Ocean Science in Canada: Meeting the Challenge, Seizing the Opportunity

The Expert Panel on Canadian Ocean Science

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

OCEAN SCIENCE IN CANADA: MEETING THE CHALLENGE, SEIZING THE OPPORTUNITY

The Expert Panel on Canadian Ocean Science

THE COUNCIL OF CANADIAN ACADEMIES
180 Elgin Street, Suite 1401, Ottawa, ON Canada K2P 2K3

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This report was prepared for the Canadian Consortium of Ocean Research Universities (CCORU). Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Canadian Ocean Science, and do not necessarily represent the views of their organizations of affiliation or employment.

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Expert Panel on Canadian Ocean Science

David Strangway, O.C., FRSC (Chair), Former President and CEO, Canada Foundation for Innovation; Former President and Vice-Chancellor, University of British Columbia; Former Chief of Geophysics, NASA; Founding Chancellor, Quest University (Kelowna, BC)

Louis Fortier, O.C., O.Q., Professor, Department of Biology, Université Laval (Québec, QC)

Jim Hanlon, Chief Executive Officer, Halifax Marine Research Institute (HMRI) (Halifax, NS)

Peter Herzig, Executive Director, GEOMAR Helmholtz Centre for Ocean Research (Kiel, Germany)

Barbara Neis, Professor, Department of Sociology, Memorial University; Co-Director, SafetyNet Centre for Occupational Health and Safety Research (St. John's, NL)

R. Ian Perry, Research Scientist, Fisheries and Oceans Canada (Nanaimo, BC); Adjunct Professor, University of British Columbia (Vancouver, BC)

Martin Taylor, Professor of Geography, University of Victoria; Former President and CEO of Ocean Networks Canada (Victoria, BC)

Wendy Watson-Wright, Executive Secretary and Assistant Director General, Intergovernmental Oceanographic Commission (IOC), UNESCO (Paris, France)

Message from the Chair

Ocean science is at the heart of understanding the complex relationships through which the ocean affects Canadian lives and through which Canadians affect the ocean. It provides the basis for developing ways of sustainably using ocean resources (biological, mineral, and energy) for the benefit of society while assuming the role of a responsible steward of the global ocean. Ocean science is unique because it draws on excellence from many sources. As an academic field, it knows no disciplinary or geographic boundaries. It combines knowledge generated by scientists in many disciplines from around the globe, and draws on the efforts of people in all parts of society. It benefits from universities and their role in teaching and research, as well as the research, monitoring, and policy development conducted by governments (federal, provincial, and municipal). Ocean science taps into the expertise of the private sector to responsibly develop ocean resources, often working together with public and private innovators to develop the necessary technologies and tools, which in turn enable new ways of conducting academic research. Ocean science also builds on the knowledge and experiences of large and small communities along Canada's three coasts as well as those of many interested citizens across the country.

The Expert Panel on Canadian Ocean Science was asked to assess what capacities would be needed to address a set of major research questions that were determined by a larger Core Group of Canadian ocean experts, and which of these capacities are currently available in Canada. Above all, these questions challenged us to expand our way of thinking about ocean science. Understanding the ocean, its coasts, and the continental shelf is a three-dimensional endeavour that requires ever more sophisticated methods of study and increasing detail in monitoring and observation. To enable societies to maintain healthy ocean systems that can deliver benefits now and in the future, we must also understand how marine social-ecological systems change over time, which adds a fourth dimension to the challenge. Canadian ocean scientists are part of a global community that is continuously pushing the boundaries of research to develop the methods, tools, and approaches necessary to meet the complex challenges embodied in these research questions, and to seize the opportunities arising from a better understanding of Canada's role as an ocean nation.

I would like to thank my fellow panel members for their commitment and their excellent spirit which has made this process a very enjoyable experience. The Panel is also very appreciative of the many individuals and organizations that have assisted in accessing much of the evidence reviewed in this report. Finally, the Panel and I express our sincere thanks to the staff members of the Council for their excellent support in collecting and synthesizing evidence from many sources and their help in amalgamating the diverse ideas of the Panel into a high-quality report.

David Strangway, O.C., FRSC
Chair, The Expert Panel on Canadian Ocean Science

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Project Staff of the Council of Canadian Academies

Assessment Team:	Stefan Jungcurt, Acting Program Director Jonathan Whiteley, Researcher Weronika Zych, Program Coordinator Emily Maddocks, Research Associate CarolAnne Black, Intern
With assistance from:	Clare Walker, Editor and Copyeditor Eve Rickert, Editor, Talk Science to Me Jean Pierre Toupin, Translation from English to French Accurate Design & Communication, Report Design

Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and broad representation of academic, industrial, policy, and governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered in full by the Panel, and many of their suggestions were incorporated into the report. They 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 Panel and the Council.

The Council wishes to thank the following individuals for their review of this report:

Tim Cowles, Vice President and Director, Ocean Observing Activities, Consortium for Ocean Leadership (Washington, DC)

Ken Croasdale, FCAE, President, K R Croasdale & Associates Ltd. (Calgary, AB)

John Cullen, FRSC, Department of Oceanography, Dalhousie University (Halifax, NS)

Anthony Edward Hill, Executive Director, National Oceanography Centre (Southampton, UK)

Leslie O'Reilly, Executive Director, OceansAdvance Inc. (St. John's, NL)

Rosemary Ommer, Adjunct Professor, University of Victoria (retired) (Salt Spring Island, BC)

Lori Ridgeway, Senior Advisor, Associate Deputy Minister, DFO (retired) (Ottawa, ON)

Paul Snelgrove, Professor and Canada Research Chair, Memorial University of Newfoundland (St. John's, NL)

Rashid Sumaila, Professor and Director, Fisheries Centre, University of British Columbia (Vancouver, BC)

Verena Tunnicliffe, FRSC, Professor and Canada Research Chair, Biology and Earth/Ocean Sciences, University of Victoria (Victoria, BC)

The report review procedure was monitored on behalf of the Council's Board of Governors and Scientific Advisory Committee by **Dr. Joseph D. Wright, FCAE,** former President and CEO, Parpican. The role of the report review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the report reviewers. The Board of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Dr. Wright for his diligent contribution as report review monitor.

Elizabeth Dowdeswell, O.C.
President and CEO, Council of Canadian Academies

Executive Summary

Canada is shaped by the ocean. Three ocean basins and the world's longest coastline define Canada's borders, affect the weather, provide valuable resources and other benefits, and link Canada to neighbours both near and far through trade, transportation, and ocean currents. Canadians derive a wealth of goods and services from ocean systems: food from fish and other marine organisms, energy from offshore oil and gas and renewable sources, subsea minerals, biodiversity, transportation routes, recreational opportunities, and associated employment.

The ocean is a complex system under stress from unprecedented global change, including climate change, ocean acidification, and increasing pressure on ocean resources from a growing and more affluent world population. Canada's extensive exposure to the ocean and the rapidly changing Arctic offers almost unlimited opportunities in fundamental research to improve understanding of ocean processes, as well as applied research on sustainable ocean and coastal development and management for the benefit of Canadian society. At the same time, it bestows on Canada the responsibility to act as a steward of the global ocean.

Ocean science provides the foundation for understanding the many ways in which the ocean affects life on Earth, and the interactions between human societies and the ocean. The extent of these research concerns relative to Canada's small population creates a key challenge for Canadian society: how to ensure that capacities for ocean science are comprehensive and adaptive (taking advantage of insights and input from multiple disciplines, sectors, and groups), appropriately designed, and efficiently deployed. Ocean science, as considered in this report, includes all research disciplines related to the study of the ocean, the coast, and their relationships with societies: the natural, health, and social sciences, as well as engineering, the humanities, and multidisciplinary research. Ocean science seeks to understand complex, multi-scale social-ecological systems, which requires multidisciplinary and collaborative research.

Recognizing the importance of ocean science, the Canadian Consortium of Ocean Research Universities (CCORU) asked the Council of Canadian Academies (the Council) to undertake an assessment of the state of ocean science in Canada. The Council undertook this work in two phases. First, the Council asked a Core Group of ocean experts from Canada and abroad to develop a set of priority research questions, which were published as *40 Priority Research Questions for Ocean Science in Canada*. Second, CCORU asked the Council to convene a panel of Canadian and international ocean science experts to address the following charge, using the 40 research questions as a guide:

What are Canada's needs and capacities with regard to the major research questions in ocean science that would enable it to address Canadian ocean issues and issues relating to Canada's coasts and enhance its leading role as an international partner in ocean science?

To determine the capacity needed to address the 40 research questions and assess Canada's existing capacity (the "needs and capacities" of the charge), the Panel considered evidence in five categories of capacity and grouped the questions into nine themes (Figure 1). Some cross-cutting questions were assigned to more than one theme. The Panel used bibliometric analysis of peer-reviewed journal articles to estimate Canada's current research performance in ocean science, complemented by a review and analysis of other available information on capacity, such as data on funding and highly qualified personnel, academic literature, and reports, to identify opportunities and challenges for each theme.

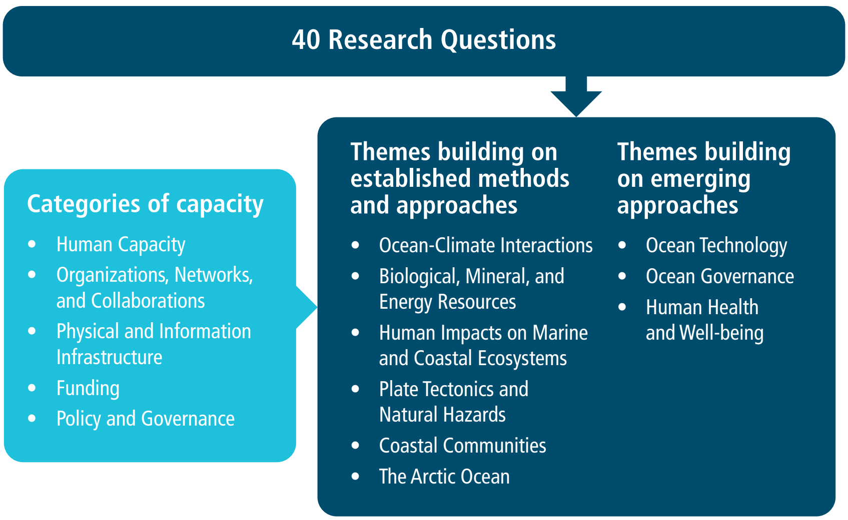

Figure 1

Conceptual Framework to Address the Charge

The Panel defined five categories to identify the capacities that would be needed to address the 40 research questions determined in phase 1 of the assessment and to assess Canada's existing research capacity. To facilitate the analysis, the Panel grouped the research questions into nine themes: six themes contain questions that build on established methods and approaches in ocean science; research questions in the other three themes are more forward-looking, with uncertain future research needs and anticipated paradigm shifts.

THE SEASCAPE OF OCEAN SCIENCE IN CANADA

Ocean science in Canada is organized into a network of regional clusters of diverse organizations with different research interests and capacities. While much of the capacity in Arctic research is located along the St. Lawrence River, for example, the main hubs for offshore oil and gas research are concentrated along the east coast, and a world-leading cabled observatory on the sea-floor is located off the west coast. This structure avoids some of the risks of relying on a central oceanographic research institution, which can lead to a strong geographic concentration of capacity. Canada's dispersed network of clusters, however, can create challenges for certain kinds of collaboration, alignment of research strategies, and coordination and use of large-scale infrastructure investments.

Bibliometric analyses show the historical importance of federal government organizations within this network, in particular Fisheries and Oceans Canada (DFO), Natural Resources Canada, Environment Canada, and the National Research Council of Canada. These decentralized organizations with national mandates are vital hubs for collaboration and access to essential expertise and infrastructure, such as vessels, specialized labs, databases, and computing and communication infrastructure. Universities are also important hubs that collaborate with government departments, and increasingly with each other through research networks. The activities of government departments, universities, and other actors vary by research theme. The private sector has significant research capacity in areas such as offshore oil and gas development, deep-sea mining, and ocean technology. Ocean science capacity in Canada is thus not only geographically dispersed, but also distributed across a variety of organizations with diverse mandates and priorities. This adds another dimension to the challenge of coordinating activities and scarce ocean science resources across the country.

THE STATE AND CAPACITY OF OCEAN SCIENCE IN CANADA

The Panel found that the data and information needed to assess ocean science capacity are held by a large number of institutions, recorded in formats that are not comparable, and often incomplete or not accessible to the public. The multidisciplinary nature of ocean science also made it difficult to delineate it within existing data sets. The Panel identified a number of areas in which the information was limited or structured in a way that reduced its usefulness for the assessment, e.g., the number of researchers active in ocean science, capacity within universities, private-sector research activities, ocean science spending across government departments, inventories of large instruments, and international collaboration. Based on the best available information, the Panel developed an overview of ocean science capacity in Canada and the following key findings:

- **The state of human capacity in ocean science cannot be determined because of data limitations**. Despite a steady increase in undergraduate and graduate students in many fields related to ocean science in Canada from 2001 to 2009, it is unclear whether overall trends in human capacity are positive on balance or whether the skills needed to address the 40 research questions are available. Due to its interdisciplinary character, ocean science draws on highly qualified personnel from many programs and departments, which makes human capacity one of the most challenging categories to assess. This is a particular concern, since human capacity determines the use and productivity of all other elements of ocean science capacity.
- **Canada has a substantial but aging research fleet**. The Coast Guard operates the Canadian research fleet, which includes several large oceanographic vessels and a dedicated research icebreaker that provides access to the Arctic. Half of these vessels were built over 25 years ago, and older vessels lead to more breakdowns, higher costs, and operational days lost to maintenance. Furthermore, the Panel observed that other countries have established more transparent systems of ship time allocation, which allow for more efficient use of ship time, and provide data to inform the planning of infrastructure investments. The ongoing renewal of the Canadian research fleet provides an opportunity not only to update aging infrastructure but also to improve the alignment of vessel specifications with science needs.
- **Canada has several world-class systems for ocean observation and monitoring; however, challenges exist in achieving geographical coverage and integration of data management**. Canada has recently invested in innovative observation platforms, such as the NEPTUNE cabled observatory and the Ocean Tracking Network, which build on historical strengths in development of remote sensing and observation technology. While these systems are ground-breaking and will attract leading ocean scientists from around the world, challenges exist with regard to the geographical coverage of observation and monitoring, in particular in the Arctic. Other challenges remain with regard to data integration and accessibility through the use of modern data portals. Addressing these challenges is especially important for research on global change, including climate change.

- **Although funding for ocean science in Canadian universities is increasing, trends in total funding are unclear due to insufficient data**. Total spending by funding agencies in Canada increased from 2002 to 2011, but direct funding for individual research projects has declined since 2008. While more funding is available for large research networks and investments in major infrastructure, changes in the policies and programs of funding organizations require higher levels of coordination among researchers, and alignment of funding from multiple sources. DFO expenditures on science activities also peaked between 2006 and 2008, followed by a decline to the same level as 2002. Overall, data on ocean science expenditures of government organizations and the private sector were insufficient to estimate national trends in funding for ocean science.
- **Canada ranks among the top countries in output and impact of ocean science papers, but this position is at risk**. The Panel used bibliometric analysis as a proxy indicator for an international comparison of the performance of ocean science in Canada. According to this analysis, Canada ranks 7th in the number of peer-reviewed papers, and 11th in scientific impact, by average relative citations. Ocean science in Canada is growing at a slower pace than other fields of science in Canada. Canada also has the lowest domestic growth index of the 25 leading countries in ocean science. This implies that ocean science is losing ground relative to other fields faster in Canada than in other countries, which could lead to a decline in Canada's position in research output and impact.

ADDRESSING THE MAJOR RESEARCH QUESTIONS: OPPORTUNITIES AND CHALLENGES

The Panel evaluated the capacity required to address the research questions in each of the six themes dealing with established methods and approaches in ocean science. This was followed by an assessment of the existing capacity using bibliometric analysis and other available information. Based on these assessments, the Panel then identified opportunities and challenges for ocean science in Canada for each theme:

- **Ocean-climate interactions**: Canada has substantial capacity in remote sensing and climate modelling which provides opportunities to advance research on ocean-climate interactions, particularly in addressing questions requiring better integration of ocean and sea ice in climate models. Realizing this opportunity, however, requires sustained observation and monitoring of climate-related ocean data. This is a challenge for Canada, primarily due to its vast and remote coastline, much of which is in the Arctic where observation and monitoring are inherently more costly.

- **Biological, mineral, and energy resources**: Canada has significant capacity for fundamental research in this theme, which is based to a large extent on historical strengths in government research, particularly fisheries science and marine geology, as well as fisheries research conducted by several top-publishing university research institutes. These strengths create opportunities in fisheries science and provide the basis for emerging capacity in marine biodiversity research using genomic technologies and approaches. The main challenges in this area are to prevent further loss of capacity in taxonomy and to continue the transition towards more holistic approaches such as ecosystem-based and social-ecological frameworks. The private sector holds substantial research capacity in mineral and energy resources, particularly in geological databases and other information resources. The main challenges in this area are to better coordinate and align capacity held by private, government, and academic institutions; and to effectively integrate research on the environmental and societal impacts associated with ocean resource development.
- **Human impacts on marine and coastal ecosystems**: Research in this theme also benefits from historical strengths in government departments and universities. The challenge is to adapt existing capacity to the changing context and priorities of this research. Adjustments made to date have led to a gap in research on invasive species — a gap that may soon be filled through a new network project — as well as on monitoring and understanding the behaviour of contaminants, in particular novel contaminants and known contaminants under new and changing conditions. (e.g., oil spills under sea ice). At the same time, there are shifts and overlaps in the responsibilities of government departments for research and monitoring of existing and novel contaminants. These parallel dynamics make it challenging for research on human impacts to keep pace with the development of new ocean resources and emerging sources of land-based pollution.
- **Plate tectonics and natural hazards**: Past achievements in geological and hydrographic surveying and recent investments in cutting-edge cabled observatories offer major opportunities in this theme. These investments also create challenges in ensuring long-term coverage of costs to operate and use these platforms for research. Other challenges lie in mobilizing the capacity necessary to comprehensively map the geology and bathymetry of Canada's vast ocean floor.
- **Coastal communities**: Canada has an active community of scientists from various disciplines that performs research in this theme, including the impacts of climate change, resource degradation, expanding coastal populations, and increasingly diverse uses of coastal areas and the ocean. Interdisciplinary networks that cut across the natural and social sciences and engineering are essential to mobilizing this potential. A key challenge is therefore to ensure continuing support for interdisciplinary collaboration and training in these areas.

