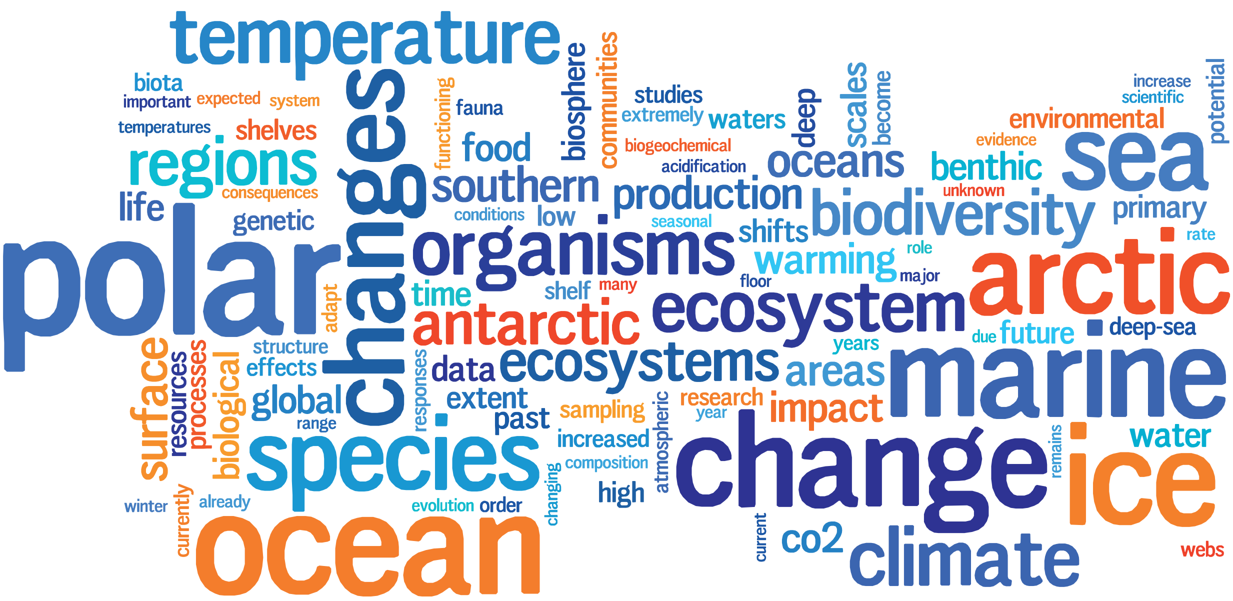
Chapter 2: The Polar Marine Biosphere



Introduction

The polar regions are currently confronting changes in oceanic and atmospheric circulation, temperature and sea ice cover. These climatic shifts will alter marine ecosystems. However, the complexity of the food webs, combined with chronic undersampling, constrain efforts to predict their future and to manage and protect marine resources.

Several positive feedback mechanisms in the Arctic, such as ice and snow melting that decreases surface albedo, atmospheric stability that traps temperature anomalies near the surface, and cloud dynamics, amplify global climate change (Overpeck et al., 1997). As a consequence, the temperature in the Arctic is increasing at a rate of two to three times that of the global average temperature increase, which is estimated to be 0.4°C over the past 150 years (IPCC, 2007). The Arctic marine ecosystem already shows clear evidence of response to climate change. Responses of the polar biosphere have been documented, involving range shifts and changes in abundance, growth/condition, behaviour/phenology and community/regime shifts (Wassmann et al., 2011). However, most of the published reports address marine mammals and fish, whereas well-documented changes in planktonic and benthic systems is low, except for the work of the Arctic Ocean Diversity (ArcOD) and the Census of Antarctic Marine Life (CAML) projects within the Census of Marine Life (CoML) international effort[2]. Very few footprints of climate change have been reported in the literature from regions such as the wide Siberian Shelf and the central Arctic Ocean, due to the limited research effort (linked to logistical difficulties) made in these ecosystems.

In the Southern Ocean, the Antarctic Peninsula is experiencing one of the fastest rates of regional climate change on Earth, with the Western Antarctic Peninsula warming at a rate exceeding 0.1°C per decade over the past 50 years (Steig et al., 2009). A result of this is the collapse of ice shelves, the retreat of glaciers, and the exposure of new terrestrial habitat (Clarke et al., 2007). Although Antarctic coastal waters at all depths might provide a refuge for cold-adapted species (since the continental ice cap will significantly block the warming), it is still unknown whether a decrease in the size of the Antarctic ice sheet might affect the deep-water production, and ultimately begin to influence the Southern Ocean deep-sea temperature and food availability. Regional atmospheric warming of the Antarctic Peninsula area is linked to oceanographic changes, for example, winter sea ice in the Bellingshausen and Amundsen seas has decreased in extent by 10% per decade, and shortened in seasonal duration. Surface waters have warmed by

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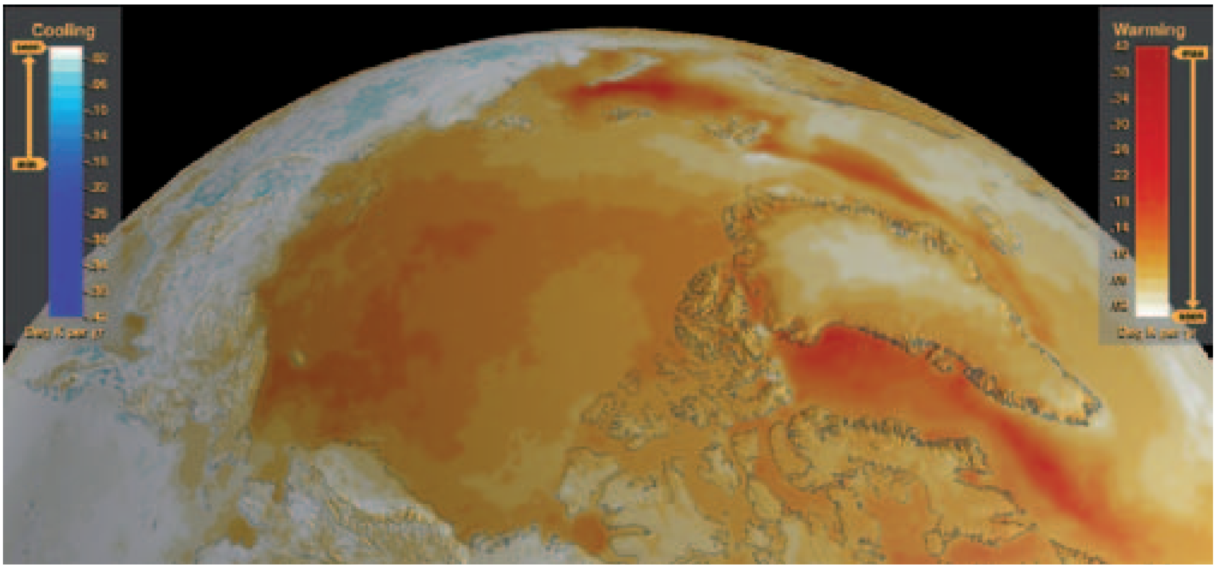

Figure 2.1. Image depicting the 28-year surface temperature trend over the Arctic region determined from data collected between August 1981 and July 2009. The warming and cooling regions are shown in steps of 0.02°K per year from the regions of greatest change to the areas of least change. Blue hues indicate cooling regions; red hues depict warming. The neutral region of -0.02 to +0.02 is shown in white. Light regions indicate less change while darker regions indicate more. The temperature scale used ranges from -0.42 to +0.42 degrees Kelvin, although the minimum data value is -0.1825 degrees Kelvin per year, while the maximum value is 0.4185.

more than 1°C since the 1950s, and even the Circumpolar Deep Water of the Antarctic Circumpolar Current has become warmer. A distinct latitudinal gradient has been observed in the difference between seabed temperatures on the shelf (up to 2°C warmer) and in the deep sea (up to 2°C colder) around sub-Antarctic islands (Clarke et al., 2009), which will probably have consequences for the benthic ecology and biogeography of Antarctic marine biota. However, the complexity of the Southern Ocean food web and species' physiological adaptations and interactions make predictions of ecological responses to future changes impossible to date, and we can only guess which species will migrate in or out of the Southern Ocean, which ones will be able to adapt to the changing conditions and which will become extinct (Brandt and Gutt, 2011).

The endemic species in the polar oceans are extremely exposed to climate change, but characterising how sea-water properties alter marine ecosystems is a challenge, since many key species are mobile, so sampling networks need to span a wide range of spatial and temporal scales (Schofield et al., 2010). Far more work is required before polar marine biodiversity is sufficiently well-known to allow reliable monitoring of ecosystem responses to climate warming, especially in the rather unknown deep-sea basins (Brandt et al., 2007).

This core theme addresses four focus areas, each of which addresses one or more key questions:

Evolution of Marine Organisms With Changing Climate and Ice Dynamics

- *How did polar marine organisms adapt to past change and what does this tell us about their capacity to adapt to future change?*

Changing Biodiversity of Polar Marine Biota

- *What are the threats to biodiversity and what are the wider implications of biodiversity changes in polar regions?*

Biogeochemistry of Polar Oceans

- *How will changes in the biological systems of the polar regions influence global biogeochemical cycles?*

Responses of Marine Organisms in Polar Environments Under Rapid Transition

- *To what extent, in what direction, and on what time scales will polar organisms and ecosystems change?*

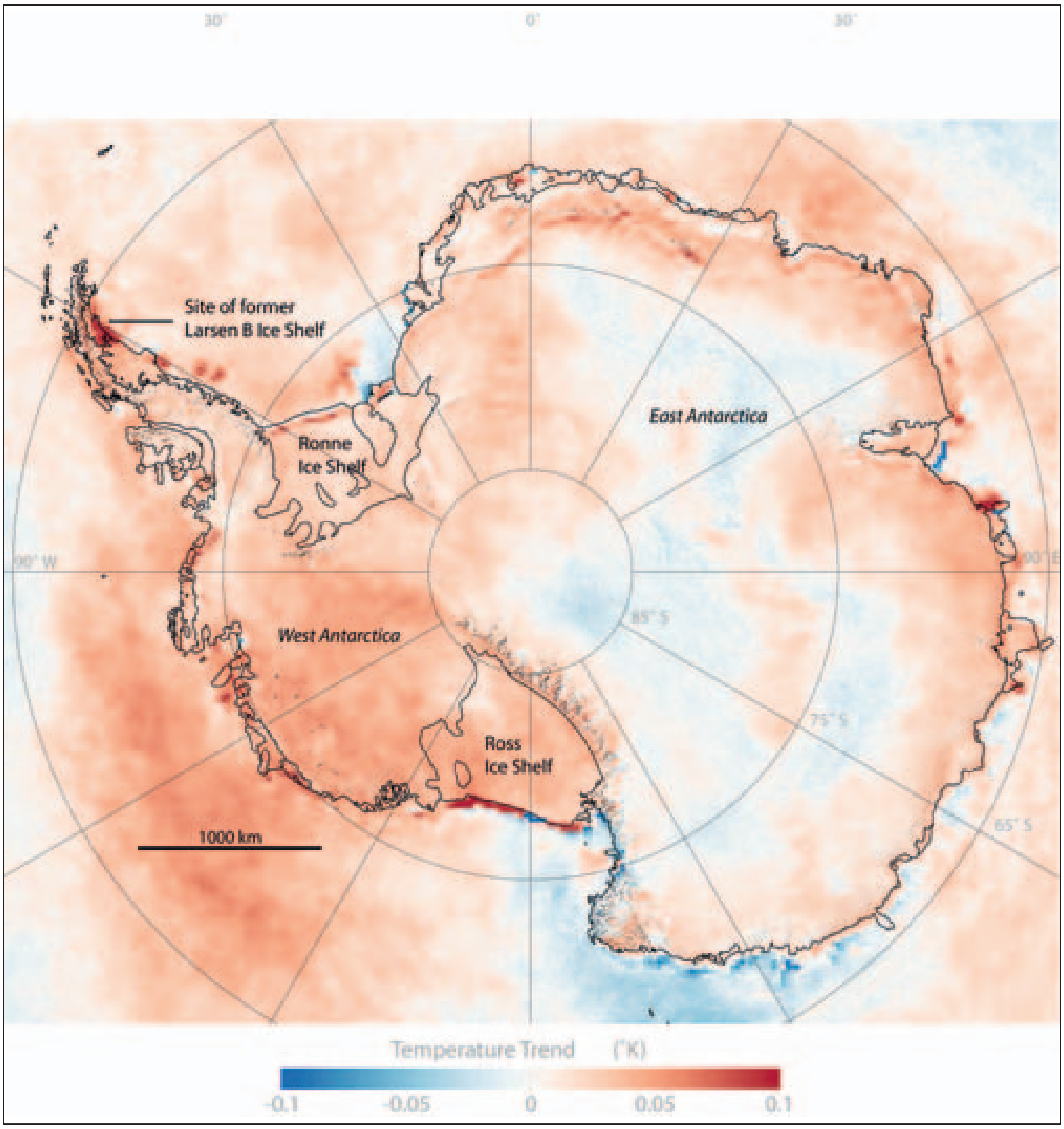

Figure 2.2. Image illustrating long-term changes in yearly surface temperature in and around Antarctica between 1981 and 2007. Places where it warmed over time are red, places where it cooled are blue, and places where there was no change are white.

Understanding the processes and changes affecting the polar marine biosphere requires an integrated approach involving observations, laboratory studies, field studies, sample recovering and integration and data processing. The results of this field of research have a key impact not only on other scientific fields but also on society, since the adaptive capacity of marine living resources to current change will determine the impact on world-wide fisheries.

Table 2.1. Links and interrelationships between the focus areas of Chapter 2 and the other chapters addressed in this Science Perspective.

● Forcing ● Response ● Variability

Chapter 1: Sea Ice, Ocean, Atmosphere	Chapter 2: Polar Marine Biosphere	Chapter 3: Polar Palaeoclimate and Marine Palaeo-Environments	Chapter 4: Geological History	Chapter 5: Natural Hazards
● ● (Forcing, Response)	Evolution	● ● (Forcing, Response)	● (Response)	● (Response)
● ● ● (Forcing, Response, Variability)	Biodiversity	● ● ● (Forcing, Response, Variability)	● (Response)	● (Response)
● ● ● (Forcing, Response, Variability)	Biogeochemistry	● ● ● (Forcing, Response, Variability)	● (Response)	● (Response)
● ● (Forcing, Response)	Responses of Marine Organisms	● ● (Forcing, Response)	● (Response)	● (Response)

(See Table 1.1. for guidance)

KEY QUESTION 1

How did polar marine organisms adapt to past change and what does this tell us about their capacity to adapt to future change?

How and on what time scales will ecosystems change, on a gradient from the North Atlantic into the Arctic Ocean and its shelves? What has been and will be the variability of these processes? What are the likely consequences of an emerging changing environment for ecosystem functioning and ecosystem services provided by the polar biosphere?

Plate tectonics, palaeoceanography and the resulting changes in the global climate (greenhouse to icehouse) have impacted the polar oceans' marine fauna and flora over millions of years, caused extinctions and radiation of benthic marine organisms, and led to the present biodiversity including a high degree of endemicity (Brandt, 2005).

The sensitivity of the polar oceans to climate change makes its records critical not only for palaeoclimate reconstructions, but in providing important clues to polar oceans behaviour in near-future warmer climates. Under greenhouse conditions, Arctic seasonal primary production was dominated by diatom algae occurring within a stratified water column, involving specially adapted species in blooms, which resemble those of the modern North Pacific subtropical gyre (Dore et al., 2008), or those indicated for the Mediterranean sapropels (Kemp et al., 1999). With increased CO_2 levels and warming currently driving increased stratification in the global ocean (Sarmiento et al., 1998), this style of primary production may become more widespread. More recent evidence for the impacts of past climate fluctuations on Arctic marine biota is abundant (Wassmann et al., 2011). Oral as well as written records from the past few centuries and archaeological remains of Inuit hunting communities from the last 4000 to 5000 years provide evidence of large migratory fluxes in sea mammals and sea birds in response to climatic fluctuations (Vibe, 1967). More evidence might become available from the study of decadal time resolution of sediment cores that can only be achieved in high accumulation regions in the Arctic Ocean.

The Southern Ocean displays some unique environmental characteristics, such as a deep continental shelf reaching 1000 m in depth, and a weakly stratified water column, and it is characterized by a unique and highly diverse fauna of benthic invertebrates (Brandt et al., 2007). In the Southern Ocean, the dramatic palaeoceanographic changes during the Tertiary (Brown et al., 2006) resulted in the generation of the present day system of bottom waters of the world oceans (Tripati et al., 2005), which has shaped the evolution of many Antarctic marine species. The cooling of the Southern Ocean occurred rapidly on geological time scales. However, for the life in the ocean the temperature decrease with time equalled a cooling rate of 0.003°C per millenium. Even though this rate of temperature change was very unlikely to have had a catastrophic impact on benthic communities, many species became extinct, especially during the Late Cretaceous, while some survivors experienced a dramatic radiation (Clarke and Johnston, 2003).

Little is known about life in the deep-sea area of the polar oceans. Today it still remains extremely difficult to obtain animals alive and undamaged from great depths, and as a result little is known about the physiology, autecology[3] or life histories of the polar ocean deep-sea biota.

Changes in the biotic composition of the polar ecosystems will ultimately cause faunal changes and shifts in the trophic composition of the fauna and the food web. Due to the high proportion of endemic species (especially in the Southern Ocean), future changes will have a lasting impact on the species composition, at least on evolutionary time scales (Brandt and Gutt, 2011).

To measure the changes in benthic populations or communities, extensive monitoring programmes in polar areas would be necessary. Environmental protection, basic research on climate change and its effects on the biodiversity composition and functioning (morphologic and genetic), biochemistry and physiology are needed in order to address the effects and consequences of current environmental change in polar ecosystems.

KEY QUESTION 2

What are the threats to biodiversity and what are the wider implications of biodiversity changes in polar regions?

Where are the habitats and the refugia of key organisms? What are their functional roles in the ecosystems? What are the natural fluctuations and what effect has ongoing change on ecosystem services in polar oceans on different time scales, especially in midwinter? Do rare species or communities buffer the ecosystems? Are the deep-sea micro-organisms in permanently ice-covered oceans different in terms of biodiversity and physiological and biochemical features from the rest of the ocean? How and how fast will alien species introduction impact the system?

Biodiversity in polar regions is threatened by the potential effects of global warming. Air temperatures on the Arctic land surface increased at an average rate of 0.09°C per decade from 1900 to 2003, which is greater than the 0.06°C per decade trend documented for the Northern Hemisphere as a whole (ACIA, 2005). This warming is paralleled by a decrease in the extent and thickness of Arctic sea ice cover. In addition, surface-water acidification (because of raised atmospheric CO_2), and increased human activity, such as the introduction of pest species, pollution and fishing (Cheung et al., 2009), further complicate the stability of polar ecosystems.

Responses to current environmental changes have already been observed in the Arctic (Wassmann et al., 2011) and include:

- Northward range shifts for various subarctic and even temperate species.
- Changes in the abundance of key organisms
- Rearrangement of food webs and communities, affecting fisheries yields (e.g., shifts in cod and shrimp fishery in Greenland).
- Abundance and reproductive output of some Arctic species has declined.
- Increased phytoplankton biomass and primary production in the open Arctic Ocean, particularly the Pacific sector.

The pattern of climate change impact on biodiversity, particularly in polar areas, will produce further changes in distributions and community structure of marine species, and this will affect fishing and have socio-economic impacts on vulnerable coastal communities. If the complete Arctic Ocean develops into a seasonal ice zone, its ecosystem will change fundamentally because sea ice is a major component of the polar oceans. In addition, a lower sea-ice extent will allow access to shipping and exploration of the natural resources, increasing the anthropogenic pressure on the relatively pristine ecosystems of the Arctic Ocean. However, since there is a lack of biological data from key areas, such as the central Arctic Basin and the Russian shelves, which predates anthropogenic climate change, it is not possible to assess the impact of climate change in these key Arctic regions. Physiological experiments analysing adaptation and macro-physiological processes of polar organisms are employed at rates of change which are 10–100,000 times faster than climatically induced oceanic changes (Peck et al., 2009), in view of which it remains difficult to measure or anticipate the potential biological responses.

Although environments have changed frequently all through the Earth's history, Southern Ocean marine organisms have been exceptionally resistant to temperature and ice changes in the past. For instance, even though the last Ice Age ended only ~11.000 years ago, the Antarctic shelf biota has recovered and is exceptionally rich across taxonomic levels (Clarke and Johnston, 1996). Nevertheless, recent eco-physiological studies indicate that the strong stenothermy displayed by many Antarctic marine biota makes them vulnerable to ocean warming, as experimental exposure to higher temperatures results in the loss of critical physiological and behavioural functions (Peck et al., 2009). In an ecological context, anthropogenic or natural disturbance comprises temporal and spatial changes in a variety of

3. The study of individual species in relation to the environment.

Figure 2.3. Ascidians found at the sea floor of the Larsen A region (East Antarctic Peninsula). As fast growing animals, they can be an indication of a first step towards biodiversity change after the collapse of the ice shelves. © Julian Gutt, Alfred Wegener Institute.

environmental conditions over different scales such as, for example, sea ice, ice scouring, anchor-ice formation, "drop stones", large-scale glacial or pack-ice melt due to temperature increase, sediment instability, CO_2, UV-B radiation and precipitation (Barnes and Conlan, 2007). Critical for the Southern Ocean can be sudden or prolonged temperature changes, and perhaps Milankovitch cyclicity (Clarke and Crame, 2010). Regarding the deep-sea communities, the drivers of their biodiversity are still unknown, in view of which it remains extremely important to study abyssal biodiversity and the key factors generating and maintaining it, in order to establish a solid benchmark against which future change can be measured (Brandt et al., 2007).

In any case, one of the main problems in documenting ecological impacts in polar areas is the lack of reliable baseline information from which change can be identified (Wassmann et al., 2011), due to the shortage of information on ecosystem structure and functioning that predates anthropogenic climate change in both spatial and temporal scales.

KEY QUESTION 3

How will changes in the biological systems of the polar regions influence global biogeochemical cycles?

What feedback is there from biological processes to the global climate system? What is the magnitude of ongoing decoupling of fluxes in biogeochemical elements (e.g., C, N, Si)? How and to what extent are sea ice dynamics regulating the exchange of climate-relevant substances between ocean and atmosphere? What role does biology play here? How will the vertical ocean pumps transport biogeochemically relevant elements to the deep sea? And how will benthic life respond?

The surface of the ocean plays a critical role in absorbing atmospheric CO_2 in a chemical equilibrium which is largely responsible for controlling the pH of seawater. As a consequence, the increased CO_2 uptake has resulted in changes in the chemical balance and a reduction of the

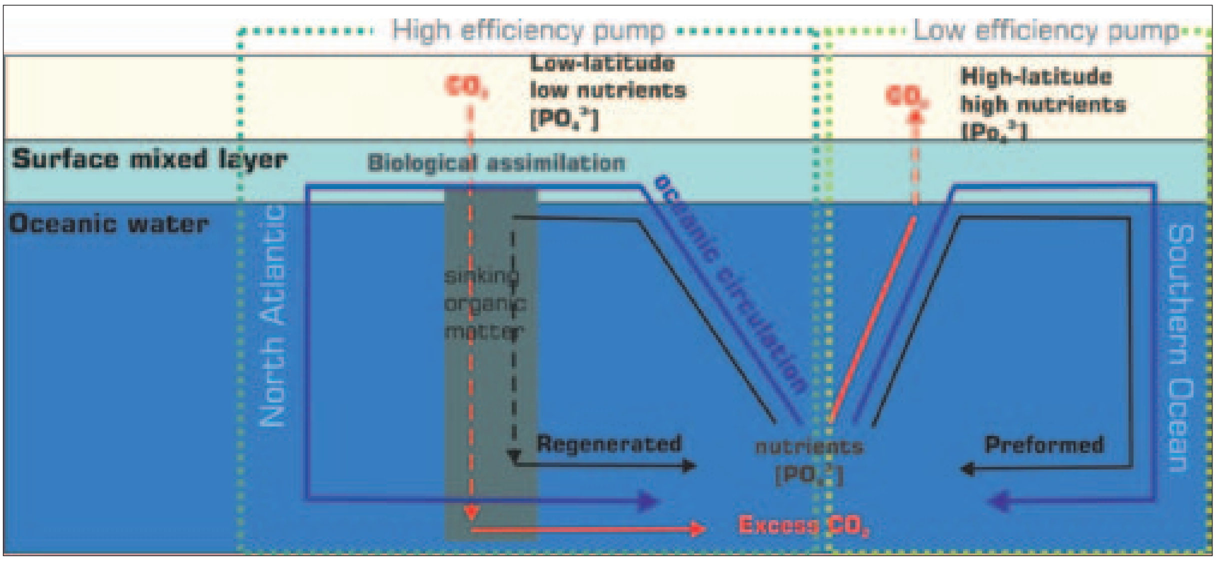

Figure 2.4. Schematic figure representing the high and low latitude CO_2 pump. Blue line represents oceanic circulation, red line CO_2 and black line nutrients (represented by phosphate, PO_4^{3-}). The high efficiency pump in low latitudes (on the left) is characterised by low-nutrient surface waters. In these regions the complete biological assimilation of the major nutrients into the production of particulate organic matter takes place. The CO_2 is sequestered from the atmosphere and transferred to the deep ocean through the sinking of the organic matter. The nutrient-poor surface waters are cooled in the North Atlantic and transferred to the deep ocean. On the right we see the low efficiency pump at high latitudes (currently dominated by the Southern Ocean). There, nutrient-rich and excess CO_2-rich water comes to the surface and descends again with most of its dissolved nutrient remaining. In so doing, this loop releases into the atmosphere CO_2 that had been sequestered by the regenerated nutrient loop. Modified from Sigman et al. (2010).

seawater pH. This process is called “ocean acidification” (Doney et al., 2009).

The solubility of CO_2 in the oceans depends on physical (i.e., temperature), chemical (i.e., carbonate chemistry) and biological (i.e., biological productivity) factors.

Acidification of the water masses has the potential to become one of the major problems for the polar ecosystems because of the cold waters and naturally low carbonate saturation levels. Model simulations predict that the Arctic Ocean will face the greatest level of acidification within the global oceans because cold water has greater capacity to take up CO_2, a change that is amplified due to the impact of fresh water input and increased carbon uptake in response to sea ice retreat (Steinacher et al., 2008). However, both polar regions are expected to become undersaturated in biogenic $CaCO_3$ by 2100 (Orr et al., 2005). Many calcifying organisms, such as pteropods, which are important components of the plankton in high-latitude systems (Bathmann et al., 1991), will find their habitat extremely reduced, or even eliminated, with major consequences for food web dynamics and other ecosystem processes (Guinotte and Fabry, 2008).

The polar benthos, together with other components of the global marine ecosystem, plays an important role in global CO_2 budgets, because of the biological incorporation of carbon into benthic organisms. Benthic processes will determine whether the organic matter that sinks to the seafloor will be fixed for millions of years in biogenic sediments or will be recycled. This process will depend on the composition of species, such as highly dynamic populations or organisms with extremely low metabolic rates (Gutt et al., 2011).

