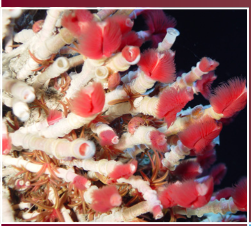

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40 PRIORITY RESEARCH QUESTIONS FOR OCEAN SCIENCE IN CANADA

A Priority-setting Exercise by the Core Group on Ocean Science in Canada

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SUMMARY

The ocean is of key importance to Canada's environment, culture, public health, economy, and society. The scientific study of the ocean provides the basis for understanding and sustainably managing ocean resources, particularly in the context of accelerating global change. Ocean science matters far beyond Canada's borders because of inextricable links among ocean regions; between the ocean, the seabed, and the atmosphere; and between the ocean and different societies. Because of these linkages, the impacts of global change can only be understood through research with a global perspective.

While Canada has an excellent track record in ocean science, and is respected for its contributions to international scientific projects and assessments, the nature of ocean science creates a number of challenges that require careful planning, coordination, and prioritization of research activities and related infrastructure investments. Canada's relatively small population as compared to its coastline, offshore exclusive economic zone, and continental shelf, also make it difficult to mobilize adequate resources for large-scale and long-term research projects.

This report presents 40 priority research questions that, if answered, would have the greatest impact on addressing future opportunities and challenges relating to ocean science in Canada. The questions were developed in a collaborative, open, and democratic process by a Core Group of experts from scientific and policy-making fields, and the private sector, based on candidate questions solicited from the wider community of Canadian ocean sciences. The process was adapted from previous priority-setting exercises in different fields.

The 40 questions are grouped according to research themes: improving fundamental scientific understanding; monitoring, data, and information management; understanding impacts of human activities; and informing management and governance. The questions reflect a strong interest in increasing the fundamental understanding of the impacts of global change on the ocean, including climate change, acidification, and nutrient loading. Major knowledge gaps in areas such as the Arctic, deep water, and marine biodiversity are especially important in the context of global change, and are highlighted in several questions. Questions aimed at understanding global processes, as well as those addressing impacts of direct relevance to coastal communities and Canada's economy, reflect the multidisciplinary nature of ocean research and the need for improved international collaboration. These questions could inform decision-making at several levels, including research planning at universities and the development of more coordinated and efficient strategic priorities by research funders and policy-makers.

40 Priority Research Questions for Ocean Science in Canada: *A Priority-setting Exercise by the Core Group on Ocean Science in Canada*

INTRODUCTION

This report presents 40 priority research questions that, if answered, would have the greatest impact on addressing future opportunities and challenges relating to ocean science in Canada. The questions presented in this report should not be seen as outlining a research plan. Rather, they identify priority research areas that could provide the basis of a research plan for ocean science in Canada. "Science" is interpreted broadly in this context to include physical, biological, chemical, geological, health, and social sciences, as well as engineering, the humanities, and multidisciplinary research on the relationship between humans and the ocean. This section outlines some of the opportunities and challenges of Canadian ocean science and provides a brief overview of the methodology used. The next section presents the 40 questions and background to put them in context. The final section highlights overarching issues emerging from the questions and discusses their implications.

The ocean is of key importance to Canada's culture, environment, public health, and economy. It is also an integral component of the culture of many Aboriginal peoples and coastal communities. Canadians depend on the ocean to supply food, mineral resources, transportation routes, recreation, and employment. Ocean-related industries employ about 315,000 Canadians and contribute more than $26 billion of Gross Domestic Product (GDP) each year (DFO, 2009). This figure does not include the $100 billion trade industry that is helped, in part, by Canada's marine shipping industry. A healthy ocean also contributes to many global cycles essential for life on Earth. At the same time as our dependence on ocean resources is growing, the ocean is changing at accelerating rates in response to many drivers of global change, including climate change, acidification, overfishing, pollution, and resource extraction, as well as cumulative and indirect impacts of multiple drivers.

Canada has the world's longest coastline, surrounded by the Pacific, Arctic, and Atlantic oceans, which are characterized by distinct research challenges. The Pacific Ocean contains some of the oldest deep water in the world, rich in nutrients, yet low in oxygen (Schmitz Jr., 1995). Large amounts of freshwater inputs to the Pacific Ocean contribute to a lower salinity than the Atlantic Ocean, and drive large-scale transport of ocean water from the Pacific to the Atlantic, via the Arctic Ocean (Wijffels *et al.*, 1992). Sea ice and associated temperature and light conditions dominate the Arctic Ocean's unique physical environment (Johannessen *et al.*, 2004). This ocean is central to a human environment in the Arctic that is characterized by a sparse population with special vulnerabilities, needs, desires, and legal frameworks for self-determination (Brosnan *et al.*, 2011). Cold Arctic waters discharge into the North Atlantic, where surface water from the south cools and sinks, driving vertical mixing within the Atlantic (meridional overturning) and contributing to global circulation (Schmitz Jr., 1995). Despite large-scale exchanges of water, ocean areas may differ in circulation patterns, physical environment, and geography, which contributes to differences in biogeography (Vermeij, 1978), biogeochemical cycling (Schmitz Jr., 1995), and contaminant concentrations (Wu & Boyle, 1997; Jaffe *et al.*, 1999).

The interconnected nature of the world's oceans has prompted some researchers to adopt a "one ocean" perspective (O'Dor *et al.*, 2009): marine species migrate between countries; ocean currents transport energy, nutrients, and contaminants over immense distances; and the ocean is linked to global climate through a complex web of atmosphere-ocean interactions and feedback mechanisms. Thus, research in ocean science must extend beyond national boundaries to develop a coherent and holistic model of ocean processes.

The ocean is a major component of planetary systems and is affected by global change. Global change refers to planetary-scale changes in the Earth system, including changes in atmospheric circulation, ocean circulation, climate, water, carbon and nitrogen cycles, sea ice changes, sea-level changes, food webs, biological diversity, pollution, health, fish stocks, and changes driven by human civilization, including population changes, the economy, resource use, energy, development, transport, communication, land use and land cover, urbanization, and globalization.[1] A global change perspective considers multiple drivers and consequences, as well as the linkages between them. For example, *ocean acidification* and ocean warming associated with *climate change* are distinct but interlinked consequences of a higher concentration of CO_2 in the atmosphere (NRC, 2011). They differ, however, in important ways: other atmospheric gases contribute to climate change but not acidification (Valdès *et al.*, 2010), and the direct effects on ocean ecosystems are different, even though both drivers may occur in combination. The ocean's role in planetary systems implies that ocean science makes essential contributions to understanding many impacts of global change on land. Changes in sea ice cover, for example, affect global weather patterns[2] (Deser *et al.*, 2004; Serreze & Barry, 2011), including extreme events in the Canadian Prairies (NRCAN, 2008).