- **The Arctic Ocean**: Recent and upcoming investments in icebreakers and research labs in the Arctic will create opportunities to address research questions on the Arctic Ocean. Some of these opportunities will be driven by the increasing strategic and economic importance of the Arctic region. As many of the questions relate to impacts of climate change, similar challenges arise in ensuring sustained observations. There are other challenges in prioritizing research on specific impacts of human activities in the Arctic such that research keeps pace with development dynamics.

The remaining three themes comprise research questions of a more forward-looking nature that describe future research needs or anticipate paradigm shifts that cannot be captured by bibliometric analysis. The Panel therefore focused on emerging research approaches, and the conditions that support their development and adoption. Using this approach, the Panel identified the following opportunities and challenges:

- **Ocean technology**: Canada's diverse and dynamic ocean technology sector has ample capacity to develop tools and technologies for advancing ocean science in Canada and abroad. These technologies can enable new kinds of observations and experiments and lower the cost of large-scale and long-term monitoring which also contributes to reducing challenges in other research themes. A key challenge for technology development for ocean science is to better align the research-driven technology development in the science sector with opportunities for commercial technology development, and to improve access to international markets for science instruments so as to make such innovations economically viable.
- **Ocean governance**: This theme faces growing uncertainty in both ecological and social elements of social-ecological systems, and increasingly requires the integration of knowledge from multiple sources. The need to develop adaptive and participatory approaches to ocean governance opens up opportunities for developing innovative approaches to research as well as new alignments and collaborations between researchers, policy-makers, and practitioners.
- **Human health and well-being**: Research on the relationship between the ocean and human health and well-being is undergoing a paradigm shift from a focus on contaminants and disease towards a more holistic understanding of the social and environmental determinants of health. Although several research questions allude to this shift, current research in Canada mostly addresses selected biological determinants such as pathogens and biotoxins. The main challenges relate to integrating research capacities in ocean-specific determinants of health with research framed by a broader population health perspective.

NEW ALIGNMENTS FOR CANADIAN RESEARCH ON THE GLOBAL OCEAN

Ocean science is becoming increasingly complex, multidisciplinary, multi-scale, and internationally connected. Addressing the 40 research questions will require new forms of alignment and collaboration both nationally and internationally. The Panel found that the seascape of ocean science in Canada is already changing in response to these needs. Innovative networks, such as the Networks of Centres of Excellence, are facilitating collaboration between scientists from universities, government, the private sector, civil society organizations, and communities. Novel funding opportunities, such as those offered by the Canada Foundation for Innovation, are enabling the establishment and management of large-scale infrastructure, such as vessels and observation networks, outside of federal government organizations. Consortia of actors, such as CCORU, are emerging to create momentum for change. These new networks and alignments have already resulted in several innovative, world-leading initiatives.

Despite these advances, the Panel identified the following gaps in the coordination and alignment of the ocean science community in Canada, which are currently not being addressed:

- **The vision gap**: In contrast to other countries, or other disciplines in Canada, no comprehensive national strategy or vision currently exists for ocean science in Canada. This makes it difficult to prioritize needs and comprehensively plan investments for ocean science.
- **The coordination gap**: Addressing the increasingly complex issues of ocean science requires enhanced collaboration at the local, regional, national, and international levels, and across disciplines and sectors. Despite the many instances of successful collaboration in Canada, coordination in key areas, such as ocean observation, is lacking, and support for research networks has often been constrained by temporary funding. More generally, there is no effective national-level mechanism to coordinate the allocation of resources and facilitate the sharing of infrastructure and knowledge among ocean scientists. This also hinders the sharing of resources and knowledge at the international level.
- **The information gap**: Limitations in access to, and availability and comparability of, information made it difficult to assess several categories of ocean science capacity (e.g., the number of active researchers, comprehensive data on research spending, or inventories of large instruments relevant to ocean science). While many actors in ocean science maintain inventories for internal use, no existing mechanism or repository systematically collects and regularly updates information on key research activities, infrastructure, and other capacities in ocean science for the entire country. Although gathering this information is a complex task in other countries as well, some, such as

the United States, Germany, and the United Kingdom, have established institutions and processes to collect such data and make it available to ocean science stakeholders. The information is then used not only to assess capacity, but also to inform development of national science strategies and plans on a regular basis and to prioritize decision-making on research infrastructure investments. The absence of such inventories in Canada makes it difficult to identify capacity needs at the national level. Similarly, opportunities to address research questions through national or international collaboration are more difficult to identify.

The Panel concluded that addressing these gaps is essential if Canada is to meet the growing needs of ocean science with limited resources, and make best possible use of existing capacities to meet the challenges and seize the opportunities of ocean science. None of the current and emerging alignments, consortia, or networks can address these gaps singlehandedly. Doing so requires a national effort involving the entire community of ocean scientists in Canada, as well as users of ocean science including policy-makers, entrepreneurs, communities, and civil society.

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Frequently Used Acronyms

ARC	average relative citations
AUV	autonomous underwater vehicle
CCG	Canadian Coast Guard
CCGS	Canadian Coast Guard Ship
CCORU	Canadian Consortium of Ocean Research Universities
CERC	Canada Excellence Research Chairs
CFCAS	Canadian Foundation for Climate and Atmospheric Sciences
CFI	Canada Foundation for Innovation
CFIA	Canadian Food Inspection Agency
CFRN	Canadian Fisheries Research Network
CHARS	Canadian High Arctic Research Station
CHONe	Canadian Healthy Oceans Network
CHS	Canadian Hydrographic Service
CIHR	Canadian Institutes of Health Research
CRC	Canada Research Chairs
C-CORE	Centre for Cold Ocean Resource Engineering
DFO	Fisheries and Oceans Canada (formerly Department of Fisheries and Oceans)
DRDC	Defence Research and Development Canada
GI	growth index
GCOS	Global Climate Observing System
GOOS	Global Ocean Observing System
GSC	Geological Survey of Canada
ICES	International Council for the Exploration of the Sea
IGBP	International Geosphere-Biosphere Programme
IOC	Intergovernmental Oceanographic Commission of UNESCO
ISDM	Integrated Science Data Management
MEOPAR	Marine Environmental Observation Prediction and Response Network
NCE	Networks of Centres of Excellence
NEPTUNE	North-East Pacific Time-series Undersea Networked Experiments
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council of Canada

OBIS	Ocean Biogeographic Information System
ONC	Ocean Networks Canada
ONCCEE	Ocean Networks Canada Centre for Enterprise and Engagement
OTN	Ocean Tracking Network
PICES	North Pacific Marine Science Organization
R&D	research and development
SI	specialization index
SSHRC	Social Sciences and Humanities Research Council of Canada
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
VENUS	Victoria Experimental Network Under the Sea

Labels for Canadian Organizations

The following labels are used to identify Canadian organizations in figures throughout this report.

Acadia U	Acadia University
BCMF	British Columbia Ministry of Forests, Lands and Natural Resource Operations
Brock U	Brock University
Carleton U	Carleton University
CEN	Centre for Northern Studies (Centre d'études nordiques)
CM nature	Canadian Museum of Nature
Concordia U	Concordia University
Dal U	Dalhousie University
DFO	Fisheries and Oceans Canada
DND	National Defence Canada
EC	Environment Canada
Geotop	Geotop Research Centre in Geochemistry and Geodynamics
INRS ETE	INRS University, Research Centre on Water, Earth, and the Environment
Lakehead U	Lakehead University
Laval U	Laval University
McGill U	McGill University
McMaster U	McMaster University
MUN	Memorial University of Newfoundland
NRC	National Research Council Canada

NRCan	Natural Resources Canada
Québec-Océan	Québec-Océan
Queen's U	Queen's University
RRU	Royal Roads University
Ryerson U	Ryerson University
SFU	Simon Fraser University
SMU	Saint Mary's University
StFX U	St. Francis Xavier University
Trent U	Trent University
U of Manitoba	University of Manitoba
U of Regina	University of Regina
U of Waterloo	University of Waterloo
U of Windsor	University of Windsor
UBC	University of British Columbia
UdeM	University of Montréal
UNB	University of New Brunswick
UofA	University of Alberta
UofC	University of Calgary
UofG	University of Guelph
UofT	University of Toronto
uOttawa	University of Ottawa
UPEI	University of Prince Edward Island
UQAM	University of Quebec at Montréal
UQAR	University of Quebec at Rimouski
USask	University of Saskatchewan
UVic	University of Victoria
WesternU	Western University (University of Western Ontario)
WLU	Wilfrid Laurier University
York U	York University

Labels for International Organizations

The following labels are used to identify international organizations in figures throughout this report.

CAFS	Chinese Academy of Fishery Science
CalTech	California Institute of Technology
CEFAS	Centre for Environment, Fisheries & Aquaculture Science
Chinese Academy Geo. Sci.	Chinese Academy of Geological Sciences
Chinese Academy Sci.	Chinese Academy of Sciences
CNRS	National Centre for Scientific Research (France)

CSIRO	Commonwealth Science and Industrial Research Organisation
Dal U	Dalhousie University
DFO	Fisheries and Oceans Canada
EC	Environment Canada
Helmholtz	Helmholz Association of German Research Centres
Ifremer	French Institute for Exploitation of the Sea
IMR	Institute of Marine Research (Norway)
INRA	French National Institute for Agricultural Research
IRD	French Institute of Research for Development
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
J-FRA	Fisheries Research Agency (Japan)
Leibniz	Leibniz Association
McGill U	McGill University
MIT	Massachusetts Institute of Technology
MNHN	National Museum of Natural History
MPG	Max Planck Society
MUN	Memorial University of Newfoundland
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NRCan	Natural Resources Canada
Ocean U	Ocean University of China
Russian Academy Sci.	Russian Academy of Sciences
SFU	Simon Fraser University
SOA	State Oceanic Administration (China)
Statoil	Statoil ASA
U Aix-Marseille	University Aix-Marseille
U Montpellier	Montpellier 2 University
U of Bergen	University of Bergen
U of C Boulder	University of Colorado at Boulder
U of Kiel	University of Kiel
U of Miami	University of Miami
U of Otago	University of Otago
U of Southampton	University of Southampton
U of Tasmania	University of Tasmania
U of Tokyo	University of Tokyo
UBC	University of British Columbia

UH Manoa	University of Hawaii at Manoa
UofA	University of Alberta
UofT	University of Toronto
UPMC	Pierre and Marie Curie University
US Navy	U.S. Navy
US-DOE	U.S. Department of Energy
USGS	U.S. Geological Survey
UVic	University of Victoria
WHOI	Woods Hole Oceanographic Institution

1

Introduction

- Charge to the Panel
- Interpreting the Charge
- Conceptual Framework
- Organization of the Report

1 Introduction

Canada is shaped by the ocean. Canada has the longest coastline in the world, stretching 243,792 km along the Atlantic, Arctic, and Pacific, including the unique interior seas of Hudson Bay, James Bay, Strait of Georgia, and the Gulf of St. Lawrence (DFO, 2008b). The ocean defines much of Canada's borders, affects the weather, provides valuable resources, and throughout history has linked Canada to neighbours both near and far through trade, transportation, currents, and shared experience. The ocean shapes the lives of all Canadians, directly and indirectly, regardless of how far they live from the coast.

Canadians derive a wealth of benefits from marine ecosystems: food from fish and other marine organisms; biodiversity; energy from offshore oil and gas deposits, wind, and tides; subsea minerals; transportation routes; recreational opportunities; and associated employment (DFO, 2009a). The ocean supports the majority of the world's ecosystems and species, and acts as the main regulating force for the planet's atmosphere and climate, for example by supplying vast amounts of oxygen and acting as a major carbon sink. The ocean can also be a hostile environment, of which we are reminded by natural hazards such as recent hurricanes and storms along the Atlantic coast, or the tsunami that devastated coastal Japan in 2011.

Increasing human activity and resource use is changing the ocean at a global scale. As human populations grow, demand for ocean resources, and the risks of ocean hazards for coastal populations, will also increase. Climate change affects ocean circulation, as well as sea-ice loss and sea-level rise (Johannessen *et al.*, 2004; IPCC, 2007; DFO, 2012b), while rising atmospheric carbon dioxide dissolves in ocean water, causing acidification (Rockstrom *et al.*, 2009; DFO, 2012b; National Research Council, 2013). Overfishing has changed ocean ecosystems around the world (FAO, 2010; Hutchings *et al.*, 2012), with wide-ranging economic and social feedbacks (Ommer *et al.*, 2011) such as the collapse of the Grand Banks cod fisheries. The consequences of ocean change for humans can be seen in recent events, some of which are unprecedented in human history. The Deepwater Horizon oil spill in the Gulf of Mexico, for example, caused wide ranging social-ecological consequences. Climate change has been associated with a series of storms and hurricanes along the east coast of North America that caused flooding and damage in coastal areas such as New York City. Similarly, the rapid disappearance of Arctic sea ice is disrupting ecosystems (DFO, 2012b); traditional lifestyles (Ford *et al.*, 2006; ICC Canada, 2008); and regional weather patterns (Deser *et al.*, 2004; Sommerkorn & Hassol, 2009; Serreze & Barry, 2011). In contrast, receding sea ice creates access to new Arctic resources and transportation routes (Arctic Council, 2009; Brosnan *et al.*, 2011; DFO, 2012b).

The ocean is a complex system under stress from multiple interacting pressures across a range of scales, from local fisheries to global climate change and acidification. These multidisciplinary, global challenges require integration of knowledge and coordination across traditional boundaries. The ocean is an internationally shared responsibility. Canada's exposure to the ocean offers vast opportunities to generate societal benefits, and bestows the responsibility to act as an ocean steward and a reliable international partner in sustainable ocean management. Ocean science is at the heart of developing innovative ways to both *use* and *protect* the ocean.

1.1 CHARGE TO THE PANEL

In March 2011 the Canadian Consortium of Ocean Research Universities (CCORU)[1] asked the Council of Canadian Academies (the Council) to assess the state of ocean science in Canada. In a preliminary exercise (phase 1), the Council convened a Core Group of 22 ocean experts from Canada and abroad to develop a set of priority research questions, which were published as *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a).

CCORU then asked the Council to follow up with an assessment of Canada's capacity to address these research questions (phase 2). CCORU submitted the following charge:

> *What are Canada's needs and capacities with regard to the major research questions in ocean science that would enable it to address Canadian ocean issues and issues relating to Canada's coasts and enhance its leading role as an international partner in ocean science?*

CCORU provided more direction through three sub-questions:

> *How do these capacities and needs relate to the varied dimensions of ocean research, such as the technological, economic, environmental, social, policy, as well as the governance aspects of this kind of research?*

1 CCORU is composed of the following member institutions: 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.

What infrastructure does Canada presently have, and what will it need to acquire in order to address the major ocean research questions with their varied dimensions?

What are the arrangements and new innovative alignments among the stakeholders of ocean research (governments, universities, industries, and communities) that could enable Canada to continue to address its ocean issues and enhance its leading role as an international partner in ocean science?

To address the charge, the Council assembled a diverse group of leading Canadian and international ocean experts with broad knowledge of the seascape and history of ocean science in Canada. The Expert Panel on Canadian Ocean Science (the Panel) met four times between September 2012 and May 2013 to consider evidence from bibliometric analysis and other sources such as data on funding and highly qualified personnel, academic literature, and reports from institutions and agencies involved in ocean science.

1.2 INTERPRETING THE CHARGE

Human activity affects the biophysical properties of the ocean while changes in ocean characteristics affect human health and well-being. These reciprocal feedback relationships form a co-evolutionary system that may be described as a "marine social-ecological system" (Perry *et al.*, 2010; Berkes, 2011). The Panel therefore adopted an inclusive definition of "ocean science" that encompasses the full range of disciplines related to the study of the ocean and its relationship with human societies, consistent with the widely adopted "one ocean" concept and social-ecological approaches to research (see Box 1.1). The definition includes science activities performed by a wide range of public- and private-sector actors.

The 40 research questions identified in the priority-setting exercise are the "major research questions" referred to in the charge, and guide the assessment. The Panel considered what capacities would be needed to address these research questions and compared these capacity "needs" to the existing capacities currently available to ocean science in Canada. Rather than producing a detailed inventory of platforms, researchers, labs, and organizations, the Panel decided to focus on assessing core capacities in several categories to determine opportunities and challenges for Canadian ocean science in the light of the 40 questions. Opportunities are created through past and current investments in research capacity, current research output, as well as historical strengths and expertise in specific areas. Challenges arise, among other reasons, from gaps in capacity, difficulties in accessing infrastructure and data, or in areas in

Box 1.1
Key Definitions and Concepts

Ocean science, as used in this report, includes all research disciplines related to the study of the ocean: physical, biological, chemical, geological, hydrographic, health, and social sciences, as well as engineering, the humanities, and multidisciplinary research on the relationship between humans and the ocean. Ocean *science* is broader than *research* and includes activities that apply or make use of scientific knowledge, such as monitoring, data integration and management, peer review, knowledge mobilization, integration of local and traditional knowledge, and outreach. These activities occur in a wide range of institutions, including universities, government departments and agencies, not-for-profit organizations, and private companies.

Research is understood to be a subset of science activities focused on formal knowledge generation from discovery to applied research and technology development, deployment, and commercialization (see CCA, 2012c).

Traditional ecological knowledge "is a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes, 1999, as cited in Berkes *et al.*, 2001).

In keeping with the prevailing view of the ocean science community, this report adopts the perspective of **one global ocean** with many ocean basins, such as the North and South Pacific, North and South Atlantic, Indian, Southern, and Arctic (IOC/UNESCO, 2002; Valdès *et al.*, 2010; OLN, 2011).

A **social-ecological** perspective of the ocean emphasizes the interdependence of human-social systems and marine ecosystems, and recognizes that the boundary between social and biophysical systems is often arbitrary (Perry *et al.*, 2010; Berkes, 2011). Human activity affects the ocean, and vice versa, forming reciprocal feedback relationships between human societies and ocean ecosystems.

which little research has been conducted in the past. In addition, Canada's vast coastline and exposure to three ocean basins, including the rapidly changing Arctic, present natural opportunities as well as challenges.

Box 1.2
Scope of the Report

This report:
- Adopts a broad definition of ocean science and views the ocean as a complex, multi-scale social-ecological system.
- Provides a framework for assessing Canada's ocean science capacity.
- Uses available data and metrics to estimate Canada's research capacity in ocean science.
- Identifies challenges and opportunities for ocean science in Canada, based on available evidence, in nine themes spanning the 40 research questions.

This report does not:
- Make recommendations or advocate policy.
- Provide a detailed inventory of ocean science infrastructure, researchers, or organizations.
- Compare research agendas or strategic priorities of organizations or countries.

1.3 CONCEPTUAL FRAMEWORK

To determine the capacity needed to address the 40 research questions and to assess Canada's existing capacity (the "needs and capacities" of the charge), the Panel developed a framework of five categories of capacity and nine themes encompassing the issues described by related research questions (Figure 1.1). The Panel used this framework to collect and evaluate available evidence on each category of capacity and to analyze opportunities and challenges in addressing the research questions in each theme.