Marine ecosystem studies suffer from inadequate seasonal coverage. Good winter data are only available from accessible regions in the Arctic Ocean like the Chukchi Sea, Franklin Bay, and Banks Island. However, these studies do not constitute a baseline for detecting footprints of climate change in the polar oceans.

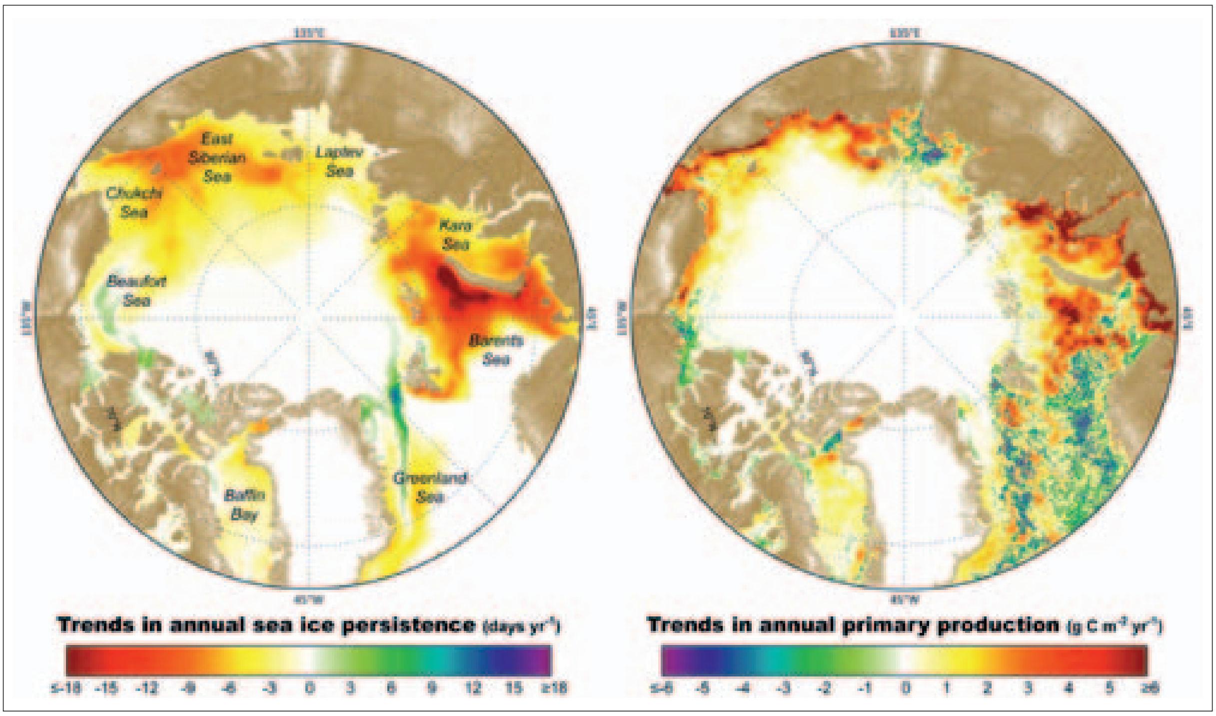

Figure 2.5. Trends in annual sea ice persistence (left) and total annual net primary production (right) across the Arctic Ocean and its adjacent shelf seas from 1998-2009. Sea ice persistence data (based on a 15% sea ice concentration threshold) are derived from Special Sensor Microwave/Imager passive microwave radiances (Cavalieri et al., 2008) and primary production data are from Arrigo and van Dijken (2011). Figure from Frey et al. (2011). Reprinted with permission. http://www.arctic.noaa.gov/reportcard/primary_productivity.html.

KEY QUESTION 4

To what extent, in what direction, and on what time scales will polar organisms and ecosystems change?

How will the trophic structure of different ecosystems be affected by fast-changing environmental conditions, and what impact would a loss of organisms and populations have in terms of ecosystem maintenance and preservation of biodiversity? How do ocean acidification and temperature rise influence polar organisms? What role does permanent ice cover have in maintaining ecosystem structure and functioning? How crucial is the duration and extent of winter sea ice in maintaining species capability and thus ecosystem structure and functioning? What time and space scales are relevant for the transmission of surface ocean climate signals to the long-lasting deep-sea environments? What will be the corresponding effects? Will the primary production increase or decline in changing polar oceans?

As surface sea ice continues to be lost, there are likely to be further large changes in the ecosystems and primary production (Carmack and Wassmann, 2006):

The life cycles of the majority of the Arctic species are strongly tied to the timing of sea ice melt. At present, most of the phytoplankton primary production takes place when the sea ice is melting and retreating towards the pole, but at present it is difficult to estimate what will be the balance between planktonic production in a summer sea ice-free ocean and sea ice margin production. Temperature, sea ice cover and light penetration in the enlarged ice-free zones are expected to change, but not the light season, so primary production will increase within the same growing month.

There is already evidence showing that a climate-induced reduction of sea ice cover duration on Arctic shelves will favour the population growth of several key zooplankton species (e.g., Ringuette et al., 2002), perhaps with a transition to a "phytoplankton–zooplankton"-dominated ecosystem rather than a "sea ice algae–marine benthos" ecosystem (Piepenburg, 2005).

Also expected is increasing seasonal penetration of subarctic species, but the degree to which Arctic species may be displaced is uncertain. Such reorganization in the way the ecosystem operates will ultimately alter the pathways and magnitude of energy that passes into upper trophic levels, such as fish, sea birds and marine mammals, and impact the people dependent on those resources. Potential feedbacks from all these biological changes are unclear, as an integrated ocean-wide view of the structure and function of Arctic Ocean food webs is not yet available (Carmack and Wassmann, 2006).

In the Southern Ocean, benthic shelf species have – as in the past – the potential to retreat to, or survive at, greater depths. or alternatively into more southern areas where warming is less pronounced; in other words, range shifts have to be expected (Barnes and Kuklinski, 2010). Alien species are almost blocked from invading Antarctic shallow waters as long as the steep gradient in sea-surface temperature (SST) between warmer water masses to the north of the Polar Front and colder water masses to the south of it persists (Clarke et al., 2005). The predicted 1°C increase by 2100 (Turner et al., 2009) will remain below a threshold that makes the temperature-barrier generally more permeable. However, this does not mean that single species might not progressively invade, nor that species living in the Antarctic at the margin of their distribution might not colonise larger areas and outcompete the original local fauna.

Molecular techniques are key tools in resolving diversity and phylogeny (Schiaparelli and Hopcroft, 2011). Genomic approaches to identifying the types of genetic mechanisms that provide organisms with the abilities to adapt to environmental change and determining the genetic limitations of stenothermic organisms regarding the toleration of, and acclimatisation to, temperature changes are needed in order to fully understand the effects that climate change will have on polar marine biodiversity (Peck et al., 2005) . New strategies will be required to gain further insight into how the marine climate system has influenced such changes and how it will do so in the future (Schofield et al., 2010).

BOX 2.1. The Frozen Biosphere: What Do We Lose?

Are there unknown genetic potentials embedded in polar organisms from rather inaccessible ice-covered polar and deep-sea areas? What can we learn from organisms surviving in ice-associated habitats? What genetic potential is hidden in ice organisms?

There is a significant interest in the biotechnological potential of polar biodiversity and Arctic genetic resources, covering several key areas including enzymes (such as those used in life-sciences research and a range of industrial applications), anti-freeze proteins, bioremediation, pharmaceuticals, dietary supplements, cosmetics and other health-care applications.

Studies of the genomics of Arctic and Antarctic organisms have already provided unique insights into the evolution of natural populations, such as one of the most dramatic examples of selection in nature: the generation of antifreeze proteins in notothenioid fish through the sequestration of digestive enzymes. In other species, entire genes have been erased or silenced by evolution, as they have been selected against or become irrelevant in a constant low temperature environment. The natural silencing of genes may be of high relevance in the biomedical sciences for the identification of physiologically important proteins.

Polar genetic resources have moved beyond research by the academic community to commercialisation by industry. In fact, currently there are more than thirty-one patents or patent applications based on Arctic genetic resources (Leary, 2008).

Figure BOX 2.1. Antarctic ice fish. As an adaptation to low temperatures, the Antarctic ice fish has no red blood pigments (haemoglobins) and no red blood cells. Thus, the blood is more fluid and the animals save energy otherwise needed to pump blood through their bodies.

BOX 2.2: The Deep-Biosphere: Secrets of a Recently Discovered World

What are the biogeochemical functions, activities and ecological roles of sub-sea floor life? How far can evolution extent limits of life on Earth?

The biosphere that occupies the deep sub-sea floor is strongly associated with fluid flow regimes and biogeochemical-elements cycle (Yamamoto et al., 2009). Those organisms depend mainly on the supply of nutrients and energy substrates from the overlying surface world (i.e., land and ocean) and/or the underlying lithosphere (i.e., the Earth's crust and mantle), and thus the fluid flow regimes and the geophysical conditions play a key role for ecosystem existence. The sub-sea floor biosphere extends to at least 1600 meters below the sea floor and probably deeper, with an upper temperature limit for prokaryotic life of at least 113°C (Roussel et al., 2008). However, it is currently unknown what kinds of microbes play major roles in particular biogeochemical reactions in the food and chemical chains, nor do we know how they metabolize intermediates from buried recalcitrant organic materials or other abiotic substrates in the final feeding processes in the ecosystem (Yamamoto et al., 2009). An interdisciplinary approach involving microbiology, geochemistry, hydrogeology and geology is required to address the geosphere-biosphere interaction in the modern Earth's system and the past and future co-evolution of life and planet (Yamamoto et al., 2009).

BOX 2.3: Alteration of Ocean Living Resources Distribution

The Arctic and Antarctic marine food webs are very complex and susceptible to disturbance not only through temperature increases but also loss of sea ice. As a result of this, marine ecosystems will suffer the effects of rising water temperatures, decreasing oceanic pH, altering stream flow patterns, increasing storm events and sea level rise. These environmental changes are expected to have a substantial impact on the abundance and distribution of marine species as well as ecosystem functioning and food webs (IPCC, 2007). The current warming trends have already begun having an impact on marine flora and fauna, with poleward shifts of native communities (Sorte et al., 2010). The consequences of those shifts are still uncertain, mainly because little is currently known about polar ecosystems and food webs. The logistical difficulty of sampling in any kind of ice-covered waters makes studies of the polar regions, and the deep basins in particular, extremely challenging (Arrigo, 2003). Only during the favourable season, with minimum sea ice extent, is access to the high Arctic continental shelves for scientific sampling somewhat easier; but thick multi-year ice persists all year round over much of the basins. The summer multi-year ice area and winter season remains inaccessible to the scientific community. In the Southern Ocean too our knowledge of biodiversity is largely conditioned by the relative inaccessibility of the region. Benthic sampling is largely restricted to the shelf; little is known about the fauna of the deep sea. The location of scientific bases determines the distribution of samples and observation data, and the routes used for logistical supply are the focus of much of the at-sea and pelagic work (Griffiths, 2010).

Research Needs

In order to investigate the changes and processes affecting polar biology and to project future climate change with confidence there is an urgent need for a polar-research dedicated platform to:

- Generate regular hydrographic surveys and underway shipboard surface observations all year round (including winter) in order to produce long-term ocean and atmospheric time-series.
- Conduct surveys in order to quantify the CH_4 and carbon reserves in the Arctic marine sediments.
- Deploy and recover AUVs and ROVs (able to navigate under ice shelves and permanent ice-caps) to collect valuable year-round measurements, such as temperature, in situ chemistry, ice formation, freshwater flux, heat flux and bottom melt. The use of ROVs will reduce sampling costs and permit data collection in regions difficult to access using conventional sampling methods. Instrumentation on the ROVs should include means of sampling the biota.
- Investigate remote and rather inaccessible areas, such as deep-sea basins in the Arctic Ocean or areas under ice shelves.
- Promote ecosystem based research, including microbes.
- Generate numerical models able to represent climate effects and the response to multiple ecosystem components.

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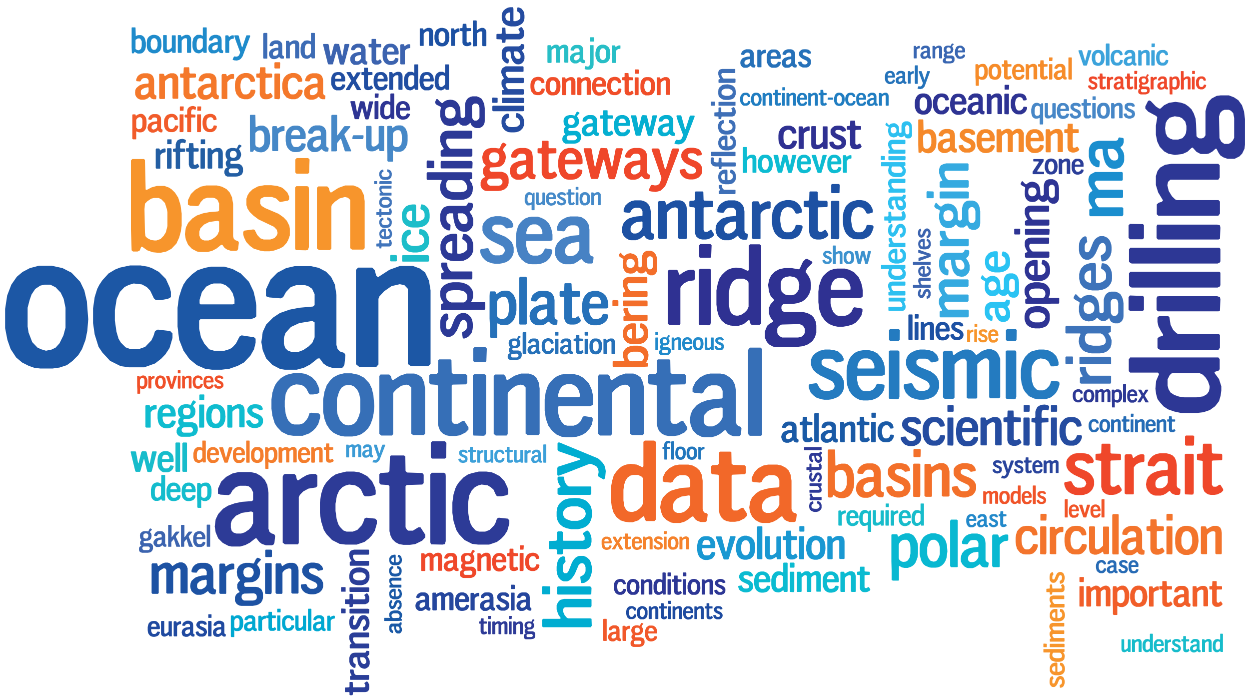
Chapter 3: The Polar Ocean's Geological History



Introduction

The two polar oceans have dramatically different geological histories. The Arctic Ocean evolved from a land-locked basin into a semi-enclosed basin four times the area of the Mediterranean; while the Antarctic Ocean is the result of the fragmentation of a super-continent to open up a continuous circumpolar seaway. In the Arctic Ocean, while the origin of the Gakkel Ridge is kinematically well understood in a plate tectonic framework (Cochran et al., 2003), its relations with the Eurasian continent and the dynamics of ultra-slow seafloor spreading have not been explored by drilling yet. The origin of the Amerasia Basin is complicated and still poorly understood (Grantz et al., 2011). Sampling the high standing ridges and the basement in regions of reduced sedimentary cover could provide observations critical for understanding the development of this basin.

The oceanography of the two polar regions is also strikingly different, but in each case dominated by the opening of gateways, which permitted the influx of waters into the Arctic Ocean (e.g., Engen et al., 2008), but facilitated the climatic isolation of Antarctica by circulation around the continent (e.g., Lyle et al., 2007). In each case the development of the gateways dictated the evolution of the oceans. One of the primary targets for drilling should be to improve our understanding of the opening of these gateways, thus setting palaeooceanographic boundary conditions, a factor indispensable in constraining the consequences of these events (Jokat and Stein, 2011).

The Southern Ocean is well understood in a plate tectonic framework from the magnetic stripes that date the seafloor and track the relative motions of the adjacent continents (Müller et al., 2008). In this ocean, key questions remain concerning the history of the extended margins, their conjugates and the Large Igneous Provinces (LIPs), and their relationship to seafloor spreading and mantle processes.

How continents and oceanic areas are distributed determines the pathways of the MOC, an important component in poleward energy transfer and climate control. Under present day conditions, the poleward energy transport in the ocean exceeds that of the atmosphere at low latitudes, but in mid-latitudes the atmospheric transport is two to three times that of the ocean. Modelling suggests that while ocean depth is not critical, zonal barriers are important in shaping circulation

(Vallis and Farneti, 2009). Oceanic circulation interacts with changing plate boundaries, the break-up of continents, the formation of sedimentary basins and, through the distribution of nutrients and biological productivity, establishes the basis for the resource potential of the polar regions.

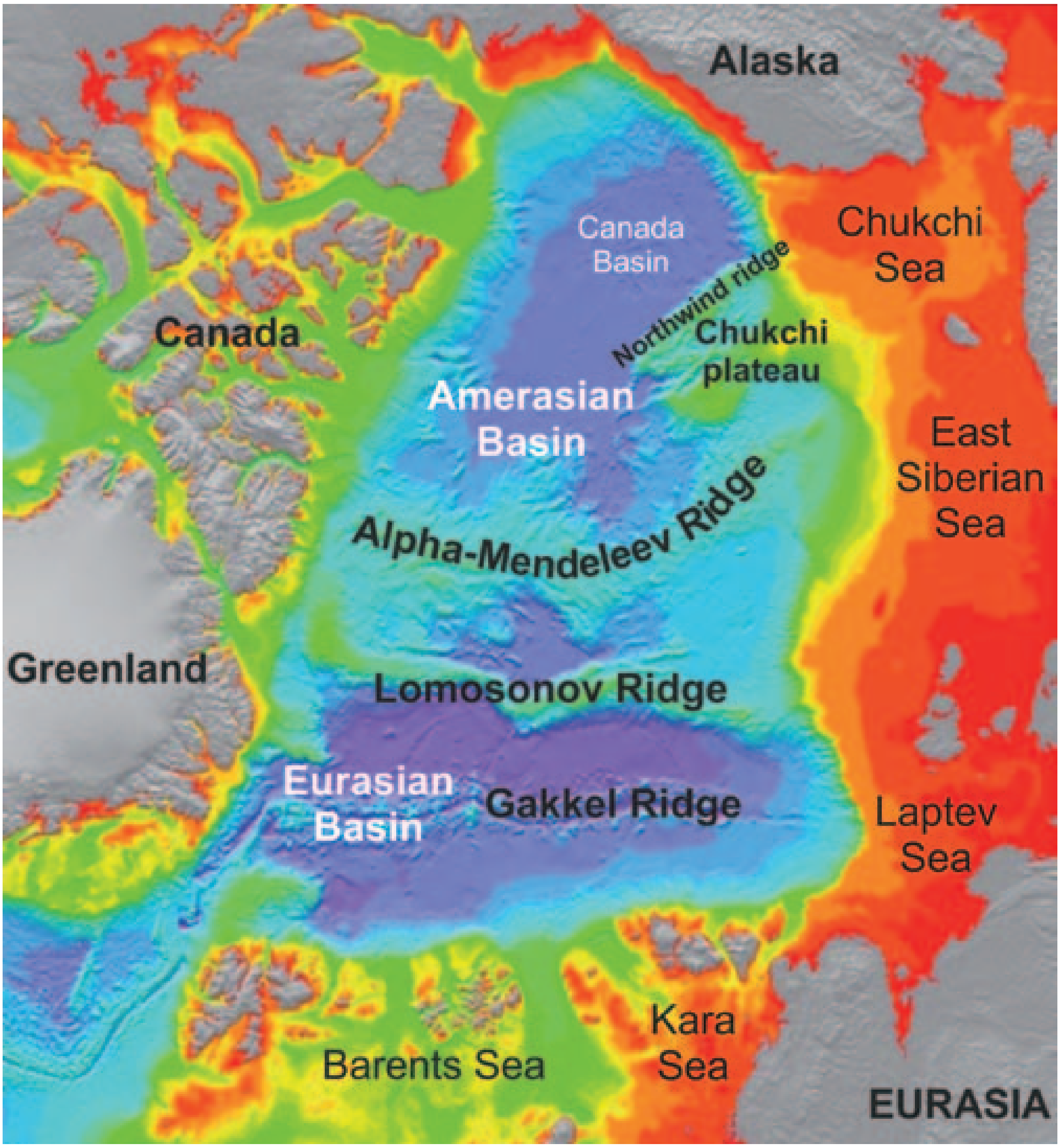


Figure 3.1. Major structural features of the modern Arctic Ocean.

Table 3.1. Links and interrelationships between the focus areas of Chapter 3 and the other scientific chapters addressed in this Science Perspective.

● Forcing ● Response ● Variability

Chapter 1: Sea Ice, Ocean, Atmosphere	Chapter 2: Polar Marine Biosphere	Chapter 3: Geological History	Chapter 4: Polar Palaeoclimate and Marine Palaeo-Environments	Chapter 5: Natural Hazards
● (Forcing)	● (Forcing)	Timing and Mechanisms	● (Forcing)	● (Forcing) ● (Response)
● (Forcing)	● (Forcing)	Gateways	● (Forcing) ● (Variability)	● (Response)
● (Response)	● (Response)	Stratigraphy	● (Response)	● (Forcing) ● (Response)

(See Table 1.1. for guidance)

This core theme targets three focus areas with four overarching key questions.

Timing and Mechanisms

- *How and when were the Arctic Ocean basins formed?*
- *How and when did the supercontinent Gondwana break up?*

Gateways

- *What is the history of the polar gateways leading to the current oceanographic boundary conditions?*

Stratigraphy

- *How is the spatial and temporal glaciation history reflected in the stratigraphic framework of the polar regions shelves, slopes and basins?*

Understanding the past geological and structural evolution of the polar regions is the key to understanding the present configuration. This information forms the basis for understanding the rest of the scientific disciplines, particularly over long time scales.

KEY QUESTION 1

How and when were the Arctic Ocean basins formed?

Where are the continent-ocean transitions in the Arctic Ocean? What are the processes of ultra-slow sea floor spreading at the Gakkel Ridge in the Eurasia Basin? How does the Gakkel Ridge interact with the Eurasian continent? What is the magmatic history of the basins? What is the history of sediment deposition?

The bathymetry of the Arctic Ocean reveals two large sub-basins; the Amerasia Basin and the Eurasia Basin (Jakobsson et al., 2008). Two important data sets, the first concerning the continuity of earthquake epicentres from the Norwegian-Greenland Sea into the Eurasia Basin, and the second a first order grid of airborne potential field data (gravity and magnetism), allow us to associate the evolution of Eurasia Basin with passive rifting and sea floor spreading at the Gakkel Ridge (Engen et al., 2003). These data show that the Eurasia Basin was formed by northward propagation of the Mid-Atlantic ridge during the Cenozoic.

However, the history of the older Amerasia Basin is still completely elusive, despite a growing data base. The basin has been described as "a rather enigmatic rounded deep hole surrounded by continents without clearly detectable mid-ocean ridge and without clear connection to any other major spreading system" (Tessensohn and Roland, 2000). Published data can support radically different models in the absence of a systematic magnetic anomaly pattern or morphologically distinct spreading ridge and fracture zone system (Cochran et al., 2006). The Amerasia Basin is widely considered to be of late Mesozoic age based on geological evidence from the surrounding continental margins and a few sediment and rock samples from Alpha Ridge. Six to ten km of sediments effectively mask basement fabric in the Canada Basin (Grantz et al., 1990). No fossil plate boundaries have been convincingly identified. Lawver and Scotese (1990) have grouped the proposed models into three classes: i) clockwise rotation of Alaska away from Arctic Canada described by a pole of rotation in the region of the Mackenzie River, ii) an Arctic Islands transform with Alaska rifting off the polar margin of Europe, and iii) the margins of Lomonosov Ridge and Alaska initially being transform margins. The complexities of the observed bathymetry and potential field data lead to complex multistage models for the evolution of the Amerasia Basin. While these data provide valuable constrains on the basin history, drilling is necessary to gather the data required to expand these images into truly historical records. Unravelling the first-order plate boundaries during basin formation is definitely a high-priority issue, which can be approached by considering the specific predictions of each model. To study these issues, drilling should focus on areas away from the continental margins where basement is within reach of the drill string, i.e., mainly around plateaus and ridges.

The transition from continental to oceanic crust at passive continental margins can often be assessed from differences in basement reflector smoothness, intra-basement reflections on the continental side, or simply a landward facing scarp. This may identify the type of plate boundary and constrain models to be tested by drilling in areas like the Amerasia side of Lomonosov Ridge, the Northwind Ridge and where the Mendeleev Ridge adjoins the continental margin.

A first-order question relates to the role of the 250-400 km wide Alpha-Mendeleev ridge complex during the evolution of the Amerasia Basin. Did the complex progressively develop concurrent with sea floor spreading, or form during later discrete events? Also, does the complex include any crustal components of continental affinity? Long range seismic refraction experiments on both ridges show velocity-depth relations distinctly different from families of global average velocity-depth curves representing a wide range of continental settings (Forsyth et al., 1986; Christensen and Mooney, 1995; Lebedeva-Ivanova et al., 2006). Acoustic basement on the ridges has seismic velocities in the range 2.3-4.0 km/s, which are interpreted as representing sequences of basalt flows and sills in voluminous tuff deposits and possible intercalated sediments, and which compare more closely with basement on Ontong Java- and Kerguelen plateaus than normal ocean crust or wedges at volcanic margins (Bruvoll et al., 2012). Large volumes of tuff (and possibly other sediments) were most likely emplaced during a brief igneous episode no later than Campanian (80 Ma) and probably part of the latest events of Late Cretaceous circum-Arctic volcanism (Maher, 2001). Ridge composition and emplacement history can be tested by scientific drilling through the ~700 m thick sediment cover, which drapes the ridge topography, and into the underlying basement.

KEY QUESTION 2

How and when did the supercontinent Gondwana break up?

Was there an early rift phase between East and West Antarctica prior to the opening of the Weddell Sea? What processes created the extensive regions of transitional crust?