Although the state of knowledge of the world's ocean has made steady progress, certain areas and processes remain poorly understood. In particular, areas of deep water, cold water, and sea ice lack adequate data, while the role of microbial life and biodiversity in general remains understudied. Additional questions also arise regarding interactions among the various components and processes that have, so far, often been studied in isolation. Interactions among biological, physical, and chemical processes or between the ocean, sea floor, and atmosphere are examples of complex interactions that are known, but in need of further research. Ocean research, therefore, requires blending knowledge and research methods from numerous disciplines. Ocean and coastal research also requires large-scale investments in research infrastructure, such as ships, satellites, platforms, and networks for observation and measurement. Conducting research underwater or in extreme environments, such as cold or deep water, poses additional challenges. This type of research requires strategic planning and collaboration, not only across disciplines but also among researchers from different institutions, regions, and countries. Coordinating these activities on a national level can be challenging, given Canada's geographic size and simultaneous contact with the Atlantic, Pacific, and Arctic oceans (DFO, 2005).

Canada's interest in understanding the global ocean has inspired leadership in ocean science. Canada has an outstanding record of contribution to ocean science in several fields (Coward *et al.*, 2000; Charles, 2001; for other examples of Canadian leadership and contributions, see: de Wit & Muir, 2010; AMAP, 2011; Greenan & Klymak, 2011; Picard-Aitken *et al.*, 2011). Canada also has a history of excellence in ocean research facilities and networks (DFO, 2005; Ricketts & Harrison, 2007; Taylor, 2008). For example, the Bedford Institute of Oceanography[3] is the largest of a network of research stations across Canada,[4] which also includes institutes operated by the federal Department of Fisheries and Oceans (DFO), such as the Institute of Ocean Sciences and the Pacific Biological Station, and stations operated by networks of Canadian universities, such as the Bamfield[5] and Huntsman[6] Marine Science centres. The VENUS and NEPTUNE Canada networks at the University of Victoria[7], as well as the ArcticNet consortium and its Arctic Research Icebreaker CCGS Amundsen[8], are examples of world-class research infrastructure networks based in Canada

[1] Definition of global change from the International Geosphere-Biosphere Programme (IGBP). See: http://www.igbp.net/4.d8b4c3c12bf3be638a80001040.html
[2] See also http://nsidc.org/icelights/2012/02/02/the-arctic-oscillation-winter-storms-and-sea-ice/ for an explanation of how the Arctic Oscillation affects weather in the Northern Hemisphere.
[3] http://www.bio.gc.ca/
[4] For example: http://www.dfo-mpo.gc.ca/science/regions/index-eng.htm
[5] http://www.bms.bc.ca/
[6] http://www.huntsmanmarine.ca/
[7] http://www.oceannetworks.ca/
[8] http://www.amundsen.ulaval.ca/

(Taylor, 2008). Canadian ocean science also has a long track record of contributions to international research projects, including the International Geosphere-Biosphere Programme (IGBP);[9] initiatives of the International Council for Science (ICSU);[10] the International Council for the Exploration of the Sea (ICES);[11] the World Climate Research Programme (WCRP);[12] the Census of Marine Life (Snelgrove, 2010); the Argo global ocean observing system;[13] and the Integrated Ocean Drilling Program (IODP).[14]

In addition to Canada's active and productive community of university-based ocean scientists, the Canadian government also engages in collaborative research and international ocean governance. DFO plays a central role in collaboration networks, both nationally and internationally (Picard-Aitken *et al.*, 2011). The Government of Canada has participated and invested in international collaborations on the Arctic Ocean, including the International Polar Year (2007–2008) program (AANDC, 2011) and the Northern Strategy (Government of Canada, 2009). Canada will also chair the Arctic Council in 2013, continuing its tradition of strong Arctic foreign policy (Government of Canada, 2011).
Despite these investments, several recent reports and assessments have identified the need to improve national and international coordination and planning of ocean research in Canada (AANDC, 2011; DFO, 2007, 2008, 2009;; Government of Canada, 2011; Hutchings *et al.*, 2012; OSTP, 2007). There are also efforts to coordinate ocean policy and decision-making at the federal level, such as Canada's Oceans Action Plan (DFO, 2005), which articulates a framework for sustainable ocean development and management. Nevertheless, effective policy- and decision-making must be supported by timely and relevant scientific information. For example, the Royal Society of Canada Expert Panel on Marine Biodiversity (Hutchings *et al.*, 2012) recently recommended that Canada "establish strategic research initiatives to strengthen scientific advice on sustaining marine biodiversity."

SUMMARY OF METHODS AND BACKGROUND

In light of the challenges and opportunities facing ocean science in Canada, this report presents 40 research questions that address important gaps in knowledge, including those ultimately linked to essential policy and management questions. The Core Group convened for this exercise was composed of ocean experts from scientific and policy-making fields and the private sector. Candidate questions were solicited via an online survey of the Canadian ocean research community. To allow preliminary ranking and screening, Core Group members voted on submitted questions, based on their suitability as research questions. The Core Group then met for a 1.5-day workshop in early 2012 to discuss the remaining questions and reach agreement on the final list of 40 questions, according to an open, inclusive, and democratic process. The questions are not ranked, but presented as a collection of overall priorities based on discussions at the workshop. The methodology for this process was adapted from similar exercises for national and international priority setting in different contexts (Sutherland *et al.*, 2011b). A more detailed description of the methodology can be found in Annex A.