1.3.1 Categories of Capacity

Based on a review of similar reports (National Research Council, 2011; CCA, 2012c; NSTC, 2013), the Panel developed five categories to structure its analysis of overall research capacity in ocean science:

Human capacity is the sum of the abilities and physical and cognitive output of the people who work in ocean science. Human capacity includes researchers, teachers, administrators, students, technicians, assistants, and volunteers. Human capacity includes highly qualified personnel, which Statistics Canada (2008) defines as individuals with a university degree at the bachelor's level or higher.

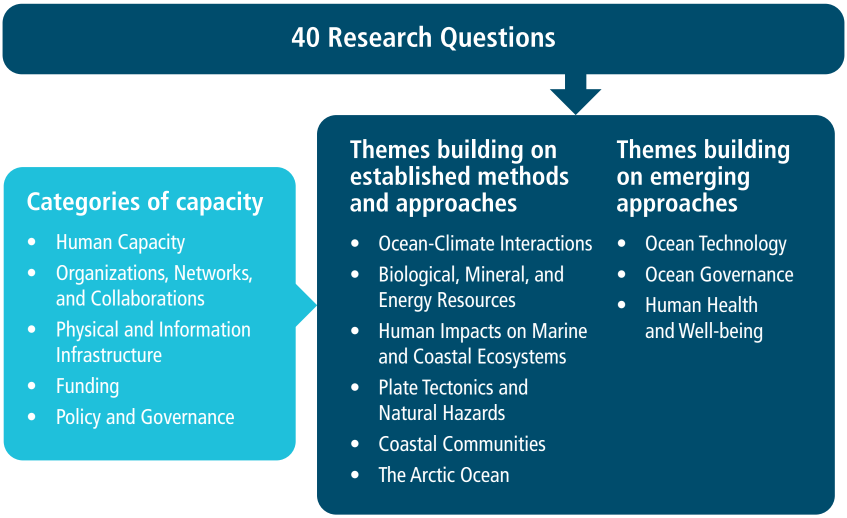


Figure 1.1

Conceptual Framework to Address the Charge

The Panel defined five categories to identify the capacities that would be needed to address the 40 research questions determined in phase 1 of the assessment and to assess Canada's existing research capacity. To facilitate the analysis, the Panel grouped the research questions into nine themes: six themes contain questions that build on established methods and approaches in ocean science; research questions in the other three themes are more forward-looking, with uncertain future research needs and anticipated paradigm shifts.

Organizations, networks, and collaborations are the realized opportunities for researchers to interact, share information and knowledge, and create synergy. They create interaction within and across disciplines, and link researchers with the wider ocean community, including industry, policy-makers, and civil society. They include research labs, institutes, universities, and agencies; national and international research networks and formal or informal collaboration; and professional associations and peer networks.

Physical and information infrastructure includes all physical elements required to gather, store, process, and transmit data and information. Physical infrastructure includes vessels and other human-operated platforms, autonomous and remotely controlled vehicles, measurement instruments, lab equipment, and satellites. Information infrastructure includes all forms of data storage, computing systems, methods, models, and algorithms for collecting and analyzing data, as well as the data sets themselves.

Funding includes all sources of spending on ocean science, including science budgets of federal and provincial government departments, university revenues, industry research spending, investments in construction and operation of infrastructure, and competitive grants from councils and agencies that support research activities and collaboration.

Policy and governance define the context in which ocean science activities are embedded by setting the priorities and rules used to allocate resources to ocean science activities and categories of capacity. This category, which includes political leadership, decision-making, and development of policies affecting ocean science, is an important determinant of the efficiency of use for all categories of capacity.

Most elements of one category depend on elements of other categories. For example, human capacity is a common factor that makes use of other categories, whereas all research activity is embedded in a context of broader funding priorities, policies, and governance.

1.3.2 Indicators and Evidence Used to Assess Capacity

A suite of indicators, including quantitative metrics, is available to assess research quantity, quality, trends, and capacity of a given field (CCA, 2012c). This report uses bibliometric analyses to assess ocean science output, and as a proxy indicator of overall research performance. In the Panel's view, quantitative indicators should inform rather than replace expert judgment (CCA, 2012c), so the report also draws on other available evidence, found in peer-reviewed and "grey" literature as well as expert interviews, to describe trends, and identify challenges and opportunities, in Canada's ocean science capacity. This report presents evidence from a review of literature; review of reports from federal and provincial agencies, non-governmental organizations (NGOs), and other organizations; bibliometric analyses; data from funding agencies; and data from Statistics Canada (see appendices[2] for more detailed information).

1.3.3 Research Themes

To facilitate the analysis of the existing research capacity in Canada and the capacity needed to address the 40 research questions, the Panel grouped the questions into themes representing more general areas of research. Some questions were allocated to several themes to accommodate the breadth of research necessary to address them (see Chapters 4 and 5). Six themes comprise research questions that can be addressed by building on established methods

2 There are two appendices that supplement this report. These appendices are available as one electronic document for download, free of charge, from the Council's website, www.scienceadvice.ca.

and approaches in ocean science. For each of the six themes, the Panel used bibliometric analyses and other available information to assess existing research capacity in Canada, followed by an analysis of the capacity required to address the research questions in that theme and the associated opportunities and challenges for ocean science:

- **Ocean-climate interactions** are important, yet complex, processes to capture in improved climate models.
- **Biological, mineral, and energy resources** support much of Canada's ocean economy. Understanding their supply, interactions, and methods of extraction provides direct socio-economic benefits.
- **Human impacts on marine and coastal ecosystems** result from activities such as fishing, drilling, marine transportation, land-based pollution, and coastal development.
- **Plate tectonics and natural hazards** include submarine earthquakes, volcanic eruptions, landslides, and tsunamis that are associated with plate tectonic processes.
- **Coastal communities** experience greater exposure to risks and benefits from the ocean.
- **The Arctic Ocean** encompasses aspects of other themes in the context of specific biophysical and social conditions that are being rapidly altered by global change.

Many of the 40 research questions describe future research needs or anticipate paradigm shifts and emerging approaches, making bibliometric analysis an unsuitable tool for assessing existing capacity. The Panel instead considered the conditions that support the development and adoption of emerging research methods and approaches, as indicators of existing capacity. The opportunities and challenges of identifying and developing uncertain research needs are considered under the following themes:

- **Ocean technology** benefits from basic research, and in turn enables new forms of observation and communication in ocean science.
- **Ocean governance** requires novel adaptive and participatory governance mechanisms to enable sustainable ocean management.
- **Human health and well-being** are increasingly recognized as linked to the ocean in a broader social-ecological framework.

1.4 ORGANIZATION OF THE REPORT

Chapter 2 provides an overview of the seascape of ocean science in Canada, including the key actors engaging in research, and major existing elements of each category of capacity.

Chapter 3 assesses Canada's research output and performance in ocean science compared to other leading countries, based on bibliometric analyses.

Chapter 4 discusses Canada's current research output, capacity needs, and existing capacity for the first six research themes identified by the Panel. Bibliometric analyses provide a partial snapshot of Canada's research output by theme in comparison to that of other leading countries, and identify major Canadian collaborations. These findings provide the backdrop for discussing examples of current research capacity, and anticipated capacity needs based on available evidence, and outlining key opportunities and challenges for each theme.

Chapter 5 discusses the remaining three research themes, which contain the more forward-looking research questions building on emerging research methods and approaches. Canadian and international experiences are compared in order to identify the opportunities and challenges of developing and adopting new approaches to complex research questions, and preparing for uncertain future research needs.

Chapter 6 synthesizes the findings from the previous chapters, and presents the Panel's overall conclusions and answers to the main charge and its sub-questions.

Two appendices are available as an electronic document for download, free of charge, from the Council's website, www.scienceadvice.ca. Appendix A provides details of methods used for the analyses presented in Chapter 2. Appendix B provides technical details of the bibliometric analyses performed for the report, and additional results including network indicators and analyses of Canada's international collaboration in ocean science. Appendix B also includes high-resolution collaboration network diagrams that can be magnified onscreen to explore details not visible in the print versions.

2

Canada's Capacity in Ocean Science

- Human Capacity
- Organizations, Networks, and Collaborations
- Physical and Information Infrastructure
- Funding
- Policy and Governance
- Conclusion

2 Canada's Capacity in Ocean Science

Key Findings

- Despite a steady increase in undergraduate and graduate students in many fields of ocean science in Canada from 2001 to 2009, it is unclear whether trends in human capacity are positive on balance or whether the skills needed to address the 40 research questions are available.
- Canada's ocean science seascape is diverse and dispersed, forming a network of regional clusters. The geographic distance between clusters on Canada's coasts presents challenges for collaboration.
- Canada has a substantial, but aging, research fleet.
- Canada has several world-class systems for ocean observation and monitoring, but lacks a national strategy to align its observation and monitoring efforts and establish a modern system for integrated data management and facilitated access.
- Research funding for ocean science in Canada provided through funding agencies has increased over the last 10 years, but funding for research activities excluding infrastructure operation peaked in 2008. NSERC has provided the majority of funding over this period, and CFI has made substantial additional investments in infrastructure.
- Ocean science in Canada is embedded in a context of federal and provincial legislation and policies, as well as obligations deriving from Canada's membership in international organizations and agreements.

This chapter provides an overview of Canada's existing ocean science capacity in five categories. It describes the ocean science seascape in terms of human resources; organizations and networks, including key actors and research facilities; physical infrastructure, with a focus on research vessels and observation systems; funding; and the policy and governance context.

2.1 HUMAN CAPACITY

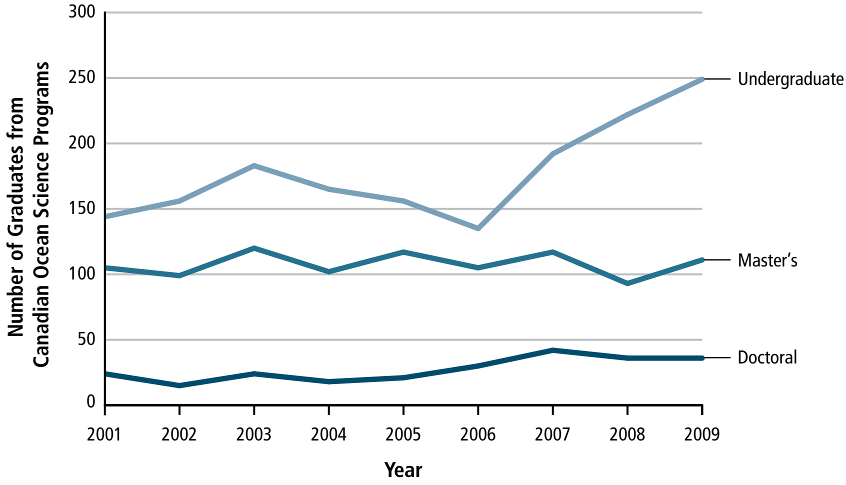
An adequate supply of people with the right skills is a key component of science capacity. While some fields, such as oceanography, are clear subsets of ocean science, it also encompasses aspects of many other research fields. Some, but not all, areas of Earth science, biology, law, and social sciences are directly relevant to ocean science. Similarly, many government departments and agencies have areas of responsibility that include, but are not limited to, the ocean. Bearing these challenges in mind, this section examines recent trends in human capacity in ocean science in Canada using the following data sources: information on post-secondary graduates in ocean science, data on researchers who have received direct funding for projects in ocean science, and data from the Canada Research Chairs (CRC) and Canada Excellence Research Chairs (CERC) programs. Although suitable for estimating general trends, the data are not structured in ways that allow assessment of capacity in specific research areas referred to by the 40 research questions or the themes identified by the Panel, nor are they sufficiently disaggregated to analyze representational factors such as gender or nationality.

2.1.1 Graduates of Post-Secondary Education Programs

The number of graduates of Canadian post-secondary institutions provides an indication of the supply of highly qualified personnel in ocean science fields in Canada. The Classification of Instructional Programs (CIP) was used to identify graduates with training relevant to ocean science, from Statistics Canada's Postsecondary Student Information System. CIP codes for fields that were unambiguously or predominantly related to ocean science were selected for analysis (see Appendix A). Although aspects of engineering, ecology, population health, legal studies, social sciences, and humanities are all directly applicable to ocean science, they are not included in this analysis because they cannot be distinguished from non-ocean-science sub-fields by available CIP codes.

The number of undergraduate degrees in identified ocean science programs increased from 2001 to 2009 (Figure 2.1), despite a temporary decline in the middle of the period (2003–2006). The number of master's degrees awarded in ocean science fields has varied little, remaining at between 90 and 120 graduates per year. Although these trends are positive, it is unclear if they represent an improvement in human capacity in ocean science in Canada. The availability of employment opportunities and suitable facilities also affects whether these graduates ultimately work as ocean scientists in Canada, or whether graduates from other fields are attracted into ocean science over the course of their careers.

The data do not indicate whether graduates are acquiring the interdisciplinary skills necessary to address many of the 40 research questions. Similarly, they are not suitable for determining if there is a surplus or shortage of particular skills required in highly specialized or emerging fields of ocean science. The increasing use of new observation technologies, for example, creates the need for technical support staff with appropriate training. The skills required may depend on available technologies and the research approaches adopted by the community, which underscores the need to consider both supply and demand for personnel with skills relevant to ocean science.



Data source: Calculated using data from Statistics Canada Postsecondary Student Information System (PSIS)

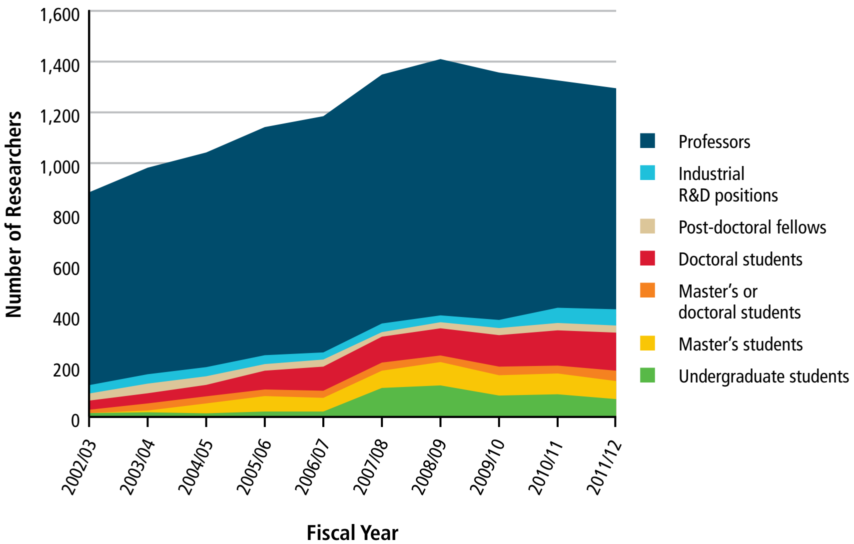
Figure 2.1

Number of Graduates from Canadian Post-Secondary Ocean Science Programs, 2001–2009

The number of students graduating from undergraduate programs declined from 2003 to 2006, but increased rapidly to 250 graduates per year in 2009. The number of master's graduates has varied only slightly at around 100 graduates per year from 2001 to 2009. The number of doctoral graduates (PhDs) has increased, but remains below 50 graduates per year.

2.1.2 Researchers Receiving Funding for Ocean Science

Data from Canadian funding agencies provide an estimate of human capacity over the previous decade (i.e., the total number of researchers, including undergraduate and graduate students, post-doctoral researchers, and faculty researchers receiving funding for research in ocean science). Funding data details are presented in Section 2.4.1. The total number of researchers supported by grants for ocean science projects from five of the largest funding agencies increased by almost 50 per cent from fiscal year 2002/03 to 2008/09, followed by a decline, particularly among professors (Figure 2.2). During the recent decline, the number of researchers supported by various Natural Sciences and Engineering Research Council of Canada (NSERC) programs for industrial research and development (R&D) actually increased slightly, along with a rise in funded doctoral students. These trends are driven primarily by changes in NSERC funding, which supports a large proportion of researchers in these data.



Data source: Calculated using data provided by NSERC, SSHRC, CIHR, CFCAS, and Genome Canada

Figure 2.2

Number of Ocean Science Researchers Supported by Selected Funding Agencies, Fiscal Years 2002/03 to 2011/12

The graph shows the number of researchers receiving ocean science grants from some of Canada's largest funding agencies, including undergraduate and graduate student scholarships, post-doctoral fellowships, and research grants to university faculty. Researchers were assigned to categories based on the target group of the program for each grant: some programs target multiple groups, such as doctoral and master's students at the same time, which meant that these researchers could not be assigned to one group or the other. Fiscal years start on April 1st and end on March 31st of the following calendar year.

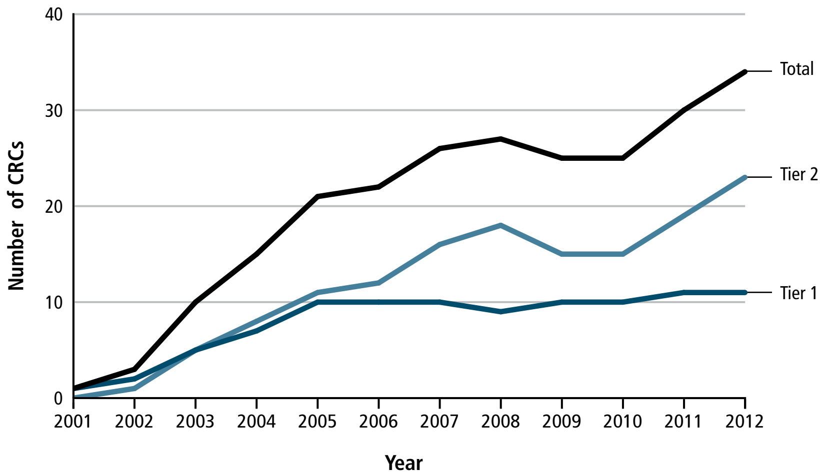
Figure 2.2 shows an increase in undergraduate students receiving funding for ocean science research projects from 2006/07 to 2008/09, followed by a slow decline, which is generally in line with the trend in undergraduate degrees displayed in Figure 2.1. The number of funded master's students and master's graduates has remained relatively stable in both data sets, apart from an increase in master's scholarships and awards from 2002/03 to 2005/06 (Figure 2.2). There are slightly fewer master's students with direct funding than those graduating over the 2002–2009 period (the years common to both data sets). A possible reason for this difference is that most graduate students receive funding directly from their supervisors or university scholarships, or support their research through teaching assistantships and other sources.