About 13,900 km of the 15,900 km-long continental margins of the Antarctic plate are of rifted divergent type, and of that length, 70% contains extended continental crust which continues more than 50 km oceanward from the shelf edge (Gohl, 2008). Only a quarter of the rifted margins seem to be of volcanic type. Along most of the extended margins, the transition from continental to oceanic crust is more than 100 km wide, and in many cases up to 300 km wide, as determined by seismic, magnetic and gravity data. The circum-Antarctic margins (the Australian and Indian Oceans, and Southwest Pacific sectors) and conjugate counterparts are of particular interest for studies of the rifting process. While the amount of crustal stretching during break-up has implications for dynamic plate-tectonic reconstructions and calculations of palaeobathymetry for the development of accommodation space and evolution of early seaways, these examples of extreme lithosphere thinning give insight into what boundary conditions and initial states are required for particular evolutionary paths of the rifting process. In case studies of the rifting process, it is important to find mappable pre- and synrift stratigraphic packages in order to define the brittle deformation history. Depth-dependent extension of the continental lithosphere is manifested by exposures of exhumed mantle rocks near the continent-ocean transition, a process which seems to be the rule rather than the exception (e.g., Karner et al., 2007). However, dynamic lithosphere-scale models with a single weak seed show a range of asymmetric and symmetric rifting modes, where pure shear-type extension can be transformed into simple shear-type extension depending on rheological layering and/or strain rate (Dyksterhuis et al., 2007;

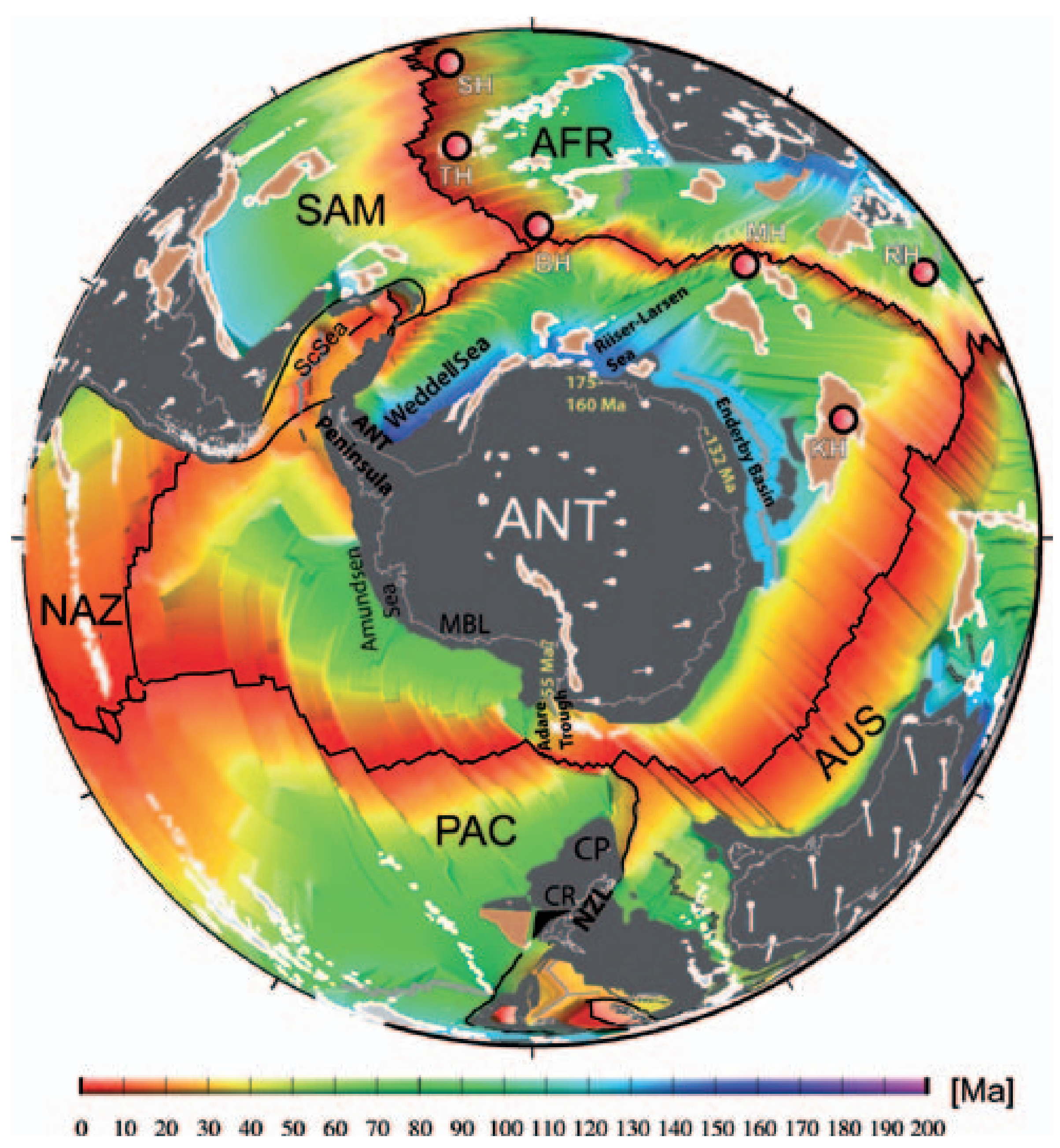


Figure 3.2. Age of the ocean floor surrounding Antarctica. White arrows show "absolute" motion of some tectonic plates based on a moving hotspot frame for the last 5 Ma. Red circles denote hotspot locations (BH = Bouvet; KH = Kerguelen; MH = Marion; RH = Reunion; SH = St. Helena; TH = Tristan). Large igneous provinces and other volcanic provinces (including seaward-dipping reflectors) are shown in brown and white. Active plate boundaries shown in black (mid-ocean ridges) and extinct mid-ocean ridges in grey. ScSea = Scotia Sea (modified after Torsvik et al. (2008)). Courtesy of Carmen Gaina, University of Oslo.

Huismans and Beaumont, 2008). The continental margin of Antarctica presents special opportunities for further case studies of continental lithosphere rifting.

First-order questions in understanding the driving forces leading to continental break-up are: **1)** What is the cause of large-scale volcanism that can occur either before or contemporaneously with continental break-up, and **2)** What causes break-up in the absence of volcanic activity? Both questions can be addressed in offshore East Antarctica by studying the continent-ocean transition and oceanic basins that formed in the Jurassic (Larsen-Riiser Sea) and Cretaceous (Enderby Basin) as a consequence of the African, Madagascar, and Indian plates drift. In the case of the oldest oceanic basin offshore Antarctica, magnetic anomaly data cannot resolve the break-up timing, as this occurred during the Jurassic quiet zone[4] at some time between 165 and 180 Ma (e.g., Gaina et al., 2010). The Cretaceous break-up age (ca. 132 Ma) inferred from magnetic anomaly data in the Enderby Basin (Gaina et al., 2007) requires an unusual kinematic scenario between India and Madagascar between 132 and 85 Ma. Both Larsen-Riiser and Enderby basins are relatively well covered by magnetic anomaly and seismic data, but the Jurassic quiet zone and an extended continent-ocean transition region permit multiple interpretations of the oceanic crust age. Scientific drilling is the only method of settling these questions.

East Antarctica has been affected by at least two major LIP events, Karoo (182 Ma) and the smaller Maud Rise event. Twenty-five reconstructed Large Igneous Provinces (LIPs) with ages as old as ~300 My lay vertically above the edges of the Large Low Shear Wave Velocity provinces (LLSVPs) on the core-mantle boundary at their time eruption (Torsvik et al., 2006). The age of the Maud Rise, however, is critical in determining the nature of the LIP and its relation to possible other LIP-related magmatism, like the Agulhas Plateau or Georgia Rise (Parsiegla et al., 2008) and perhaps even the Mozambique Ridge, all of which could have been sourced by the Bouvet hotspot (Torsvik et al., 2008; Torsvik et al., 2009). Sampling of the basement of the Maud Rise by scientific drilling combined with detailed plate reconstructions will be necessary to constrain this history.

The break-up of Gondwana, which involved Zelandia (New Zealand, Campbell Plateau and Chatham Rise) moving away from Marie Byrd Land, Antarctica, is associated with a zone of extended continental crust interpreted as being up to 650 km wide. This zone is littered with volcanic seamounts near Marie Byrd Land (Wobbe et al., 2011). The Wilkes- and Adélie Land margin is characterised by up to 200 km wide major rift basins bounded by major faults approximately beneath the continental shelf edge. A continent-ocean transition zone of massively extended continental crust, terminated by a basement ridge (Colwell et al., 2005) has a similar structural position and composition to a ridge on the margin of the Great Australian Bight (Totterdell et al., 2000). The southwest Pacific- and Australian sectors of the Antarctic continental margin are first-order examples where modes of lithosphere response to extension can be investigated by scientific drilling. Both conjugate margins in the Australian sector are well covered by seismic reflections surveys, while only a few lines presently exist on the Marie Byrd Land margin.

West Antarctica has undergone extension distributed across many small basins within the West Antarctic Rift System (WARS). One of these basins, the Adare Trough, proceeded to sea floor spreading between chrons C20 and C9 (middle Eocene to late Oligocene, 43 to 26 Ma (Cande et al., 2000). Adare Trough is regarded as an important global circuit node, as it hosts the only (extinct) extensional plate boundary between the Indo-Atlantic and the Pacific realm. If Adare Trough rifting was initiated at 55 Ma, it coincided with rapid denudation - and inferred uplift - of Trans-Antarctic Mountains, with associated alkaline volcanic and igneous activity in the Western Ross Embayment, which began approx. 50 Ma. Scientific drilling is required to test the Adare Trough opening in order to: 1) tighten the global plate circuits through the Antarctic link and 2) understand the connection between the break-up, uplift and denudation of the Trans-Antarctic Mountains and the timing thereof.

KEY QUESTION 3

What is the history of the polar gateways leading to the current oceanographic boundary conditions?

Is there a direct relation between the opening of the Fram Strait gateway and the early Miocene transition to a ventilated Arctic Ocean? What has been the significance of Cenozoic seaways through the Bering Strait?

Arctic Gateways

By connecting independently stratified bodies of water, the opening and closing of ocean gateways modifies the composition and stratification of the water column,

4. The Jurassic Quiet Zone (JQZ) is a region of low-amplitude magnetic anomalies whose distinctive character may be related to geomagnetic field behavior.

causing dramatic shifts in the basin circulation. It might be expected that changing circulation and, perhaps, the dramatic changes associated with reorganisation of the water column would also influence the basinal stratigraphy, leaving a record to be recovered by drilling. High-standing ridges in much of the Arctic Ocean basins are draped with an approximately 200 m thick hemi-pelagic unit underlain in many places by an erosional unconformity below the upper flanks of the ridges. Although capped by an unconformity, the underlying laterally uniform sequences show no evidence of bottom current activity.

Fram Strait: The Cenozoic Fram Strait gateway opened and expanded following a shift to transtensional relative motion between Greenland and Svalbard during the earliest Oligocene (Talwani and Eldholm, 1977). This development of a deep water connection to the world ocean permitted exchange of water and almost certainly had a substantial influence on global circulation and climate.

Enhanced circulation in the polar basin in the ~22-14 Ma time-frame has been related to the opening of the Fram Strait gateway (Jakobsson et al., 2007; Bruvoll et al., 2010). However, the tele-connection between the Arctic Ocean and the North Atlantic is also controlled by another tectonic barrier. To the south, the Iceland-Faeroes Ridge and the Denmark Strait were still at or above sea level at 15-18 Ma. (Thiede and Eldholm, 1983), and the flow of Northern Component Water in the deep North Atlantic became significant only after 12 Ma (Poore et al., 2006). The early Miocene transition to a ventilated Arctic Ocean may have had a more complex evolution, controlled by two gateways north of 60°N rather than the Fram Strait alone.

It appears that the opening of a deep-water connection to the Northern Atlantic was a one-time, progressive event that had a cumulative effect on the Arctic Ocean and world climate. In contrast, the Bering Strait has been, depending on glacially modulated sea level, both open and closed during the last few glacial cycles. There is some controversy about how this switch might have provided an important feedback to accelerate or diminish the effects of glaciation. The age constraints that could be gleaned from scientific ocean drilling might eliminate the uncertainties that presently exist, facilitating more precise studies of climate connections and feedbacks.

Bering Strait: The complementary history of connection to the North Pacific is not well known. There is evidence that the Bering Land Bridge existed during the Mesozoic, permitting communication between reptile populations in Eurasia and North America (Fiorillo, 2008). Opening of the Bering Strait at about 5 Ma is considered to result from far field tectonic interaction between the Pacific plate and the southern margin of Alaska (Marincovich, 2000). Today the Bering Strait is a ~ 85 km wide ~ 50 m deep gateway between the Pacific and the Arctic. Initially, flow was southward, but a change to a predominantly northward flow after 3.6 Ma., coeval with closure of the Central American seaway, may be a consequence of the latter event (Marincovich and Gladenkov, 1999). Modelling suggests that the effect of the strait on the transport of relatively fresh Pacific water into the Arctic and onwards to the North Atlantic does influence the strength of the MOC (Hu et al., 2010), since the through-flow contributes ~ 1/3rd of the freshwater input and possibly ~ 1/5th of the oceanic heat input to the Arctic (Woodgate et al., 2010). With low sea level during glaciations, the Bering Strait is choked off and the Atlantic grows more saline, which may intensify Atlantic overturning, sending warmer water northward from the tropics. The consequence is to reverse the advance of ice sheets. Times with high sea level and inflow through the Bering Strait weaken the MOC, which results in a cooling trend over Greenland and North America. High resolution stratigraphic information is needed from both sides of the Bering Strait to constrain the history of flow and test the hypothesis of the Bering Strait gateway as a modulator of climate.

Antarctic Gateways

The opening of the Drake Passage/Scotia Sea gateway between South America and the Antarctic Peninsula and the Tasmanian gateway between Tasmania and Northern Victoria Land of East Antarctica changed the global ocean circulation, permitting the initiation of the Antarctic Circumpolar Current (ACC) (Kennett, 1977). The changing plate constellation caused the thermal isolation of the Antarctic continent, which has been considered as one of the main drivers for its larger glaciation. However, age estimates for the development of the Pacific-Atlantic connection range from mid-Eocene to early Miocene (Eagles et al., 2005; Livermore et al., 2005). This uncertainty obscures the ACC's role in Antarctic glaciation (Scher and Martin, 2006). To further underpin our hypothesis concerning links between gateways, ocean circulation and climate changes, the direct signals in the sedimentary record have to be obtained from drilling on both sides of the gateway.

KEY QUESTION 4

How is the spatial and temporal history of polar region glaciation reflected in the stratigraphic framework of its shelves, slopes and basins?

As our knowledge of the shelves and high-standing ridges in the Arctic Ocean has improved through numerous cruises for oceanography, law of the sea mapping and marine geology, understanding of the impact of ice on the sea bed has rapidly increased. This effort began with the recognition of significant modification of the shallow (> 1000 m) Lomonosov Ridge by iceberg plough marks and the grounding of a substantial ice shelf against the ridge (Polyak et al., 2001; Kristoffersen et al., 2004) and expanded through the mapping of glacial grooves parallel with the coast, tracking along the Beaufort Shelf Edge (Engels et al., 2008). These features demonstrate that contemporary sea level was not a significant barrier to Pleistocene glacial ice from the continents, but the timing of these glacial advances into the basin are not well constrained. Drilling into sediments remobilised through ice contact and into other deep-sea deposits can expand our knowledge of this previously unknown aspect of the Northern Hemisphere's continental glaciation.

Sediments deposited on the circum-Antarctic continental margin are the result of down-slope sediment supply and interaction with along-slope ocean bottom currents before, during and after repeated advances of individual lobes of the East and West Antarctic ice sheets (Kuvaas et al., 2005). Improved coverage through seismic reflection surveys and the existence of the Antarctic Seismic Data Library System (SDSL, http://sdls.ogs.trieste.it/) has now allowed us to start constructing continuous circum-Antarctic seismic transects, which will ultimately provide an internally consistent temporal and spatial record of erosion of the continent and sediment input to the margin (Lindeque et al., 2011). However, present coverage of scientific drill sites and incomplete recovery provides sparse but much needed chronostratigraphic control. Stratigraphic drilling of the major depocentres on the circum-Antarctic margin is needed to capture the temporal ice sheet response to major past changes in climate.

BOX 3.1. Requirements for Polar Ocean Drilling

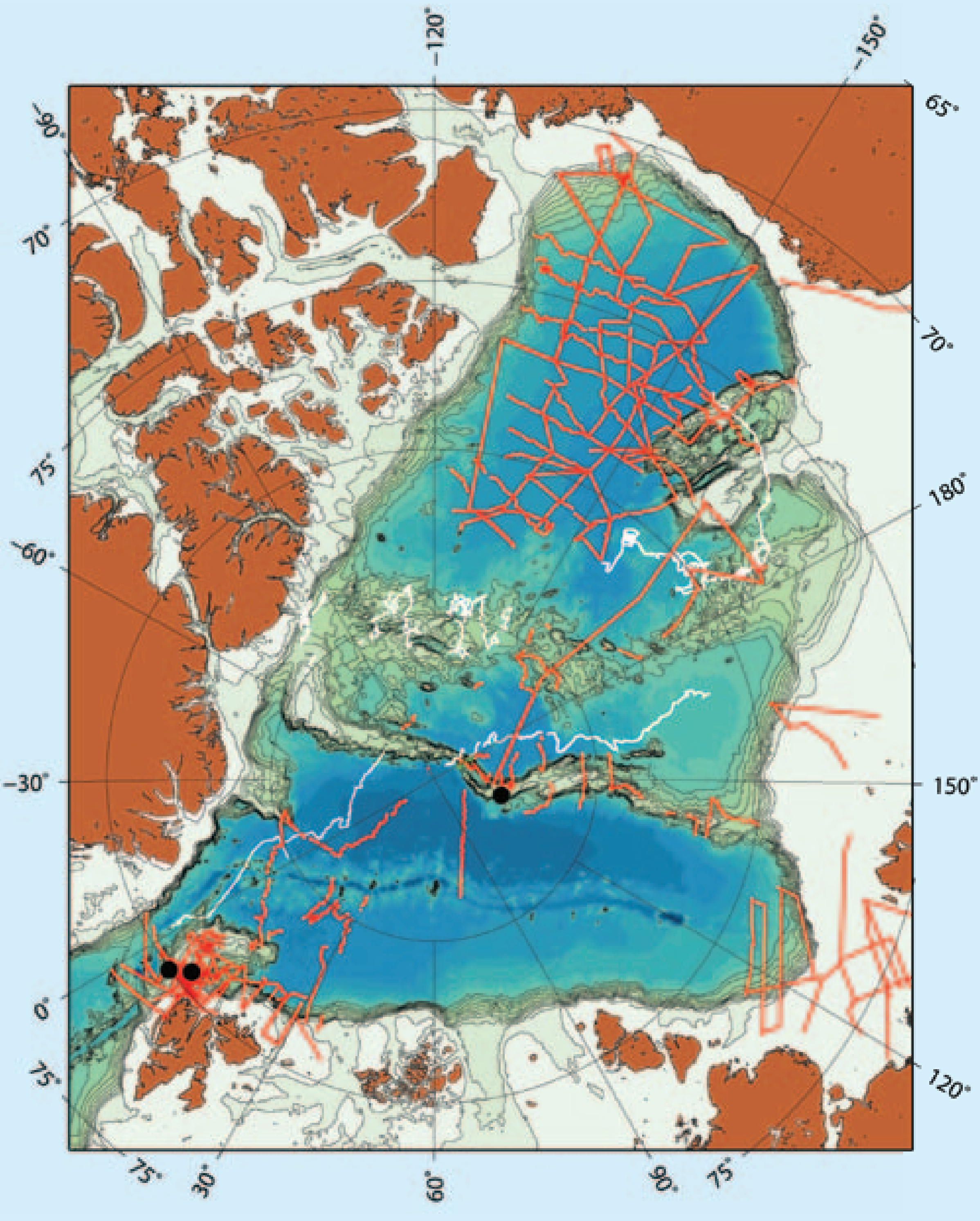
Identifying drilling targets in regions where strong sea ice conditions occur is problematic due to the logistic and operational challenges posed by the fact that near-constant sea ice limits ship access. The result is a paucity of marine seismic reflection data.

During recent years, regular cruises on board the icebreakers *Polarstern* and the Canadian Coast Guard Ship (CCGS) *Louis St Laurent*, as well as single cruises on the USCGC *Healy* and the RV *Langseth*, have substantially expanded the seismic reflection data base for the Arctic Ocean. These data consist of long regional lines imaging the basins and ridges that subdivide this basin, loose grids collected to document sediment thickness and establish the limits of the extended continental shelves of the circum-Arctic nations, as well as well-defined survey grids laid out to test particular hypotheses about the origin of the Arctic Ocean. Although these data reveal complicated histories of sedimentation and deformation, age control is needed to date the reflectors and thus the structures, in order to further evaluate potential drilling sites for their scientific value or to test hypotheses.

Recently a workshop entitled "Overcoming barriers to Arctic Ocean Drilling: the site survey challenge" was held near Copenhagen from November 1st – 3rd 2011. While the lack of good site-survey data has been identified as an important problem, there are other issues preventing the development of good Arctic Ocean drilling proposals and programmes. In particular, one of the biggest issues to target is the absence of good age control on seismic reflection profiles. A secondary problem for Arctic Ocean drilling is the need to collect crossing lines at potential drill sites. These lines are required to establish the safety of drilling at particular locations by demonstrating the absence of structural closure on the sediment layers that might be sampled.

In the Southern Ocean, seismic coverage is greater than in the Arctic Ocean. However, critical regions still remain uninvestigated, especially close to land, under the ice shelves and in the Ross and Weddell seas. Those areas have been defined as "key areas to be still explored" at the Antarctic Climate Evolution Workshop held in Granada, Spain, in 2009, on "Developing an Integrated Strategy to Recover Paleoclimate Records from the Antarctic Margin and Southern Ocean" (De Santis et al., 2009).

Figure BOX 3.1. Tracks of existing seismic reflection data in the Arctic Ocean (from Yngve Kristoffersen, UiB, Norway). White tracks represents ice stations, red lines indicate multi-channel data collected by RV *Polarstern*, *Oden*, *Healy* and Russian vessels.


-120°
-150°
65°
-90°
70°
70°
75°
180°
-60°
-30°
150°
0°
75°
120°
75°
30°
60°
90°
75°

BOX 3.2. Ultra-Slow Spreading Ridges and the Deep Biosphere

Does heat from sources other than crustal cooling of basal melt contribute significantly to hydrothermal circulation at ultraslow ridges?

Ultraslow spreading ridges, such as Gakkel Ridge, are characterized by deep axial valleys, nearly avolcanic spreading and near zero crustal thickness (Klein and Langmuir, 1987; Cannat et al., 2006). The Gakkel spreading centre is filled with sediments over a distance of more than 800 km. The investigation of modern hydrothermal systems in this environment offers an opportunity to understand the formation processes of metal-rich deposits at ultraslow spreading centres ranging from massive sulphides to epithermal occurrences.

Living organisms have been identified in the upper crust at depths of several hundred meters. The spatial distribution of the deep biosphere is still unknown, and its relation to thermal gradient, crustal age and lithology is unconstrained. These highly important and novel questions can only be answered by drilling.

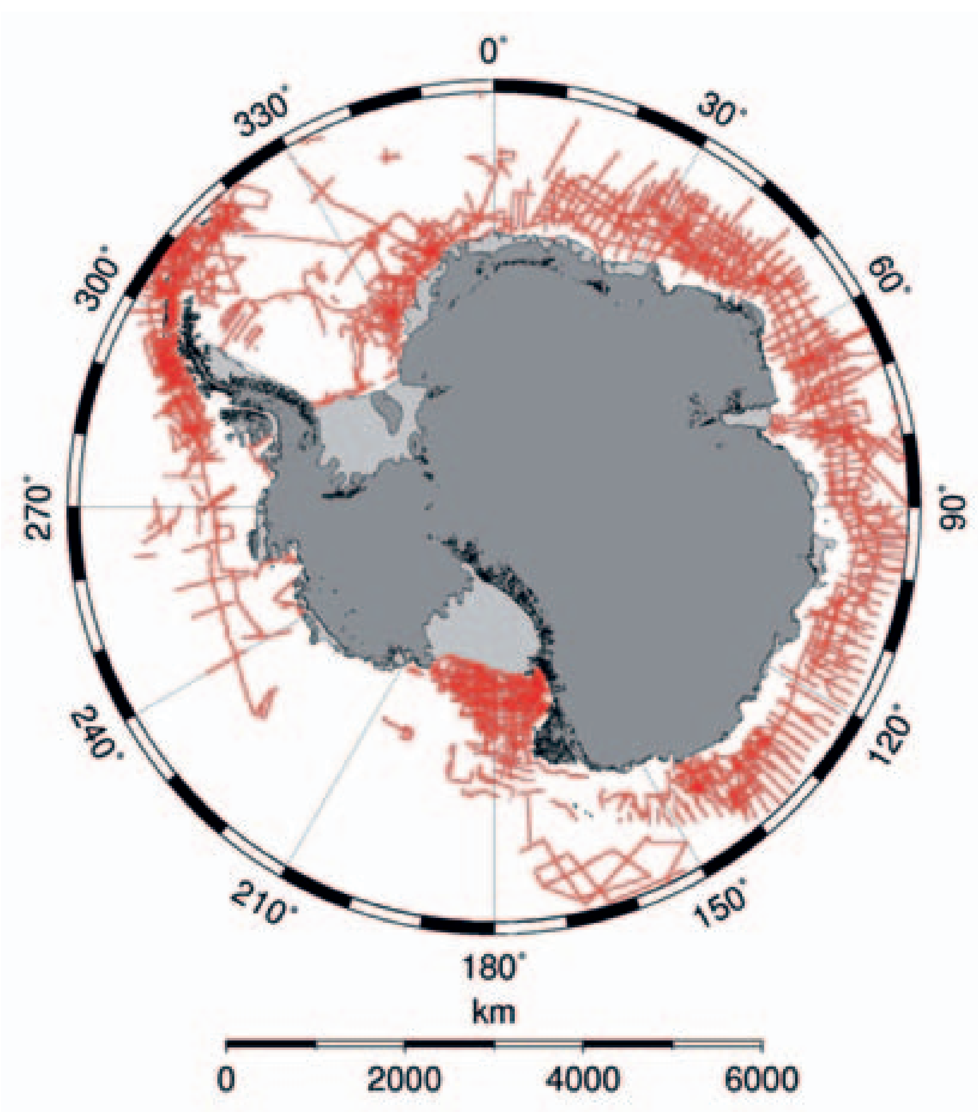


Figure BOX 3.2. Multichannel reflection seismic reflection data collected by all countries and archived into the Antarctic Seismic Data Library System (SDLS, http://snap.ogs.trieste.it/SDLS).

Research Needs

In order to investigate the past geological evolution of the polar regions there is a need for a polar-research-dedicated platform with seismic and drilling capacities to collect:

Seismic profiles: there is a need to collect crossing lines at potential Arctic drill sites. These lines are required to establish the safety of drilling at particular locations by demonstrating the absence of structural closure on the sediment layers that might be sampled.

Scientific drilling is required to:
- date seismic reflectors and thus understand the seismic stratigraphy
- understand the links between gateways, ocean circulation and climate changes
- understand the connection between continental break-up and the uplift and denudation of specific areas, and the timing thereof.