This exercise aims to promote collaboration between providers and users of ocean science, the results of which are relevant to three main audiences: (i) policy-makers and policy analysts

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[9] In particular, contributions to the following Core Projects: Integrated Marine Biogeochemistry and Ecosystem Research (IMBER); Past Global Changes (PAGES); the Global Ocean Ecosystem Dynamics programme (GLOBEC); and the Surface Ocean Lower Atmosphere Study (SOLAS). For details see project reports and science plans, available at: http://www.igbp.net/4.59fd12ff12c94e1eeb380001800.html
[10] ICSU recently elected a distinguished Canadian researcher as its future president, see: http://www.icsu.org/news-centre/news/press-releases/press-releases-2011/canadian-climate-scientist-elected-as-next-president-of-the-international-council-for-science
[11] Canada has been represented at high administrative positions within ICES, and the current president is Mike Sinclair, former director of the Bedford Institute of Oceanography; see: http://www.ices.dk/aboutus/History/presidents.asp
[12] In particular, contributions to the following projects: Climate Variability and Predictability (CLIVAR); Global Energy and Water Cycle Experiment (GEWEX); Stratospheric Processes and their Role in Climate Change (SPARC). For details see: http://www.wcrp-climate.org/
[13] http://www.argo.ucsd.edu/
[14] http://www.iodp.org/

who apply research outputs in a policy setting; (ii) research funders, such as granting organizations or private foundations; and (iii) ocean scientists who aim to inform policy through their research. The results should help to develop systematic and transparent schemes for (i) research funding and investments in research infrastructure; (ii) translation of research results into usable information; and (iii) improvements to the efficacy, efficiency, and policy relevance of Canadian ocean research.

The Council of Canadian Academies (the Council) conducted this priority setting exercise in response to a request by the Canadian Consortium of Ocean Research Universities (CCORU).[15] In August 2011, CCORU asked the Council for expert help to develop a research plan around marine science and to determine what is needed to support ocean science in Canada. The exercise summarized in this report was conducted as a first step to identify the priority research themes that could guide the development of such a plan. The results could also inform an evidence-based assessment of Canada's capacity to address these questions.

CANADA'S TOP 40 RESEARCH QUESTIONS FOR OCEAN SCIENCE

The Core Group organized the final questions according to the general motivations for research activities rather than by overarching issues, such as climate change. The questions are grouped under four themes that identify research designs and approaches appropriate for addressing each group of questions. This structure avoids distinctions between common research disciplines, since many questions require multi-disciplinary research designs. Therefore, the themes should not be seen as research priorities themselves. *The questions are not ranked*. The allocation of a question and its position within a thematic grouping does not indicate its relative importance.

The first theme, **Improving fundamental scientific understanding**, contains questions that address basic knowledge needs for understanding the complex interactions among ocean systems, the seafloor, coasts, and the atmosphere, as well as resulting impacts on land. While many of these questions address the ocean's responses to global change, the research design needed would provide fundamental knowledge of these responses, rather than directly address the development of interventions for global change impacts. Research that improves fundamental understanding of the ocean is nonetheless often directly relevant to decision-makers, even if the applications are not apparent until further research is concluded. A better understanding of how the ocean reacts to different drivers of global change can inform areas of policy-making that affect those drivers, such as decisions on climate change mitigation.

The second theme, **Monitoring, data, and information management**, contains questions that address issues of data gathering and ocean observation that are relevant to both basic and applied research. The theme recognizes the particular challenges of conducting research on highly complex interconnected systems with many diverse measurements in areas that are difficult to access and have challenging working conditions.

Most of the questions in the third theme, **Understanding impacts of human activities**, focus on the impacts of human activities on the ocean and coastal areas, including longer-term responses and impacts on socio-ecological systems (the combination of marine ecosystems and human societies). While most questions primarily consider impacts of human activity on the ocean, others recognize that changes in ocean and coastal areas also have consequences for communities and societies. In most cases, research that addresses these questions requires applied research designs. The motivation driving this type of research goes beyond understanding systems-level responses to large-scale change in order to include the impacts of activities like fishing and oil exploitation, with a view to developing adequate means for monitoring and mitigating negative impacts.

[15] CCORU includes the following Universities: Dalhousie University; Université du Québec à Rimouski; Université Laval; University of British Columbia, University of Victoria, Memorial University, University of Prince Edward Island, University of New Brunswick, and the University of Manitoba.

The final theme, **Informing management and governance**, comprises questions that go beyond understanding impacts and approaches to mitigation to include governance frameworks and necessary management approaches. Governance, as used here, includes policy-making and management as well as other forms of decision-making that involve a wider range of stakeholders. By definition, the social sciences play a fundamental role in the research approaches needed to answer these questions. Furthermore, the questions all adopt the normative notion that the management of ocean activities should be sustainable.

Explanatory text within each of the themes places related questions in context, and explains some of the terms and reasons for formulating the questions as they appear. The text introducing each theme is based on comments made by Core Group members during and after the workshop. The questions also refer to several issues that cut across themes, reflecting a broader context for the way these particular questions were phrased and why they have emerged as research priorities.

CROSS-CUTTING ISSUES

Several questions refer to global change so as to include the full range of drivers affecting ocean systems, whereas others refer to specific aspects of global change, such as climate change, ocean acidification, or nutrient loading. Climate change is prominent in current ocean research because the ocean is an important component of the global climate system and climate change will have a profound impact on the ocean and its ecosystems. Nevertheless, climate change is but one of several drivers of global change affecting the ocean.

Understanding the impacts of global change is particularly important in areas that are under-studied, such as the Arctic Ocean, the Labrador Sea, and areas of deep water. Marine biodiversity is also poorly understood across most of the ocean (Snelgrove, 2010), but provides services that humans rely on for food, employment, recreation, and other benefits (de Groot *et al.*, 2002; DFO, 2005; Hutchings *et al.*, 2012). Marine biodiversity and ecosystem health are also under pressure from several drivers of global change, resulting in changes to species abundances, distributions, and interactions, or other effects that remain undescribed due to lack of knowledge (Halpern *et al.*, 2008; Hellmann *et al.*, 2008; Snelgrove, 2010).

Changes in the ocean environment and marine ecosystems have consequences for human society and vice versa. Although researchers may define "ecosystems" to include humans as individuals, this definition does not capture the importance of social organization to the relationships between humans and the ocean. Several of the questions, therefore, refer to "socio-ecological systems," which is used in the broad sense to reflect the mutual effects that human societies and marine ecosystems have on each other, and the impact that social change can have on human activities in the ocean.