The data indicate an increase in both active doctoral students (Figure 2.2) and doctoral graduates (Figure 2.1) over the previous decade. The number of doctoral students receiving funding for ocean research is at least double that of graduated doctorates in ocean science programs over a similar period. A PhD is counted only once upon completion, whereas a doctoral student receiving funding may be counted several times over the duration of their studies. Allowing for a lag between research funding and degree completion, these data suggest a continual increase in graduated PhDs in ocean science for the next three to five years. Counts may also differ between data sets as a result of differences in methodology used to delineate ocean science from other fields, students supported by other sources of funding, or students receiving funding but not graduating.

2.1.3 Canada Research Chairs and Excellence Research Chairs in Ocean Science

Several specialized funding programs in Canada can indicate numbers of top ocean scientists. The CRC program offers two levels of funding: Tier 1 Chairs for outstanding researchers in their field, and Tier 2 Chairs for exceptional emerging researchers. A list of Chairs in ocean science was compiled by using similar search terms to those used by funding agencies (see Section 2.4.1), matched to titles and keywords in the CRC program database. Since the start of the program in 2000, 21 Tier 1 Chairs and 44 Tier 2 Chairs have been awarded to leading ocean scientists in Canada, representing three per cent and five per cent, respectively, of Chair positions filled. The number of active Tier 1 positions in any given year has hovered around 10 since 2005, while the number of Tier 2 Chairs in ocean science surpassed 20 in 2012 (Figure 2.3). This represented $4.5 million in funding for excellence in ocean science in 2012 alone.

The CERC program, launched in 2008, aims to attract leading international scientists to Canada by providing research funds of up to $10 million over seven years (CERC, 2013b). Of the initial 18 CERCs announced in 2010, 4 (22 per cent) were awarded to researchers in ocean science (CERC, 2013a), demonstrating the program's success in attracting international leading ocean scientists to Canada. It was not possible to determine the number of leading Canadian ocean scientists who have moved to other countries in recent years.



Data source: Calculated using data provided from the Canada Research Chairs program

Figure 2.3

Number of Active Canada Research Chairs (CRCs) in Ocean Science, 2001–2012

Chairholders were classified as "active" in a given calendar year between the start and end dates of their awards if the start date was in the first half of that year, or the end date in the second half (to avoid double-counting positions that were renewed or "advanced" from a Tier 2 to a Tier 1 Chair in a given year). Since the start of the program in 2000, the number of Tier 2 Chairs in ocean science has increased, while the number of active Tier 1 Chairs in ocean science has stabilized at around 10 since 2005. This represents five per cent and three per cent, respectively, of all filled Chair positions (CRC, 2013a).

2.2 ORGANIZATIONS, NETWORKS, AND COLLABORATIONS

This section describes the key actors and their activities in ocean science in Canada. Figure 2.4 displays the locations of Canada's major ocean science institutions and organizations. The figure shows a decentralized structure of regional clusters, which reflects the importance of local and regional expertise. Canada's vast coastline and three ocean basins create a unique challenge, intensified by Canada's small, dispersed population. Nevertheless, a wide variety of organizations contribute to ocean science across the country.

Figure 2.4

Locations of Major Ocean Research Facilities and Organizations in Canada

Although many facilities and organizations are located along Canada's coasts, other centres also occur farther inland, sometimes in association with other related facilities. Many smaller facilities are located throughout the Arctic, but are not shown on this map.

* Note: Many federal departments have offices in Ottawa-Gatineau (e.g., DFO, Canadian Hydrographic Service, Environment Canada, NRCan, and NRC), where much of the science conducted elsewhere is translated into policy and decision-making advice.

LEGEND

EXCLUSIVE ECONOMIC ZONE (EEZ)	
TECHNOLOGY CLUSTERS	
●	Pacific Ocean Technology Cluster (Vancouver and Victoria, BC)
◢	Technopole Maritime du Québec (Marine Resource, Science and Technology Cluster) (Rimouski, Mont-Joli, Rivière-du-Loup, Gaspé, Baie-Comeau, and Sept-Îles, QC)
⬢	Halifax Ocean Technology Cluster (Halifax, NS)
■	St. John's Ocean Technology Cluster (St. John's, NL)

GOVERNMENT INSTITUTIONS

UNIVERSITY INSTITUTIONS

OTHER INSTITUTIONS

1	**Vancouver Island, BC**
	Bamfield Marine Science Centre
	BC Centre for Aquatic Health Science
	Canadian Centre for Climate Modelling and Analysis (Environment Canada-UVic)
	Institute of Ocean Sciences (DFO)
	Pacific Biological Station (DFO)
	Pacific Geoscience Centre (NRCan)
	Ocean Networks Canada (ONC) (UVic)
	University of Victoria (UVic)
	Vancouver Island University
2	**Vancouver, BC**
	Centre for Aquaculture and Environmental Research (DFO-UBC)
	Simon Fraser University
	University of British Columbia
3	**Edmonton, AB**
	University of Alberta
4	**Winnipeg, MB**
	Freshwater Institute (DFO)
	University of Manitoba
5	**Toronto, ON**
	University of Toronto
6	**Ottawa, ON/Gatineau, QC***
	Canadian Hydrographic Service (DFO)
	Integrated Science Data Management (DFO)
	Marine Performance and Evaluation Testing Facilities (NRC)
	National Offices of DFO, Environment Canada, NRCan and NRC
7	**Montréal, QC**
	McGill University
8	**Québec City, QC**
	Université Laval
9	**Rimouski and Mont-Joli, QC**
	Maurice Lamontagne Institute (Mont-Joli) (DFO)
	Université du Québec à Rimouski
10	**Saint Andrews and Saint John, NB**
	Huntsman Marine Science Centre
	St. Andrews Biological Station (DFO)
	University of New Brunswick
11	**Moncton, NB**
	Gulf Fisheries Centre (DFO)
12	**Charlottetown, PE**
	Charlottetown Aquatic Animal Pathogen Biocontainment Laboratory (DFO)
	University of Prince Edward Island
13	**Dartmouth and Halifax, NS**
	Atlantic Storm Prediction Centre, and National Laboratory for Marine and Coastal Meteorology (Environment Canada)
	Bedford Institute of Oceanography (DFO, Environment Canada, NRCan)
	Centre for Marine Environmental Prediction (CMEP) (Environment Canada)
	Dalhousie University
	Defence Research and Development Canada (DRDC) Atlantic
	Halifax Marine Research Institute (Dalhousie University)
	Saint Mary's University
14	**St. John's, NL**
	Marine Performance and Evaluation Testing Facilities (NRC)
	Memorial University of Newfoundland
	Northwest Atlantic Fisheries Centre (DFO)
	Ocean Technology Enterprise Centre (NRC)
15	**Cambridge Bay, NU**
	Canadian High Arctic Research Station (AANDC—Planned)

2.2.1 Federal Government Departments and Agencies

To identify federal activities, the Panel drew on *Federal S&T Map: Oceans Science Case Study*, an existing "map" of ocean science and technology in federal departments and agencies (GC, 2010). Although the map does not cover all themes discussed in this report, it provides the best available overview of the departments and agencies engaged in ocean science and the kinds of research in which they participate.[3] While information on individual programs and initiatives may be out of date, the summary provides a useful overview of the areas in which government departments contribute to ocean science.

Fisheries and Oceans Canada (DFO), Environment Canada, and Natural Resources Canada (NRCan) are the most active performers of research relevant to the 40 research questions (as described by the themes in Chapter 4). The National Research Council of Canada (NRC) also played an important role in many areas at the time this report was published, although its role may be changing as a result of recent restructuring. Almost all of the 12 departments and agencies included in the ocean science technology map contribute to research relating to the 40 research questions, such as pollutants, waste, and harmful substances, as well as safe food and water. The number of departments and agencies with a role in ocean science and technology reflects the breadth of the 40 research questions, as well as the wide distribution of the capacity to address these questions across many agencies with specialized abilities.

2.2.2 Provincial and Territorial Governments

Provincial and territorial governments support ocean science through different mechanisms and, as a group, represent the largest funding source for university education and research. In 2009 the provinces provided 46 per cent of total university revenues in Canada (Statistics Canada, 2009). Many provincial governments support specialized education programs that contribute to human capacity in ocean science, as well as physical institutions, such as museums or aquariums that serve as venues for education and research. Provincial government departments are also major partners in consortia for large-scale investments in physical research infrastructure.

For example, the Fonds de recherche du Québec – Nature et technologies funds three strategic clusters with an ocean-related research mandate, including Québec-Océan, which coordinates the efforts of oceanographers from six universities and one federal institute in Quebec (Québec-Océan, 2013). The British Columbia Knowledge Development Fund is a major funder of Ocean

3 See Appendix A for a summary of the activities described in the map that are relevant to the research themes identified by the Panel.

Networks Canada (ONC) and the NEPTUNE and VENUS observatories (see Box 4.3), the Bamfield Marine Sciences Centre, Genome BC, and several BC Leadership Chairs on ocean science. New Brunswick funds the New Brunswick Aquarium and Marine Centre, and is a supporter of the Huntsman Marine Science Centre. Nova Scotia is a major funder of the Fundy Ocean Research Centre for Energy (FORCE) (see Section 4.2.2).

The provinces also support applied research, innovation, and technology development in areas important for economic development, such as fisheries and aquaculture, offshore conventional or renewable energy, and marine biotechnology. Newfoundland and Labrador, Nova Scotia, British Columbia, and Quebec, for example, support the development of ocean technology clusters to advance applied research in these areas (see Box 5.2). Many provincial departments also conduct science activities in support of conservation and sustainable management, such as identifying and monitoring protected areas, risk assessment, and monitoring environmental impacts of human activities.

The governments of Canada's three territories maintain colleges for education and research that also provide services and support for research projects in the territories (Nunavut Arctic College, Yukon College, and Aurora College). The territories also regulate access to research sites and administer research programs that support their responsibilities in wildlife management and sustainable resource development.

These are just a few illustrative examples of how provincial governments and other institutions contribute to ocean science. The level of activity varies with geographic location, size, and priorities; nevertheless, the examples show that provincial governments and associated institutions are major sources of funding and act as important partners for research in ocean science (for additional examples, see DFO, 2009b).

2.2.3 Universities and Colleges

After federal government departments, universities are the second most important producers of research output in ocean science (see Chapter 3). More than half of Canadian universities engage in ocean science activities. Colleges have an important role in educating highly qualified personnel and conducting applied research relevant to ocean science. Due to the multidisciplinary character of the field, ocean scientists work in many different departments, and in disciplines that include research outside of ocean science. This makes it difficult to evaluate the level of activity and thematic focus of university engagement in ocean science, according to the broad definition used in this report.

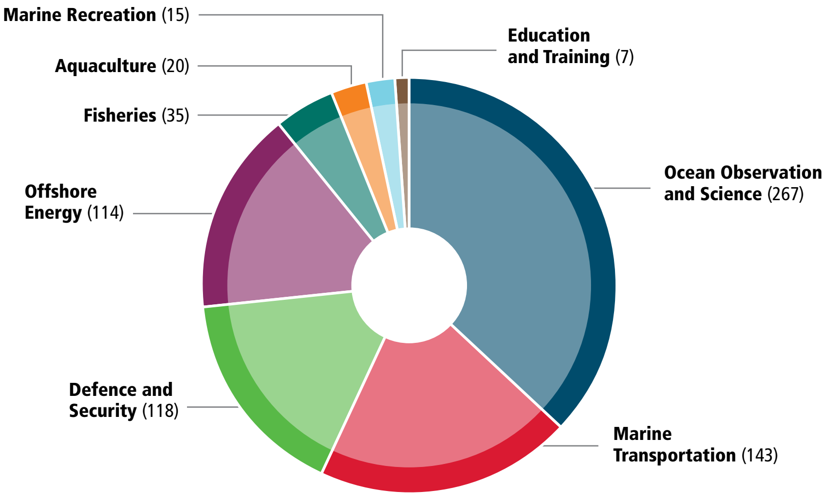
The Panel could not identify any prior inventories or evaluations of ocean science activities by post-secondary institutions. Therefore, a request for information was sent to the 20 Canadian universities with the highest output in ocean science. Universities were asked whether they had produced inventories, reports, or any other documents about their activities in ocean science from which information about capacity could be extracted. If no such inventories were available, the universities were asked to submit a summary of their institutes or departments engaged in ocean science, the focus of research, key elements of infrastructure, and sources of funding.

Eleven universities responded to the request, but only five were in a position to submit comprehensive information. This return was insufficient to perform a detailed assessment of university activities and capacities. The response rate suggested that, with few exceptions, Canadian universities do not systematically collect information about their capacity and performance in ocean science, or basic data such as the number of researchers or students in ocean science. Furthermore, the information that universities present in their strategic plans is not sufficiently detailed to allow for an analysis of capacity.

2.2.4 Private Sector

Much of Canada's ocean science takes place in the private sector, particularly the areas of defence and security, offshore energy (see Section 4.2), and marine transportation. A feature of the ocean science seascape in Canada is the large number of small and medium-sized enterprises that engage in the development of technologies for ocean research and observation.

In 2011 Industry Canada, in collaboration with the Oceans Science and Technology Partnership (OSTP), released an interactive map and inventory of organizations active in ocean technology. The inventory comprises 719 listings across various industries, with up to three listings per company. More than one-third of all listings (37 per cent) is in the "ocean observation and science" category (Figure 2.5). Technology demand is driven to a large extent by the offshore oil and gas industry, whose expenditures account for 43 per cent of domestic spending on ocean technology (Industry Canada, 2012). The development of technology for ocean observation is a Canadian strength, in both science capacity and market development and technology transfer (see Section 5.1).



Data source: Cinmaps (2013)

Figure 2.5

Number of Private-Sector Organizations by Ocean Technology Sector in Canada

Over one-third of ocean technology firms are in the category "ocean observation and science." The inventory of ocean technology firms includes 719 listings in total. Organizations self-register to the database, and can be listed in up to three different categories.

2.2.5 Non-Governmental Organizations

Non-governmental organizations play an important role in contributing to ocean science, and mobilizing scientific and other knowledge for action. The National Framework for Canada's Network of Marine Protected Areas, for example, recognizes NGOs as a stakeholder in marine protected areas, and their role in developing conservation and management plans (GC, 2011). NGOs also provide expertise based on scientific and other information, such as traditional ecological knowledge, for decision-making relating to ocean conservation and ecosystem management. An example of recent collaboration between DFO and NGOs includes a multi-year project to study the past, present, and future health of Pacific salmon using epidemiological assessments and new genomic technologies, involving DFO, the Pacific Salmon Foundation, and Genome British Columbia (Genome BC, 2013). International NGOs, such as the International Union for the Conservation of Nature (IUCN), Conservation International, and the Pew Trust Institute of Ocean Science, provide science-based advice for international environmental governance. The Ramsar Convention on Wetlands, for instance, recognizes Birdlife International, Wetlands International, and other NGOs as equal partners next to country delegates (Ramsar Convention on Wetlands, 1987).

Other NGO contributions include the development of frameworks and guidelines for implementation (see, for example, CEC, 2012). Through these activities, NGOs provide important channels for scientists to interact and collaborate with other scientists, decision-makers, and practitioners. This dialogue with various user communities in turn informs the setting of research priorities and the development of collaborative research endeavours (Gemmill & Bamidele-Izu, 2002; Calado *et al.*, 2012).

NGOs are also increasingly involved in research activities, such as generating data through monitoring programs or enabling public engagement through citizen science approaches. The Vancouver Aquarium, for example, maintains a cetacean sightings network in collaboration with DFO and the Government of British Columbia, through which anybody can report sightings of whales, dolphins, or porpoises for environmental monitoring and scientific research (Vancouver Aquarium, 2013).

2.2.6 Networks and Collaborations

Scientists collaborate in many ways, including co-authoring publications, participating in joint research projects, or engaging in longer-term arrangements such as research groups or virtual networks of expertise that include researchers from several institutes or departments. The geographically dispersed nature of ocean science in Canada creates challenges for collaboration at the national level and for the management of certain types of infrastructure. Collaborations and networks can address some of the challenges arising due to geographical dispersion; however, collaboration still generally increases with physical proximity (Colbourne, 2006; Doloreux & Melançon, 2008; Westnes *et al.*, 2009). Intranational research collaboration is inherently more difficult and costly in large countries like Canada than in smaller countries like the United Kingdom, France, or Norway. DFO plays an important role in overcoming these challenges with its regional approach, and its role as manager of the research fleet and major data sets and as provider of other physical and information research infrastructure.

The network graphs developed as part of the bibliometric analyses presented in Chapter 3 provide insights into the collaborative relationships within Canada as well as with international institutions. Similar analyses presented throughout Chapter 4 give insights into collaborations in the respective themes. This section focuses on more formal large-scale networks and other collaborative arrangements.

NSERC Strategic Network Grants support research in areas that could strongly enhance Canada's economy, society, or environment (NSERC, 2013a). Currently active strategic networks addressing issues in ocean science include the Canadian

Healthy Oceans Network (CHONe), the Canadian Fisheries Research Network (CFRN), the Canadian Aquatic Invasive Species Network (CAISN), the Canadian Barcode of Life Network, and the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN). NSERC also funds the network component of the Ocean Tracking Network (OTN), hosted at Dalhousie University, to complement a Canada Foundation for Innovation (CFI) grant for innovative acoustic sensing infrastructure (see Box 2.1).

Networks of Centres of Excellence of Canada (NCE) aim to mobilize Canada's best research, development, and entrepreneurial expertise for specific issues and strategic areas (NCE, 2011). The currently active ocean-related NCEs are ArcticNet; the Marine Environmental Observation Prediction and Response Network (MEOPAR); the Ocean Networks Canada Centre for Enterprise and Engagement (ONCCEE); and Leading Operational Observations and Knowledge for the North (LOOKNorth). The NCE program includes Knowledge Mobilization Networks, Centres of Excellence for Commercialization, and Business-led Networks of Centres of Excellence. It primarily provides funding for research and commercialization activities. Host institutions must provide office space, telecommunications, and other administrative services, which require additional funds and administrative capacity. Other important networks include the Centre for Occupational Health and Safety Research of Marine and Coastal Work (SafetyNet), funded as a Community Alliance for Health Research by the Canadian Institutes of Health Research (CIHR) and Coasts Under Stress (2000-2005), which was funded as a joint initiative by NSERC and Social Sciences and Humanities Research Council of Canada (SSHRC).

The overall impact of NSERC Strategic Networks and NCEs on ocean science has not yet been evaluated. They reflect innovative approaches to scientific collaboration across disciplines and with other stakeholders such as industry, environmental organizations, and local and aboriginal communities. The expected benefits reach beyond the production of scientific knowledge and include tangible benefits of ocean science to society.