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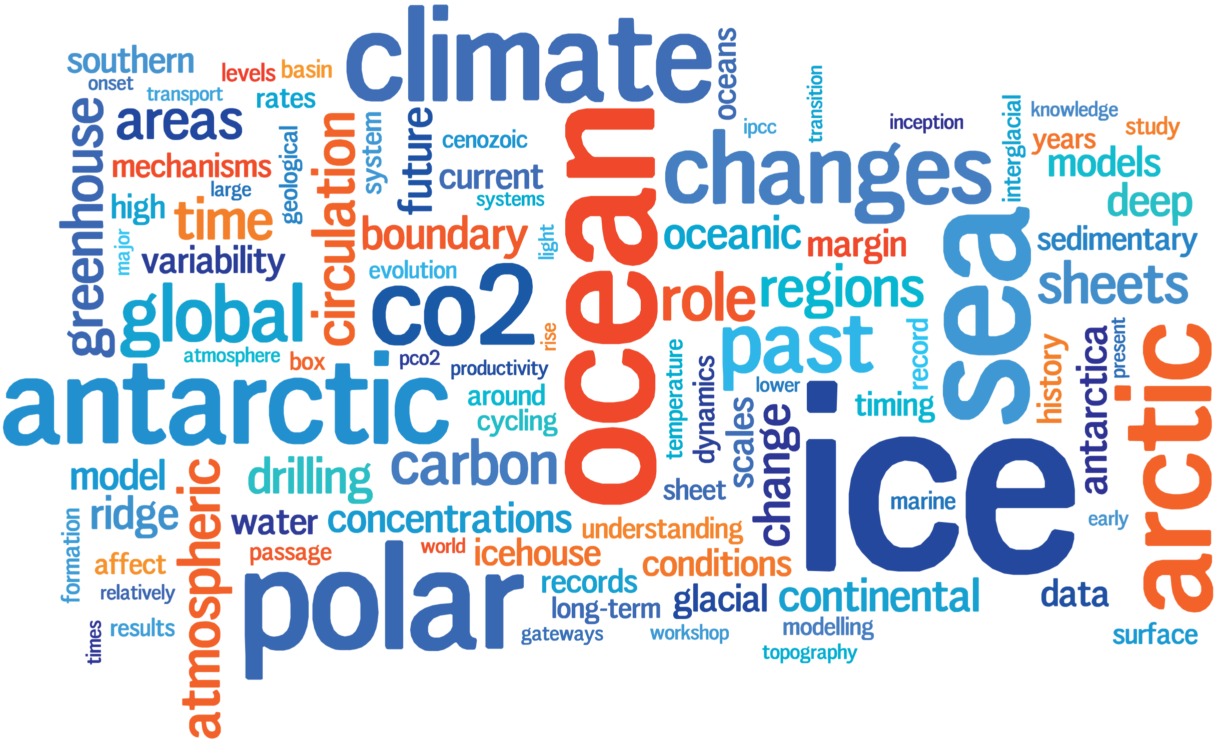
Chapter 4: Polar Palaeoclimate and Marine Palaeo-Environments



Introduction

In geological terms, the present-day ice caps are a relatively young phenomenon. The glaciation of some parts of Antarctica started only about 34 Ma ago, whereas in the Northern Hemisphere permanent continental ice started only about 3 Ma ago. (e.g., Zachos et al., 2008). Polar continental and sea ice are important components of the climate system, affecting such phenomena as planetary albedo, sea level, ocean circulation and heat transport and the evolution of biota. While there is an urgent need for accurate reconstructions of short- and long-term polar ice variability , the climate archives buried below polar sea floors have not really been probed yet. As a consequence, our knowledge of the palaeoceanographic and palaeoclimatic history of the polar oceans is extraordinarily limited in comparison with other regions. The reasons for our lack of knowledge mainly lie in the major technological and logistical problems in reaching the permanently ice-covered regions using conventional research vessels and in retrieving long, undisturbed sediment cores. Palaeoclimatic records thus play a key role in our understanding of the Earth's past and present climate system and in our confidence in predicting future climate changes by placing the short –term instrumental record into a longer term context, as well as permitting models to be tested beyond the limited time for which instrumental records are available.

The Arctic and Antarctic cryospheres may be regarded as two contrasting geo-eco systems.

- The Arctic is a landlocked ocean basin with the world's widest oceanic shelves, characterised by huge freshwater discharge, quasi-permanent sea ice cover and central deep water. The Antarctic is largely a continental setting, characterized by both terrestrial and large marine-based ice sheets, surrounded by deep oceanic basins and narrow, shallow shelves.
- The Arctic and subarctic ice sheets and glaciers are young, dynamic, latitudinally spread and with polythermal (temperate to polar) thermal character. The Antarctic ice sheets are truly polar, much older, and the continental margin is typically shaped (overdeepened) by a longer glacial history than the Arctic continental margins.

Therefore Antarctica is subject to specific processes that do not occur in the Arctic continental margin, and vice versa. However, there are also many analogies between Arctic and past Antarctic glaciations (notably from before the establishment of its polar conditions, during the transition from "Greenhouse to Icehouse Earth").

Table 4.1. Links and interrelationships between the focus areas of Chapter 4 and the other scientific chapters addressed in this Science Perspective**.**

● Forcing ● Response ● Variability

Chapter 1: Sea Ice, Ocean, Atmosphere	Chapter 2: Polar Marine Biosphere	Chapter 3: Geological History	Chapter 4: Polar Palaeoclimate and Marine Palaeo-Environments	Chapter 5: Natural Hazards
Forcing, Response, Variability	Forcing, Variability	Response	Timing and Mechanisms	Forcing, Response
Forcing, Response, Variability	Forcing, Response, Variability	Response	Palaeo-Atmospheric CO_2	Forcing, Response
Response	Forcing, Response	Response	Palaeo-Ecosystems	Response
Forcing, Variability	Forcing	Response	Palaeo-Bathymetry	Forcing, Response

(See Table 1.1. for guidance)

This core theme targets four focus areas, each of which addresses one or more key questions.

Timing and Mechanisms
- *What is the timing of the inception, variability (growth and collapse) of polar ice sheets and sea ice systems and what are the underlying forcing mechanisms?*

Palaeo-Atmospheric CO_2
- *How did varying palaeo-atmospheric CO_2 affect polar regions (on different time scales)?*

Palaeo-Ecosystems
- *What was the role of the polar oceanic ecosystems including the deep biosphere in global carbon cycling, budgets and turnover rates?*

Palaeo-Bathymetry
- *What was the impact of past polar shallow- and deep oceanographic changes for global oceanic circulation?*

Understanding the past evolution of the polar regions is the key to understanding future ecological, oceanographic and atmospheric responses to current and future changes in the cryosphere and consequently is a key component of the various other scientific disciplines.

KEY QUESTION 1

What is the timing of the inception, variability (growth and collapse) of polar ice sheets and sea ice systems and what are the underlying forcing mechanisms?

Can we identify causes and consequences of abrupt past changes in the polar ice sheet dynamics? Do we have enough spatial and temporal information to constrain the causes of regional versus local changes? Are the palaeoclimate and environmental proxies validated?

• Arctic

What was the role of the circum-Arctic smaller-scale ice sheets in relative sea-level, atmosphere-ocean circulation and biological dynamics? When was the onset of perennial sea ice, what were the rates of sea ice change on seasonal to millennial time scales and how did sea ice influence water mass stratification, productivity and other ocean parameters ?

• Antarctic

When was the onset of the major Antarctic ice sheets? How, when, and where, were the oldest nuclei of Antarctic ice formed? What was the variability of the earliest ice? How did the size of the eventual ice sheet and the resulting changes in isostasy and gravity relate to regional sea-level changes around the world?

Arctic Ice Inception

A major limitation in our ability to understand and model global environmental change is a dearth of knowledge about the role the Arctic plays in sustaining the climatic extremes. ODP Legs 151 and 162, as well as previous drilling legs, have revealed that there existed, probably in Greenland, small-scale glaciers and ice sheets which calved into the ocean and delivered ice rafted detritus to the sea floor sediments from melting icebergs, possibly as far back as the late Eocene at ~35 Ma ago (Eldrett et al., 2007), and at the middle/late Miocene boundary, about 12 Ma ago (Fronval and Jansen, 1996).

The sediment cores recovered on the Lomonosov Ridge during the ACEX IODP expedition suggested that sea ice appeared in the Arctic about 46 Ma ago (Stickley et al., 2009) in a two-phase establishment of sea ice with an initial episodic formation in marginal shelf areas 47.5 Ma ago, followed by the onset of seasonally paced sea ice formation in offshore areas of the central Arctic, documenting the transition from a warm, subtropical ice-free environment to one dominated by winter sea ice. The data may suggest that sea ice formed in the Arctic before it did in Antarctica, which would imply that the threshold for sea ice formation was crossed in the Arctic first. However, such a hypothesis contradicts glacial ice models whereby Antarctica is shown to glaciate much earlier (at higher levels of CO_2 than circum-Arctic continents) (DeConto et al., 2007). Currently, debates on the chronology of the ACEX sedimentary sequence (Poirier and Hillaire-Marcel, 2011) prevent unequivocal interpretation about the timing of the onset of the transition to a winter sea ice environment in the Arctic.

There is evidence of perennial and stable Arctic sea ice cover at least for the last 14 Ma (Darby, 2008). Thus its predicted demise in the next 50 years is indeed cause for concern. The initiation of the perennial land ice cover remains unknown, and the interpretation of the ACEX core depends upon the chronology, which was assumed to be marked by a 26 Ma hiatus (Brinkhuis et al., 2006; Moran et al., 2006; Backman, 2008), though this has now been challenged (Poirier and Hillaire-Marcel, 2011). This substantial uncertainty in the timing of the onset of perennial ice in the Arctic underscores the crucial need for the recovery of Cenozoic sedimentary sequences by drilling in the Arctic Ocean.

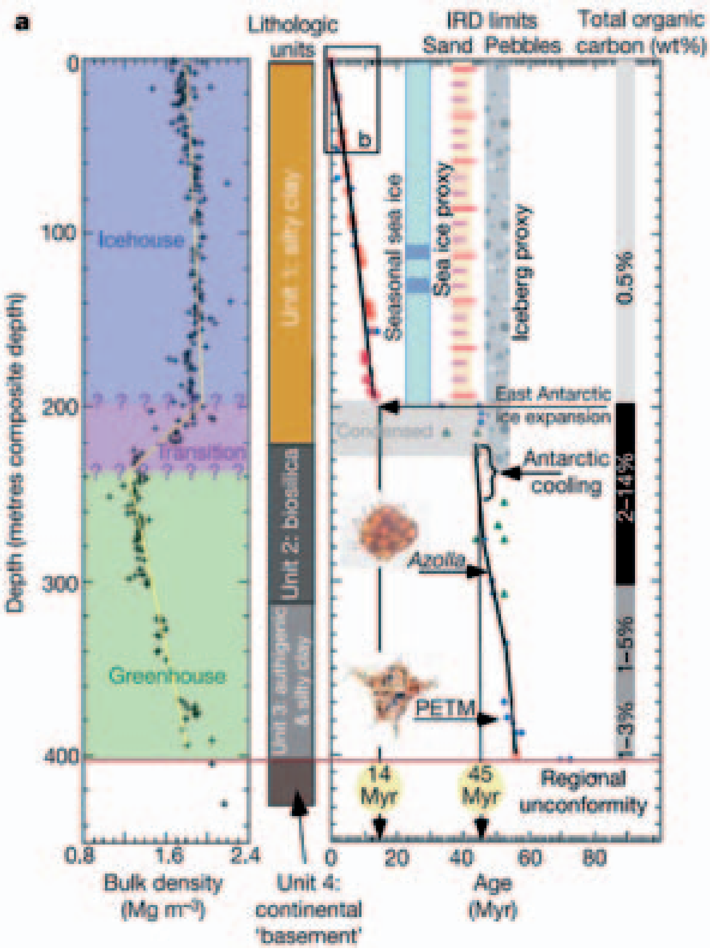
The recovery of key sedimentary sections will not only cast light on the boundary conditions which initiated the Northern Hemisphere glaciation but also on where and when glaciers and ice sheets nucleated around the Arctic, clarifying the possible triggering mechanisms.

Antarctic Ice Inception

Antarctica's relatively sudden glaciation at the Eocene/Oligocene boundary (~34 Ma) (Zachos et al., 2001; Coxall et al., 2005; Zachos et al., 2008) is one of the most important climatic events we know of in the geologic record. Initially it was thought to result from the tectonic opening and deepening of the ocean gateways between Antarctica and Australia (the Tasmanian Passage), and Antarctica and South America (the Drake Passage), leading to the formation of the Antarctic Circumpolar Current (ACC) and the 'thermal isolation' of Antarctica around the time of the Eocene/Oligocene boundary (Kennett, 1977). However, recent reconstructions place the opening of the Tasmanian Passage at 35.5 Ma (Stickley et al., 2004), close to, but still 2 Ma older than, the Eocene/Oligocene boundary. Furthermore, the Drake Passage was probably already open around 45 Ma, but did not deepen until the Miocene (Barker and Burrell, 1977).

The cooling and sudden growth of an Antarctic Ice Sheet is principally evidenced through marine isotope records (Zachos et al., 1996; Lear et al., 2000; Zachos et al., 2001; Coxall et al., 2005), in which the gradual cooling from the presumably ice-free warmth of the Early Tertiary to the cold 'icehouse' of the Late Cenozoic is marked by a sudden >1.0‰ rise in benthic $\delta^{18}O$ values at 34 Ma ago; and from the record of circum-Antarctic ice-rafted debris and fossil Antarctic vegetation from drilling on the East Antarctic margin near the Eocene/Oligocene boundary (Zachos et al., 1996; Escutia et al., 2011).

The combination of numerical climate models (DeConto and Pollard, 2003; Huber et al., 2004; Pollard and DeConto, 2009) and palaeoclimatic proxy data (e.g., Pagani et al., 2005) now suggest that the main triggering mechanism for the inception and development of the polar caps was decreasing levels of CO_2 (and other greenhouse gases) in the atmosphere, while the opening of critical gateways played a secondary role. However, more proxy estimates of Paleogene CO_2 around the Eocene/Oligocene boundary, along with more explicit modelling of changes in ocean circulation using coupled atmospheric–oceanic GCMs, will help to reveal the relative role played by climate forcing factors in Cenozoic Antarctic glaciation. These, in turn, must be tested and cross validated by studies on sedimentary records obtained through ocean drilling.



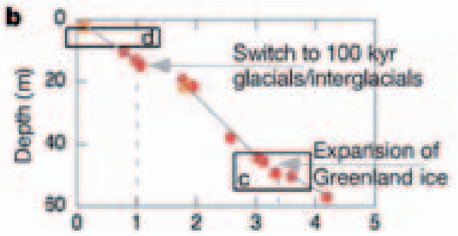


Figure 4.1. a. Synthesis of the ACEX coring results. The Eocene greenhouse world is separated from the Miocene icehouse world by a transition period whose timing is not well constrained and still a subject for debate. Bulk density shows a normal increase in depth during both greenhouse and icehouse times; yellow solid lines are consolidation trends, suggesting uninterrupted sedimentation. Ice-rafted debris (IRD) in the form of pebbles begins in the greenhouse, and IRD (sand) starts at 14 Ma ago (as noted by the black arrow, bottom of right panel, consistent with the timing of the East Antarctic ice expansion). Interpreted seasonal ice occurrences are noted as darker blue bars within lighter blue shading. The arrow pointing to 45 Ma, bottom of right panel, indicates concurrence with the Antarctic cooling time span. The upper box shows the position of panel b. **b.** The age model from 5 to 0 Ma ago, showing changes in sedimentation rates concurrent with global climate events.

KEY QUESTION 2

How did varying palaeo-atmospheric CO_2 affect polar regions (on different time scales)?

How did the polar regions respond during the various past periods of high CO_2, ~ice-free, greenhouse and icehouse worlds? What was their significance in terms of biological productivity, albedo and carbon cycling? What was the magnitude of polar amplification during periods of higher CO_2? Can we identify polar amplification in the past?

• Arctic
What was the role of the hydrological cycle in sea ice formation, water mass stratification and productivity under Greenhouse and Icehouse conditions? What is (and was) the role of the Arctic Basin in the long-term global carbon cycle? How did circulation changes and sea ice dynamics affect marine productivity, carbon cycling and burial?

• Antarctic
How did Southern Ocean circulation changes affect carbon cycling and what are the processes that control the Southern Ocean's role as a carbon sink (i.e., carbon uptake, burial) and source during times of elevated pCO_2 and warmer climates? How did environmental factors (e.g., atmospheric

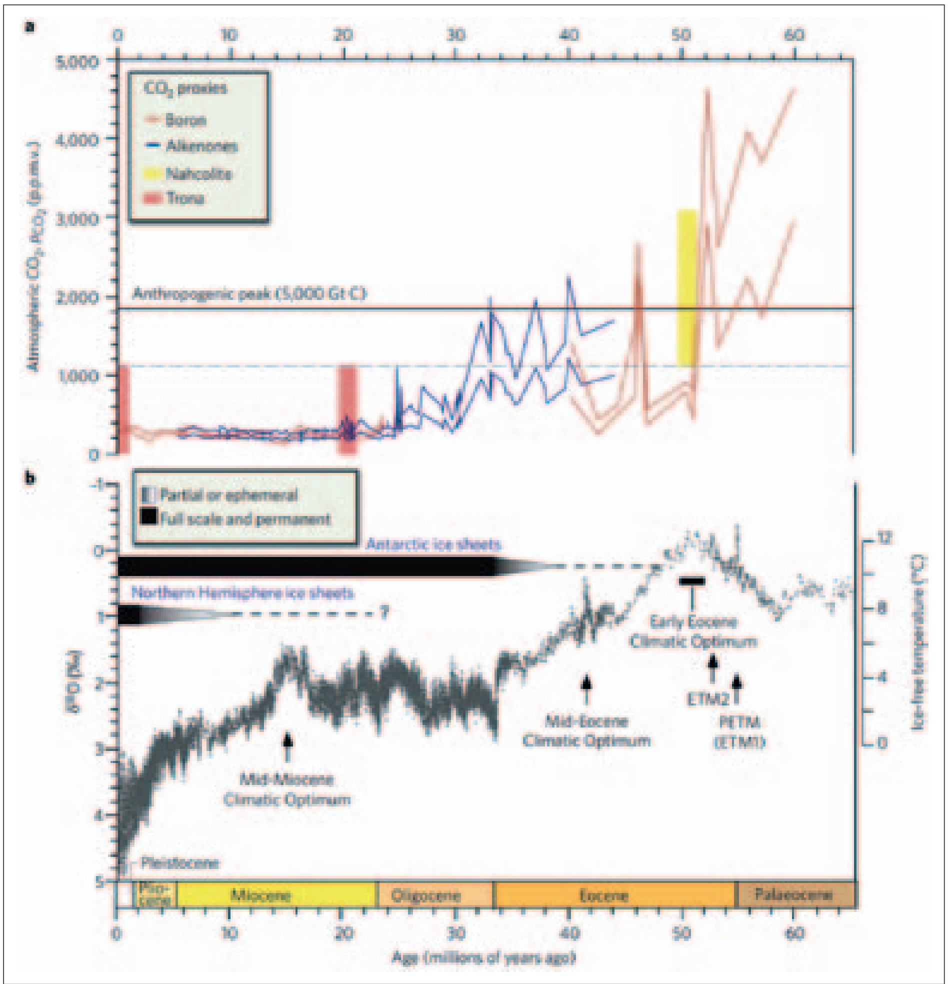


Figure 4.2. Evolution of atmospheric CO_2 levels and global climate over the past 65 Ma and timing of the hyperthermals.

ρCO_2, topography, subglacial thermal regime, melting from warm marine water incursion, orbital cycles, etc.) control changes in the size and ice distribution of the ice sheet on Antarctica and how did they affect the rates of change in ice cover during the various periods of elevated atmospheric ρCO_2? How did these processes affect both marine and terrestrial based ice sheets? What are the linkages and feedback mechanisms between the Antarctic cryosphere, global thermohaline circulation, oceanic gateways, and climate from the Greenhouse (65-34 Ma) to the start of the Icehouse World (34-14 Ma) and in the following glacial and interglacial cycles?

The current rise in anthropogenic CO_2 over the past century is driving a series of chain reactions conducive to an increase in ocean temperatures and ocean acidification. Other periods in the Earth's history, characterised by high CO_2 levels (e.g., much of the early Cenozoic era), much warmer mean global temperature and poles with little or no ice, provide ideal examples for our understanding of the relationships between carbon cycling and climate (Zachos et al., 2008). It is only during the past 34 Ma that CO_2 concentrations have been low, temperatures relatively cool and the poles glaciated. On shorter time scales, atmospheric CO_2 concentration and temperature can change rapidly, as demonstrated by a series of events during the early Cenozoic known as hyperthermals (relatively brief interludes of a few tens of thousands of years of extreme global warmth and massive carbon addition, but with widely differing scales of forcing and response).

Understanding the dynamics and stability of continental ice caps and sea ice is especially relevant given that the IPCC (2007) forecasts that atmospheric CO_2 will double and global temperature rise by 1.8°–4.2°C by the end of this century. The lower values of these estimates have not been experienced on our planet for 10–15 Ma, and the higher estimates have not been experienced since the ice sheets in Antarctica formed.

To evaluate climate theories, particularly with regard to feedbacks and climate sensitivity to p CO_2, it is desirable to study samples obtained when CO_2 concentrations were high. Of special interest would be an evaluation of the role played by physical and biogeochemical feedbacks in amplifying or moderating increases in concentrations of greenhouse gases, as well as investigating the basic sensitivity of climate to extreme changes in concentrations of greenhouse gases (e.g., Zachos et al., 2008).

KEY QUESTION 3

What was the role of the polar oceanic ecosystems, including the deep biosphere, in global carbon cycling, budgets and turnover rates?

Although the geological record shows that atmospheric CO_2 concentrations in the early Cenozoic era were higher than at present, there is still a disagreement regarding the exact CO_2 levels and the mechanisms controlling CO_2 concentrations over geological time scales.

Concentrations of CO_2 in the atmosphere have varied like a seesaw in tandem with glacial and interglacial cycles (Barnola et al., 1987; Petit et al., 1999). During interglacial times, such as the present one, the atmospheric partial pressure of CO_2 (pCO_2) has been typically around 280 parts per million by volume (p.p.m.v.). During peak glacial times, such as the Last Glacial Maximum about 18,000 years ago, atmospheric pCO_2 was roughly 80-100 p.p.m.v. lower. CO_2 is a greenhouse gas, and model calculations suggest that changes in its concentration play a significant role in the energetics of glacial and interglacial climate change (Webb et al., 1997). Even though CO_2 variations over geological time show a consistency in 100-year cycles and in the values of the upper and lower CO_2 limits, the mechanism underlying past CO_2 changes is still unknown. One of the current hypotheses is related to changes in the completeness of nutrient consumption in high-latitude surface waters through its effect on the global efficiency of the biological pump (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984). In the polar regions, the nutrient-rich, CO_2-charged waters of the deep ocean are exposed to the atmosphere, and increased nutrient utilisation in the high latitude surface ocean has been invoked as the cause for the lower atmospheric pCO_2 of glacial times (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Keir, 1988; Broecker and Peng, 1989).

Work is ongoing to understand what limits phytoplankton growth in these high-latitude regions. Both light and trace metals, such as iron, are limited in these regions and together probably represent the dominant controls on polar productivity, with light increasing in importance toward the poles due to the combined effects of low irradiance, sea ice coverage, and deep vertical mixing. The Southern Ocean holds the largest amount of unused surface nutrients, yet the surface chlorophyll suggests that it is perhaps the least productive of the polar oceans (Arrigo et al., 2008); iron and light probably both play a role in explaining this pattern (Martin et al., 1990; Mitchell et al., 1991).

In spite of efforts to explain the natural carbon cycle, the present state of knowledge prevents full understanding of the causes of glacial and interglacial atmospheric CO_2 changes. The discrepancy between observations and model simulations is still unsatisfactory, and a solution to this open question awaits further investigation, notably in polar and subpolar oceans.

KEY QUESTION 4

What was the impact of past polar shallow and deep oceanographic changes for global oceanic circulation?

- **Arctic**

What role did gateway exchanges play in the Arctic Ocean and in the global thermohaline circulation under Greenhouse and Icehouse conditions?

- **Antarctic**

How can sediment budgets and palaeobathymetry reconstructions constrain palaeotopography, which directly affects ice sheet dynamics?

The short history of modern oceanographic observations – less than a century - does not provide a long-enough track record for an evaluation of the past behaviour of ocean circulation. Nor does it provide enough data to assess how changes in the ocean shifted

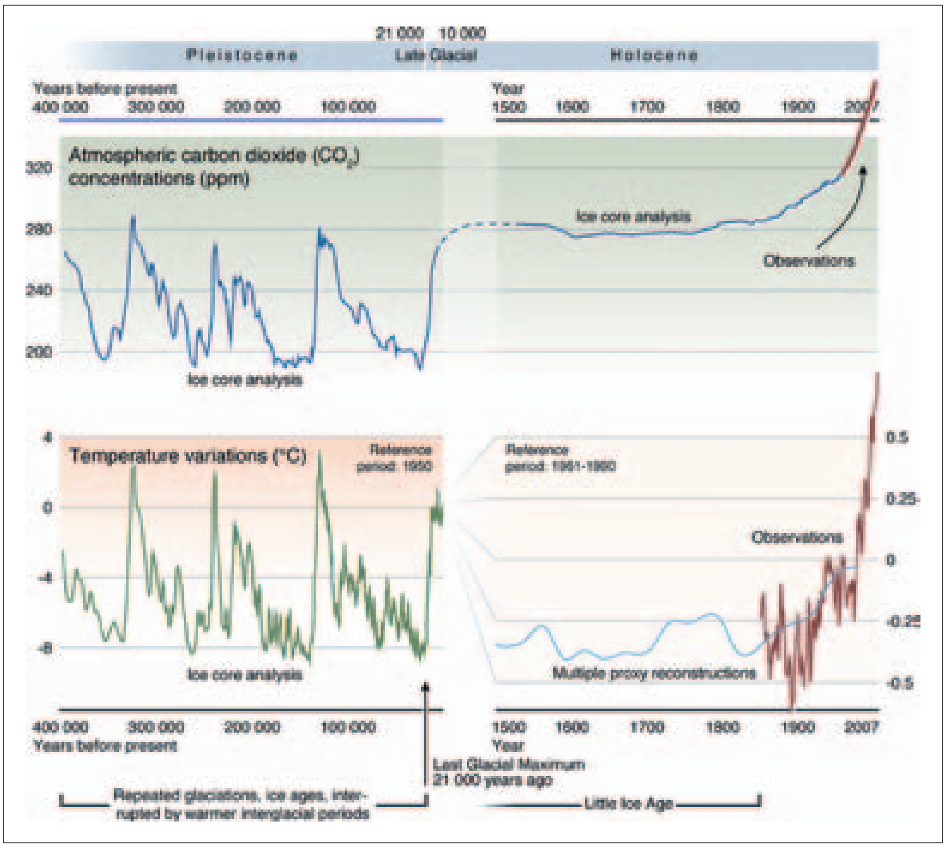


Figure 4.3. Historical trends in carbon dioxide concentrations and temperature, on a geological and recent time scale. Over the past 400,000 years the Earth's climate has been unstable, with very significant temperature changes, going from a warm climate to an ice age as rapidly as over a few thousand years. These rapid changes suggest that climate may be quite sensitive to internal or external climate forcings and feedbacks. The more recent history, from the middle ages and up until now, show increasing temperatures, rising as the world emerged from the Little Ice Age (LIA), around 1850. With the industrial era, human activities have at the same time increased the level of carbon dioxide (CO_2) in the atmosphere, primarily through the burning of fossil fuels.

the Earth's climate in the past, or how they could cause climate changes in the future.