Most questions focus on these and other issues relevant to the global ocean, rather than on specific geographic regions (with the exception of the first four questions on the Arctic). In most cases, the Core Group opted for broader questions that capture research priorities for many ocean regions. This does not mean that important differences among parts of the ocean should be ignored. On the contrary, users of these questions should feel encouraged to develop specific research questions based on those presented here. For example, questions on ocean currents and biogeochemical fluxes could be modified to build on existing research on the different conditions in the Atlantic and Pacific oceans with regard to freshwater input or thermohaline circulation (see, for example, Wijffels *et al.*, 1992; Schmitz Jr., 1995). Similarly, questions on pollution could be adjusted to reflect existing knowledge on wind patterns and their impact on long-range transport of contaminants in different areas (see, for example, Wu & Boyle, 1997; Jaffe *et al.*, 1999). Some of the questions may also be useful guides to developing research projects for specific geographic areas such as Canada's inland seas, the St. Lawrence and Hudson Bay, the semi-enclosed Strait of Georgia, and the Labrador Sea.

IMPROVING FUNDAMENTAL SCIENTIFIC UNDERSTANDING

The Core Group identified many fundamental gaps in knowledge of the ocean, in particular in the context of the ocean's increasing importance for food, transportation, energy, resources, and recreation. There is a growing need to understand large-scale interactions among ocean regions, and between the ocean, the sea floor, coasts, and the atmosphere, as well as the resulting impacts on land. The Core Group considered these needs to be all the more urgent given accelerating global change, which reduces the reliability and predictability of the benefits provided by a healthy ocean. The questions in this section reflect a view of the ocean as a complex dynamic system that requires better understanding of interactions of its components, such as biodiversity and ecosystems, biogeochemical cycles, deep and surface waters, and interactions among the Arctic, Atlantic, Pacific, and other oceans.

The first four questions are concerned with different aspects of climate change in the Arctic. The Arctic Ocean is of particular interest to ocean science in Canada for several reasons. Scientific understanding of the Arctic is still limited and closing gaps in understanding is becoming increasingly important in the face of exceptionally rapid environmental and social change in the region (Weller *et al.*, 2005; IPCC, 2007). The Arctic is not only a key component of regional and global climate systems; it is also more sensitive to changes, which manifest more quickly and at greater magnitudes than in other areas of the world. Changes in seasonal ice cover profoundly affect Arctic ecosystems, biogeochemical cycles, and interactions between the ocean and atmosphere (Johannessen *et al.*, 2004; Lenton *et al.*, 2008). A seasonally ice-free Arctic is seen as a major tipping point that will further amplify warming (Lenton *et al.*, 2008; Serreze & Barry, 2011), and feed back into the climate in the Northern Hemisphere with far-reaching ecological and socio-economic consequences in Canada and elsewhere. Less sea ice also allows easier access to mineral deposits, transportation routes through the Northwest Passage, and increased activity by other nations. The likelihood of such changes is increasing rapidly, heightening the strategic importance of the Arctic Ocean for Canada's national security (Government of Canada, 2011).

1. *What are the processes affecting sea ice change in the Arctic? What is the time horizon for a seasonally ice-free Arctic Ocean? What will be the climatic, biogeochemical, ecological, socio-economic, cultural, and geopolitical impacts of the seasonal disappearance of sea ice?*

2. *What is the effect of climate change on biogeochemical cycles (carbon, nutrients, essential elements, contaminants) in the Arctic Ocean, and what are the feedbacks and connections to the global ocean?*

3. *How will ocean-ice-atmosphere interactions in the Arctic Ocean and surrounding seas be affected by and affect climate change, and how will the productivity, biodiversity, and services of Arctic benthic, pelagic, and sea ice ecosystems respond?*

4. *How do the ocean, land, and continental sea floor interact in the Arctic? How will interactions evolve under climate change? What regions are at risk of being affected by erosion, flooding, infrastructure destabilization, permafrost thawing, or gas hydrate sublimation?*

The next six questions deal primarily with feedbacks between the ocean, the sea floor, and the atmosphere, as well as effects of climate change beyond the Arctic Ocean. The movement of greenhouse gases between the atmosphere, ocean, and the sea floor is important for understanding feedbacks between the ocean and climate. These long-term feedbacks are captured in paleo-oceanographic records, which provide a glimpse into past processes and ocean states, and, in turn, provide data to improve modelling predictions. Knowledge of the past improves our understanding of basic processes, but it is important to recognize that relatively recent human activities and drivers add a new degree of complexity to projections of future ocean states. Other questions focus on mechanisms that could be used to remove greenhouse gases from the atmosphere. Although there is a growing interest in using such mechanisms for climate change mitigation, many elements of the feedback cycle and potential associated risks are still unknown. Sea floor fluxes are a key component of global nutrient cycles, including carbon and nitrogen, yet remain poorly understood. The nitrogen cycle, in particular, has been transformed, especially in the coastal zone, by a variety of human activities, such as fertilizer use on land and combustion of fossil hydrocarbons (Gruber & Galloway, 2008). It can, therefore, serve as a useful organizing concept for understanding and studying other biogeochemical fluxes.

5. *What is the spatial extent, frequency, and risk of marine hazards affecting Canadian coastal waters (e.g., hydrate-triggered landslides, tsunamis, earthquakes, extreme storm events), and what is needed for better forecasting of these hazards in a time of climate change and changing coastal populations and infrastructures?*

6. *How do global biogeochemical fluxes – between the surface ocean, the ocean interior, and the seabed (e.g., carbon and nitrogen transport) – affect the ocean system, how do they respond to environmental change, and how are they recorded in accumulating sediments?*

7. *How did the ocean function under past climates, and how can paleo-oceanographic records be used to predict the future state of the ocean-atmosphere system?*

8. *How will climate change affect the magnitude and spatial patterns of atmosphere-ocean-sea-floor exchanges of important greenhouse gases (e.g., methane, carbon dioxide) and aerosols?*

9. *What are the natural mechanisms through which the ocean and the seabed can mitigate climate change (e.g., CO_2 sequestration), and what are the risks of manipulating these mechanisms (e.g., changing the albedo, fertilizing the ocean)?*