The main Canadian scientific organization in ocean science is the Canadian Meteorological and Oceanographic Society (CMOS). At this time, no single academic organization includes all disciplines contributing to ocean science. Major international scientific organizations with Canadian participation include the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific, and Cultural Organization (IOC/UNESCO); the Scientific Committee on Oceanic Research (SCOR) and its Canadian committee affiliated with CMOS; the International Council for the Exploration of the Sea (ICES); the North Pacific Marine Science Organization (PICES); and the U.S. Consortium for Ocean Leadership.

Canadian researchers also participate in and often lead international collaborative initiatives and research projects that bring together ocean researchers from around the world. Some current and recent examples of organizations with Canadian leadership or strong Canadian involvement include the Census of Marine Life, the OTN, and the International Geosphere-Biosphere Programme (IGBP) and its core projects, such as the Joint Global Ocean Flux Study, the Global Ocean Ecosystem Dynamics Project (GLOBEC), the Integrated Marine Biochemistry and Ecosystem Research (IMBER) Project, and the Surface Ocean Lower Atmosphere Study (SOLAS).

Technology clusters are alignments of industry, academia, and government that form a hub for innovation in research and development. Technology clusters have various governance structures, but often form a hub in areas with a high density of research institutes, physical research infrastructure, and a pre-existing group of technology companies (see Section 5.1).

While many of the networks and collaborations noted above include scientists from across the country, no network, body, or forum currently represents the ocean science community in Canada as a whole. Many other countries have an institutional mechanism or organization that fulfils this role. Despite their various institutional forms, these mechanisms commonly provide leadership and coordination for the national ocean science community. In addition, many of these organizations provide fora for developing a national vision and strategic plan for ocean science. Some examples of such mechanisms and their institutional structure include the following:

- In the United States, the Ocean Studies Board of the National Academies provides a forum to explore science, policies, and infrastructure needed to understand, manage, and conserve coastal and marine environments and resources. The board takes a leadership role within the ocean science community and conducts studies on specific issues, either upon request by federal agencies or other sponsors, or on its own initiative (NAS, 2013).
- The German Research Foundation (Deutsche Forschungsgemeinschaft; DFG), Germany's principal granting council for academic research, maintains a permanent commission that plans and coordinates DFG activities in ocean science. Among other activities, the commission publishes reports on the state of ocean science and analyses of research needs, as well as strategic and policy papers (DFG, 2012).

- While no permanent body exists in the United Kingdom, the Marine Science Coordination Committee brought together the key ocean science stakeholders to develop the U.K. Marine Science Strategy (DEFRA, 2010).
- The Australian Marine Sciences Association (AMSA) aims to advance marine sciences and promote cooperation among diverse organizations from all disciplines involved in ocean science. AMSA also publishes regular policy papers and submissions on the role of marine science in specific policy areas (AMSA, 2013).
- The European Marine Board serves as a platform for European research councils and marine science organizations to develop common priorities and strategies for marine science in Europe and facilitate cooperation among marine science stakeholders (European Marine Board, 2013b).

2.3 PHYSICAL AND INFORMATION INFRASTRUCTURE

Much of ocean science is technology-intensive and often depends on the availability of large-scale infrastructure, making it similar to other "big science" disciplines such as high energy physics and space exploration. In addition, many researchers in ocean science depend on the availability of research vessels and other mobile or fixed platforms for access to the sea. Although the use of remote and automated systems for ocean observation and data collection has expanded rapidly in past years, these systems still depend on a foundation of ships, as well as the human capacity to design, build, deploy, and maintain them in the ocean (National Research Council, 2011).

Ocean observation is at the brink of a technology revolution driven by the emergence of powerful new technologies in fields such as nanotechnology, biotechnology, information technology, computational modelling, imaging technologies, and robotics. While most of these developments originate outside of ocean science, their convergence is creating a new generation of observation tools that will greatly expand access to the ocean and enable observation at much larger spatial and temporal scales (Delaney & Barga, 2009).

New *in situ* chemical and biological sensors and automated sampling devices can be mounted on autonomous platforms that travel the ocean for months without human intervention. They transmit data via satellite, and greatly increase the frequency and density of observations (Valdès *et al.*, 2010). New generations of remotely operated vehicles (ROVs) allow observations, manipulations, and experiments in previously inaccessible areas at much lower cost than human-operated submersibles. Cabled networks that provide power and bandwidth to sub-sea nodes create a new form of human telepresence in the ocean that allows researchers from all over the world to take continuous and concurrent measurements of physical, chemical, biological, and geological processes, and to witness short-lived events such as the eruption of a sub-sea volcano that could previously only be observed by chance (Delaney & Barga, 2009; Taylor, 2009).

These developments are creating enormous opportunities for ocean science. More frequent and spatially dense observations can increase understanding of how changes in climate and ecosystem functioning affect different levels of biological organization (Valdès *et al.*, 2010). They are also instrumental in validating and improving models of ocean-climate interactions, thereby enabling better forecasts of changes in climate, weather, and sea ice. Telepresence also enables new ways to engage the public in research activities through "citizen science" (Hand, 2010). Digital Fishers, for example, invites members of the public to participate in the recording of marine species using video observations provided by the NEPTUNE cabled network (Digital Fishers, n.d.).

The availability of smaller autonomous platforms such as autonomous underwater vehicles (AUVs) and gliders greatly reduces the cost of access to observation and sampling to a level at which they can be purchased and customized by individual researchers (Kintisch, 2013), if the necessary technical staff and support infrastructure are available. Some of the 40 research questions address the development of these new technologies and their application (see Section 5.1), while many others anticipate the ability to expand monitoring and observation to unprecedented scales.

2.3.1 Research Vessels

New technologies can greatly facilitate access to the ocean and increase the range and efficiency of larger platforms; however, they do not replace the need for ships (National Research Council, 2011; Kintisch, 2013). Many researchers still need to go to sea to deploy and recover autonomous systems, and some observations and samples can only be collected by human-operated equipment. Specialized vessels are necessary to install and service fixed platforms such as cabled networks or moored floats. The increasingly rapid pace of technology development therefore poses a challenge to fleet planning and management (National Research Council, 2009). Given a lifespan of several decades for most ships, future demand, use, and technology requirements can be difficult to anticipate in ship design and construction.

The Canadian Coast Guard (CCG), a specialized operating agency of DFO, operates Canada's civilian fleet and provides maritime services. The CCG's mandate includes ensuring safe and accessible waterways by providing aids to navigation, search and rescue, icebreaking, marine environmental response, and many other services. The CCG fleet comprises 120 vessels, 20 of which are dedicated entirely to ocean research (Table 2.1). Furthermore, 5 icebreakers and 11 multi-purpose vessels have some science capacity, but are mainly used for other CCG missions (CCG, 2012b). In addition to the CCG vessels, Defence Research and Development Canada (DRDC) operates *CFAV Quest*, a purpose-built military research ship designed as an ice-strengthened, quiet surface vessel (DRDC, 2012). Data collection is also performed using other ships whose primary function is not research, such as commercial fishing vessels or other "ships of opportunity" that provide voluntary observations during their regular operation (see, for example, JCOMMOPS, 2008).

Access for internal and external (i.e., non-DFO) clients to CCG vessels is granted on a cost-recovery basis, subject to regional availability and according to program priorities (CCG, 2011). Researchers must apply separately for funding to cover these costs. NSERC provides funding to holders of NSERC Discovery Grants to access DFO (i.e., CCG) or other vessels (NSERC, 2012a). A notable exception to this process is the research icebreaker *Amundsen*, which is managed by a consortium of Canadian universities and ArcticNet, based on a cost-sharing agreement with the Government of Canada (CCGSAS, 2013b) (see Box 4.6).

The CCG does not consistently monitor the actual capacity or utilization of the fleet, making it difficult to assess whether available resources are used efficiently and meet researchers' needs (DFO, 2012c). The age of the fleet has repeatedly given rise to concerns about the CCG's ability to continue meeting research needs (OAG, 2007; Arctic Council, 2009). In 2009/10, more than 70 per cent of CCG vessels had passed the halfway mark of their anticipated life cycle (CCG, 2010, 2012e). Aging vessels and deteriorating shore-based infrastructure lead to more breakdowns, higher costs, and operational days lost due to maintenance (CCG, 2010). From 2006/07 to 2010/11, planned and delivered operational days for science declined every year but one (Figure 2.6). Over this period, five per cent of planned days were not delivered, with the shortfall due to vessel breakdowns, weather delays, and changes in client priorities (CCG, 2011).

Table 2.1

Canadian Coast Guard Ships (CCGS) Dedicated to Ocean Research

Vessel Type	Vessel Name	Home Region	Year	Age (years)	Length (m)	Range (nautical miles)	Endurance (days)
Medium Icebreaker	*Amundsen**	Quebec	1979	34	98.2	35,000	100
Offshore Oceanographic Science	*John P. Tully*	Pacific	1984	29	65.7	12,000	50
	*Hudson***	Maritimes	1963	50	90.4	23,100	105
Offshore Fishery Science**	*Alfred Needler*	Maritimes	1982	31	50.3	3,000	30
	Teleost	Newfoundland and Labrador	1988	25	63.0	12,000	42
	W.E. Ricker	Pacific	1978	35	58.0	6,000	50
Midshore Science***	*Otter Bay*	Pacific	1992	21	13.4	250	5
	Matthew	Maritimes	1990	23	50.3	4,000	20
	Frederick G. Creed	Quebec	1988	25	20.4	870	3
	Vector	Pacific	1967	46	39.7	3,500	16
Nearshore Fishery Research***	*M. Perley*	Maritimes	2012	1	22.0	12,000	7
	Leim	Quebec	2012	1	22.0	12,000	3
	Vladykov	Newfoundland and Labrador	2012	1	25.0	1,800	8
	Neocaligus	Pacific	1989	24	18.8	–	–
	Calanus II	Quebec	1991	22	19.9	2,000	30
	Opilio	Maritimes	1989	24	18.2	800	4
	Shamook	Newfoundland and Labrador	1975	38	24.9	2,500	5

continued on next page

Vessel Type	Vessel Name	Home Region	Year	Age (years)	Length (m)	Range (nautical miles)	Endurance (days)
Specialty (Multi-disciplinary and Hydrographic Science)***	*Viola M. Davidson*	Maritimes	2010	3	18.0	–	–
	F.C.G. Smith	Quebec	1985	28	34.8	1,500	7
	G.C. 03	Quebec	1970	43	18.5	400	5

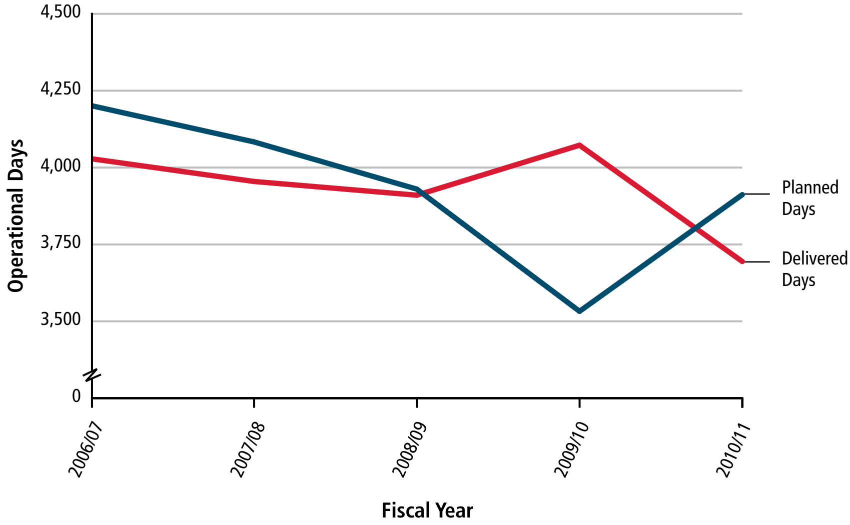
(CCG, 2012b)

"Year" represents the year a vessel was launched; the age of each vessel is as of 2013.

* *CCGS Amundsen* is allocated to icebreaking services during the winter and to research during the summer, except for years in which it performs science missions that require overwintering in the Arctic.

** The National Shipbuilding Procurement Strategy (NSPS) includes construction of one Offshore Oceanographic Science vessel to replace *CCGS Hudson*, and three replacement Offshore Fishery Science vessels (PWGSC, 2013).

*** DFO recently announced funding of $488 million to procure 18–21 new Coast Guard vessels, including an unspecified number of Midshore Science, Nearshore Fishery Research, and Channel Survey and Sounding vessels (DFO, 2013e).



Data source: CCG (2011). Fisheries and Oceans Canada.
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Figure 2.6

Number of Canadian Coast Guard Operational Days Allocated to DFO Ecosystems and Oceans Science, 2006/07 to 2010/11

The number of planned and delivered operational days allocated by the Canadian Coast Guard to DFO Ecosystems and Oceans Science gradually declined between 2006/07 and 2010/11. Over this period, 95 per cent of planned operational days were delivered. The five per cent under-delivery was primarily due to vessel breakdowns, weather delays, and changes in client priorities.

In 2012 the ongoing fleet renewal process was complemented by a decision under Canada's Economic Action Plan to replace three offshore fishery science vessels, one offshore oceanographic science vessel, and a polar icebreaker that will include scientific equipment and facilities (CCG, 2010, 2012d). While the primary goal of the fleet renewal is to "maintain current programs and services" (CCG, 2012c), the investment also offers an opportunity to expand capacity by better aligning vessel specifications and equipment with the science needs of DFO and other CCG clients.

Comparisons with the research fleets of other countries based on the number of vessels alone are of limited value because this is only one factor affecting the supply and accessibility of ship time for researchers. Other factors include scientific equipment, home port and area of operations, the number of days of suitable weather conditions per year, operational cost, and the efficiency and transparency of the process for submitting and evaluating applications for ship time. The most adequate criterion for assessing fleet capacity would be the ratio between supply of and demand for ship time in specific regions and for specific purposes. In Canada no data are currently available that would allow an appropriate estimation of supply and demand for ship time. A comparison with other countries does nonetheless reveal important differences in the governance of research fleets and the management of ship time.

While the CCG acts as owner, operator, and manager of many research vessels in Canada, these functions are often separated in other countries, allowing for consortia or other scientific organizations to become involved in the management and allocation of ship time.

The following examples show that governance models for ownership, operation, and management of research fleets vary by country. Ownership and operation of large research vessels demand substantial physical and human infrastructure beyond the capacity of many research institutions. This leads to a separation of supply of and demand for ship time among different organizations (such as the CCG and university research institutes). The arrangements described below are examples of mechanisms that can bridge this divide and provide direct access to ship time for researchers, increase efficiency in allocating ship time, facilitate international cooperation and exchange of research infrastructure, and inform decisions on future infrastructure investments.

- In the United States, the University National Oceanographic Laboratory System (UNOLS) provides access to a total of 23 research vessels owned by the U.S. Navy, the National Science Foundation, and other institutions, including three icebreakers owned and operated by the U.S. Coast Guard (UNOLS, 2004). In addition, the National Oceanographic and Atmospheric Administration (NOAA) manages its own fleet of 17 vessels (NOAA, 2013).
- The German Research Vessels Portal provides access to information on seven large research vessels owned by the German federal or provincial governments or private owners. The portal is maintained by an arms-length organization acting on behalf of several research institutions, the German Federal Ministry of Education and Research, and the German Research Foundation (Portal deutsche Forschungsschiffe, n.d.).
- The Institute of Marine Research (IMR) in Norway provides access to five large research vessels owned by IMR, other research institutions, or the Norwegian government (IMR, 2011).

- In Europe, the Eurofleets project has developed a virtual platform and database providing information from 28 countries about research vessels, cruise programs, and cruise summary reports. The system aims to develop a dynamic project for cruise planning, and the exchange and use of large instruments. While not yet fully operational, researchers can currently use the database to search for information on research vessels, including available slots for upcoming cruises. The Eurofleets portal uses this information to facilitate more efficient and harmonized planning of research infrastructure use with the aim of promoting a more coherent, pan-European approach to infrastructure policy (Eurofleets, n.d.).

2.3.2 Observation and Information Infrastructure

As noted above, technologies for ocean observation are evolving rapidly, providing unprecedented opportunities. Ocean observing systems are a combination of physical and information infrastructure. They deliver important baseline and contextual data for more specific research questions. Canada is home to several cutting-edge observation systems (Box 2.1), as well as many other observation efforts at different scales and pursuing diverse objectives. Canada also contributes to several components of the Global Ocean Observing System (GOOS), including the OTN and the Argo network of autonomous floats. Canada's participation in the U.S. Integrated Ocean Observing System (IOOS) is currently limited to the North-East Atlantic Component (NERACOOS), with a small number of stations covering only a fraction of Canada's coastal and ocean area.

A recent study by DFO and the OSTP identified 67 unique ocean observation systems, most of which maintain publicly accessible websites (OSTP, 2011b). The report noted that most Canadian ocean observing systems focus on meeting specific local or regional information needs, to which data and information output is tailored. While the report identified a leadership role for Canada in innovation and technology development for observation, it pointed out that this innovation is not being effectively used across government operations, and that existing opportunities to augment ocean observation data through integration with remote sensing data are currently not being exploited (OSTP, 2011b). A parallel study that evaluated the environmental, economic, and societal value of ocean observing systems identified a need for a national strategy to maximize the benefits of investments in ocean observing systems (OSTP, 2011a).

Advances in ocean observation and the increasing amount of data available place new demands on information infrastructure to store and handle increasingly large and complex data sets from different sources and to provide timely access for different users (Baker & Chandler, 2008; DFO, 2008b; Hall *et al.*, 2009; Ribes & Lee, 2010). In addition, use of data by scientists is changing. Rather

Box 2.1
Highlights in Ocean Observation

Recent highlights of Canadian and international observation initiatives:

- **Argo** is a global array of more than 3,500 automated floats that transmit data via satellites. The system covers almost the entire global ocean, with the notable exception of the Arctic. Canada is contributing about one-tenth of the active Argo floats and was one of the early developers of the Argo Software System (Argo, n.d.).
- The **Ocean Tracking Network (OTN)**, based at Dalhousie University, collects data on sea animal movements in relation to the physical characteristics of the surrounding ocean. It uses a global network of acoustic receivers to track individual tags attached to a variety of aquatic species (OTN, n.d.).
- The **Census of Marine Life** (2000–2010) used human-operated vehicles (HOVs), ROVs, AUVs, and towed platforms in a concerted effort to establish a baseline of marine biodiversity (Snelgrove, 2010).
- The **Ocean Networks Canada** (ONC) observatory combines the North-East Pacific Undersea Networked Experiments (NEPTUNE) and the Victoria Experimental Network Under the Sea (VENUS) into one of the world's most potent cabled networks (Taylor, 2009).

than collecting additional data, mining the data provided by observing systems is becoming increasingly important in ocean science. As more and more data are being shared among researchers internationally, interoperability and accessibility of data are becoming priorities for information infrastructure (Delaney & Barga, 2009).