The circulation of the oceans is controlled in part by the configuration of the ocean basins, which includes shelf morphology, sea floor topography, and the configuration of oceanic gateways. Considerable efforts are being made to generate global ocean and atmospheric circulation models which adequately incorporate the role of oceans in the climate system. Our attempts to use these models in the simulation of past climates are hampered by our inability to adequately reconstruct the modelled system's boundary conditions. In the case of the ocean model, most attention has been given to the upper boundary conditions: surface wind stresses and the flux of heat and moisture across the atmosphere–ocean interface, but less attention has been focused on the lower ocean boundary conditions and on the reconstruction of complex ocean basin configurations and seafloor topography.

There is abundant evidence in the marine geological record that the presence or absence of barriers to flow in the ancient oceans (such as oceanic gateways, shallow shelf seas and sea floor features) is likely to have influenced water mass production and global oceanic nutrient and heat transport in ancient ocean circulation patterns (e.g., Kennett, 1977; Pak and Miller, 1992). Current measurements in Drake Passage indicate that the speed of the Antarctic circumpolar current and the mass transport of deep water out of the Weddell Sea are strongly influenced by the topography of local meridional seafloor ridges (Reid and Nowlin Jr, 1971; Carmack and Foster, 1975). Early numerical model experiments suggested that the existence of zones of barrier-free flow at surface, intermediate and deep levels can affect the formation of intermediate and deep water-masses and the meridional transport of heat. The volume of Antarctic Intermediate Water formed in the Southern Ocean is dependent on the depth of Drake Passage (Gill and Bryan, 1971; England, 1992), and varying the shape of the Southern Ocean sea floor in the model results in a change in the volume of transport by the Antarctic Circumpolar Current and the rate of production of Antarctic Bottom Water (Mikolajewicz et al., 1993).

BOX 4.1. Key Areas for Future Arctic Ocean Drilling

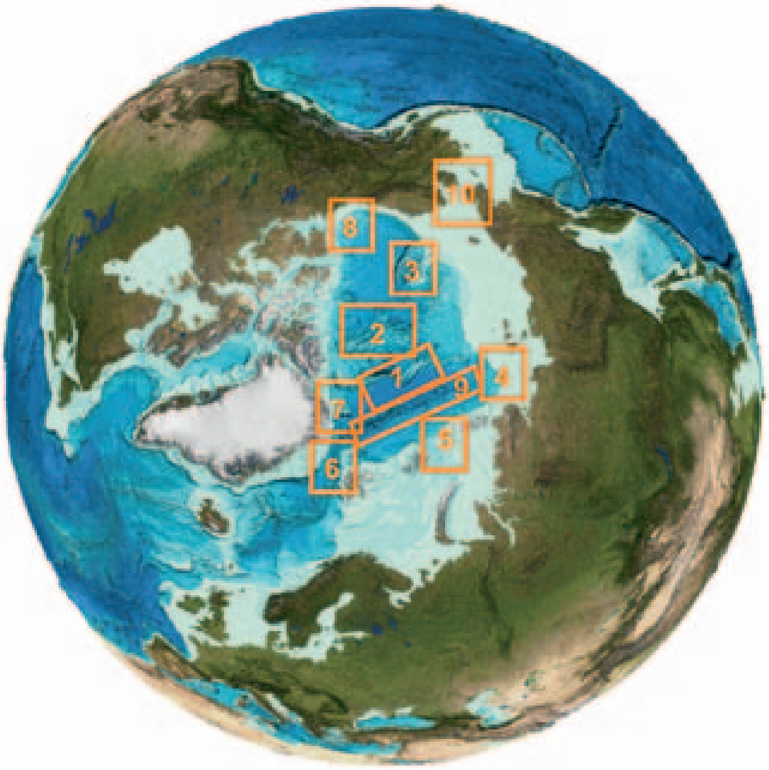


Figure BOX 4.1. Key areas for future drilling in the Arctic Ocean: 1. Lomonosov Ridge; 2. Alpha-Mendeleev Ridge; 3. Chukchi Plateau/Northwind Ridge; 4. Laptev Sea continental margin; 5. Kara Sea continental margin; 6. Fram Strait/Yermak Plateau; 7. Morris Jesup Rise; 8. Mackenzie shelf/slope; 9. Gakkel Ridge; 10. Northern Bering Sea/Bering Strait area.
Modified from Stein (2011).

The modern Arctic Ocean appears to be changing faster than any other region. To understand the potential extent of high-latitude climate change, it is necessary to sample the history stored in the sediments filling the basins and covering the ridges of the Arctic Ocean. These sediments have been imaged with seismic reflection data but, except for the superficial record, which has been piston cored, they have been sampled only on the Lomonosov Ridge in 2004 during the Arctic Coring Expedition (ACEX-IODP Leg 302; (Backman et al., 2006)) and in 1993 in the ice-free waters in the Fram Strait/Yermak Plateau area (ODP Leg 151; (Thiede et al., 1995)).

In November 2008 an international workshop was held at the Alfred Wegener Institute in Bremerhaven, Germany to discuss and plan the future of scientific drilling in the Arctic Ocean. About 95 scientists from Europe, US, Canada, Russia, Japan, and Korea and observers from oil companies participated in the workshop (Stein and Coakley, 2009).

Ten key areas have been identified for Arctic drilling (Stein, 2011):

- To study the long-term Mesozoic-Cenozoic climate evolution, it will be crucial to obtain undisturbed and complete sedimentary sequences drilled on depth transects across the major ocean ridge systems, i.e., the Lomonosov Ridge, the Alpha-Mendeleev Ridge, and the Chukchi Plateau/Northwind Ridge (key areas 1 to 3).
- High-resolution records allowing the study of climatic variability on Milankovich and millennial to sub-millennial time scales can be drilled along the continental margins characterised by high sedimentation rates. Key areas here are the Kara, Laptev and Beaufort seas, due to the large river discharges characterising these bodies of water (key areas 4, 5 and 8).
- Key locations for studying the history of exchange between the Arctic Ocean and the world's oceans are the Fram Strait/Yermak Plateau, Morris Jesup Rise and Chukchi Plateau/Northwind Ridge and Bering Sea areas (key areas 3, 6, 7 and 10).

BOX 4.2. Key Areas for Future Antarctic Ocean Drilling

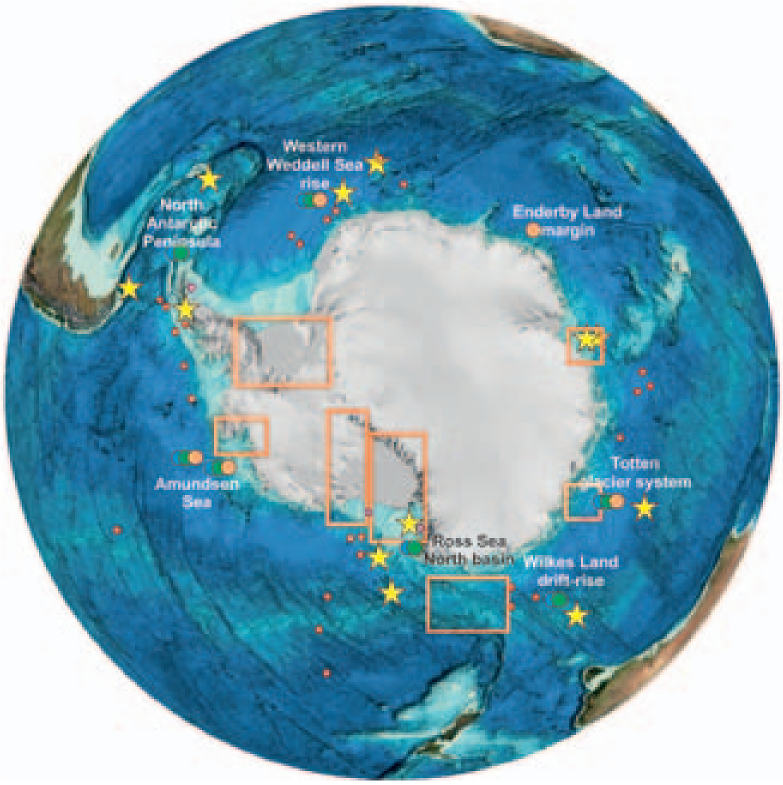


Figure BOX 4.2. Integrated strategy to recover palaeoclimate records from the Antarctic margin and Southern Ocean. Outcomes of the INVEST conference held in Granada on 12-13 September 2009. Modified from De Santis et al. (2009).

With current increases in atmospheric greenhouse gases concentrations resulting in rapidly rising global temperatures (IPCC, 2007), studies of polar climates have become increasingly prominent on the research agenda. Although progress has been made over recent decades in Antarctica and the Southern Ocean by the ODP-IODP, the Cape Roberts and ANDRILL Projects, the short- and long-term palaeoceanographic and palaeoclimatic history still remains poorly understood because only a few sectors of the Antarctic margin have been sampled and the available technology only allows adequate core recovery in a few cases. A Workshop on Developing an Integrated Strategy to Recover Paleoclimate Records from the Antarctic Margin and Southern Ocean was held on 12-13 September 2009 in Granada, Spain (De Santis et al., 2009). The outcome of this workshop was a multinational, multiplatform scientific drilling strategy to recover key physical evidence constraining past and future Antarctic Ice Sheet behaviour, with the aim of solving key knowledge gaps about the role played by Antarctic ice sheets in climate change as identified by the Intergovernmental Panel on Climate Change (IPCC, 2007).

Eight key areas were identified at the workshop as objectives for deep-sea drilling (De Santis et al., 2009):

- High-resolution records allowing the study of climatic variability on Milankovich and millennial to sub-millennial time scales, can be drilled along the continental margins characterised by high sedimentation rates. Key areas here are the North Antarctic Peninsula, Western Weddell Sea, Totten glacier system, Ross Sea north basin and Amundsen Sea;
- To study the long-term Miocene-Pleistocene climate evolution it is crucial to obtain undisturbed and complete sedimentary sequences at the North Antarctic Peninsula, Western Weddell Sea, Totten glacier system, Wilkes Land, Ross Sea North basin and Amundsen Sea;
- Key locations for studying the Greenhouse to Icehouse transition include Western Wedell Sea, Enderby Land margin, Totten glacier system and Amundsen Sea.

BOX 4.3. Understanding Past Polar Variability as a basis for modelling Future Global Changes

In order to evaluate climate variability and change in both polar regions, formal assessments (e.g., IPCC, AMAP, ACIA) are used by policy- and decision-makers to create a science-based consensus which constitutes a fundamental means of communication between science and society.

These assessments are largely based on the results of modelling studies, mostly carried out with sophisticated fully coupled Atmosphere-Ocean General Circulation Models or increasingly by more complex Earth Systems Models that include ice sheet, vegetation and carbon cycle dynamics amongst other components. As each model is exhibiting specific weaknesses or strengths and results usually diverge, these results are then checked and bolstered by both comprehensive inter-comparison projects and ensemble modelling with the aim of increasing their reliability.

The polar regions deserve special attention in modelling studies for three main reasons: firstly, especially in the Northern Hemisphere models predict a systematically larger than global average change in climate, evident in basic parameters like surface sea and air temperature, precipitation and air pressure. This implies polar amplification of future climate change in some of the world's most ecologically vulnerable regions. Secondly, the forecast changes in all models used in past assessment reports (e.g., IPCC, ACIA) are accompanied in polar regions by large inter-model offsets and differences, as well as high scatter of results and low signal-to-noise ratios. Thirdly, the natural variability, in particular of the cryosphere (ice sheets, sea ice, glacier sensitivity), is large on seasonal to interdecadal time scales, but at present not well understood in terms of the physical mechanisms and their parameterization into models. Together, these factors constitute a formidable challenge to the earth system science community and society in general.

The prime request from the modelling community regarding empirical research and data was for morelateral and temporal information from the polar oceans, with dedicated long-term regular sampling, monitoring and measurement programmes in relation to fundamental physical, chemical and biological parameters. Together with re-analysis and remote sensing efforts, these data will provide the baseline for model validation, evaluation and systemic improvement over the coming years.

While land-based data are available from relatively numerous stations, for the Arctic Ocean and the Southern Ocean the gaps in sustained measurements and data collections are especially large. A platform that carries out long-term and systematic expeditions into these ice-infested regions, collects data continuously (including during winter) and acts as a forward deployment base for airborne, ice and sub-sea measurements with advanced technology, would be a major asset.

Research Needs

In order to investigate the past evolution of polar ice sheets there is an urgent need for a polar research-dedicated platform with the drilling capacity to recover key sedimentary sections:

- to cast light on the boundary conditions which initiated both hemispheres' glaciations, clarifying the possible triggering mechanisms.
- to study sediment samples obtained in sedimentary sections deposited when pCO_2 concentrations were high, and to make observations for intervals longer than those of ocean overturning and carbon cycling (i.e., more than 1,000 years), with the aim of evaluating climate theories more thoroughly, particularly with regard to feedbacks and climate sensitivity to pCO_2.
- to increment the seismic and bathymetric coverage, thus allowing the reconstruction of past complex ocean basin configurations and seafloor topography.
- to reconstruct the conditions and dynamics of the current interglacial and last deglaciation in high resolution records.

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Chapter 5: Arctic and Antarctic Sea-Floor Processes and Natural Hazards

Introduction

Periods of exceptional climate change in Earth history are associated with a dynamic response from the geosphere, involving the intensification of certain hazardous geological processes. The geospheric response to hydrological adjustment during times of warming is associated with ice-mass loss, rapid sea-level rise, and greater availability of liquid water, in the form either of ice melt or of increased precipitation levels (Liggins et al., 2010). These environmental transformations in turn drive load-pressure changes and increase in pore-water pressure that, together, produce the adjustment, modulation or triggering of a broad range of surface and crustal phenomena, including volcanic and seismic activity, submarine and subaerial landslides, tsunamis and landslide 'splash' waves, glacial outburst, and rock-dam failure floods, debris flows, and gas-hydrate destabilization (Liggins et al., 2010).

Gas hydrate is a crystalline solid comprising gas molecules, usually methane, each surrounded by a cage of water molecules. Gas hydrates occur in the natural environment, where they are mainly composed of methane and water. Their distribution is controlled by the interrelating factors of temperature, pressure and composition. When these conditions are changed by processes such as increase in bottom water temperatures or fluctuations in sea level, there is a significant risk of an increased flux of methane into the atmosphere. In addition, gas hydrates occurring in the sediments of the world's continental margins and associated with deep permafrost represent the single largest known source of mobile carbon (Kvenvolden, 1993). Our current estimates of gas hydrate storage in the Arctic region are, however, extremely poor, and non-existent for Antarctica.

The shrinking of both the Greenland and Antarctic ice sheets in response to regional warming may also in fact eventually lead to destabilization of gas hydrates. As ice sheets shrink, the weight removed allows the coastal region and adjacent continental slope to rise through isostacy. This removal of hydrostatic pressure could destabilize gas hydrates, leading to massive slope failure, and may increase the risk of tsunamis (Maslin et al., 2010).

When gas hydrates adjust to new pressure-temperature conditions, the gas hydrates' dissociation and dissolution may produce an overpressured layer at the base of the gas hydrate stability zone. Submarine slope failure can follow, giving rise to debris flows, slumps, and slides, accompanied by the release of methane gas into the water column (Masson et al., 2006). Large-scale submarine landslides can generate tsunamis of different intensity (Grilli et al., 2009). Although large-scale submarine landslides are rare, tsunamis of various origins

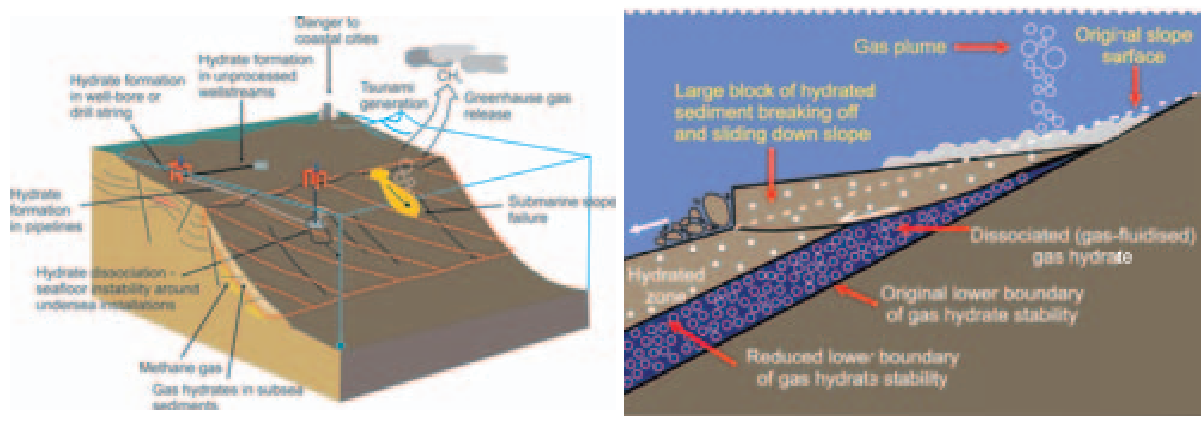

Figure 5.1. A. Major issues of gas hydrates. B. Potential scenario whereby dissociation of gas hydrates may give rise to subsea slope failure and massive methane gas release.

are relatively frequent on a global perspective, and must be considered as geohazards not only locally, but also at a trans-oceanic level.

The investigation of submarine landslides remains an important task for the evaluation of risks in coastal management and offshore industrial activities. Submarine landslides occur as a consequence of pre-conditioning factors, among which are sedimentary processes, diagenesis, geological history of the continental margin, and trigger mechanisms, like earthquakes. Being able to analyse the recurrence rates and potential impact helps understand risks. In the light of a changing globe with warming oceans and rising sea-levels, accompanied by increasing human population along coasts, and enhanced near- and offshore activities in the Arctic region, slope stability issues gain more importance than ever before.

In relation to anthropogenic climate change, modelling studies and projections of current trends point towards increased risk in relation to a spectrum of geological and geomorphological hazards in a warmer world, while observations suggest that the ongoing rise in global average temperatures is already generating a hazardous response from the geosphere (McGuire, 2010). The degree to which comparable responses to projected future climate changes could modify the risk of geological and geomorphological hazards is likely to be dependent in significant measure on the scale and rate of future climate change.

Subsea permafrost degradation is expected to have an impact on the use of the seafloor, as foreseen as a consequence of increased exploitation of natural resources (ACIA, 2004; Arctic Council, 2009). The physical changes in properties of continental shelf marine sediments, the likelihood of shallow water gas emission from the seabed, and gas hydrate dissociation, will affect the design of seafloor structures (platforms foundations, subsea installations, pipelines, cables). This will require dedicated monitoring, and may affect maritime shipping.

This core theme addresses four focus areas, each of which includes one or several key questions, linking with the interdisciplinary scientific chapters.

Permafrost

- *What is the real extent of subsea permafrost on Arctic continental shelves?*

Gas Hydrates

- *How to quantify the role of gas hydrate systems in marine Arctic sediments?*

Sedimentary Processes

- *Which is the glacial sedimentary model that describes the polar depositional environments, the sedimentary processes involved, and the recurring pattern of sedimentation?*
- *Which are the sedimentary systems, within glacial depositional systems, that favour the accretion of unstable continental slopes?*

Understanding the polar sedimentary processes and natural hazards requires an integrated approach including a hierarchy of observations, laboratory and field studies, sample recovery, and modelling. The results of this field of research are key components for the rest of the core themes, since it provides the basis for interpretation of sedimentary sequences, gas release to the atmosphere, and its interactions with the environment and surrounding organisms.

Table 5.1. Links and interrelationships between the focus areas of Chapter 5 and the other scientific chapters addressed in this Science Perspective.

● Forcing ● Response ● Variability

Chapter 1: Sea Ice, Ocean, Atmosphere	Chapter 2: Polar Marine Biosphere	Chapter 3: Polar Palaeoclimate and Marine Palaeo-Environments	Chapter 4: Geological History	Chapter 5: Natural Hazards
Forcing, Response, Variability	Response, Variability	Forcing, Response, Variability	Response	Permafrost
Forcing, Response, Variability	Forcing, Variability	Forcing, Response, Variability	Response	Gas Hydrates
Response	Forcing, Response	Forcing, Response, Variability	Response	Sedimentary Processes

(See Table 1.1. for guidance)

KEY QUESTION 1

What is the real extent of subsea permafrost on Arctic continental shelves?

What is the dynamics of subsea permafrost in response to environmental changes?

What is the shallow methane gas reservoir associated with subsea permafrost?

Subsea permafrost (ice-bearing sediments) forms in the polar oceans' continental shelves as a response to negative sea bottom temperatures, or during periods of low sea level. Later periods of higher sea level, i.e, interglacials, cause the inundation of terrestrial permafrost and its slow thawing from the top to the bottom. Thawing of the subsea permafrost occurs even at negative temperatures because of the infiltration of seawater salts into the sediments. Subsequently, the subsea permafrost is composed of an upper thawed layer or *talik* (still considered permafrost because the sediment temperature is below zero, but the pore water is not frozen due to pressure and salinity effects on the phase boundaries) and of the relict ice-bearing (frozen) marine sediments. The boundary between the upper unfrozen and lower frozen sediments progressively deepens away from the coast. In addition, in near shore areas there is a thin active layer where subsea permafrost forms and thaws seasonally, in places where sea ice formation reaches the seabed (Osterkamp, 2002).

For subsea permafrost to form, polar continental shelves must meet the following conditions during glacial periods: 1) They must include extensive areas that are shallower than about 120 m in order to remain above sea level for substantial times during the glacial periods; 2) They must not be occupied by grounded continental ice (ice sheet, ice streams) during glaciations. In polar regions such conditions are met only by the extensive shallow Arctic continental shelves that were not covered by the Fennoscandian and Laurentide ice sheets (offshore East Siberia, Alaska and western Canada). Conversely, Antarctic continental shelves were covered by grounded ice sheets during glacial periods, and as a result of combined subsidence and glacial erosion they are generally much deeper than the glacial sea-level fall. Consequently, subsea permafrost on Antarctic continental shelves has not been documented so far.

The frozen nature of subsea permafrost makes it an effective barrier to the upwards migration of pore fluids, including natural gases (Romanovskii and Hubberten, 2001). Large volumes of methane in gas-hydrate form can be stored within or below the subsea permafrost, and the stability of this gas-hydrate zone is sustained by the existence of permafrost (Collett et al., 2011). The stability of permafrost and associated gas hydrates depends on pressure, temperature, gas concentration in the surrounding pore water, and the activity of water (Sloan and Koh, 2007). Degradation of subsea permafrost and the consequent destabilization of gas hydrates could significantly increase the flux of methane to the atmosphere(Kvenvolden, 1988).

Most of the present day knowledge on subsea permafrost is the result of physical and chemical modelling. Therefore, there is an extreme need for extensive geophysical surveys and observational data in boreholes, hampered until now by severe climate conditions and high operational costs. Only a very limited number of case studies with field data acquisition exist, all located in very shallow waters close to shore (< 10 m), where the subsea permafrost table has a very irregular and

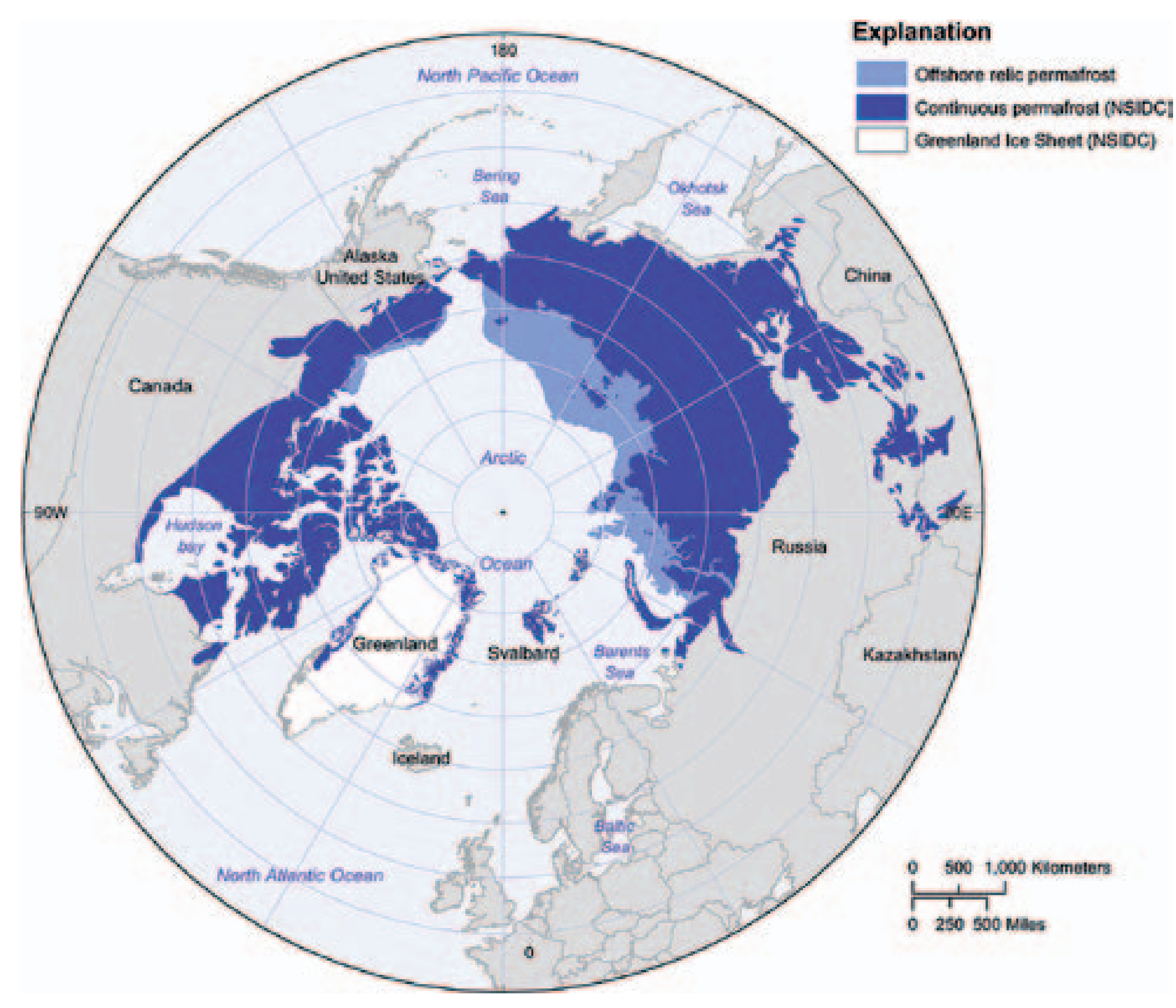

Figure 5.2. Distribution of permafrost in the Northern Hemisphere (source of permafrost data: http://nsidc.org/data/ggd318.html). Onshore continuous permafrost areas are shown in dark blue, while areas under which conditions may be favourable for the accumulation of gas hydrate (possible offshore relic permafrost) are shown in light blue.
From Collet et al. (2011).

dissected upper surface (Rekant et al., 2005). There is almost no information available about upper and lower limits of submarine permafrost on the outer continental shelves. Given the frozen nature of subsea permafrost and its large thickness (the bottom of the ice bearing sediments is possibly located between 300 and 700 m below the seabed in the Laptev Sea (Hinz et al., 1998), sampling cannot be performed with traditional marine sediment sampling tools such as gravity and piston corers. Rotary drilling from a stable anchored or dynamic positioned platform is required for subsea permafrost studies.