10. *How will the sea level change over the next century from various sources (melting of continental glaciers and ice sheets, seawater expansion, regional circulation, geological rebound, and gravitational field), and what will the impacts be on coastal ecosystems as well as broader impacts in human societies on global and regional scales?*

The remaining questions in this theme focus on marine biodiversity and ecosystems, which are generally understudied, due to the difficulties of observing them at appropriate scales, and in remote, extreme environments throughout the ocean. The lack of data on marine biodiversity and ecosystem processes makes it difficult to establish baselines for management or monitoring changes. This challenge is particularly relevant in the context of multiple interacting stressors and drivers of change that ecosystems currently experience. For example, climate change and ocean acidification, which are both consequences of rising carbon dioxide concentrations in the atmosphere, have distinct effects on marine organisms and ecosystems. More generally, understanding the factors and processes that contribute to patterns and dynamics of biodiversity remains a major challenge. Environmental change is expected to cause many species to shift their distributions, leading to losses of species in some areas and arrivals of new species in others (Kerr & Packer, 1998; Hellmann *et al.*, 2008). The effects of these changes in species composition are particularly challenging to predict because the associated changes in species interactions can have cascading effects throughout ecosystems, from microbial food webs to commercially important fish and mammal species. Biodiversity change, at the species level, as well as in terms of genetic diversity within species, also has implications for ecosystem function, including biogeochemical cycling of carbon, nitrogen, sulfur, and phosphorous, as well as other environmental parameters (Rockstrom *et al.*, 2009; Snelgrove, 2010).

11. *How do changes in species interactions affect food web structure within and across ecosystems?*

12. *How will changes in biodiversity affect the functioning of ocean ecosystems?*

13. *What are the patterns and drivers of the temporal and spatial dynamics of biological diversity and marine genetic resources, especially poorly sampled taxa and areas?*

14. *How do management practices and natural variability influence how pathogens and parasites affect the abundance of marine species?*

15. *What will be the impacts of climate change and ocean acidification on marine ecosystems, biodiversity, resource management, and coastal communities?*

16. *How will changes in water quality, as a result of hypoxia, eutrophication, land-sea coupling, pathogens, contaminants, particles, and acidification, affect marine organisms associated with fisheries and aquaculture, especially sensitive life stages?*

17. *How are the movements and survival of marine organisms, including invasive species, being affected by environmental change, and what are the socio-ecological impacts?*

MONITORING, DATA, AND INFORMATION MANAGEMENT

Continued developments in observation technology, capacity, and data management will be essential for ocean research (Hall *et al.*, 2010). Advances in data quality and quantity can help improve monitoring and baseline characterization, which can contribute to the development of ocean management approaches and the mitigation of negative impacts. Many areas of the ocean remain difficult or expensive to observe, such as the ocean floor, deep water, or areas under sea ice. These areas are more easily observed using *in situ* sensors, which are necessary to complement surface measurements available from satellite remote sensing platforms. Availability of ship time and platforms is also a major constraint on conducting required research using current technologies. The resulting lack of data severely limits our understanding of these remote areas. Understanding ocean processes requires data sets of sufficient spatial resolution and temporal scale provided by long-term monitoring programs and the ability to integrate data from various sources into standardized, comparable data products. These data sets can help improve forecasts and predictions of phenomena, such as extreme weather, marine hazards, and climate (Hall *et al.*, 2010; Moore *et al.*, 2008; Stammer *et al.*, 2007). Sustainable management of resources, marine safety, forecasting, and other ocean services also require rapid and open access to these data (Hall *et al.*, 2010). With these goals in mind, standards and strategies have been developed by the international community, but they ultimately rely on adequate sensors and sound data management (Hall *et al.*, 2010).

18. *What in situ sensors and platforms need to be developed to expand observation capacity for biological, chemical, physical, and geological ocean properties?*

19. *What is the detailed bathymetry and character of the sea floor in Canada's three ocean margins? What new technologies are required to map and characterize the sea floor and its habitats?*

20. *What observations are required to monitor and understand processes affecting deep water circulation, such as the meridional overturning circulation (MOC) in the North Atlantic, ventilation of the North Pacific, freshwater flux out of the Arctic Ocean, and the thermohaline circulation in the Southern Ocean?*

21. *What are the long-term trends in three-dimensional distributions of key oceanographic variables (temperature, biomass, oxygen saturation, salinity, carbon system, sea-level change, currents, etc.) in the world's oceans? Where and how should these variables be measured to monitor long-term trends?*

22. *How can both meteorological and oceanographic observations and development of an operational coupled atmosphere-ice-ocean assimilation and prediction capability be used to improve prediction of climate and marine ecosystem change?*

23. *How can autonomous and networked platform infrastructures and sensors be developed to deliver comparable ocean data and data products for observation, monitoring, analysis, and decision-making?*

24. *How can a network of Canadian ocean observations be established, operated, and maintained to identify environmental change and its impacts?*

UNDERSTANDING IMPACTS OF HUMAN ACTIVITIES

Human activity in the ocean is growing and changing, and ocean resources and environments are becoming more important to society. These include the rapid expansion of offshore resource extraction and fishing, change in spatial distribution of coastal populations, and increase in leisure uses. Oil spills are of particular concern in the context of activities of Canada's resource extraction industries in northern waters, because hydrocarbons behave differently in cold water and under sea ice conditions than in warmer waters, making it more difficult to predict or mitigate their impacts (Robertson, 1998; Fingas, 2003). Increasing human activity on the sea floor is a concern because of lack of data on the sea floor and benthic ecosystems and their functioning in deep water, such as deep sea corals. Human activity also creates underwater noise from ships and oil exploration guns, as well as chronic noise from industrial activities, which is increasingly affecting marine mammals around the world. The changing and often increased acoustic noise levels is of particular concern in the waters under sea ice cover as the opening of commercial shipping routes leads to an increased use of icebreakers. The questions also address ocean pollution, such as the need to study the sources, fates, and impacts of existing and emerging synthetic contaminants, including nanomaterials and novel pharmaceuticals.