In Canada the DFO Integrated Science Data Management (ISDM) program has the mandate to manage, archive, and provide access to ocean data collected through federal programs or acquired through government participation in international initiatives. ISDM also serves as the Canadian national oceanographic data centre for the International Oceanographic Data and Information Exchange (IODE) of the IOC under UNESCO. While scientists frequently use ISDM, the Panel could not find any systematic evaluation of its performance. ISDM does not include resource and socio-economic data, most of which is stored in other DFO databases. Outside of ISDM, there are many other data repositories, including the DFO/NRCan Geosciences for Oceans Management Program, and the geophysical data sets of the Offshore Petroleum Boards of Newfoundland/Labrador and Nova Scotia and the National Energy Board for offshore drilling in the Arctic.

2.4 FUNDING

This section assesses trends in public funding for university-based ocean science using available data from funding agencies, followed by a brief analysis of science spending by DFO. This section focuses on the two most important sources of public spending on ocean science at the federal level. Data on ocean science funding from other federal or provincial government departments, private foundations, or R&D spending in the private sector could not be accessed, and so are not included in the analyses. The results should therefore be seen as a minimum estimate of spending on ocean science.

2.4.1 Support from Major Funding Agencies

In fiscal year 2010/11 funding from major federal agencies accounted for 27.3 per cent of university spending on research in all disciplines (Statistics Canada, 2013). This was the second largest share after spending from university budgets (44.2 per cent), followed by provincial governments (10.6 per cent), private not-for-profit organizations (9.1 per cent), and business enterprise firms (7.5 per cent). Spending by universities typically includes salaries for professors and full-time researchers, and costs of basic infrastructure such as office and lab space. Spending on university-based research by other sources includes higher shares of spending on specialized infrastructure and direct research costs, but may also include a proportion of project-specific salaries. While the shares of funding sources vary by discipline, it can nonetheless be assumed that the data used in this analysis cover approximately one-quarter to one-third of total university spending on ocean science. Information from the following funding agencies was analyzed to estimate federal funding provided to ocean science in Canadian universities:

- Canada Foundation for Innovation (CFI);
- Natural Sciences and Engineering Research Council of Canada (NSERC);
- Social Sciences and Humanities Research Council (SSHRC);
- Canadian Institutes of Health Research (CIHR);
- Canadian Foundation for Climate and Atmospheric Science (CFCAS, now the Canadian Climate Forum); and
- Genome Canada.

A combination of search terms and selected categories within each agency's classification system was used to extract data for grants relevant to ocean science. The exact search terms and filtering criteria were adjusted slightly for each agency, depending on the number of false positives and the nature of the terms used in project titles and descriptions in each agency's database.

Data from these agencies identified over $920 million in public funding to nearly 4,900 ocean science projects and facilities in fiscal years 2002/03 to 2011/12, translating to roughly $92 million per year (Table 2.2). This funding was merit-based and not allocated specifically to ocean science by a funding agency. NSERC provided the majority of the funding (65 per cent), and CFI made sizeable investments in major infrastructure projects (23 per cent).

Table 2.2

Expenditures by Funding Agencies on Ocean Science in Canada, Fiscal Years 2002/03 to 2011/12

Funding Agency	Expenditures on Ocean Science	Number of Projects	Number of Researchers
NSERC	594,488,611	4,322	2,769
CFI	212,171,690	208	–*
SSHRC**	40,011,916	328	276
CIHR	28,527,181	47	44
Genome Canada**, ***	25,079,144	9	9
CFCAS**	20,129,980	21	18
Total	**920,408,522**	**4,935**	**3,116**

Data source: Calculated using data from CFI, NSERC, SSHRC, CIHR, CFCAS, and Genome Canada

Dollar amounts are the total amounts expended by each funding agency between fiscal year 2002/03 and 2011/12. The number of *projects* is reported, rather than the number of *grants* over the same period: some projects received funding from more than one granting program (e.g., Discovery, Ship Time grants, and other supplements). "Researchers" includes students with scholarships, post-doctoral fellows, and faculty researchers who were the principal investigators on grants. Due to data limitations, only the name of the first principal investigator on each grant was available to be counted: therefore the many researchers participating in networks, partnership grants, or other group projects could not be included in the counts.

Notes:

* The number of researchers supported by CFI grants is not shown: Infrastructure funding supports many more researchers than are listed in available data from CFI.

** SSHRC, CFCAS, and Genome Canada provided total grant amounts awarded and start and end dates: average amounts expended in each year were estimated based on these values.

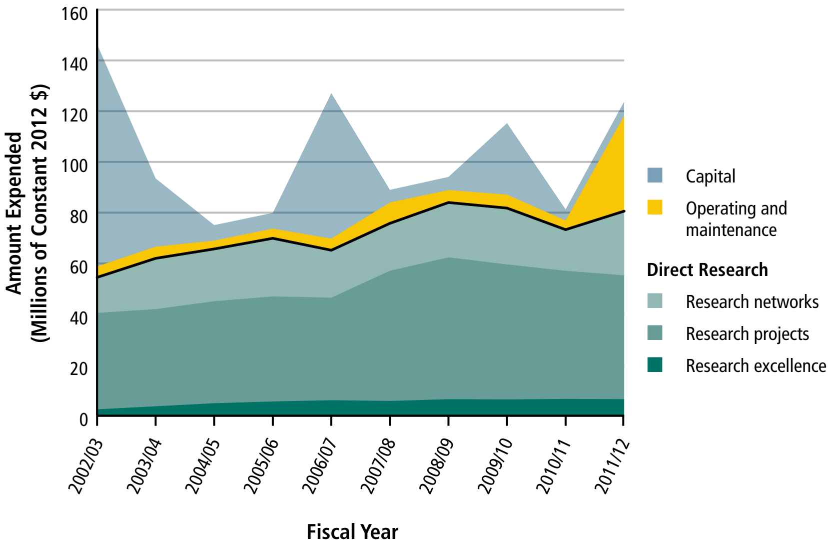
*** Genome Canada data also includes data from Genome BC.

Genome Canada and the CFCAS were established in 2000, shortly before the time period covered by these data, and these agencies have provided targeted funding for large projects in genomics and climate change research, respectively, related to ocean science. The federal funding mandate for the CFCAS ended in 2012 (CFCAS, 2012). NSERC, however, recently launched the Climate Change and Atmospheric Research (CCAR) program, with grants of up to $1 million per year (NSERC, 2013b).

Ocean science funding can be divided into capital, operating and maintenance, and direct research categories, based on the programs of an agency (Figure 2.7). Capital expenditures include NSERC's Research Tools and Infrastructure (RTI) grants and many CFI grants used to purchase or build infrastructure, ranging from lab instruments to major investments such as the refit of *CCGS Amundsen* or the NEPTUNE cabled observatory. While capital funding helps create infrastructure, putting this infrastructure to use for research incurs operating and maintenance costs. Direct research includes funding under most other programs for individual projects or research networks to support research activities, materials, travel, and dissemination. Direct research funding also includes excellence programs designed to recruit and retain top Canadian researchers (e.g., CRC and CERC); and funding to large research networks, such as NCE, NSERC Strategic Networks, and SSHRC Community-University Research Alliances (CURA) and Partnership Grants (see Section 2.2.6).

Capital spending is variable, particularly CFI grants, which are large sums awarded in a single year rather than spread out over several years (Figure 2.7). Less than 10 per cent of the funding in this data set came from programs for operating and maintenance of infrastructure, such as NSERC's Major Facilities Access and Major Resources Support programs. At the time of writing, these programs were not accepting new applications (NSERC, 2012b). In 2011, however, CFI launched a Major Science Initiatives Fund for operation and maintenance of CFI-funded large-scale research facilities (CFI, 2013b). This program is currently funding the operation of the ONC observatory, which accounts for the sharp increase in operating expenditures in 2011/12 shown in Figure 2.7. CFI also supports the operation of CFI-funded infrastructure through its Infrastructure Operating Fund, which provides funds directly to managing institutions (CFI, 2013a). Funding for infrastructure operation and maintenance is therefore increasingly coming from CFI.

Most of the ocean science funding identified has supported research directly, including excellence programs, large networks, and individual projects (Figure 2.7). About one-quarter to one-third of this research funding has supported research networks, which themselves support multiple researchers and their related projects, for up to seven years in some cases. The amount spent on ocean science networks increased in 2011/12 while other research funding continued to decline (Figure 2.7). This corresponds to the launch of the MEOPAR NCE and three SSHRC Partnership Grants, and could also indicate a transition towards a greater proportion of ocean science funding going to networks, rather than to individual projects.



Data source: Calculated using data provided by CFI, NSERC, SSHRC, CIHR, CFCAS, and Genome Canada

Figure 2.7

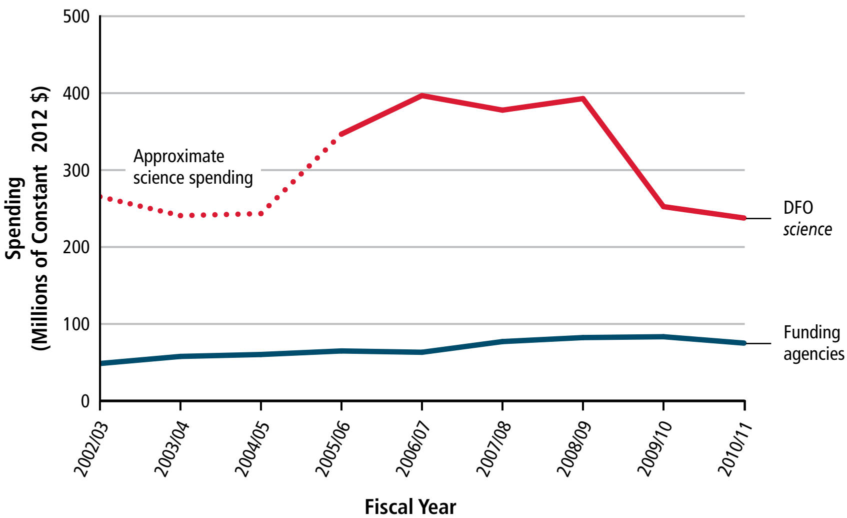
Funding Agency Expenditures on Ocean Science, in Constant 2012 Dollars, Fiscal Years 2002/03 to 2011/12

The graph shows amounts expended by six federal funding agencies on ocean science projects, identified by search terms within each agency's database. *Capital* spending is more variable than other funding, due to the nature of infrequent but large investments. Funding for *operation and maintenance* costs of infrastructure has comprised a relatively small portion of this funding, with the notable exception of a Major Science Initiatives fund awarded by CFI in early 2012. Funding for *direct research* (and *research excellence*) peaked at just over $60 million in 2008/09, falling slightly by 2011/12. In contrast, funding of *research networks* increased sharply in 2011/12 with the start of the MEOPAR NCE and three SSHRC Partnership Grants. Fiscal year 2012/13 was in progress at the time of writing. Fiscal years start on April 1st and end on March 31st of the following calendar year.

Such a transition may also account for the observed decline in the number of researchers supported by these funding agencies (Figure 2.2), if researchers are receiving funding from networks rather than directly from funding agencies. Alternatively, long-term trends in funding opportunities, priorities, and available facilities can also influence individual researchers' decisions on whether to remain active in ocean science in Canada, change fields, or move to another country.

2.4.2 DFO Spending on Ocean Science

Government departments are another source of significant spending on ocean science in Canada. While DFO is the lead federal department dealing with ocean issues, its responsibilities also include freshwater fisheries and other non-ocean areas. Other federal departments engaged in science and other activities related to the ocean include Environment Canada, NRCan, DRDC, NRC, Transport Canada, Health Canada, the Public Health Agency of Canada, CFIA, and the Canadian Space Agency (see Table A2 in Appendix A). Many provincial and territorial departments also have some ocean-related responsibilities, in particular those on Canada's coasts (see Section 2.2.2).



Data source: DFO (2013f) and data provided by NSERC, SSHRC, CIHR, CFCAS, and Genome Canada

Figure 2.8

DFO Spending on Science, and Spending by Funding Agencies on Ocean Science, in Constant 2012 Dollars, Fiscal Years 2002/03 to 2010/11

Spending by funding agencies does not include CFI grants, which are highly variable (large amounts awarded in a single year). Including CFI grants, total expenditures by funding agencies did not exceed $150 million per year during this period. DFO strategic areas and budget lines changed in 2005/06. Science spending for fiscal years 2002/03 to 2004/05 was approximated by combining lines for science activities similar to those used from 2005/06 to 2010/11 (Hydrography, and Fisheries and Oceans Science). DFO spending on science includes a share of DFO spending on salaries for researchers and technical support staff. Most spending by funding agencies does not include salaries for professors and full-time university staff, which are largely paid for by host institutions. DFO is the lead federal department in ocean issues, but is only one of several federal organizations that engage in ocean science activities. Fiscal years start on April 1st and end on March 31st of the following calendar year.

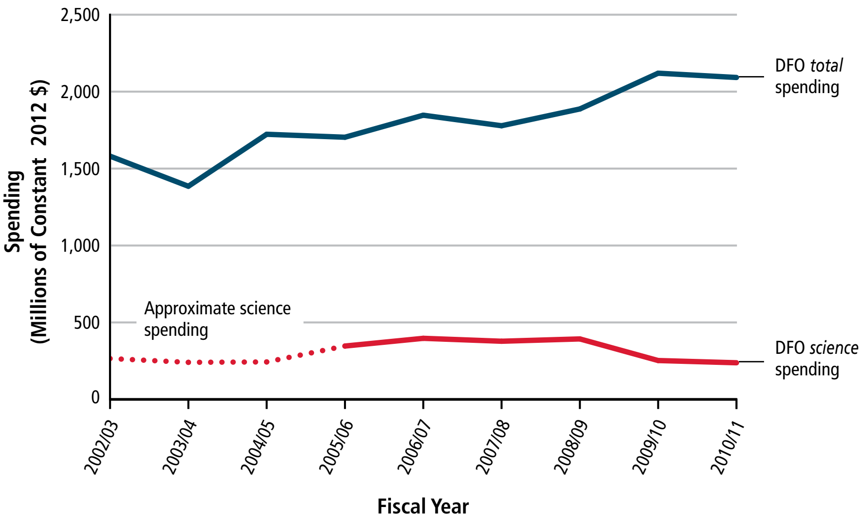
Departmental Performance Reports for DFO prior to 2011 include budget lines for science spending, which were used as an indication of the minimum spending on ocean science in the federal government. These budget lines cover a range of science activities, including data collection and management, as well as products and services in support of navigation and ocean management. DFO spending includes salaries for researchers and technical support staff. The salaries of such personnel at universities are largely paid for by host institutions supported by provincial transfers, and not included in many of the expenditures by the funding agencies presented above.

Expense reporting changed in 2005 to include budget lines for "science" in each of DFO's strategic areas, which were added together to estimate total science spending from 2005/06 to 2010/2011. DFO spending on science prior to 2005 was estimated by combining individual budget lines for activities such as "Hydrography," "Fisheries and Oceans Science," and others. DFO expense reporting and strategic areas changed again in 2011, in ways that made it impossible to reliably delineate science spending for comparison with previous years.

Science spending by DFO has fluctuated more strongly than spending by funding agencies over the timeframe included in this analysis (Figure 2.8). Similar to that of funding agencies, DFO science spending has declined since 2008/09. Total DFO spending increased from $1.5 billion in 2002/03 to $2.0 billion in 2010/11, while spending on science fluctuated independently, such that spending on science is not a constant proportion of DFO's total budget (Figure 2.9).

Although ocean science spending by funding agencies appears to be lower than spending by government departments, the activities and costs also differ. In addition to providing science advice to decision-makers, government departments are responsible for operating large-scale observation and monitoring systems, and managing the resulting data for products and services.

Large infrastructure and monitoring activities are usually beyond the scope and resources of university researchers, but networks and consortia allow resources to be pooled and open up opportunities for new capacity development. Examples of infrastructure led by groups of universities include the research icebreaker *CCGS Amundsen* (see Box 4.6) and the OTN.



Data source: DFO (2013f)

Figure 2.9

Total Spending and Science Spending by DFO, in Constant 2012 Dollars, Fiscal Years 2002/03 to 2010/11

DFO strategic areas and budget lines changed in 2005/06, but total science spending was approximated by combining lines for similar science activities as those used from 2005/06 to 2010/11 (Hydrography, and Fisheries and Oceans Science). Changes in DFO science spending appear to be unrelated to changes in total spending. Science spending is therefore not a constant proportion of DFO's total spending. Fiscal years start on April 1st and end on March 31st of the following calendar year.

2.5 POLICY AND GOVERNANCE

The policy framework for ocean science in Canada is determined by a variety of federal and provincial acts and regulations as well as international agreements to which Canada is a signatory. The *Oceans Act*, adopted in 1997, provides the basis for federal ocean governance and science in Canada, and establishes DFO as the lead department for Canadian ocean stewardship. The act defines principles for ocean governance and provides a specific science mandate to DFO, including data collection; basic and applied research; surveying; and publication of data, maps, research reports, and other documents. Another important part of DFO's science mandate is the provision of science advice to the federal government and other stakeholders. DFO also participates in ocean technology development; research collaboration; and operation of ships, research institutes, laboratories, and other facilities for research, surveying, and monitoring. Ocean science in Canada is influenced by other federal acts, such as the *Fisheries Act, Marine Conservation Act, Species at Risk Act, Environmental Protection Act, Quarantine Act,* and *Health of Animals Act*, among others (see GC, 2010).

In 2002 DFO published *Canada's Ocean Strategy* to provide a policy and operational framework for integrated ocean management (DFO, 2002). The strategy recognizes the role of the academic science and research community in integrated management, and recommends its engagement in the governance process. In 2005 DFO released the *Oceans Action Plan*, which presents initiatives for implementation clustered around four themes: international leadership, sovereignty, and security; integrated ocean management for sustainable development; the health of the ocean; and ocean science and technology (DFO, 2005). Soon after, DFO released a science framework (DFO, 2008b) and a five-year research agenda outlining priority areas for DFO's research program (DFO, 2007). This was complemented by a *Five-Year Research Plan* for 2008–2013, which presents specific DFO research initiatives in Canada's major ocean ecosystems (DFO, 2008a).