Large-scale multi-disciplinary geocryological investigations on the Arctic continental shelves are required for the full understanding of the distribution and dynamics of subsea permafrost and associated gas hydrates reservoirs. The results of this new field of observation will be fundamental for constraining and validating numerical models.

KEY QUESTION 2

How to quantify the role of gas hydrate systems in marine Arctic sediments?

Which is their role in the climate change, global carbon cycle, and in sedimentary processes including sediment mass movement and methane release?

Gas hydrates are crystalline substances composed of gas and water molecules, that are stable at high pressure, low temperature, and high gas concentration. Gas hydrates in the Arctic may be confined (1) to relict permafrost occurrences (cryogenic gas hydrates), (2) to methane seepage sites (shallow-seated gas hydrates), or (3) to dissipated hydrocarbon infiltration (deep-seated gas hydrates). Thermal conditions favourable to the formation of gas hydrates within permafrost have existed since the end of Pliocene (about 1.88 Ma) (Collett and Dallimore, 2000). Geological studies and thermal modelling (Romanovskii and Hubberten, 2001; Romanovskii et al., 2005) indicate that gas hydrate may exist within the continental shelf of the Arctic Ocean and, in particular, within and under sub-sea relic permafrost. Available estimations suggest that submarine sediments occurring within the permafrost zone fulfil the required pressure-temperature conditions for gas hydrates stability from depths shallower than 260 m (independently from water depth) (Soloviev et al., 1987). If the temperature of the permafrost or water at the seafloor rises a few degrees, it could initiate gas hydrate dissociation and, therefore, induce catastrophic methane emission to the water column, and eventually into the atmosphere.

Extensive natural gas hydrate has been found in two regions: on land and shallow seas in Arctic permafrost areas, and beneath some continental slopes at all latitudes. Besides, indirect indication of gas hydrate presence such as Bottom Simulating Reflector (BSR) has been found at the South Shetland Margin (Antarctic Peninsula) (Tinivella and Accaino, 2000). Marine gas hydrates are known to cause problems during drilling and production of conventional hydrocarbons, for example through gas releases, blowouts, casing collapse, and well-site subsidence.

Difficulty in carrying out seismic, bathymetric, and geological surveys has yielded little data for the ice-covered Arctic basin in general and for gas hydrates in particular. Field data are sparse, and investigations are still producing surprising results indicating that our understanding of gas hydrate formation and distribution within sub-sea permafrost and outside is incomplete. Estimations of the amount of methane trapped in Arctic hydrates are based mainly on assumptions of constant distribution of hydrates within sediments across significant areas in a large interval of depths using regional hydrate content percentage. Although the real amount is still uncertain, the most recent review cites figures in the order of 3×10^{12} m^3; 1.5 GtC (Boswell and Collett, 2011). Lack of information on sub-sea permafrost conditions and processes over the long time scales required for permafrost to aggrade and degrade, and inadequacies in the theoretical models, make it difficult to formulate reliable predictions regarding gas hydrate distribution and decomposition within sub-sea permafrost.

Gas hydrates are important because of: 1) their potential as a source of fuel; 2) their impact upon global climate, and 3) their impact upon seafloor stability and continental margin geological processes. Considering the estimate of hydrate reservoir in permafrost (400,000 Tg; MacDonald, 1990), a disturbance of the hydrate reservoirs may have a significant influence on climate. In each case, it is essential to estimate the quantities of gas hydrates present in marine sediments and to understand the processes leading to gas hydrate accumulation and decomposition. Since natural gas hydrates are a vast potential source of unconventional gas, though not yet commercially, and a possible factor in geohazards, it is necessary to attract considerable attention to the submarine gas hydrate research in the Arctic shelf (within submarine permafrost) and deep-water areas.

Estimates of the current and future release of methane from gas hydrates and the evaluation of the hydrates as a potential energy source requires knowledge, not only on the recent geological history of polar regions, but also on the current spatial distribution of the hydrate. Research should draw on better integration of observations (in situ and remote sensing), and state-of-the-art models, including more accurate representation of gas hydrate sensitivity to permafrost dynamics, with the aim of improving the quantitative predictions of the feedback of Arctic hydrate pools to the geohazards. Interdisciplinary and comprehensive field studies focused on achievement of specific targets, as well as development and use of new equipment and methods, are required.

KEY QUESTION 3

Which is the glacial sedimentary model that describes the polar depositional environments, the sedimentary processes involved, and the recurring pattern of sedimentation?

The dynamics of the glaciers and ice sheets exerts a major influence on the sedimentary processes, rates, and patterns on the polar continental margins. Major changes in the glacial, climatic and oceanic parameters through time, from full glacial to interglacial conditions, have led to the deposition of a wide variety of sedimentary facies (Dowdeswell et al., 2002).

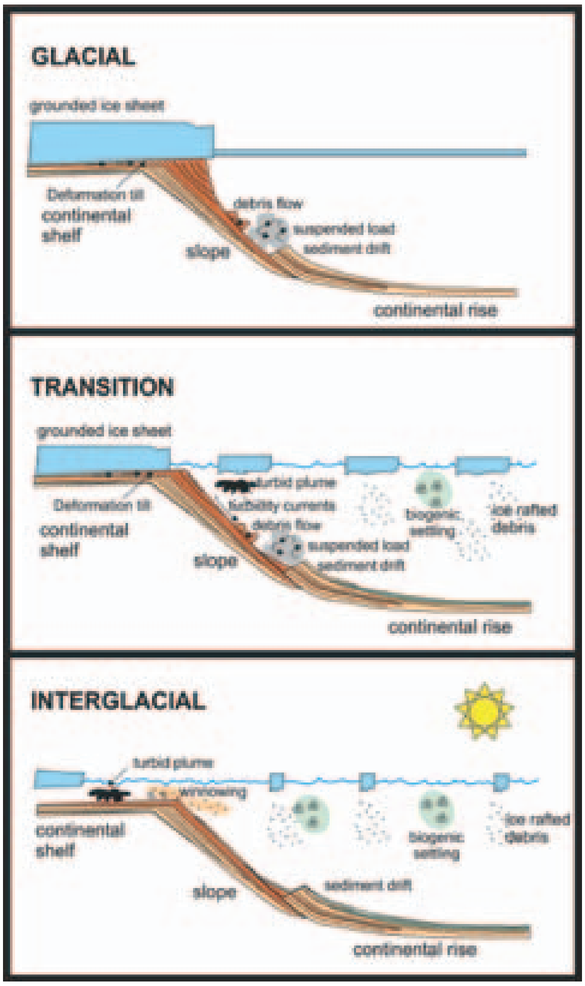

Figure 5.3. Polar sedimentary processes and controlling factors. Modified from Lucchi et al. (2002) and Laberg (unpublished).

Under full glacial conditions, the glacier influence is strongest, and this is reflected in the glacial and glaciomarine facies deposited at these times. But even during interglacials, both the margins and associated deep ocean basins retain a glaciomarine overprint derived from far-travelling icebergs and bottom currents (van Weering et al., 2008).

The sedimentary processes and sedimentary evolution of polar continental margins are hence different from low latitude ones. Nevertheless, the current sedimentary models are based on the knowledge derived from the more accessible low latitude margins like, for example, the turbidite model established in the last 60 years with the contribution of the oil industry. A specific and comprehensive glacial sedimentary model is still missing (Armitage et al., 2010).

Sub-glacial facies are common on polar continental shelves, where the ice sheets may reach the shelf break during glacials. The shelf sediments are generally constituted by rather discontinuous lenses of structureless and homogeneous diamictite overcompacted by the load of the ice (Anderson, 1999). However, expanded glaciomarine deposits may have developed locally within overdeepened basins during the Holocene, or during previous sub-glacial "lake" stages, when the ice was not grounded at the bottom of the basins (Rebesco et al., 1998). Large differences in basal conditions within the ice sheet are reflected by areas of fast flowing ice (ice streams), separated by areas where the ice is moving very slowly. The ice streams, which drain huge basins within the parent ice sheet, transport a large amount of unsorted glacigenic debris at the base of the ice and deliver it to the shelf break. On the continental slope, prominent prograding fans are made up of stacked glacigenic debris flows mobilizing the sediments delivered to the shelf break. The trough-mouth fans, which are fans at the mouth of ice stream troughs or channels, tend to be steeper than alluvial fans, and do not display the same degree of downslope sorting (Laberg and Vorren, 1996). The downslope movement of the sediment can be triggered by high sedimentation rate, earthquakes, oversteepening, and excess of pore-pressure. Large-scale mass failures, turbidity currents, and gas-escape structures, may rework debris in continental slope settings. The main erosional features on the polar continental slope are gully systems (on upper slope) and channels on the fans (at the base of the slope). The presence of major erosive canyons on polar margins is unusual (Ó Cofaigh et al., 2006). Although most of the fans consist of glacigenic debris flows, considerable areas of trough-mouth fans include sedimentation of suspension deposits, associated with extensive turbid subglacial meltwater plume release from warm-based ice sheets, especially during deglaciations (Taylor et al., 2002).

The need to define the glacial sedimentary model, and the understanding of the polar sedimentary processes in general, are essential for most of the other scientific chapters. Paleoclimatic reconstructions using sedimentary samples require information of the sedimentary processes involved in the deposition, essential for defining paleoenvironmental conditions.

The poor comprehension of the glacial sedimentary model is related to the difficult accessibility to polar continental margins. Indirect (satellite) information has proven to be insufficient for careful mapping of the seafloor beneath the ice. In addition, some sedimentary processes (e.g., offshore sediment delivery by cascading of dense water masses) develop essentially during the winter season, when the area is inaccessible to most research vessels. The understanding of the sedimentary processes taking place nowadays may help to understand the accumulation of the geologic record, and vice-versa.

KEY QUESTION 4

Which are the sedimentary systems, within glacial depositional systems, that favour the accretion of unstable continental slopes?

What is the recurrence of submarine landslides on polar continental margins? Glacial-cycle scale, or faster? With the predicted rates of warming, can the anthropogenic environmental change determine conditions of increased instability of polar continental margins? Can the mechanics of sediment mass transport in the polar oceans determine a tsunamigenic potential of submarine landslides? How sensitive are Arctic continental margins to changes in stress induced by the increased use of the seafloor?

Submarine landslides, and sediment-mass wasting phenomena in general, occur on continental slopes of passive and active continental margins worldwide, as well as on the flanks of volcanic islands and in fjords (Masson et al., 2006; Owen et al., 2007; Lee, 2009). However, it is on polar continental margins where some of the largest recent (late Pleistocene) submarine landslides have occurred, like the Storegga slide, on the mid Norwegian margin (Bryn et al., 2005), or the Hinlopen/Yermak slide on the northern Svalbard margin (Winkelmann et al., 2006).

Submarine landslides are recognized as geohazards for the threat they produce to seafloor structures (rigs, pipelines, cables), for the potential to generate tsunamis, and for their impact on the marine natural environment (e.g., Morgan et al., 2009). In addition, the decrease of lithostatic stress, induced by the instantaneous removal of sediment overburden during the emplacement of a submarine landslide, may trigger the release of gas stored in shallow over-pressured sediments.

Although the state-of-the-art investigation is still far from understanding completely the mechanisms that determine the failure of submarine slopes, there is common agreement on the fact the submarine slope instability depends upon a delicate equilibrium between several pre-conditioning factors (many related to sedimentary processes), determining the decrease of the strength of the sediments and the increase of the stress acting on the sediments. Such factors vary through time and are strictly dependent on the local geological evolution (Locat and Lee, 2002; Lee, 2009). The trigger of a landslide on a weakened slope can be an instantaneous event, like an earthquake, the dissociation or dissolution of gas hydrates, or an increase in pore water pressure (Sultan et al., 2004).

On polar continental margins, and especially on glacial trough-mouth fans, pre-conditioning factors that favour continental slope instability have been identified in the alternation, at the glacial cycle scale, of glacially derived debris flow deposits, and deposition of deglacial or interglacial sediments such as fine grained contourites, biogenic oozes, plumites (Dimakis et al., 2000; Elverhøi et al., 2002; Solheim et al., 2005; Lucchi et al., 2012). The extremely rapid accumulation of glacial debris flow deposits during short-lived periods of glacial maxima is thought to determine a decrease in the effective stress in the underlying water-rich but low-permeability deglacial or interglacial sediments. Locally, gas charging along fluid migration paths can also contribute to strength reduction (Berndt et al., 2005).

In the Arctic continental margins, the enormous extension of the Russian continental shelves, and the clustering of older sea ice towards the North American margin, makes overall knowledge of Arctic continental slope very. Until now, models for understanding continental slope instability on glacial margins have been developed mainly on highly accessible sub-polar margins (e.g., Barents Sea, Norwegian Sea, East Greenland, Labrador margin).

On the Antarctic margin, accessibility to continental slopes and fjords is often limited. Logistics and ice conditions have produced a clustering of available data (seismic, coring, and rarely drilling) only on the Pacific Margin of the Antarctic Peninsula, Ross Sea, Wilkes Land, Prydz Bay, and Weddell Sea. However, with the exception of regional seismic coverage (O'Brien et al., 2006), the structure of the majority of the continental slopes is virtually unknown. For similar reasons, only a limited number of Antarctic fjords, especially those of the Antarctic Peninsula, have been accessed by research vessels.

The risk associated with submarine mass wasting phenomena depends on the magnitude and recurrence of the hazard, and the vulnerability of the surrounding environment. The foreseen growing exploitation of natural resources and coastal population in the Arctic Ocean (ACIA, 2004; AMAP, 2007; Arctic Council, 2009), with the consequent increased use of the seafloor, indicate that it will become more vulnerable. This vulnerability is not associated just with the economics of offshore man-made structures and installations, but can also affect the population of coastal areas. In a relatively small, enclosed oceanic basin (much like the Mediterranean Sea), tsunami waves generated by submarine landslides, as well as earthquakes, would quickly impact coastal areas with little warning time, possibly affecting the coasts of the entire rim of the ocean. Moreover, there is no tsunami warning system in the Arctic Ocean.

Facing increased vulnerability, the challenge is to produce hazard assessment that takes into account the evidence from the present and past, rates of observable changes, and models to predict future scenarios. A deep knowledge of the sub-seafloor condition of Arctic continental slopes must take into account not only natural processes, but also anthropogenic activity, like force anchors from ships or floating platforms, rock-filling for pipeline supports, temperature change around oil and gas wells in the offshore field development area, underground blowout, reservoir depletion, and subsidence, including induced seismicity.

BOX 5.1. The Impact of Arctic Methane Seepage on the Global Climate

One of the most significant contributors to climate change in the Arctic is the global warming induced by methane emission to the atmosphere. Pockmarks, seeps, mud volcanoes, and other features associated with the methane fluxes from the seabed, have been widely reported, particularly during the last three decades. Furthermore, processes associated with seabed fluid flow have been shown to affect benthic ecology, and to supply methane to the hydrosphere and the atmosphere (Judd, 2003). Recent investigations confirmed that improved estimation of the role of gas seeps and related gas hydrate formation processes is necessary for the understanding of global methane balance, and the geological risks associated with gas and global climate changes (Judd et al., 2002; Westbrook et al., 2009; Shakhova et al., 2010).

According to current views, massive releases of oceanic methane may have played an important role in past climate change, leading to questions about the role of oceanic methane in future climate change (Valentine et al., 2001). This will trigger changes in ecosystems that will be largest in the permafrost areas because of the extreme sensitivity of the natural systems in these regions. The stability of the ecosystems in the permafrost regions relies in turn on the stability of ice that is possibly endangered by the climate change.

Warming of Arctic Ocean water masses, as presently observed and predicted for the future by models, (Archer et al., 2008; Shakhova et al., 2010) may eventually cause degradation of subsea permafrost, consequently introducing in the Arctic marine hydrosphere significant quantities of methane (Zimov et al., 2006; Shakhova et al., 2009) contributing to the greenhouse gas composition.

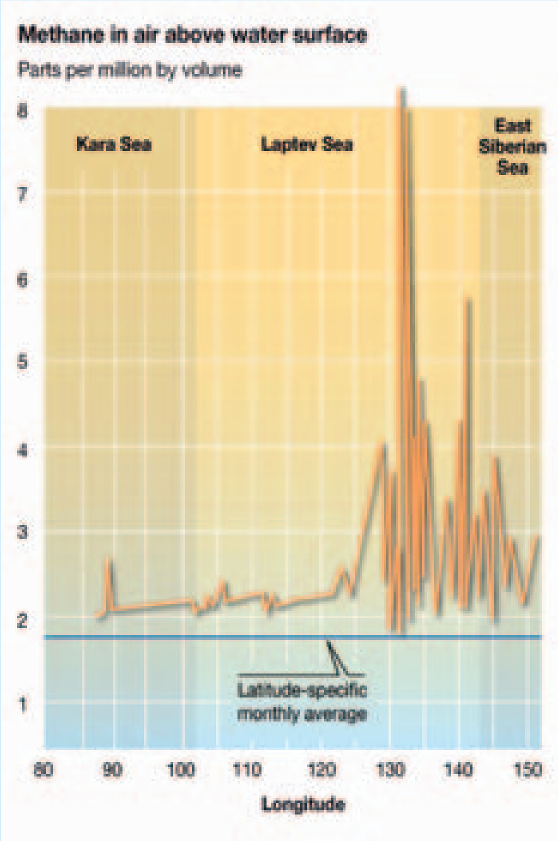

Figure BOX 5.1. Mixing ratio of methane in the air above the water surface measured along a ship's route in September 2005. The dotted line shows the latitude-specific monthly average of 1.85 ppm by volume established for the Barrow, Alaska, USA, monitoring station at 71 ° 19' N, 156 ° 35' W (http://www. cmdl.noaa.gov/ccgg/insitu.html); this is the normal level of methane in the atmosphere at this latitude.
Riccardo Pravettoni, UNEP/GRID-Arendal) http://www.grida.no/graphicslib/detail/methane-in-air-above-water-surface_74eb.

BOX 5.2: Extending the global Climate Observing System Into Polar Oceans

The need for sustained and integrated observing systems, especially in the polar regions, has been recognized for well over a century. The polar oceans require coordinated and synchronized observations to provide information on characteristics, changes, and the distinctive nature of phenomena, in space and time. Automated approaches, combined with remote measuring and communication systems such as sub-surface floats, moorings, gliders, and autonomous underwater vehicles, automated devices deployed on other autonomous platforms, and advanced underwater acoustic communication systems, have the potential now to collect hitherto missing in situ data. However, there is a lack for available platforms devoted to deployment, collection, supervision and maintainence of such instrumentation, as well as ground truthing of remote sensing techniques all year round. As a consequence, the current data coverage is extremely poor in polar areas.

A polar dedicated platform such as AURORA would be able to provide all scientific disciplines with the polar marine extension of ocean (e.g., ARGO) and atmosphere (e.g., GAW; GCOS) observing systems, as well as provide the data needed for global climate models.

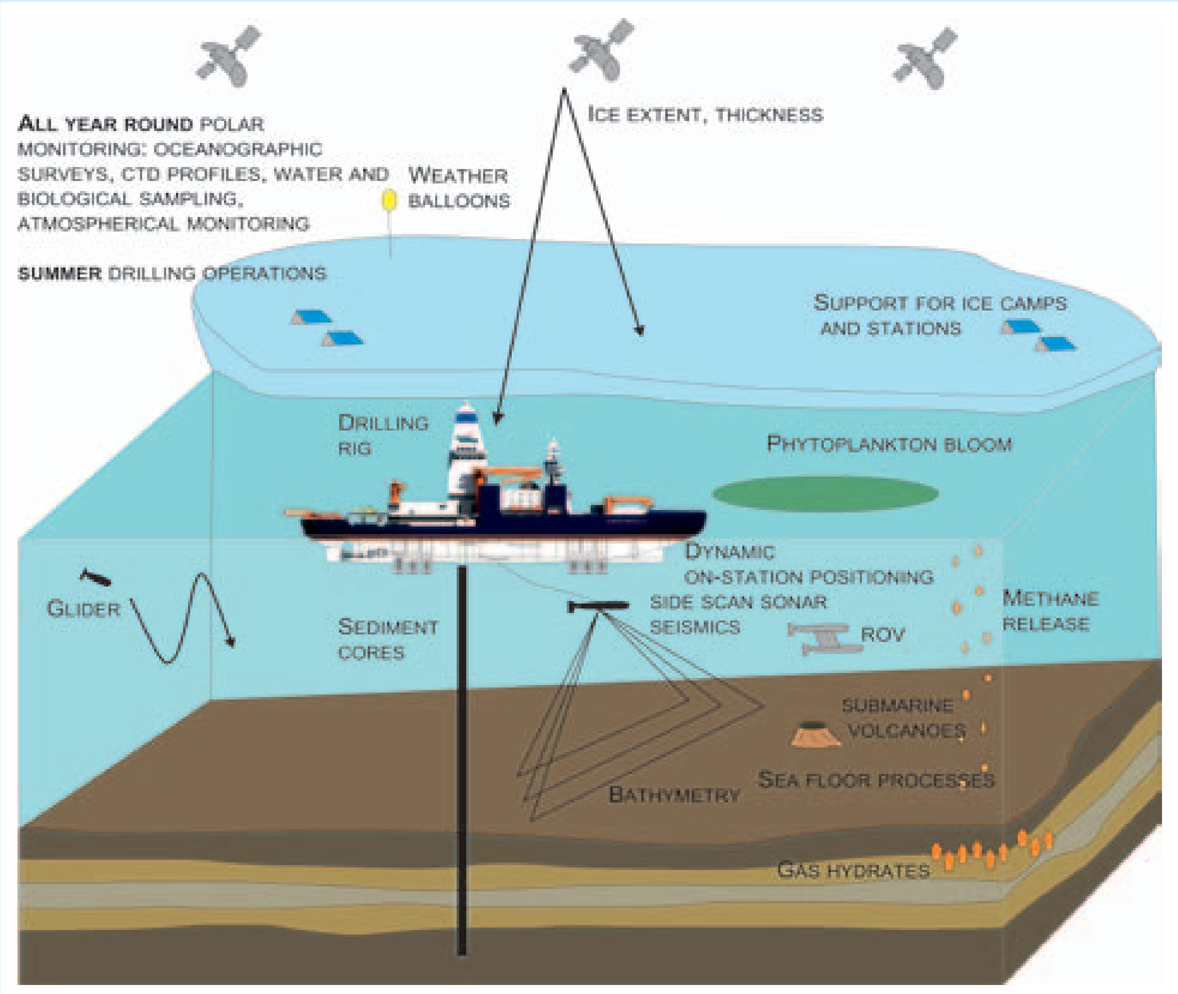

Figure BOX 5.2. Schematic figure of the stack of observations from satellites to seabed that would be necessary to study the present state and future fate of the polar regions.

Research Needs

Focused research in polar areas is advocated to: (i) better understand the mechanisms by which contemporary climate change may drive geohazards and (ii) provide a more robust appreciation of potential impacts for society and infrastructure. (iii) model increasing vulnerability, risk quantification, and predict future scenarios.

Typical surveying of continental slope areas for stability analysis and identification of gas hydrate and free gas purposes consists of:

- High resolution bathymetric, echo-sounding side scan sonar (by means also of a ROV and/or AUV under the sea ice).
- Multichannel seismic surveys including sub-bottom acoustic profiling.
- Detailed sound velocity analysis, Amplitude Versus Offset (AVO) analyses for pore pressure estimation, pre-stack depth migration.
- Drilling with continuous coring. Drilling should be planned in transects located on high resolution seismic site surveys with three dimensional information.
- Down-hole logging and borehole monitoring (sonic, electrical) including temperature probe (for heat flow determination and in situ conditions) and pore pressure.
- Onboard freeze lab facilities for treatment of ice-bearing samples.
- In situ cone penetrometer tests (CPTU) for geomechanical properties of soils (sediments) and pore pressure.
- Multibeam mapping.
- Sedimentary traps for investigation of modern sedimentation processes.

The selection of key study areas should include areas where the slope has failed recently. Monitoring should focus on areas of proto-failure (creep, incipient failure).

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AURORA SLIM. © AKER ARCTIC.

Chapter 6: Scientific-Technical Mission Requirements for an International Research Icebreaker

Introduction

The scientific challenges outlined in this Science Perspective call for the provision of a specialized platform to carry out polar marine research on dedicated expeditions. The science community needs a highly capable research vessel for the ice-covered oceans of the central Arctic Ocean and the polar Southern Ocean close to Antarctica. Such an icebreaker is currently not available for research.

From a technical viewpoint, polar research has become more multi- and interdisciplinary over recent years, and is increasingly dealing with more process-oriented synoptic studies over longer time periods and with greater spatial coverage. This development is likely to continue into the future and will require more sophisticated technical sensors, equipment and instruments used to carry out research, exerting in turn more complex technology demands on the vessel design.

Assessment Method

The ERICON project and its predecessor activities have extensively dealt with the technological requirements for the design of an advanced icebreaker platform (WR, 2006; Thiede and Egerton, 2004; Lembke-Jene et al. 2011; Niini et al., in prep). Technology and science mission requirements have been formulated through dedicated processes involving the science community and relevant experts for roughly the past ten years, and have evolved naturally over this timeframe. They have been used to develop technical design variants and specifications for an International Research Icebreaker (see references above).

From these existing documents, recent community input through workshops and meetings, and the requirements formulated through the scientific key questions in this new ERICON-AURORA BOREALIS Science Perspective, we outline in this chapter some principal Scientific-Technical Mission Requirements for a future International Research Icebreaker. Examples for engineering solutions and technical implementation of these requirements in a proprietary vessel design are or will be available separately (Lembke-Jene et al., 2011 and Niini et al., in prep). Where appropriate, these existing references have been used after review. While not citing these resources explicitly throughout this chapter, we recommend consulting these documents for more detailed technical information regarding the structural and technical layout of a research icebreaker.