Different human activities often occur simultaneously and in combination with other drivers of global change, with uncertain cumulative effects. Furthermore, the resulting changes in the ocean also have consequences for the humans interacting with the marine environment. Possible impacts on human societies include the economic implications of access to resources, cultural effects of environmental change, physical impacts of currents, tides, or weather patterns on infrastructure, and health impacts from emergent diseases or changes in species harvested for food. The final question on socio-ecological approaches to change highlights the interconnections between human activity, the ocean environment, and marine ecosystems. Although the term "ecosystem" can be interpreted in a way that includes humans as individuals, this does not capture the important role of social organization in human behaviour and large-scale activities. A socio-ecological approach facilitates the development of measures to reduce societal vulnerability to abrupt changes and increasing variability, especially in the context of global change.

25. *What indicators are available to assess the state of the ocean, what is the significance of changes observed in those indicators, and what additional indicators need to be developed?*

26. *What would be the environmental and social impacts, benefits, and risks of human activities in oceans undergoing change due to extractive industries, fishing, tourism, navigation, and traditional uses?*

27. *What are the impacts of oil spills in cold and deep oceans and under sea ice, and what are the appropriate strategies and technologies for prevention and mitigation?*

28. *What are the effects of marine exploration and exploitation of living and mineral resources on benthic ecosystems and sea-floor conditions, especially in deep water?*

29. *What factors are impeding the recovery of depleted marine species and affected commercial fisheries and communities, and what can be done to address those factors to promote stock recovery?*

30. *What are the ambient underwater noise levels, and what are the consequences of changing underwater human-generated noise (e.g., ship noise, oil exploration, and increased noise propagation accompanying declines in pH)?*

31. *What are the fates and impacts of plastics, nanomaterials, and emerging synthetic contaminants in the ocean?*

32. *How can marine science and policy develop a more socio-ecological approach to change so as to recognize the interdependence and adaptive capacity of people and the marine environment?*

INFORMING MANAGEMENT AND GOVERNANCE

"Sustainable ocean management" means managing human activities in a strategic way that avoids causing harm to marine environments and ecosystems, and ensures human well-being in the long run (Christie *et al.*, 2005; Ricketts & Harrison, 2007). Such management requires balancing conflicting social priorities, such as aquaculture and wild fisheries, extraction of energy and other resources, and protection of vulnerable species and areas. Management of ocean activities refers to the design of ecological, physical, or social interventions intended to maintain or restore a desired state of ocean systems. The broader concept of governance includes the social structures and interactions that encompass decision-making and management processes of policy-makers and other stakeholder groups. A change in governance system and distribution of decision-making power affects who is involved in the decision-making process and who bears the costs and benefits of ocean management. Successful governance requires inclusion and engagement of all relevant stakeholders, the sharing of data and knowledge among them, and the recognition that societies and ecological systems have mutual effects on each other.

The first four questions in this section address ocean governance from a broad perspective, including types of information and institutional capacities needed to ensure sustainable governance, and the role of communities and their knowledge systems in decision-making. The next four questions address specific governance challenges. The search for adequate areas and appropriate interventions for marine protection, for instance, covers a broad range of approaches, such as the precautionary approach, ecosystem-based tools, and spatial planning including the use of marine protected areas where relevant. Management decisions are difficult in the face of multiple sources of uncertainty: e.g., global environmental change, social change, and their cumulative impacts. In general, the questions in this theme identify research needs at the interface between the natural and social sciences, requiring interdisciplinary research approaches that adequately capture the interactions and interdependencies of social and ecological systems.

33. *What are the economic, ecological, social, and political or legal impacts of alternative governance systems, and what are the appropriate capacities and institutions needed to govern for ocean and coastal sustainability?*

34. *What research, information, and tools are required to govern ocean use in the context of cumulative, interactive effects on socio-ecological systems?*

35. *What measures are required to ensure appropriate and effective participation of diverse coastal communities in ocean and coastal management and governance?*

36. *How can northern and coastal communities, and their knowledge systems, be more empowered and engaged in ocean research, monitoring, and management in order to build adaptive capacity?*

37. *How are areas and/or species of special vulnerability, such as "hotspots" of relatively high diversity or function, identified, monitored and protected under conditions of uncertainty and in the context of global change? How can the related capacities to carry out these activities be improved?*

38. *What strategic decision-making frameworks are required to establish a socially and ecologically sustainable balance between aquaculture and wild fisheries in marine ecosystems?*

39. *What technologies and strategies are needed to develop and deliver ocean-based renewable and non-renewable energy and minerals to society with minimal harm to the ocean environment?*

40. *How can the development and governance of sustainable ocean-based food production systems help to achieve local and global food security, and enhance the health and well-being of coastal communities?*

DISCUSSION

The 40 priority research questions for ocean science in Canada developed by the Core Group provide a suggested focus for Canadian ocean research in the coming decades. These questions could inform decisions on a national research plan at several levels. For universities, research institutes, and scientific networks, they could stimulate discussion on specific issues to be reflected in short-term research agendas and long-term research planning. For policy-makers and individuals or agencies that fund science, the questions address a number of themes that could inform the development of strategic priorities for research funding and investments in research capacity, infrastructure, and networks. While the questions span a range of disciplines, issues, and scales, they nonetheless highlight areas of special importance to ocean science in Canada that could form the basis of broader strategic priorities.

As expected, many questions relate to global change and its impacts on ocean processes and marine ecosystems. Most of these questions are formulated as questions aimed at increasing fundamental understanding, rather than as applied questions aimed at developing interventions for adaptation or mitigation. This focus highlights the urgent need for knowledge of how the global ocean system will respond to global change, in order to inform the design and implementation of effective interventions. There is also a clear distinction between climate change and other types of global change, such as acidification or nitrogen loading, which have distinct but potentially cumulative impacts on ocean systems.

Secondly, the fundamental research questions on global change, as well as those on applied issues of direct relevance to Canadians, are all formulated in a way that is open to transboundary and international collaboration. The impacts of oil spills in cold waters, collapsed fisheries, or coastal erosion due to sea-level rise will directly affect Canada's economy and the well-being of Canadian coastal communities. The global interconnectedness of ocean issues and the fact that many countries will suffer similar impacts provide a strong rationale for regional and international collaborative research. At the same time, the questions highlight that Canadian ocean research matters far beyond Canada's borders and can make important contributions to international research efforts.