Canada is a signatory to several international and regional agreements that influence ocean governance and create specific demands for ocean science as well as opportunities for international collaboration. The UN Convention on the Law of the Sea (UNCLOS), for example, regulates activities outside countries' exclusive economic zones (EEZs) and has jurisdiction over the process by which countries delineate the outer limits of their continental shelves, based on scientific information. The Convention on Biological Diversity applies to coastal and marine biodiversity within EEZs and advises UNCLOS on approaches to protect marine biodiversity in international waters. The UN Food and Agriculture Organization (FAO) Committee on Fisheries is an important forum for international collaboration on the science and governance of fisheries and aquaculture. The UN Framework Convention on Climate Change (UNFCCC) establishes monitoring obligations and science needs, including ocean-atmosphere interactions and climate-change impacts in ocean systems, while the Intergovernmental Panel on Climate Change provides an important forum for international collaboration and exchange on all climate-related research. Other science-based international agreements include the Convention on Migratory Species (CMS) and the Convention on International Trade in Endangered Species (CITES). Canada is also a member of several regional fisheries management organizations (RFMOs), including the Northwest Atlantic Fisheries Organization (NAFO), the North Atlantic Salmon Conservation Organization (NASCO), and the North Pacific Anadromous Fish

Commission (NPAFC).[4] Finally, Canada is a member of the Arctic Council, which promotes sustainable development and environmental protection in the Arctic, among other issues.

These and many other international agreements are important drivers of ocean science in Canada, and provide fora for collaboration as well as "science diplomacy," defined as the use of scientific collaboration to address common problems and build international partnerships (Dufour, 2012). Many of the 40 research questions directly or indirectly relate to the issues addressed by these international agreements. While Canada's participation in, and commitment to, these agreements cannot be considered an element of research capacity in its own right, it provides an important rationale for investments in ocean science as well as an essential channel for mobilizing science to inform international collaboration and governance.

2.6 CONCLUSION

Canada's ocean science seascape is characterized by many diverse actors, including government departments, universities, the private sector, and civil society organizations. Actors are organized in regional clusters on Canada's East and West coasts, with substantial research capacity also located in central Canada. This diversity allows organizations to focus on regional and local science priorities and supports the emergence of regionally specialized clusters.

Although the dispersed structure can act as a barrier to collaboration and coordination, there are many networks and other arrangements that help overcome these barriers. Recent networks focus on providing funding for and access to major physical infrastructure, which appears to be a successful model for engaging actors from all sectors of society. No overarching structure or body provides a forum for leadership and strategic direction for the entire ocean science community in Canada, however. Other countries have established permanent or temporary bodies to coordinate ocean science activities. Among other functions, these bodies provide periodic assessments of the state of ocean science and lead the development of a national vision for the future development of ocean science in their respective countries.

Canada has a substantial but aging research fleet operated and managed by the CCG. A comparison with other countries suggests that managing access to ship time, through scientific consortia using standardized access procedures and a

4 For more information on the agreements to which Canada is a signatory, as well as bilateral collaborations, see http://www.dfo-mpo.gc.ca/international/dip-eng.htm.

central information hub for available capacity and use, can improve transparency and efficiency of research vessel management. The information provided by these consortia also facilitates international sharing of research infrastructure.

Available data on highly qualified personnel suggest that the number of undergraduate and graduate degrees awarded in disciplines directly related to ocean science is increasing. From 2002 to 2008, the number of professors receiving support from funding agencies grew by more than 30 each year, but the total number of professors declined just as rapidly until 2011. Overall human capacity in ocean science in Canada is unclear because data were not available for all sectors.

Data from federal funding agencies show an increase in direct research funding provided to ocean science from 2002/03 to 2008/09, followed by declines in recent years. The data also reveal several transitions in ocean science funding, including recent growth in funding to networks, while funding for infrastructure operation is provided increasingly by CFI rather than NSERC.

3

Canada's Research Output and Impact in Ocean Science

- Bibliometric Analysis
- Ocean Science Output and Impact
- Collaboration
- Conclusion

3 Canada's Research Output and Impact in Ocean Science

Key Findings

- Canada ranks 7th in the world by number of ocean science papers published, and 11th in scientific impact of its papers, as measured by average relative citations.
- Ocean science in Canada grew at a slower pace compared with other fields of science in 2003–2011, meaning that its share of Canada's total research output declined during this period.
- Although national organizations such as DFO and Environment Canada are highly connected hubs, collaborations in Canada are otherwise more decentralized, resembling a network of regional clusters.
- Ocean science papers with international co-authors are cited more often than papers with authors from a single country, especially from Canada.

Bibliometric analysis is a standard method used to compare the publication output of entities such as countries, organizations, or individuals (CCA, 2012b, 2012c). As a measure of output, bibliometric indicators are also a proxy measurement of overall research capacity. This chapter provides an overview of ocean science output in Canada relative to the other leading countries in ocean science, as measured by bibliometric indicators. Bibliometric analyses are also used to describe patterns of collaboration and output of organizations in Canada.

3.1 BIBLIOMETRIC ANALYSIS

Bibliometric data were compiled from scientific peer-reviewed articles indexed in the Scopus database (Elsevier) and published from 2003 to 2011.[5] All articles in over 200 selected ocean science journals were included, supplemented by articles in other science journals captured by queries using more than 1,000 search terms in titles, author keywords, and abstracts. A similar approach was used to create subsets of ocean science papers for each theme presented in Chapter 4. Some papers may be classified in more than one theme, resulting in some overlap (e.g., the Arctic Ocean theme represents a cross-section of ocean science).

5 The Canadian firm Science-Metrix (Montréal, QC) performed the bibliometric analyses presented in this report.

Within each set of ocean science papers, top countries were compared at the international level, while organizations, and collaborations between them, were compared within Canada. No additional indicators were computed for entities with fewer than 30 papers, to ensure reliable and informative results.

Papers with co-authors from multiple organizations were used to create collaboration networks showing patterns of co-authorship among organizations. The Panel acknowledges that collaboration takes many forms other than authorship, including conferences and meetings, sharing data, or other activities not captured by bibliometric data. Collaboration networks were drawn using an algorithm that generally positions organizations linked by collaboration closer to each other. Organizations linked by many papers with shared authors therefore tend to group together in a network diagram, while those that collaborate with many other organizations tend to appear as "hubs" near the centre of the network.

3.1.1 Key Metrics Used in this Report

Number of publications refers to the number of papers for a given entity (country or organization) obtained using full counting. Each paper is counted once for each country and organization listed in the address field. Further metrics were not calculated for countries or organizations that had fewer than 30 publications during the study period.

Average relative citations (ARC) measures the observed scientific impact of research published by an entity, based on an average of the number of citations that each of its papers received, relative to the average number of citations received by world papers of the same type (review papers or articles) published in the same year in the same field. Citations are counted in the year of publication and the following two years. The number of citations for most scientific papers peaks at three to five years (Moed *et al.*, 1985; REPP, 2005). Furthermore, the total number of citations after two years was an excellent predictor of the number of citations after nine years ($R^2 = 0.99$) for ocean science articles published in 2003. A three-year window therefore captures the short-term uptake and impact common to most papers, standardized to control for differences in citation patterns.
- ARC score > 1.0 means the entity's research is cited more than the world average.
- ARC score < 1.0 means the entity's research is cited less than the world average.

Specialization index (SI) measures the intensity of research of an entity in a given field relative to the intensity of the world in the same field. For example:

$$SI = \frac{\text{\% of an entity's papers in ocean science}}{\text{\% of world papers in ocean science}}$$

Growth index (GI) measures the growth of scientific production by taking the ratio of the share of an entity's total papers that were in ocean science in 2008–2011 (the end of the study period) over the share that were in ocean science in 2003–2006 (the beginning of the study period). For example, if 5 per cent of a country's papers were in ocean science in the first period and this reached 10 per cent in the second period, this would result in a GI of 2 (10/5 = 2):

$$GI = \frac{\text{\% of an entity's papers in ocean science in 2008–2011}}{\text{\% of an entity's papers in ocean science in 2003–2006}}$$

3.1.2 Limitations of Bibliometric Analysis

Bibliometric indicators only measure peer-reviewed journal articles, and do not include other forms of research output, which may or may not be peer reviewed, such as patents, conference presentations, books, and consultant reports. Since type of output varies in importance by discipline, this limitation may be more acute in engineering, the social sciences, the humanities, and among private-sector firms, where outputs other than peer-reviewed journal articles are more common (see CCA, 2012b).

For example, DFO's Canadian Science Advisory Secretariat (CSAS) maintains an online archive of over 6,000 reports, proceedings, and other publications dating back to 1977 (DFO, 2012e). Of these, 2,197 were published during the period used for this bibliometric analysis (2003-2011), which coincides with the transition period from a focus on fisheries management to ecosystem-based management under the *Oceans Act* (DFO, 2008b, 2008a). Though not indexed by the Scopus database used to build the bibliometric data set for this report, the number of CSAS publications is equal to seven per cent of the total Canadian ocean science publications analyzed for this report.

Bibliometric analyses are heavily influenced by the database of publications used and the way publications are classified. The analyses presented here used the Scopus database, which has greater coverage of journals in the humanities, arts, and social sciences than most alternatives (CCA, 2012b). Nevertheless, Scopus does not index all journals published in Canada, and only includes papers with English abstracts. Given the multidisciplinary nature of ocean science, and the role of many fields that also include non-ocean science, most existing classification systems may not fully represent ocean science as a whole. The analyses presented here instead classify publications by the research themes used in this report (see Chapter 4).

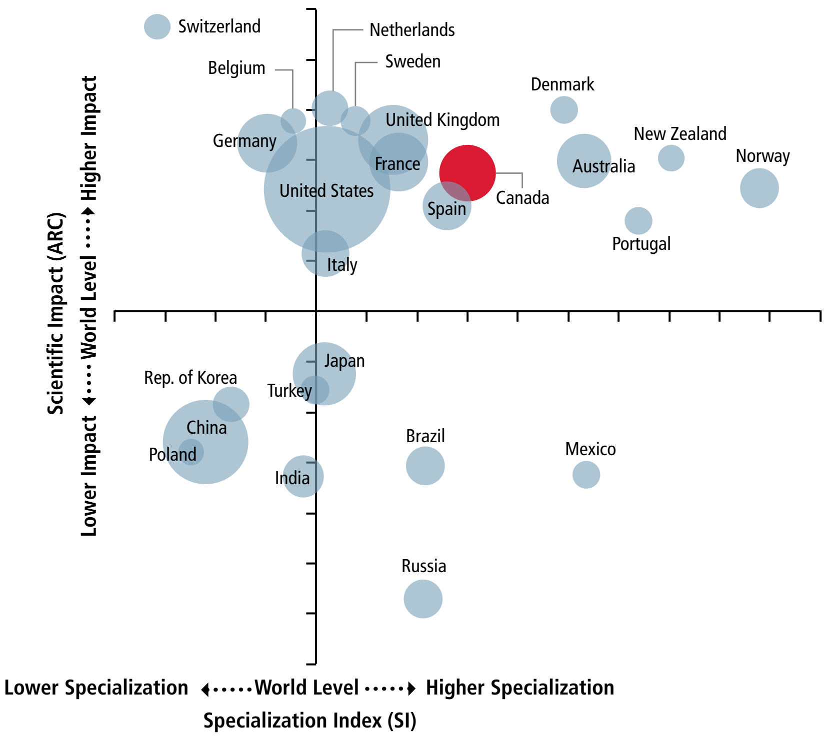
Bibliometric indicators are also sensitive to the time periods under consideration. For example, citation rates used in several indicators tend to accrue over time, such that older papers tend to be more highly cited than recent papers. Citation patterns may also change over time within the same field. To control for these differences, citation metrics are standardized relative to average citations for papers of the same type (review papers or research articles), and published in the same year and field of specialty. Recent changes in capacity are also not reflected in bibliometric analyses because they may take time to effect changes in research output before they can be measured. For example, recent major investments in infrastructure and research networks may affect patterns of collaboration at the national level, either overall or in specific research themes, over the coming years.

3.2 OCEAN SCIENCE OUTPUT AND IMPACT

This analysis considers papers to be Canadian if at least one author is affiliated with an organization that has a Canadian mailing address: this does not include Canadian authors publishing papers while affiliated with organizations based outside of Canada, such as the FAO. Of the 520,000 ocean science papers in the database for 2003 to 2011, 5.6 per cent (29,162) include at least one Canadian author. This makes Canada the seventh largest country in ocean science output (see Figure 3.1).

Canada's average scientific impact (as measured by ARC) is similar to France and Australia, and slightly higher than the United States, Norway, and Spain. Canada ranks 11th in the world by scientific impact (ARC = 1.33), behind New Zealand and several European countries: Switzerland, the Netherlands, Denmark, Belgium, Sweden, Germany, and the United Kingdom (Figure 3.1). Switzerland's scientific impact is equally high in many areas of ocean science (see also Picard-Aitken *et al.*, 2009), as a result of publishing few papers but with very high impact. As could be expected from a country without direct access to coasts, Switzerland's specialization index is low (0.72). Switzerland's high average impact can be explained by its general level of scientific excellence (ranking first in ARC for the entire Scopus database) and high rate of international collaboration (see CCA, 2012b).

Canada is relatively specialized in ocean science (SI = 1.36), which accounts for a larger proportion of Canadian papers than the world average. Canada, however, is not as specialized in ocean science as other coastal countries such as Norway, New Zealand, Portugal, Australia, and Denmark (see Figure 3.1).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 3.1

Position of 25 Leading Countries in Ocean Science Output, 2003–2011

The size of the bubble is proportional to the number of publications for that country over the study period. Canada is highlighted in red, as a relatively specialized (SI = 1.36) and high-impact (ARC = 1.33) country (top-right quadrant).

Note: The ARC and SI values were log-transformed for visualization.

Canada's growth index for ocean science (0.91) is less than 1.0, which means that, while the number of ocean science papers published by Canadian authors is increasing, the proportion of Canadian papers in ocean science is declining because the number of papers in other fields is growing at a faster rate. In addition, Canada has the lowest growth index of the top 25 countries, meaning that this proportion is decreasing faster in Canada than in other leading countries.

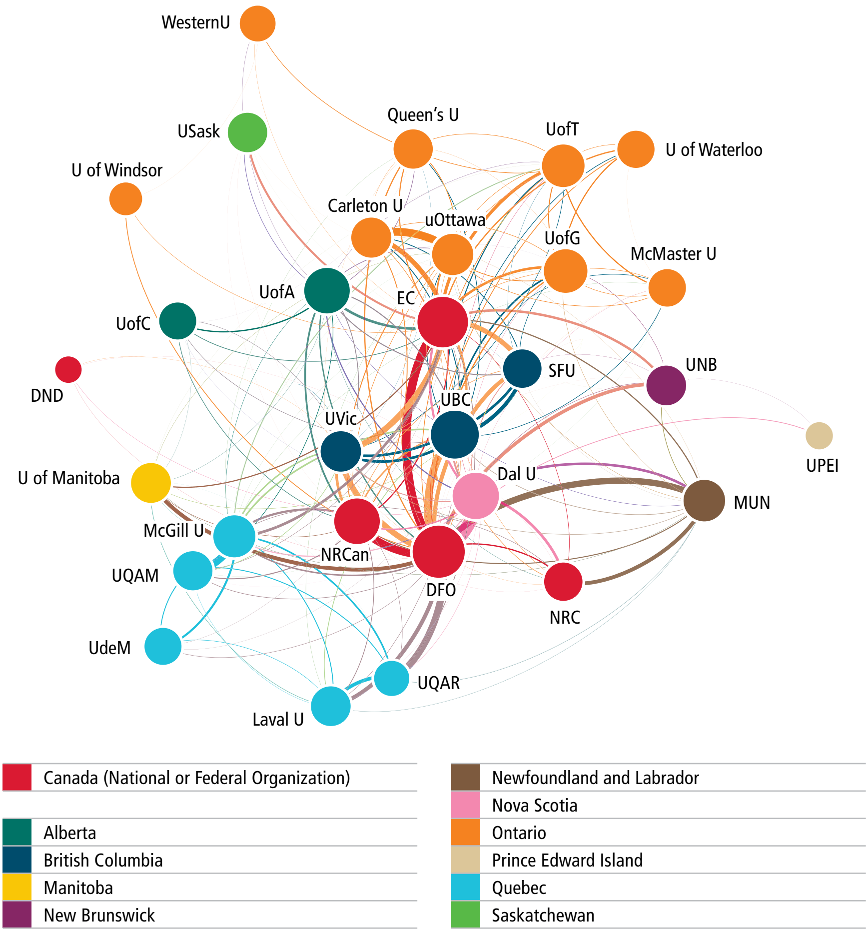
Although ocean science continues to grow as a field, it is growing slightly below the average of other fields in the Scopus database (GI = 0.99). Only 4 of the 25 top publishing countries show growth above the world average: Switzerland (1.16), the Republic of Korea (1.15), Poland (1.09), and China (1.09). For many leading countries, such as the United States and Canada, ocean science capacity is already considerable and growing at a slower pace than these rapidly growing countries, which may have comparatively more room to expand (see CCA, 2012b). Although the net effect is a reduction in established countries' share of world ocean science papers, it also means more potential collaboration partners and increased ocean science activity around the world.

3.3 COLLABORATION

The multi-scale and multidisciplinary nature of ocean science suggests that collaboration is important for continued leadership in ocean science. Nevertheless, collaboration alone is not a guarantee of interdisciplinary research, nor is it a suitable substitute for local expertise. Ocean science may benefit from a range of collaborations: some will be primarily local in focus, while national and international collaboration will allow greater knowledge sharing and pooling of resources for larger-scale research questions. Given Canada's extensive coastline across three major ocean basins, international collaborators working in the same ocean basin may be closer than other Canadian researchers and have more relevant expertise.