As the lead-time for the design and construction of such a specialized vessel is estimated to be around five years, it is recommended that the requirements are re-evaluated upon the start of a construction phase.

Purpose of Ship

A new purpose-built International Research Icebreaker (AURORA) will provide the science community with unprecedented access to all polar oceans of the world during all seasons of the year. It shall serve as an icebreaker, a multifunctional research vessel covering any marine related area of research, and a scientific drilling platform to retrieve drilled cores from the deep seafloor. The vessel shall be a successful combination of these ship types, and be built as a heavy icebreaker comparable to the world's strongest icebreaking vessels with the highest ice class according to Polar Class 1 (Polar Code of the IACS – International Association of Classification Societies).

The ship must be able to operate in ice-covered polar seas (as well as in ice-free conditions) of the polar oceans during all seasons of the year on long, autonomous expeditions. It must provide the science community with uncompromised access to heavily ice-covered regions in both hemispheres outside optimal weather windows. The ship must provide a steady working platform and allow operations through the moon pool, and deployment of diverse equipment over the side and the stern of the ship. In addition to the ice-breaking capabilities, the vessel must also perform as a research and drilling vessel in ice-free areas of the oceans, handling severe weather and sea conditions.

Design Requirements and Operational Envelope

The icebreaker shall be optimally equipped for all research activities of oceanographers, geologists, geophysicists, biologists, glaciologists, meteorologists, and other science disciplines. For this purpose the ship shall provide spacious laboratories, arranged in proximity to the main deployment areas for equipment, with adequate ceiling height, and an exceptionally large working deck. The number of container positions (for laboratory containers, reefer containers for the drill cores and samples, provision and other supply containers) shall be approximately 50. There shall be a long and high forecastle deck, and a raised poop deck to provide good protection against rough and following seas.

The vessel shall be designed to be autonomous and able to advance as far as possible into the ice covered deep-sea basins without any assistance from other icebreakers. At these most remote parts of the polar oceans, where outside assistance is often not immediately available, the vessel must be able to provide a safe platform to perform deep-sea drilling and research tasks, even after an accident or malfunction has occurred that damages the vessel's technical components partially.

All the ship's facilities must be planned to meet the highest standards of safety, reliability and redundancy. The icebreaker shall have a complete double hull, and redundant power plants positioned in entirely separated engine rooms and switchboard rooms. The pipe systems and cable trays shall be arranged for highest safety in such way that ship operation can continue in cases of flooding or fire in limited areas. A breakdown of single components or systems shall neither endanger the lives of persons on board at any time, nor shall this inevitably result in an abortion of the expedition.

1. Icebreaking

The ship shall be able to break ice of 2.5 m thickness and very strong multi-year ice at a continuous speed of about 3 knots. It shall break through ridges of up to 15 m height by ice ramming. Whether in ahead or in astern direction of driving, the debris of the broken ice shall never block the propulsion and manoeuvring systems as well as the moon pool locking devices, nor shall it cover or damage the deep-sea multibeam echo-sounders. It is crucial that the hull form shall provide sufficient discharging of the broken ice floes so that they will not jam on the hull and generate serious damage to the scientific systems in the hull and the vessel structure itself.

The ship shall be designed for full year research operations in the entire Arctic Ocean and in the polar Srn Ocean around Antarctica. This also includes also the possibility of a partial wintering period during research missions. Wintering means the vessel drifts in the ice without its own propulsion ahead.

The foundations of major equipment such as cranes, winches, and other heavy scientific equipment, shall be built for severe static and dynamic loading cases. If the vessel has to break thick ice ridges and barriers by ramming, substantial vibrations and accelerations in the entire vessel can arise. In order not to damage the vessel's scientific devices, measuring instruments and other elements on board, the platform should be laid out shake and shock safe for an acceleration of a minimum of 0.5 g in the vessel's longitudinal direction.

2. Open Water Performance

In addition to her capabilities in the ice the vessel must also perform well in the ice-free areas of the oceans, handling any weather and sea conditions. Operational theatres also include ice-free oceans between the poles, including a passage through warm tropical climate with occasional limited science operations or training, i.e., world-wide service.

During all times the ship must provide a steady working platform and allow science operations until Beaufort 8 and resulting sea state 6-7. It must be laid out to transit all tropical zones including occasional scientific works on "stations of opportunity". The environmental limits for the vessel operation are thus defined as:

- Minimum air temperature for scientific work within any safety aspects: minus 30°C
- Maximum air temperature with unlimited operational mode for all equipment: plus 30°C
- Minimum air temperature for limited ship's operation: minus 50°C
- Maximum air temperature for ship's operation: plus 45°C
- Minimum water temperature for ship's operation: minus 2°C
- Maximum water temperature for ship's operation: plus 32°C
- Maximum of assumed wind velocity: 85 kn (equals 14 Bft)
- Maximum wind velocity for scientific work: 7 to 8 Bft (equals sea state 6), according to the equipment used and the actual wind and sea conditions.

3. Propulsion and Main Engines

The necessary power has to be generated through a number of engines and diesel-electric systems, designed with the highest safety and redundancy standards in case of failure of single components.

For the widely different operating conditions and mission profiles for the research platform there will be a wide spectrum of power demands from the various consumers for ship propulsion, manoeuvring and positioning, drilling, crane operation, air compressors, and the scientific and marine equipment. In order to provide the most efficient and flexible energy supply, AURORA shall be equipped with a diesel-electric power plant of sufficient electrical capacity, according to the respective preliminary designs. A dedicated power management system should control power demands and load distribution of the generator-sets that preferentially have different sizes. The diesel-electric power plant shall also be designed for minimum noise and hull vibration, which is critical for many scientific measurements (see chapter below).

Electric azimuth propulsion systems are, besides robust conventional propulsion and thruster arrangements, a solution used in several new icebreakers and vessels operating in ice covered water for manoeuvring and station-keeping. Such azimuth propulsors must be optimized for the high power and high ice class necessary for the ERI vessel, but will likely be available in the highest ice class necessary by 2015 (communicated in writing to Aker Arctic Inc. by suppliers, 2012). A powerful ice-going azimuth propulsion system and the hull shape of the vessel must enable the vessel to turn in fast ice condition at the spot, as an important pre-requisite for drilling. With any arrangement of propulsion, adequate measures to avoid ice blocking and avoid interference between the propulsors and scientific eco-sounding systems of the vessel must be implemented.

4. Station-Keeping and Dynamic Positioning System

The vessel shall be equipped with a Dynamic Positioning (DP) System for both open water and sea ice conditions with 8/10 to 10/10 ice cover and ice thicknesses of up to 2 metres. This system shall be an integrated variant with regard to both hardware and software, where state-of-the-art technology shall be applied to provide a reliable and robust system. The system shall be of modular design and shall allow easy extension. The DP system shall ensure that no single failure of the system results in damage of any part of the machinery, equipment and systems, nor loss of safety or manoeuvrability of the vessel. A fully triple redundant system based on three control computers (one on-line and two in standby) and a separate backup shall be integrated in the DP system.

The DP system shall enable the vessel to perform safe and efficient field operation and control the vessel's propulsors in an optimum way, using mathematical modelling of the vessel's behaviour, Kalman filtering techniques, and optimum controllers, in order to provide the required positioning accuracy for the various modes of operation. The triple redundant DP System shall have majority-voting features for both input and output feedback and commands.

The field operation shall be carried out with the vessel positioned above a referenced point, with the heading up against the weather in water depths between 50 and 5000 meters. The DP system shall be designed to allow the vessel to operate, as a minimum, in various DP modes, such as manually via Joystick, in automated Station-Keeping, Auto-Heading, Auto-Track, Follow-Target and Transit-Mode.

An Uninterruptible Power Supply (UPS) system shall be available to assure continuation of the operation after a power failure. In case of a power failure, the UPS battery backup shall deliver power for 30 minutes operation. The operator stations located on the bridge and in the Backup Control Room shall be fed from a triple UPS system. All UPS shall have capacity to support the complete DP system installations. The units shall be located in dedicated rooms in (voluntary) compliance with DP3 requirements. The total system shall have several complete system program backups within the system. No single failure in backup program when reloading after start of power blackout shall fail to start up the total system or part of it.

The following sensors and reference systems, complete with all necessary controls, special cabling, and interfaces to DP and other systems shall be supplied:

- Three gyro compasses
- Three wind sensors
- Three vertical reference units (pitch, roll and heave, accuracy of pitch and roll better than 0.1%)
- Ice drift via redundant dedicated detection system

The vessel shall be equipped with the following reference systems:

- HIPAP System,
- Differential GPS,
- Surface positioning and tracking system (laser radar such as Fan-beam or equal).

5. Vessel Noise and Acoustic Performance

From the acoustic point of view the vessel shall generate as little underwater radiated noise as possible to reduce acoustic loading of environmentally sensitive sailing areas, to reduce stress on marine life, particularly mammals, and to allow testing and employment of acoustically sensitive measuring equipment. The ship shall meet the newest rules and regulations for diverse operating states, as the icebreaking process induces unavoidable additional noise into the water column.

Resilient mounting of noisy equipment shall be used as a standard noise reduction measure, requiring soft elastic elements on a stiff, well supported foundation. The ship shall be designed in such a way that conflicts between noisy and quiet rooms will be minimized. The ship can be subdivided in several acoustic zones with similar noise level requirements (See **Appendix 1** for a proposal of noise level requirements).

The diesel generators, as one main source of noise, require special attention. Their masses lead to a large input of acoustic energy into the foundations.

6. Environmental Requirements and Standards

The vessel's design shall make use of recent new developments in green and environmentally friendly technologies, both to reduce the environmental footprint of the vessel in the highly sensitive polar regions, and to minimise operational costs. The vessel must comply with newest environmental regulations for emissions and discharges, and shall surpass them where technically possible.

To allow critical research work with sensitive analytical methods, the vessel must be able to maintain a "clean ship" state for a minimum of 48 hours on a regular basis.

In order to provide the most efficient energy supply, the vessel shall be equipped with a diesel-electric power plant with a tailor-made power management system that

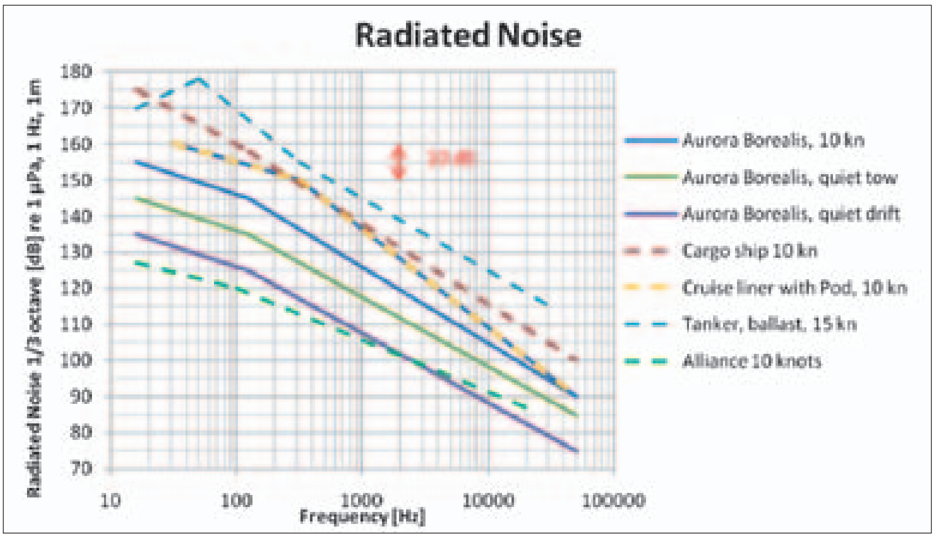

Figure 6.1. Proposal for exemplary underwater radiated noise requirements for the AURORA research icebreaker (Borealis version) in comparison to other ships. R/V *Alliance* is the NATO research vessel for comparison.
© AWI/SCHIFFKO.

controls all power demands and load distribution of the generator-sets.

Exhaust gas energy of the engines shall be utilized by advanced waste heat recovery systems that fully integrate with the vessel ventilation and power generation systems. As much energy as technically possible shall be re-used to reduce the environmental impact. It shall be possible to selectively run the generator engines either on cheaper Heavy Fuel Oil, on Marine Diesel Oil for environmentally sensitive areas, and on Liquid Natural Gas for clean small consumption over restricted periods of time, so that all ecological requirements for emissions and pollution control shall be satisfied.

In terms of mandatory requirements MARPOL VI Tier III regulations and all environmental regulations of the Antarctic Treaty System must be met (see **Apendix 2** for the list of rules and regulations the vessel must comply with).

7. Moon Pool

The vessel shall have a moon-pool of about 7x7 m size that is accessible for science operations from the decks at and above workingeck level. The moon pool shall be located as closely as possible tothe centre of the vessel to reduce impact by motions.

The moon pool shall make it possible to deploy sensitive instruments and gear in the water under fully closed pack ice conditions. Within an air-conditioned hangar over the moon pool, all lifting devices for deployment of scientific equipment and instruments shall be provided with the same scientific wires and cables as in the ship's other scientific platforms starboard and aft, including technically demanding operations like deployment of ROVs and AUVs. Adequate systems for launch and recovery will have to be designed for, or adapted to, the usage on board the vessel.

A solid closing device or hatch shall cover the moon pool at working deck level. The cover itself must allow partial opening in the centre as well. No structural elements shall disturb the light opening of the moon pool or the even working deck area.

The moon pool must be closable at the hull underside by a watertight door (preferably a hinged flap-type). The door shall be of strong design to ensure withstanding of high water pressure, caused by the draft but also the operation heavy seas, and running through ice. The bottom doors shall be arranged in recesses. In closed position the bottom doors shall not extend out of the vessel's bottom and only small gaps shall be present in the bottom in order to avoid negative impact on the scientific echo-sounding equipment by turbulence and bubble generation. The moon pool shall be equipped so that it can be pumped free of water and ice when the lower doors are closed.

8. Winches and Crane Capacities for Scientific Use

The related scientific winches with wires and cables shall be securely located in a dedicated centralized winch room.

8.1. Deck Cranes & other Lifting Gear

The vessel shall be equipped with a sufficient number of cranes and lifting devices necessary for the defined research work, in harbour as well as in offshore operation. For the arrangement and dimensioning of the cranes, particular attention has to be paid to the working radius of the cranes, so that all areas within and around the hatches, including the spaces dedicated to temporary deck stowage of containers and the scientific working areas, can be properly served. Precautions against icing and freezing of relevant components shall be taken for all cranes and lifting devices which are exposed to outside weather conditions. In addition, mobile cranes shall be provided for temporary mounting on deck by adapter pieces into the deck grid.

An example of required lifting devices is given in the tabular overview in **Appendix 3.**

8.2. Main Cranes for Research and Cargo Handling

One or more electro-hydraulic knuckle boom cranes shall serve the decks above the moon pool opening area and the related laboratory container slots on the corresponding deck levels. These cranes shall be arranged in such a way that the forward part of the boom can reach as close as possible to the water surface when swung outward during research works, to minimize free swinging wire and hook loads.

8.3. Auxiliary Travelling-Swivelling (Sickle) Cranes

To aid the main cranes in transferring smaller scientific loads between deck and hangar working areas, the arrangement of theses “sickle” cranes shall be made in such a way as to cover the largest possible working area with overlaps to the neighbouring crane. The number will depend on the layout and designed workflow of the vessel, and a proposal for adequate numbers and capacities is given in **Appendix 3.**

8.4. Supporting Mobile Telescoping Cranes for Research and Working (50-100 kN)

The vessel shall have two removable telescoping cranes for general scientific work on working deck level. Work shall be performed on deck and over the side. The crane connection has to use the deck grid for flexible mounting in any position where such a grid is available.

8.5. A-Frame

An electro-hydraulic A-frame shall be installed on a centre aft position of the vessel with a heave capacity of 100 t under all angles of inclination, and a corresponding point load applying at any location of the transversal top beam. The structure of the A-frame and the loose gear arrangement shall be able to bear oblique loads, e.g. when the ship is manoeuvring. In lowered position, the highest part of the A-frame shall not reach above helicopter landing deck level to provide an unobstructed approach.

8.6. Telescoping Sliding Beams

Telescoping sliding beams are the principal devices for most equipment deployments over the moon pool and side of the vessel. The beams shall be hydraulically moved to various positions inboard, and up to 4 m outboards. An additional hydraulic lifting gallows connected to a frap winch needs to be fitted on top of the beam, with a wire length reaching the base line of the vessel to handle equipment while attached to the beam (200 kN lifting capacity for beam and gallows reach).

These beams must be properly incorporated into the surrounding hull structure to avoid vibrations and any other negative impact to the operation. Particular care shall be taken to guarantee functionality under cold operational conditions (e.g., de-icing facilities). Automatic wire length compensation during operation is required.

The arrangement of the telescoping beams must be able to serve the area directly over moon pool area, the starboard side from the hangar through the large open door, and at least one additional main deployment zone over the starboard side on the open working deck.

For the deployment of smaller instrumentation (e.g., hydrocasts, sampling nets), a second beam shall be installed operating from the hangar area (lifting capacity 100 kN, frap winch 50 kN).

8.7. Indoor Cranes and Lifting Devices

Indoor cranes and lifting devices shall be installed in sufficient number to serve all hangar-, moon pool areas, but also scientific shops, tool stores and secondary working areas. Cranes shall cover the ire hangar area around the moon pool, preferably by travelling overhead cranes that do not obstruct the free working areas. Mobile support cranes that can be bolted to deck spaces according to needs can be a viable solution to support primary overhead lifting devices. No exact numbers, locations and capacities can be given as the exact arrangement is dependent on the technical design of the vessel’s inner spaces (an example is given in **Appendix 3**).

8.8. Scientific Winches

The vessel shall be equipped with friction and storage winches for cables, wires and fibre optic cables of diameter as specified (see **Appendix 4** for full list of needed scientific winches based on community survey and advice from science operators). The fixed winches shall be arranged in a weather protected centralized winch room. The cables, wires and fibre optic cables shall be run from the winch room to

a) the respective telescopic beams and cranes,

b) the aft A-frame,

c) the central moon pool for the deployment of scientific equipment.


Figure 6.2. Left, scientist releasing a weather balloon. Right, example of scientific helicopter deployment. © Alfred Wegener Institute.

All winches shall be electrically powered. Special care shall be taken to avoid any environmental pollution by loosing grease or other contaminating material. The outside operation winches shall be protected against seawater and icing.

A dedicated winch control system consisting of required sensors, computers and other hardware, as well as measuring, control and application software, shall be provided with additional spare connections for five or more additional winches.

Measured data like wire length, speed, and forces for all fix installed and flexible installed scientific winches, shall be recorded and fed real-time into the ship's information system, and be available for use by the scientist in the various laboratories and working areas, as well as on the navigation bridge.

9. Helicopter and Air Operations

Helicopters shall be deployed, and operate together with the research platform on a regular basis. Helicopters are needed for ice reconnaissance and forecasting, the deployment of instrumentation on the ice, as a platform for airborne measurements, for logistical support, and for emergency or search and rescue operations.

There shall be space in the hangar for two medium-sized helicopters (equivalent to, e.g., EC135 and 145), but allow to temporarily house a third helicopter if necessary.

Landing areas should permit average sizes and take-off weights of visiting helicopters (type SIKORSKY S76, HH60 and equivalents). The fully equipped main landing area with hangar shall be in the aft portion of the ship. An instrument-guided approach, take-off, and landing system from the vessel, shall be installed to aid operations during inclement weather and low light conditions. At least one main cargo crane of the vessel must be able to cover the entire helicopter landing area.

Repair and maintenance shops, and a separate preparation area and laboratory for daily weather balloon deployments, shall be provided in direct connection to the flight hangar. The balloon room shall be used to fill and launch helium filled weather balloons, and therefore shall have a large sliding door for balloon operation.

In addition, the vessel shall have facilities and space to deploy Unmanned Aerial Vehicles for research topics.

10. Drilling and Geosciences Coring Equipment

The vessel shall be regularly used as a mission-specific scientific drilling platform. No fixed drilling rig is needed on this vessel, due to the anticipated comparably little use (max. one expedition per year), high cost, and new mobile rig developments that have been successfully tested under polar conditions. The proposed solution to outfit the vessel with a rig will build on technology available through the European Science Operator (ESO) of the IODP, and specialized companies from the private sector that have been contracted in the past by scientific drilling programmes to carry out the drilling part of expeditions (e.g., Fugro-Seacore, DOSECC).

The general feasibility is supported by the experience accumulated during the last years with commercial activities in cold regions, and ice operations and the Arctic Coring Expedition in 2004 of the IODP (Expedition 302 Scientists, 2005). No substantial new development in drilling technology is required specifically for this platform. The vessel shall be able to deploy all drilling-related

Figure 6.3. Deployment of long CALYPSO-type piston corer from the French R/V *Marion Dufresne.* © A. Cathala/IPEV.

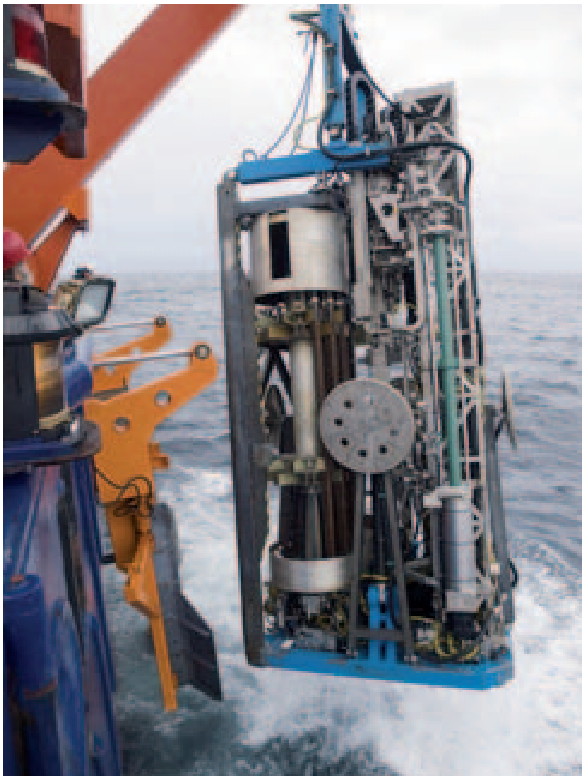

Figure 6.4. Deployment of the remotely operated seafloor drilling rig MEBO. © V. Diekamp, MARUM – Center for Marine Environmental Sciences, University of Bremen.

components as used in the scientific ocean drilling program, including borehole observatories, geophysical tools, borehole casings, and re-entry technologies.

To facilitate drilling operations in ice, the vessel must have dynamic station-keeping abilities in drifting pack ice, and the corresponding requirements are described in this Science Perspective earlier. Cores must be drilled and retrieved as fast as possible, since dynamic positioning in irregular ice will remain problematic. The ship must be able to move with extended drill pipes not touching the sea floor.

In addition, retrieving long (50 m or more), high-quality, continuous sediment cores with diverse coring devices is a major imperative for most geo-science disciplines. Thus, in total the ship shall be equipped with, or able to deploy, the following equipment:

10.1. Long-Piston Coring Capacity

Permanently available CALYPSO-type or technically similar piston coring system for acquiring continuous cores of 50 m length or longer.

10.2. Remote Seabed Drill Rig Operation

Safely deploy remotely operated sea-floor drill rigs of MEBO and similar type over the side or aft of the vessel, and preferably as an additional option through the moon pool. MEBO details and specifications are available online in documentation by the operator, MARUM Bremen (URL accessed on 15 April 2012):
http://www.marum.de/en/MeBo_Specifications.html.

10.3. Geotechnical Drilling Rig Capability

Provide layout and dimensions in the technical design of the vessel that allows installation of a geotechnical drilling rig over the moon pool to perform scientific ocean drilling according to the guidelines of the IODP as a mission-specific platform. (e.g., http://www.oceandrilling.org, accessed on 10 April 2012).

In particular, the design of the vessel must allow placement of a drilling rig whose specifications should be those used by the IODP during mission-specific campaigns (like the Fugro-Seacore R100 or better) above the moon pool with shelter from the weather in the at least partially covered hangar of the vessel's central working area. Thus, the area around the moon pool must consist of a freely accessible layout plan with wide, open spaces. The open working deck and hangar area must provide space, lifting capacity, and structural integrity, to safely install and operate such a rig without the need for the vessel to undergo major modifications in a shipyard or longer docking periods. Major components of the rig must be installable with the vessel's own lifting devices and technical support. The central working space around the moon pool area must allow the spare drill pipes, bottom hole assemblies, spare parts, and any other material related to the drilling process, to be stored and quickly accessed during drilling operations. Containerised mud pumps and tanks, as well as other systems, e.g. riser-less mud-recovery systems, will be used and must find space in proximity to the drilling rig, while being effectively ventilated and supported by the vessel's infrastructure (electricity, ventilation, etc.), and at the same time isolated from the laboratory spaces to avoid disturbance from noise and dirt. The space for drilling operations must allow for convenient extraction of cores and samples from the drill floor, and safe transport of this material in a fast and efficient manner to connected laboratories and sample and analysis tracks, preferably with elevators and lifting devices such as jack lifts, pallets, electrical fork-lifts, etc.

Figure 6.5. Drilling technology with mobile rigs. The R100 drill rig by Fugro Seacore, one of Europe's leading marine exploration drilling contractors, mounted on the polar-class vessel *Vidar Viking*. This rig layout was originally designed and built for drilling and core sampling on the Arctic Coring Expedition on Lomonosov Ridge in the Arctic Ocean in summer 2004. © IODP, Heiko Paelike.

11. Ice and Weather Observation Capabilities

11.1. Ice thickness measuring for sea ice monitoring

One operational ice thickness measurement device (impulse radar) to determine the structural aspects of ice and snow, and for measuring the related thicknesses, has to be delivered and installed. The records shall be stored in the ship's data storage facility, and the actual data shall be available via an internal ship information system.

The arrangement of the measuring devices shall be on a forward telescopic beam, and alternatively on the A-Frame aft. The devices shall be mounted, vibration and shock resistant, reaching at least 2 m ahead of the telescopic beam. Furthermore, the same equipment shall also be used as stand-alone equipment by helicopters as well.

11.2. New developments

A precise and integral method of modelling and forecasting ice drift and ice formation does not presently exist on an operational (i.e., small: metres to few kilometres) scale for the central Arctic or Southern Ocean, but is regarded as essential for operations in station-keeping mode and during adverse ice conditions. It must be developed in cooperation with experienced institutions that are nationally connected to the ERICON project, e.g. Arctic and Antarctic Research Institute (AARI), St. Petersburg, Nansen Environmental Remote Sensing Centre (NERSC), Norway, as well as outside expert organisations like the National Snow and Ice Data Center (NSIDC), NOAA, in the USA, or the Coast Guards and various maritime service organisations of the Arctic rim countries, or specialized companies from the private sector.

11.3. Weather Station / Meteorological Observatory

Rooms for the Weather Station / Meteorological Observatory and Registration Room shall be arranged in direct proximity to the Bridge Deck with a free view of the outside.