A third aspect emerges from the questions on impacts of human activities and on improving ocean and coastal governance and management. These questions highlight the responsibilities of Canadian ocean governance on the global level, as well as issues of particular relevance in the Canadian context, such as the health of coastal communities and sustainable governance of aquaculture. Overall, they reflect a concern for sustainable management of ocean activities. More importantly from a research perspective, many of the questions point to the need for engagement of a variety of expertise across disciplines to address inherently interdisciplinary problems. The study of coupled socio-ecological systems and integrated ecosystem management are notable examples of interdisciplinary approaches that are emerging as pillars of research on sustainable management that will also have an influence on ocean science.

A final issue, which was not included in the list of questions but was discussed during the final stages of the Core Group workshop, is the relationship between the need for new scientific knowledge and its impact on human behaviour. Some members noted that behavioural change requires investment in research and education to empower citizens to make informed decisions that take into account the need to protect and sustainably use ocean resources. Others argued that the priority should be to find ways to establish adequate incentives that will move people to change their behaviour regardless of their understanding of complex ocean issues. While these approaches are not incompatible *per se*, they reflect a broader debate within the scientific community on whether the creation of societies that are science-literate or, in this case, "ocean-literate," will lead to more sustainable management of natural resources. Ultimately, the Core Group agreed that gaps in data and knowledge of the changes and impacts on the ocean are not the only limiting factor in preventing or mitigating negative impacts. We also lack knowledge of how to effect changes in the activities of human societies in ways that reduce negative impacts on the ocean. Nevertheless, gaps in either field of knowledge should not be seen as a reason for inaction.

Addressing the 40 questions presented in this report will require investments in specific technologies, infrastructure, and human resources. Technology is a common tool used to answer research questions and serve the data needs of science users. Nevertheless, some of the technology needed to carry out observations and collect high-priority data is not available, and research under extreme conditions may be prohibitively expensive, particularly in the North and in deep water. Research and development of ocean instruments and other technology remains a necessary first step toward addressing fundamental and other research questions in ocean science. Even where appropriate sensors exist, they must be deployed and connected to observation networks and platforms to collect the necessary quantity and quality of data for research and, especially, for long-term monitoring. Canada faces a particularly difficult task in this regard, given the size of Canada's oceans, the remoteness and challenges of the Arctic Ocean, and the small population base relative to the extent of Canada's coastline and coastal areas. Several of the priority questions presented above define the required platforms. Conversely, limited resources and capacity may restrict the scope of questions that can be addressed by ocean science in Canada, regardless of their importance to producers and users of knowledge. Decision-makers in research institutions, granting bodies, and policy may face difficult trade-offs between intensive regional and low-resolution extensive observations, or data on a subset of desired variables.

CONCLUSION

This report presents 40 priority research questions developed by a Core Group of experts from candidate questions solicited from the wider community of Canadian ocean sciences. If answered, these questions would have the greatest impact on addressing future opportunities and challenges relating to ocean science in Canada. These questions cross disciplines and range from local impacts of human activities to ocean research questions at the global scale. They reflect a strong interest in fundamental research on major knowledge gaps in biodiversity and global change, as well as in improving our understanding of under-studied areas, such as the Arctic and deep water. The questions emphasize the socio-ecological and global nature of the ocean, and the need for ocean science in Canada to engage in global collaboration. They also reflect a strong interest in balancing human activities with the conservation of living and non-living resources in the ocean, especially in the context of global change.

These questions identify priority issues that could form the basis of a research plan for ocean science in Canada. Such a research plan would require appropriate technologies, infrastructure, and capacity of human resources and expertise, which have not yet been identified. An important follow-up to this priority-setting exercise would be an assessment of the support for such a research plan for ocean science in Canada, including the necessary tools, resources, and social engagement. Identifying and understanding the gaps between existing capacity and the research priorities highlighted in these questions will help Canadian decision-makers to support ocean sciences in a way that creates new opportunities for relevant, world-class research.

ANNEX A: METHODOLOGY FOR COLLABORATIVELY IDENTIFYING RESEARCH PRIORITIES

The process used for this exercise builds on a well-established methodology consisting of a set of methods and approaches for collaboratively identifying research priorities and emerging issues in science and policy (as presented by Sutherland *et al.*, 2011b). Its defining feature is that it engages providers and users of scientific research in a particular field in an iterative process of joint fact-finding and priority-setting within an open, inclusive, and democratic process. The objective is to develop an agreed set of questions for scientific research that, if answered, would meet the information needs of a target audience, such as policy-makers, other scientists, research funders, industry, or the general public. These methods have recently been used to determine the priority research questions in fields such as: global agriculture (Pretty *et al.*, 2010); global conservation issues (Sutherland *et al.*, 2010; Sutherland *et al.*, 2011a); national priorities in ecology and biodiversity conservation in the United Kingdom (Sutherland *et al.*, 2008); and conservation research in Canada (Rudd *et al.*, 2011) and the United States (Fleishman *et al.*, 2011). The methodology comprises several iterative stages to arrive at an agreed upon target number of questions. The Council has adapted the methodology by tuning the approaches used for each stage to the intended aims and audiences for this exercise. The result is a three-step process:

1. Soliciting questions from the wider community of producers and users of ocean science in Canada through an online survey;
2. Voting on a processed list of questions by Core Group members; and
3. Making a final selection by Core Group members at a 1.5-day workshop.

The Council chose a Core Group of 22 experts in ocean science in Canada to conduct this exercise, including representatives of relevant scientific disciplines—such as physical, chemical, and geological oceanography, marine biology, social sciences, humanities, and ocean engineering—as well as policy-makers and experts with experience in the private sector. Core Group members were selected based on expertise, taking into account the need to adequately balance composition by geography and gender. The diversity of the Core Group encouraged cross-disciplinary discussions and learning, which allowed many perspectives to be integrated into the final wording of questions. To ensure transparency and ownership of the process, the Core Group, or a subset of its members, was involved in all steps of the process from developing the initial survey for soliciting questions to the final review of this report.

To solicit the initial set of questions, a survey was developed with input from the Core Group and disseminated among the wider ocean science community in Canada. Environics Research Group was commissioned to develop the survey tool, invite participants, and collect responses. Invitations were sent to a list of 42 “gatekeepers,” who then passed on the invitation to members of their professional networks. Gatekeepers were identified from a broad cross-section of Canadian organizations that use or produce ocean science research, including public, private, academic, and non-profit sectors. In addition, 71 individuals were contacted directly to ensure adequate coverage from all sectors. The survey asked for an anonymous submission of up to three research questions that should be “the focus of Canadian ocean research in the context of environmental, economic and societal opportunities and challenges for Canada.” Participants were asked to submit questions that satisfied a list of criteria for suitability as scientific research questions (after Sutherland *et al.*, 2011b). Questions should:

1. Be answerable through a realistic research design;
2. Have a factual answer that does not depend on value judgments;
3. Address important gaps in knowledge, including those that are ultimately linked to essential policy and management questions;
4. Be of spatial and temporal scope that could realistically be addressed by a research team;
5. Not be formulated as a general topic area;
6. Not be answerable by “yes,” “no” or “it all depends;” and
7. If related to effects and interventions, contain a subject, an intervention, and a measurable outcome.

Participants were asked to assign each of their questions to one of the following six categories: (1) climate change and other environmental changes; (2) biodiversity; (3) fisheries and aquaculture; (4) the sea floor and non-living resources; (5) security and ocean governance; and (6) marine technology and innovation. Participants were also allowed to suggest additional categories if necessary. The survey was used to provide a starting set of candidate questions, not to measure priorities across disciplines, which would have required additional data collection and analysis beyond the scope of this exercise.

The survey generated 230 submissions, which contained 606 useable questions. Council staff conducted a first assessment and "winnowing" of the questions. Duplicate or similar questions were grouped into a single representative question. Compound questions, or sequences of related questions that were submitted together, were split into individual focused questions. Questions that did not meet the desired criteria were rephrased, if possible, or moved to a list of "discarded questions."

The Core Group was presented with a reduced list of 386 questions, plus 141 discarded questions. All original materials were made available to the Core Group, allowing members to reintroduce discarded questions or original wording, or to propose new phrasings as they deemed appropriate. The Core Group was asked to indicate, on a scale of 1 to 9, which questions would be most suitable as priority research questions, including options to suggest deletion or provide "no response" in cases of insufficient expertise.

The Core Group met in person, at a 1.5-day workshop from March 1 to 2, 2012 to agree on the final list of top-priority research questions. Voting results were summarized by presenting the median score for each question and the number of votes to discard questions. This process enabled a preliminary ranking of questions. However, final selection and prioritization was based on discussions between Core Group members in light of the overall objective to identify "questions that, if answered, would have the greatest impact on addressing future opportunities and challenges relating to ocean science in Canada."

During a first round of thematic breakout sessions, participants reviewed or clarified the wording and, in some cases, combined two or more original questions into one. A consensus approach led to selection of four or five questions and up to six alternate questions in each category. Questions from these sessions were further discussed during two semi-plenary sessions to combine questions, reduce overlap, and identify and fill gaps. Each semi-plenary was instructed to agree on a list of 18 priority and six alternate questions. The resulting 48 questions were discussed at a final plenary in which the Core Group further combined overlapping questions, removed less compelling ones, and agreed on a final list of 40. During the final plenary, Core Group members also provided annotations to the questions and had a preliminary discussion on the categories or themes that could be used to organize them. The themes used to structure this report were based on those discussions, and questions were grouped into those themes after the workshop.

The draft report was revised based on a thorough review by the Core Group, followed by an international peer review. The comments were incorporated into the report and submitted to the Core Group for approval. Throughout the process, no changes to the questions were made without consideration and agreement by the Core Group.

APPENDIX A: CONTRIBUTIONS

Core Group on Ocean Science in Canada

A Core Group of 22 Canadian ocean experts from scientific, policy-making fields, and the private sector, were chosen to determine the priority research questions for ocean science in Canada. The Core Group members were selected according to their expertise as well as their membership in networks and institutions to achieve the broadest possible representation.

The Core Group on Ocean Science in Canada consists of the following members:

David Fissel, (Core Group Chair), Chair and Senior Scientist, ASL Environmental Sciences Inc. (Victoria, BC)

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David Fissel
Chair, Core Group on Ocean Science in Canada

Report Review

This report was reviewed in draft form by the three individuals listed below, who were selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and experience in ocean science.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered by the Core Group, and many of their suggestions were incorporated into the report. The reviewers were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Core Group and the Council.

Susan K. Avery, President and Director, Woods Hole Oceanographic Institution (Woods Hole, MA)

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With assistance from: *(in alphabetical order)*	Erica Fleishman, Methodology Consultant Clare Walker, Editorial Consultant

APPENDIX B: FOUNDING ACADEMIES OF THE COUNCIL OF CANADIAN ACADEMIES

The **Royal Society of Canada (RSC)** is the senior national body of distinguished Canadian scholars, artists and scientists. The primary objective of the RSC is to promote learning and research in the arts and sciences. The RSC consists of nearly 2,000 Fellows — men and women who are selected by their peers for outstanding contributions to the natural and social sciences, the arts and the humanities. The RSC exists to recognize academic excellence, to advise governments and organizations, and to promote Canadian culture.

The **Canadian Academy of Engineering (CAE)** is the national institution through which Canada's most distinguished and experienced engineers provide strategic advice on matters of critical importance to Canada. The Academy is an independent, self-governing, and non-profit organization established in 1987. Members of the Academy are nominated and elected by their peers to honorary Fellowships, in recognition of their distinguished achievements and career-long service to the engineering profession. Fellows of the Academy are committed to ensuring that Canada's engineering expertise is applied to the benefit of all Canadians.

The **Canadian Academy of Health Sciences (CAHS)** recognizes individuals of great achievement in the academic health sciences in Canada. Founded in 2004, the CAHS has approximately 400 Fellows and appoints new Fellows on an annual basis. The organization is managed by a voluntary Board of Directors and a Board Executive. The main function of CAHS is to provide timely, informed, and unbiased assessments of urgent issues affecting the health of Canadians. The Academy also monitors global health-related events to enhance Canada's state of readiness for the future, and provides a Canadian voice for health sciences internationally. CAHS provides a collective, authoritative, multi-disciplinary voice on behalf of the health sciences community.

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