All installed indicators and equipment shall fulfil the requirements of a standard weather forecast station used by European official organisations. In addition the station shall be able to test newly developed equipment, and carry out scientific meteorological research activities.

A special antenna lattice bridge on the crow's nest platform shall provide space for proper installation of all antennas and sensors required. Interfaces shall link the data stream into the ship's information system. All arrangements and outfitshave to comply with rules and regulations of IMO and other concerned authorities.

12. Permanently Installed Scientific Systems

12.1. Scientific Echo Sounders

The vessel shall have a full array of state-of-the-art echo-sounding systems for scientific use. In addition, data from echo-sounding systems used for navigation shall be fed into the ship's information system. The following systems shall be installed on board, as a minimum:

Deep-sea multibeam echo sounder

One multibeam echo sounder for deep sea with a resolution of 1° by 1° shall be installed in the bow area of the vessel. Type Kongsberg EM122 or Atlas Hydrosweep DS or similar with the main features:

- Depth range >10000 m
- Coverage up to 6 times water depth
- Side scan and backscatter data
- 24/7 unattended operation
- Water column analysis
- Marine mammal protection
- Motion compensation
- Transmission power 70 kW
- Sound velocity measurements
- Ice protected sensors

Shallow multibeam echo sounder

One multibeam echo sounder for shallow depth with a resolution of 1° by 1° shall be installed in the bow area of the vessel. Type Kongsberg EM 710 or equivalent with the main features:

- Depth range 20-2000 m
- Ping rate up to 30 Hz
- Beam spacing equidistant, equiangular, high density
- Coverage sector up to 140 deg
- Transmit beam and receiver stabilized for roll, pitch and yaw
- Depth resolution 1 cm
- Ice protected sensors

Sub-bottom profiler

One sub-bottom profiler shall be installed in the bow area of the vessel. Type Atlas PARASOUND P70, Kongsberg Topas or equivalent with the main features:

- Depth range >10000 m
- Bottom penetration > 200 m
- Parametric signal 0.5 – 6 kHz with 4.5° x 5° beam
- Multi-pulse operation
- Multibeam capability
- 24/7 unattended operation
- Water column analysis
- Marine mammal protection
- Motion compensation
- Transmission power 70 kW
- Free definition of pulse shapes
- Ice protected sensors

Precision hydrographic sounder

One precision hydrographic sounder shall be installed in the bow area of the vessel. Signal shall be fed to the vessels information system. Type Kongsberg EA600 or equivalent with the main features:

- Depth range 20-10000 m
- Resolution 1 cm
- Multiple frequency (12 kHz, 18 kHz, 38 kHz, 120 kHz, 200 kHz, 710 kHz)
- Accuracy, depending on frequency from 1cm to 20 cm
- Ping rate up to 20/s

Acoustic Doppler Current Profiler (ADCP)

One ADCP shall be installed in the bow area of the vessel. The systems shall be installed on a remotely-operable extend and retract unit. The hull units shall be equipped with service dock and flange. Suitable means of access shall be provided to the service dock, remote controlled from a dedicated sounder room, with a status indication on a science workstation on the navigation bridge and on navigation console.

13. Seismic Survey Capacity

The vessel must be able to operate seismic equipment in conditions with full (i.e., 8-10/10) ice cover and ice thicknesses of up to 2.5 m. This includes towing long multi-channel seismic streamers and a source array, while underway at speeds of 3 to 4 knots. To achieve this, the hull form must be designed in such a way that a wide, open, relatively ice-free channel is created behind the vessel, and that broken ice floes are not transported under the hull to the aft of the vessel from the front, thereby risking damage to the deployed streamer and airgun arrays when they re-surface in the wake of the vessel.

A technical solution to customize the vessel on request, or at a later stage for three-dimensional (3D) seismic surveys in light ice conditions, should be envisioned and built into the design.

For work over the transom, and for towing of equipment, AURORA shall have one or more stern ramps ending as closely as possible above the water line for handling the streamers, air guns, and trawls, designed in consultation with science and technical personnel experienced in the deployment of seismic gear in polar, ice-covered areas. These ramps should have 4 m width minimum. The curvature of the ramps shall be executed in a way that ropes, umbilicals etc. will not be damaged during usage. The aft working area and the ramps need to be closable when the vessel has to weather incoming aft waves in bad weather. These filling pieces must be usable by the ship's own cranes and tools.

Two air compressors shall be installed fulfilling the following minimum requirements:

Pressure:	max. 208 bar
Capacity:	60 m³/min
Cooling:	freshwater cooling
Drive:	direct drive

The compressed air system shall be provided for the seismic air-gun service. Connections for 64 air guns shall be installed. Two independent Air-Gun Manifold Stations shall have direct access from the working deck. In addition to the required standard outfit, each Manifold Station shall be equipped with filling stations with distribution to at least 32 outlet connections.

Particularly, compressors, equipment, pipes and fittings, shall be constructed to avoid vibration, and suppress ambient noise from and to other rooms, especially the living compartments, scientific and control rooms.

In addition, storing positions shall be provided for four containers, each equipped with an air compressor of 15 m³/min capacity. For those compressors a fixed pipe system to the outlets shall be installed.

The launch-ways for seismic Air-Gun Arrays shall be designed so as not to disturb the handling of the filling pieces for the stern ramps. In case the launch-ways are not required for a longer period, they shall be stored with all related equipment in 20' containers.

Additionally, a dedicated Gravimeter- and Gravimeter Analysis Room shall be located low down and in the centre of the ship. This room itself shall accommodate the two ship's gravimeters and shall have spare platforms for the arrangement of at least two additional host gravimeters.

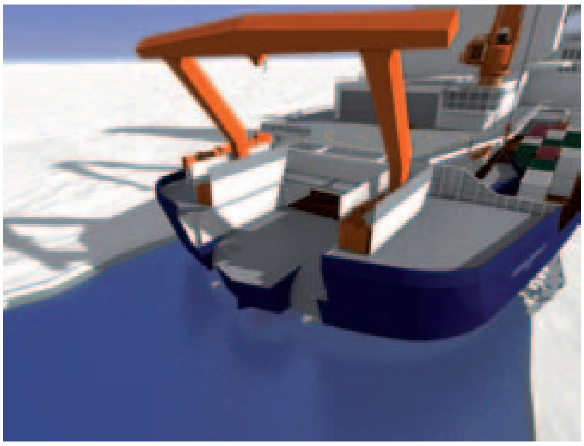

Figure 6.6. Example of twin stern ramps for geophysics deployment. © AWI/SCHIFFKO.

A seismic laboratory and data collection room for multiple uses shall be incorporated in the aft of the vessel into the general arrangement, overlooking the working deck with a clear unobstructed view of the stern area, ramps and deployed equipment.

14. Science Mast and Observation Deck Capacity

The vessel's main mast must be suited to housing permanently mounted sensors and instruments for atmospheric and meteorological measurements, and have a platform for use as an instrument base.

The mast shall house a sheltered Crow's Nest and Whale Observation Stands. The observation shall be a lightweight one and be easily dismountable with quick fastening devices and proper security bolting. The inside of the entire stand shall be made of natural wood clad to the metal structure, whereby the upper side of the cladding shall have a strong wooden top face. The entrance from the aft shall have a door. A removable floor grating made of wood shall be provided. Underneath the grating proper drainage shall be ensured.

In addition, the wheelhouse top shall be able to house four laboratory containers, two on each side, for atmospheric and other research topics. The maximum weight allocation for these containers is 8 t each.

15. Laboratories and Research Areas

Research is the primary activity for AURORA, and will consist of systematic studies and investigations in the field of biological, chemical, geological and physical oceanography, geophysics, as well as cryospheric, atmospheric, and sub-seafloor research in their respective broadest interdisciplinary senses.

The unique operational characteristics and international nature of this research icebreaker enable scientists to retrieve samples and conduct studies in regions that remain largely inaccessible today. This unmatched capacity shall be complemented by a suite of optimally equipped laboratories and working spaces. The arrangement, space, and special-purpose characteristics of the ship-based laboratories shall permit a range and sophistication of offshore measurements and lab-based studies that cannot be carried out on other ships. One principal concept that shall be employed is a mix of fixed-installed multi-purpose wet and dry laboratories and a number of hold positions, with full fittings that allow the comfortable use of specialized laboratory containers. Fixed and mobile laboratories shall be arranged in direct connection with a unified scientific workflow layout.

The laboratories should provide space for analysis, experimentation, electronic monitoring and calibration, information processing and retrieval, sample and equipment storage, scientific notation and recording. Laboratories should be adaptable and capable of supporting a wide range of research.

Research and analytical technology is advancing rapidly, and the laboratories shall be designed in a flexible and adaptive way to accommodate future advances in laboratory technology. Fume hoods shall be pre-installed in a number of the main laboratories, as the supporting system architecture needs to be coupled to the ship's ventilation systems to allow regular, safe, work with and handling of harmful and toxic substances. The need for temperature-controlled storage of samples, sediment cores, biological sample material, or ice samples that calls for specific room allocations, shall be met by a mix of pre-installed cold and deep-freezer rooms, and additional containerised storage capacities for processed and archived material.

Laboratory spaces must be equipped to easily house sophisticated electronic and analytical equipment that requires accurate temperature and humidity control, stable structure and vibration control, shielded space, clean power, and filtered water. All laboratories need to be equipped as a minimum with a suite of often-used piped services: de-ionized-filtered freshwater, seawater, potable cold/hot water, compressed air, nitrogen (N2), eyewash, safety showers, local area network (LAN), and regulated power. Additional gases like helium (He), argon (Ar) will be supplied from gas bottles, thus each room needs to be equipped with safe gas bottle holding compartments and piped systems for connection to, e.g., fume hoods, laboratory benches, etc. Additional piped services may be required in some rooms and should be easily adoptable at a later stage.

15.1. Permanent

The setup of laboratories shall follow the functional logistics of the working procedures on board and shall be optimized to enhance working efficiency. For this purpose the ship shall provide spacious laboratories around the moon-pool with adequate ceiling height, apart from an exceptionally large working deck. The number of container positions (for laboratory containers, reefer containers for cores and samples, provision and other supply containers) shall be approximately 25. The design and arrangement of permanent laboratories shall be made in such a way that these rooms can be used for the various tasks and needs resulting from the research programmes of the vessel. It is expected that mobile reefer containers will be used for special purposes such as core and sample storage. Thus, an adequate number of container locations with full utilities shall be closely connected to the main permanent laboratories.

Hangar and Large Wet Laboratory Area on Main Working Deck

This laboratory hangar with an adjacent Measuring and Registration Room, also on the starboard side, is the largest space for all kinds of work, which shall be handled under shelter from the weat. Any work requiring heavy or large equipment, and subconsequently strong lifting devices, shall be handled here. Direct access shall be ensured from the open deck working area, from the multi-purpose dry and wet laboratories, the laboratory container spaces, as well as from the ship's social/living areas. It shall have a direct connection to an adjacent Measuring and Registration Room.

The room shall have large watertight vertical sliding doors to the aft open working deck area and the starboard side, to enable the deployment of equipment directly from the hangar over the side into the water.

Over the entire hangar there will be water rinse channels covered by a strong grid. The water rinses shall be able to take all seawater for cleaning, sweeping sand, and minerals from research samples, and to drain them properly via sufficiently dimensioned scuppers through a dirt trap and separators into a centralized waste water system to be charged over boards after sufficient cleaning.

Measuring and Registration Room, Decanter Area on Main Working Deck

The Measuring and Registration Room shall have access doors from the hangar. The room shall have floating floors and resiliently mounted walls and ceilings. Vertical temperature and conductivity profiles (salinity) of the ocean are obtained with a CTD profiler.

A decanter area shall be part of the large hangar on

Figure 6.7. Example for a double deck-height preparation hangar with access to moon pool and working deck. © AWI/SCHIFFKO.

the working deck. It shall be combined with a larger stowage area for a water sampler and related equipment.

Salinometer Laboratory

To ensure proper temperature control, the entrance to the Salinometer Laboratory shall be restricted through an access lock. This room shall have its own Cold Room with direct access from the laboratory itself. The air-conditioned area shall have excess pressure against the access area and the cold area, with fine control tolerances of plus/minus 0.5°C. The well-insulated Cold Room shall have a direct access from the Salinometer Laboratory. The temperature shall be minus 3°C to plus 36°C within an accuracy range of plus/minus 0.002°C.

Clean Laboratory

For chemical analysis of samples and related research, clean laboratories are required. This laboratory shall be exclusively supplied with clean air from an independently operated air-condition plant. This plant shall control the required air exchange for processing, the excess pressure, the temperatures, and the relative humidity.

In the clean laboratories, analysis of snow, ice, rain, sea-ice and seawater samples will be accomplished. To avoid inadmissible external affects on these measurements, those clean rooms and their mechanisms must be fabricated from metal-free and softener-free materials, or coated materials.

The clean laboratory shall comply with cleanest area class 10.000 according to US 209D-1988, and also with Class 7 of ISO 14644 dated 1999.

Multi-Purpose Wet Laboratories

These laboratories shall have a direct connection to the Staging hangar, moon pool area and other laboratories. In total, five to eight wet laboratories (depending on room size and layout) shall be provided, in an arrangement next or close to each other, with wide double doors and a flexible room layout between the single rooms, so that rooms can be combined by open doors into larger spaces if necessary.

All rooms need to have through double-width doors and flush bottoms to enable unrestricted access with jack lifts and small electrical forklifts carrying palletised cargo, goods and equipment (euro-pallet minimum size).

Two of these wet laboratories shall in addition serve as aquarium laboratories and have two separate tanks, each with at least 4,000 l capacity, installed with cooling devices for cold seawater. The tanks can be loose tanks secured within the laboratories.

Multi-Purpose Dry Laboratories

These large dry laboratories shall be located and laid out within the vessel such that they can be accessed directly from the Moon Pool or atrium area. They need to be integrated into an overall workflow concept between the hangar, open working deck, the wet laboratories, and the laboratory container spaces. In total between five and ten rooms, depending on respective size and layout, shall be provided. All rooms shall be air-conditioned with individual temperature control, and have a slight overpressure. All rooms shall provide easy access as described for the wet laboratories.

Other special-Purpose Laboratory and Support Areas

In addition to the outlined general purpose rooms, dedicated smaller rooms and stores are needed:

- Weighing Room
- Chemical Stores
- Dangerous goods store for laboratory chemicals
- In addition to the dangerous goods store with access from the open working deck, additional chemical stores in various locations distributed over all research decks are needed.
- Diverse scientific stores for analytical spare parts, consumables, packi material, etc.
- Two geochemical and ice laboratories.

The following separate cold areas shall also be provided as a minimum arrangement in direct proximity to the general laboratory/hangar area:

- Scientific Cold Room for +4°C
- Scientific Deep Freezer Room -20°C
- Scientific Deep Freezer Room -30°C
- Scientific Deep Freezer Laboratory Area +4°C to -30°C (+/- 0.5°C)

15.2. Mobile (Containerized, laboratory vans)

Laboratory containers are standard 20-foot IOS (International Organization for Standardization) dimensions and fitting like shipping containers. They are configured as portable scientific laboratories and work-shops and are in use in many European research institutions. Maximum weight for these containers shall be 24 t.

Every laboratory container storing position has to provide fully equipped connection interfaces for all types of electricity, alarms, data and internet connection, air-condition / fresh pre-heated air, fresh water, clean seawater, black water, and normal drainage.

In total, about 25 positions for laboratory containers shall be provided. The majority of these locations should be inside the superstructure, clustered together close to the deployment areas of the scientific equipment/instrumentation on or above working deck level in a mid-ship position, with access from the central hangar and moon pool.

At least five container spaces should be located outside the superstructure and other laboratory spaces with no direct connection and integration, to provide space for isolated work areas, e.g. for research work with dangerous goods, contaminated or radioactive materials.

16. Scientific Berthing, Capacity and Endurance

The research platform shall be designed to accommodate a minimum of 120 persons in about 70 single and 25 double cabins, all with their own sanitary modules. The crew will differ according to the scientific mission, and could – as a typical example – comprise: ship's crew (35), meteorology + ice observation (2-4), helicopter crew (5), scientists (60), technical science support and/or drilling crew (15). All cabins shall be located with daylight and an adequate number of windows. All living quarters shall be separated from the main engine and other noisy spaces. Special attention must be paid to the thermal insulation as well as for noise, to suit existing environmental conditions and rules.

Telecommunication infrastructure designed to meet the needs of hosting live educational Internet broadcasts while at sea. Space (conference and meeting rooms), must be provided in various parts of the vessel to encourage interaction and exchange of ideas between the members of the science party.

The vessel must have an operational endurance of 90 days at sea with a contingency reserve for emergencies. The majority of these days will be in icebreaking mode, of which a significant number will be spent in DP/station-keeping mode, thus requiring bunker capabilities to maintain operations in potentially difficult ice conditions. During these times, no re-supply shall be needed.

17. Lifetime Cycle

The vessel shall be designed for an expected operational lifeof 30 to 35 years, with a significant mid-life refurbishment and conversion after approximately 15-20 years. During this period it is expected that underwater technology will further develop and provide new field methods. The ship will need to be adapted to this new technology, which includes drilling, application of automated underwater and airborne equipment, and ships' technology. This will not require an enlargement, but a modification of the installed equipment. Due to the planned modularized laboratory system an adaptation will be possible. A major prerequisite to satisfy this continuous need of adaption is the modular construction of equipment and equipment carriers.

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Appendices

Appendix 1: **Proposal of Noise Level Requirements**

Area	Cruising < 15.5 knots	Harbour
Engine room	110	85
Engine room, machinery stopped	85	85
Workshops	80	70
Engine control room	70	65
Galley	70	70
Wheelhouse	65	60
Radio room	60	60
Other working areas	85	85
Hospital	55	55
Sleeping quarters	55	50
Leisure and exercise rooms	60	55
Dining and living rooms	60	55
External leisure and rescue areas	70	65
Laboratories	65	55
Electrical propulsion room	90	85

All values are in dB(A).

Noise levels in bathrooms located in or adjacent to above spaces will not be more than 3 dB greater than the stated levels of the corresponding space. Noise levels of other spaces shall be in accordance with IMO Code 468 (XII). However, continuous levels above 85 dB(A) shall not be accepted. External areas' specification excludes noise contributions from wind and wash. Ventilation noise if operated alone (no other noise sources) will have a noise contribution of -6 dB of the above values at full capacity in cruising condition and -3 dB in harbour condition.

Appendix 2: **Rules, Regulations, Codes**

2.1. Applicable Rules & Regulations, National Codes and Regulations

All rules and regulations listed in this section shall be considered as minimum requirements and are not restrictive. In case of discrepancy between two codes, the precedence order shall be:

- Selected CLASS
- SOLAS
- International applicable regulations and codes
- Flag State regulations

However, the most restricting rule shall apply. Furthermore, the vessel shall comply with the specified modes of operation against relevant German, Norwegian, Swedish, Finnish, Danish, Russian, Canadian and US American regulations for operation in the specific Arctic waters and USCG regulations for foreign flag vessels.

2.2. Classification Society

The vessel shall generally be classified for unrestricted ocean service as “heavy ice breaker and multifunctional polar research vessel”. The hull, machinery, equipment and outfitting shall be constructed in accordance with the Rules and Regulations of an experienced IACS Classification Society for such vessel and under their survey.

The Notation of the selected IACS Classification Society (e.g., Det Norske Veritas, Germanischer Lloyd, Lloyds Register of Shipping, Russian Register Shipping) shall be fully compliant or above to those Notations as of:

GL ✠ 100 A 5

LR ✠ 100 A 1 Multi-Purpose Research Ship, Icebreaker, Ice Class PC1, Winterization H(-50) A(-50)

IWS, EP (A,B,G,N,O,P,R) ✠ LMC, UMS, CAC1, PSMR, ShipRight (SCM), ShipRight (SERS), Green Passport

2.3. Listing of other Applicable Rules and Regulations

The vessel shall comply with following rules, regulations and requirements:

- Maritime Regulations of the country of registrations of the ship
- International convention for the Safety of Life at Sea (SOLAS), 1974 with Protocol of 1978 and the amendments up to contract signing date
- International Convention on load Lines, 1966 with the protocol of 1988 as amended (2003/5 Amendments as per MSC. 1143(77))
- International Convention for Preventing Collisions at Sea, 1972 including amendments of 1981, 1987, 1989 and 1993 and latest amendments
- Including the recommendations of MSC 253(83), where required by the flag state
- International Tele-Communications union (ITU) Radio Regulations, 1982
- International Convention for the Prevention of Pollution from Ships (MARPOL) 1973 (Annexes I, IV& VI) with Protocol of 1978 and amendments up to contract signing date
- International Convention on Tonnage Measurement of Ships, 1969
- Suez Canal Navigation Regulations and Tonnage Measurement of Ships up to contract signing date
- IMO resolution A, 468(XII), “Code on Noise Level on board ships”, 1981
- ISO 6954-2000(E) “Mechanical vibration – Guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships”
- ISO 4868: Code for the measurement and reporting of local vibration data
- ICES: Co-operate Research Report 209. Underwater Noise of Research Vessels, Review and Recommendations
- U.S. Coast Guard’s Regulations for Foreign Flag Vessels Operating in Navigable Waters of the United States without certificates or inspection
- CFR title 33-part 155: Oil Pollution Prevention Regulations of Vessels
- CFR title 33-part 156: Oil and Hazardous Material Transfer Operation
- CFR title 33-part 159: Marine Sanitation Devices
- CFR title 33-part 164: Navigation Safety Regulation
- International Labour Conference concerning Crew Accommodation on board Ship (Convention No. 92, 133 (except swimming pool))
- IMO A868 (20) “Guidelines for the control and management of ships” ballast water to minimize the transfer of harmful aquatic organisms and pathogens” and

Appendix 2: **Rules, Regulations, Codes**

Resolution MEPC.127 (53) "Guidelines for Ballast Water Management and Development of Ballast Water Management Plans (G4). Also International Convention for the Control and Management of Ships' Ballast Wafer and Sediments, 2004

- International Maritime pilots Association regarding Pilot Boarding Arrangement including "IMO Resolution A.889 (21)"
- International Electro Technical Commission (IEC) publication 60092, Electrical Installations on Ships
- Development of Environmental Standards for innovative Shipbuilding DESiS – "Blauer Engel"
- International Ship and Port Facility Security Code (Equipment only)
- IMO Resolution A.962(23) - IMO Guidelines on Ship Recycling as amended by IMO Resolution A.980(24)
- IMO Guidance on Design and Construction of Sea Inlets under Slush Ice Conditions (MSC/Circ.504)
- IMO Resolution A.601 (15), "Provision and display of manoeuvring information on board ships". Reference to be made to Resolution MSC.137(76) and MSC/Circ. 1053
- MSC/Circ. 982 "Guidelines on Ergonomic Criteria for Bridge Equipment and Layout"
- AFS 2001 "International Convention on the control of harmful antifouling systems on ships, 2001"
- MSC/Circ. 1056 "Guidelines for Ships Operating in Arctic Ice-Covered Waters" and subsequent revisions
- Resolution MSC.266(84) on Code of Safety for Special Purpose Ships, 2008 (SPS Code 2008)
- Arctic Shipping Pollution Prevention Regulations (ASPPR)
- Arctic Ice Regime Shipping System (AIRSS) Standards
- Transport Canada's Navigation Safety Regulations
- Transport Canada's Steering Appliances and Equipment Regulations
- Canada: Shipping Act, Shipping Act-pursuant regulations, Oceans Act, Species at Risk Act
- "Requirements for Design, Equipment and Supply of Vessels Navigating the NSR" From "The guide to the navigating through the Northern Sea Route" (copy no. 4151B, dated 1996), Ministry of Transport of Russian Federation publication
- Helicopter Deck to comply with CAP437 - Dec. 2008
- ICS Guide Helicopter / Ship Operation - Dec. 2008

Appendix 3: **Exemplary Crane Arrangement for Research Support**

No	Type of Crane	Location	Main Boom Lifting	Working Radius SWL	
				Min.	Max.
1.	**Outdoor Cranes**				
1.1	Knuckle boom	Mid - aft; STB	300 kN	300 kN / 6 m	100 kN / 35 m
1.2	Knuckle boom	Mid - fore STB (pot. Pos. 1.1 + 1.2 combination)	850 kN	850 kN / 6 m	170 kNt / 45 m
1.4	Knuckle boom	aft; PS	100 kN	100 kN / 20 m	30 kN / 33 m telescoping
1.5	Sickle/ swivel travelling	mid	100 kN	7 m x 37 m	
1.6	Sickle/ swivel travelling	mid	100 kN	7 m x 23 m	
1.7	Knuckle boom	2 x removable	50 kN	50 kN / 4,5 m	30 kN / 8 m
2.	**A-Frame and Telescoping Beams**				
2.1	A-Frame	Center aft	1000 kN	ca. 22 m behind ship	
2.2	Telescoping Beam	mid- STB + Moon Pool	200 kN		
2.3	Telescoping Beam	mid-aft STB	100 kN		
3.	**Indoor Cranes and Lifting Devices**				
3.1	Travelling Crane	Working deck level	150 kN		
3.2	Travelling Crane	Hangar SB	100 kN	ca. 8 m x 27 m	
3.3	Travelling Sickle / swiveling Crane	Hangar SB	100 kN	ca. 5 m x 22 m	
3.4	Travelling Crane	For working deck level; winch room, Workshop	300 kN	ca. 9 m x 25 m	
3.5	Research Sickle Crane	Frame 58.5; PS	100 kN	ca. 7 m x 23 m	
3.6	Travelling Crane	Moon Pool Area	100 kN	ca. 7 m x 23 m	
3.7	Travelling Crane	Upper deck above Moon Pool Area	100 kN	ca. 7 m x 23 m	

Appendix 4: **Overview Minimum Scientific Winches for Research Support**

Item	Type of Winch	No	Type of Cable	Pull	Speed	ø in mm	Length of Wire / Cable	Arrangem. Position
1	Friction Winch	2		200 kN	0 - 2 m/s	18		fixed in winch room
2	Friction Winch	1		200 kN	0 - 2 m/s	22		fixed in winch room
3	Conducting Cable Winch	3	Fibre-optic	5 kN	0 - 2 m/s	11	8500	fixed in winch room
4	Storage Winch	1	Coaxial		0 - 2 m/s	18	10000	fixed in winch room
5	Storage Winch	1	6 Cu-Cores		0 - 2 m/s	22	10000	fixed in winch room
6	Storage Winch	2	Wire		0 - 2 m/s	18	12000	fixed in winch room
7	Rewinder Winch	1	various			11 - 22		mobile in winch room
8	Streamer Winch 1	1				2''	4000	mobile in cargo hold
9	Streamer Winch 2	1				2''	1000	mobile in cargo hold
10	Magnetometer Winch	1				1 1/4''	500	mobile in winch room
11	Airgun Winch	3				18	8500	fixed in winch room
12	Horizontal Capstan	1		20 / 10 kN	15 / 30 m/s			mobile in winch room
13	Storage Winch	1				11 - 22		mobile in winch room

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European Science Foundation (ESF), France

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