3.3.1 Collaboration within Canada

Figure 3.2 shows the network of collaborations in ocean science in Canada. Each node represents an organization, and the number of papers with authors from multiple organizations are represented as lines linking the organizations together (thicker lines represent more co-authored papers). Organizations are arranged in the graph such that those collaborating more with each other are placed closer together, while those collaborating less are pushed apart. The graph shows that most organizations collaborate frequently with multiple partners, suggesting that ocean science in Canada is well integrated. Organizations within the same geographic region appear as groups connected by high levels of co-authorship, indicating that physical proximity facilitates collaboration. The overall structure can be described as a network of regional clusters. Ontario organizations in the upper right and Quebec organizations in the lower left form prominent regional groupings. Environment Canada (closer to Ontario organizations) acts as a main hub, as do NRCan and DFO (closer to Quebec organizations).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 3.2

Collaboration Network of the Top 30 Publishing Canadian Organizations in Ocean Science, 2003–2011

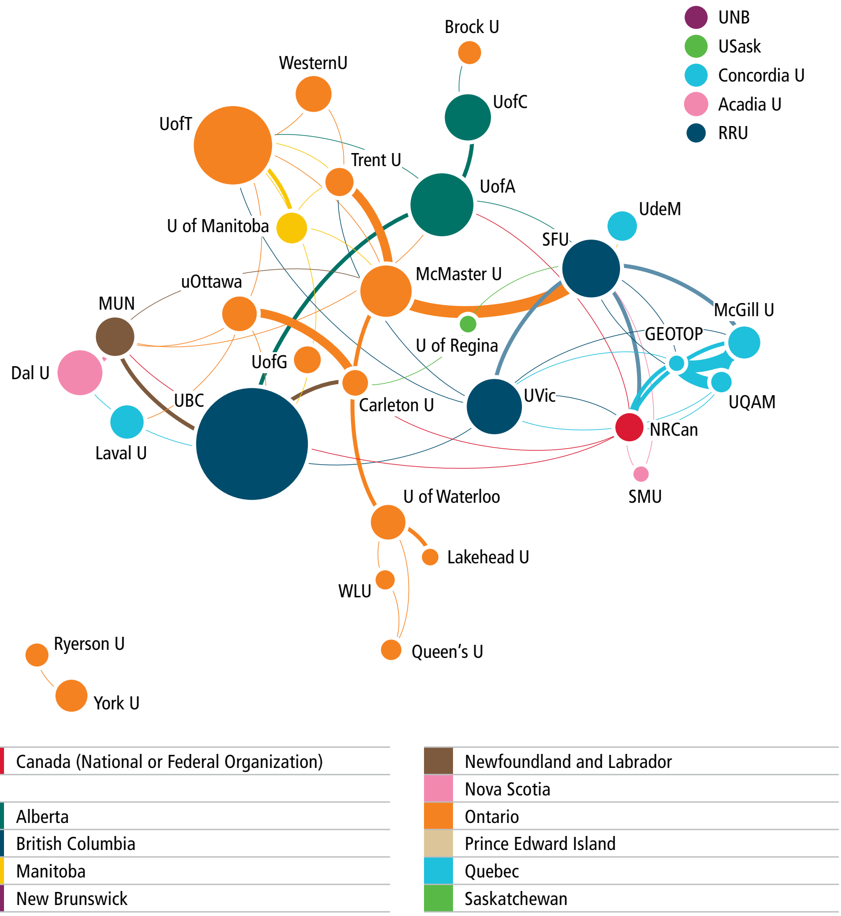
The size of the nodes is proportional to the number of publications in ocean science and the thickness of the lines is proportional to the number of collaborations (co-authored papers). Collaboration between Canadian organizations in ocean science is relatively dispersed, with federal organizations and large universities acting as central hubs. DFO and Environment Canada show high levels of collaboration with each other and with universities across the country, due in part to their decentralized structure. Regional clusters of organizations suggest a natural tendency for collaboration to increase with proximity. Note: Only links representing 10 or more collaborations between institutions are displayed, to improve readability.

Most federal government organizations are displayed at the centre of the network, which indicates that they act as partners for many Canadian organizations. Similarly, the placement of the University of British Columbia, University of Victoria, Dalhousie University, and Simon Fraser University at the core of the network implies that these universities collaborate with many other organizations across Canada, even though their total number of collaborations may be lower than that of the government departments.

While it is important to draw on multiple disciplines for ocean science, an analysis of ocean science papers might be driven primarily by patterns in those disciplines with higher publication rates. Because the social sciences and humanities may be under-represented in bibliometric data relative to other disciplines, a separate analysis of Canadian organizations was performed for papers in ocean science published in social science journals, based on the Science-Metrix classification system (see CCA, 2012b).

This method revealed a very small proportion of social science papers in the bibliometric data set: 729 out of 29,162 Canadian papers (2.5 per cent), with a similarly low percentage at the world level. This is consistent with the variety of outputs produced by researchers in these fields in addition to peer-reviewed journal articles, such as books, reports, and knowledge mobilization activities. Therefore, the bibliometric indicators used in this report are more often a reflection of other areas of ocean science with higher rates of publication in journals and more co-authors per publication.

The main producers of Canadian social science papers in the database include universities with relatively high publication outputs, such as the University of Toronto, University of British Columbia, and University of Alberta (Figure 3.3). NRCan is the only federal organization with social science journal articles in the database. According to this analysis, most social science papers in Canadian ocean science are produced by universities. Regional clusters with high rates of local collaboration are also evident in Ottawa (University of Ottawa and Carleton University); and Montréal (McGill University, Université du Québec à Montréal, and Geotop).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 3.3

Collaboration Network of Canadian Organizations Publishing Social Science Papers, 2003–2011

The graph shows that most social science papers on ocean science in Canada are produced by universities, rather than other organizations. The sparseness of the collaborations and small number of papers (fewer than 750) reflect the fact that many outputs from the social sciences in Canada may not be captured in the bibliometric data used for this analysis.

Note: All links are displayed in the network. The thickness of the links ranges from five collaborations (thickest) to one collaboration (thinnest). The size of the nodes ranges from 81 papers (largest) to 6 papers (smallest).

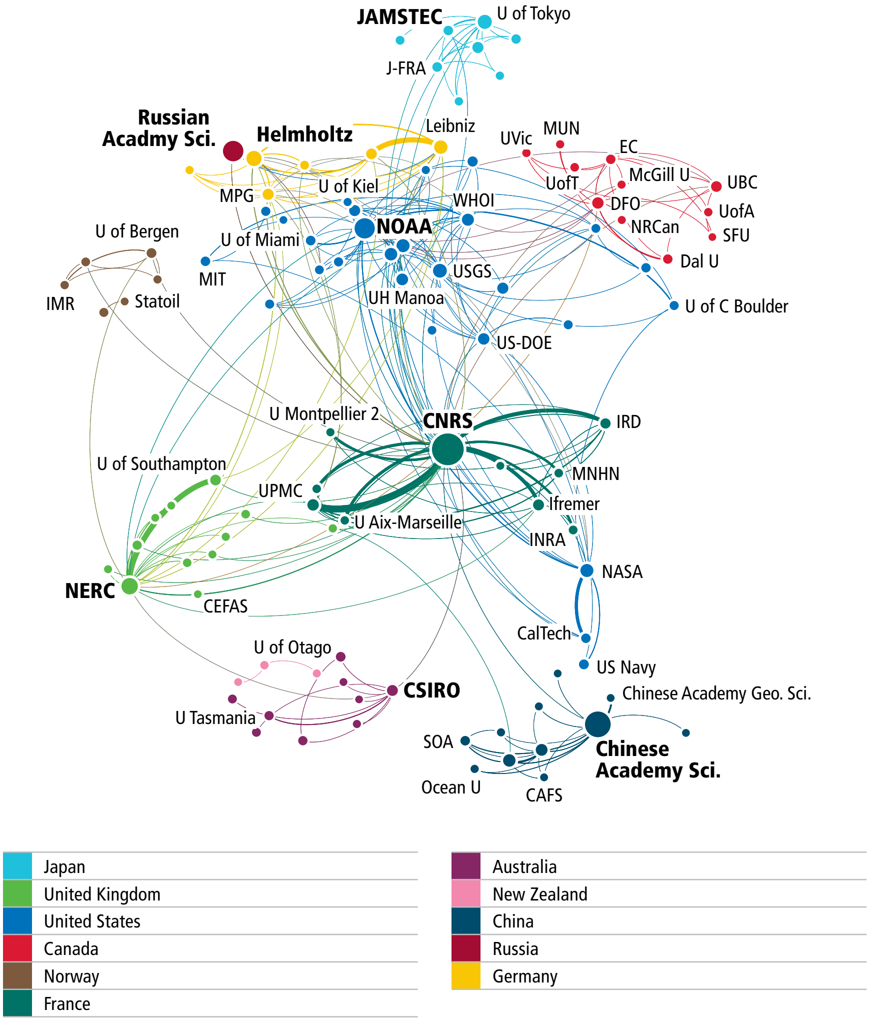
3.3.2 International Collaboration

A figure showing an international network of collaborations among 200 leading organizations was also created as part of the analysis, but is not shown in full in this chapter due to its size and level of detail (see Appendix B for the full collaboration network). Figure 3.4 presents a simplified version of the network, in which large-scale patterns remain evident with clusters of organizations emerging, primarily within countries and regions. A European cluster dominates the centre of the network, linking a large cluster of U.S. organizations with a Chinese and Oceania cluster. A cluster of Canadian organizations is tightly linked to the U.S. cluster, as a result of high rates of collaboration.

Many clusters form around a large, national organization at the core of each national network, which acts as a major regional and international hub. These include the National Oceanic and Atmospheric Administration (NOAA) in the United States, le Centre national de la recherche scientifique (CNRS) in France, the Natural Environment Research Council (NERC) in the United Kingdom, and the Chinese Academy of Sciences. Canada has no such national collaboration network with a large organization at its centre; rather it has a more decentralized, collaborative research community across multiple, comparatively smaller organizations. Although organizations such as DFO are important collaborative hubs within Canada, they do not dominate Canada's international collaborations. Network indicators show that the University of British Columbia and Dalhousie University have collaborated more internationally in ocean science than other Canadian organizations, including DFO (see Appendix B).

Ocean science papers with international co-authors tend to have higher impact, as measured by ARC (average increase of 0.45), compared with papers by authors from the same country (see Appendix B). This is especially true in Canada, where papers with international collaborators have an ARC score of 1.57, versus 1.06 for those with only Canadian authors (an increase of 0.51).

From 2003 to 2011, Canadian researchers collaborated most frequently with those in the United States, followed by the United Kingdom, France, Germany, Australia, and China. Researchers in many of these countries also have a high publication output in ocean science, so high levels of collaboration might be expected. Canada collaborated more than expected with some countries, based on publication rates, including New Zealand, the United States, China, and several other leading countries (see Appendix B); but less than expected with the Netherlands, Russia, Germany, and Poland.



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 3.4

International Collaboration Network of Selected Top Publishing Organizations in Ocean Science, 2003–2011

The size of the nodes is proportional to the number of publications in ocean science and the thickness of the lines is proportional to the number of collaborations (co-authored papers). Nodes are arranged using an algorithm where linked nodes are attracted to each other while unlinked nodes are pushed apart. This is a simplified version of a full collaboration network of the world's 200 leading ocean science organizations (the full version is available in Appendix B). Selected organizations and collaboration links were chosen to emphasize patterns of collaboration, not necessarily the top publishing organizations. Note: Links representing few collaborations were removed to improve readability.

3.4 CONCLUSION

The analysis of research output in peer-reviewed journals presented in this chapter shows that Canada is well established among the leading countries in ocean science, ranking 7th by output and 11th by impact. The analysis also shows, however, that ocean science in Canada has the lowest growth index among the 25 leading countries. This means that output in ocean science in Canada is increasing at a lower rate than output in other fields of science in Canada. The collaboration analysis highlights the importance of federal government departments in research output and collaboration at the national level. Because of their decentralized structures, DFO, NRCan, Environment Canada, and the NRC are important hubs for collaboration, particularly with universities. At the international level, however, federal departments appear alongside several Canadian partners, including Dalhousie University and the University of British Columbia. This contrasts with the domination in many countries of a single institution, which functions as the primary hub for international collaboration.

Chapter 4 presents further results of the bibliometric analysis by research theme to highlight areas of comparative strength and "major players" using publication output in peer-reviewed scientific journals.

4

Opportunities and Challenges for Ocean Science in Canada

- Ocean-Climate Interactions
- Biological, Mineral, and Energy Resources
- Human Impacts on Marine and Coastal Ecosystems
- Plate Tectonics and Natural Hazards
- Coastal Communities
- The Arctic Ocean

4 Opportunities and Challenges for Ocean Science in Canada

Key Findings

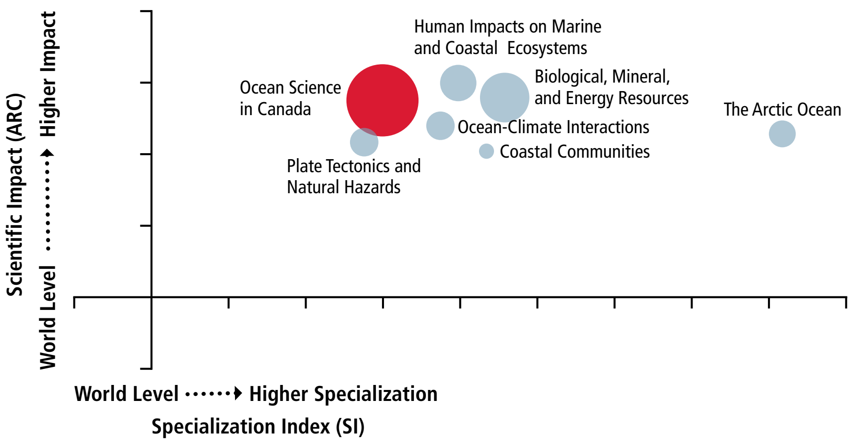
- The scales of research related to ocean-climate interactions pose many challenges for observation and monitoring, but there are opportunities for greater collaboration and knowledge sharing in modelling of ocean-climate interactions.
- Canada has accumulated substantial capacity in research related to marine biological, mineral, and energy resources, with developing capacity in emerging fields such as genomics and marine biotechnologies.
- Research related to human impacts on marine and coastal ecosystems is a historical strength in Canada, but research capacity related to existing and novel contaminants may be declining.
- Despite recent large investments in the ONC observatory and MEOPAR NCE in support of research on plate tectonics and natural hazards, there are important challenges in achieving data coverage in the Arctic Ocean.
- Although Canada has one of the highest growth rates in publications of research on coastal communities, research advancement could be greater with improved capacity in interdisciplinary collaboration and data management.
- Arctic Ocean research is a clear priority for Canada, demonstrated by the collaborative arrangements formed by researchers to share building and maintenance costs for specialized infrastructure.

This chapter discusses Canada's current capacity in the six research themes encompassing those of the 40 research questions that reflect established methods and approaches used in ocean science. To provide an overview of relevant capacity for each theme, the Panel started with bibliometric indicators, and then used additional evidence to account for observed patterns and trends. Each section then discusses the capacity required to address the research questions related to that theme and assesses existing capacities. This assessment is followed by an analysis of opportunities created by strengths in output or past and current investments in capacity as well as challenges arising from gaps in capacity, difficulties in accessing existing capacity, or gaps in expertise.

Continual technology development and the interdependence of categories of capacity complicate the ability to forecast research needs in certain areas. Research questions in such emerging areas, or complex issues with undefined research needs, are discussed under the three themes outlined in Chapter 5.

The analyses suggest important differences in Canada's relative performance by theme, and in the size and growth of the six themes worldwide (Table 4.1). On the one hand, Canada's research output is both abundant and high-impact in human impacts on marine and coastal ecosystems and biological, mineral, and energy resources – areas in which Canada has a reputation for leadership and excellence, especially in fisheries research and related fields (CCA, 2012b). On the other hand, research output in coastal communities is relatively small compared to other themes, but is growing rapidly, suggesting an important emerging research area in Canada and the world. Apart from this theme, ocean science is generally growing at a slower rate than other fields in Canada, with a growth index ranking near the bottom of leading countries in most themes.

Canada generally ranks among the top 10 countries based on research output, but ranks slightly lower by scientific impact (Table 4.1). Canada's research impact is above the world average in all six research themes, but highest in human impacts on marine and coastal ecosystems. Canada is relatively specialized in all themes, but especially so in research on the Arctic Ocean (Figure 4.1), where Canada is second only to the United States in research output (Table 4.1).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.1

Canada's Position Relative to the World Average by Ocean Science Theme, 2003–2011

The size of the bubble is proportional to the number of Canadian publications in that research theme over the study period. Canada's scientific impact and level of specialization are above the world average for all themes and ocean science as a whole. Canada is most specialized in Arctic Ocean research. Canada's highest scientific impact is in human impacts on marine and coastal ecosystems and biological, mineral, and energy resources, which are well-established areas of strength.

Note: The ARCs and SIs on the figure were log-transformed for visualization.

Table 4.1

Key Bibliometric Indicators for Canadian Output in Ocean Science by Research Theme, 2003–2011

Indicator \ Theme	Ocean Science	Ocean-Climate Interactions	Biological, Mineral, and Energy Resources	Human Impacts on Marine and Coastal Ecosystems	Plate Tectonics and Natural Hazards	Coastal Communities	The Arctic Ocean
World publications	520,734	74,541	204,413	118,739	83,305	19,583	31,261
Canadian publications	29,162	4,544	13,782	7,437	4,546	1,282	4,056
Canada's share of world publications (%)	5.6	6.1	6.7	6.3	5.5	6.5	13.0
Canada's rank, by publication count*	7	7	4	4	8	5	2
Specialization (SI) of Canadian publications	1.36	1.48	1.64	1.52	1.33	1.59	3.15
Impact (ARC) of Canadian Publications	1.33	1.28	1.33	1.36	1.25	1.23	1.26
Canada's rank, by ARC*	11	12	11	8	11	14	13
World growth (GI)	0.99	0.97	1.06	1.03	0.99	1.22	0.91
Growth (GI) in Canada	0.91	0.96	0.94	0.95	0.90	1.14	0.95
Canada's rank, by GI*	25	20	25	22	23	22	16

Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

* Canada's rank for each indicator is based on scores relative to the 25 countries with the highest publication counts in ocean science (including Canada).

4.1 OCEAN-CLIMATE INTERACTIONS

Many of the research questions reflect the expectation that climate change will be a major driver of ocean science in the next 10 to 15 years (Valdès *et al.*, 2010). Climate and the ocean are interdependent and inextricably linked by many complex processes. The ocean absorbs an estimated 25 per cent of human carbon emissions (Rockstrom *et al.*, 2009), and has so far absorbed 80 per cent of the additional heat added to the climate system by anthropogenic climate change (IPCC, 2007). Understanding the relationship between the ocean and the atmosphere is therefore critical to advance our abilities to model and forecast the climate, predict impacts of climate change, and develop appropriate adaptation strategies. These challenges are being addressed in Canada by activities in observation and modelling to better understand past, present, and future ocean-climate interactions, and research on broader impacts of climate change on ocean ecosystems, coasts, and societies.

Several of the research questions in this theme go beyond the area of observation, monitoring, and modelling, raising issues related to biochemical cycling (Q6, Q20), impacts of sea-level change (Q10, Q15), or the ocean's potential for climate change mitigation (Q9). Research addressing most of these questions benefits from the overall capacity in ocean observation and sampling described in Section 2.3. The research questions relating to impacts of climate change on ocean systems are also included in the human impacts on marine and coastal ecosystems theme (Section 4.3), whereas questions relating to impacts on coastal communities are also included in the coastal communities theme (Section 4.5).

Major Research Questions Related to Ocean-Climate Interactions

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q2. 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?

Q3. 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?

Q4. 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?

Q5. 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?

continued on next page

Q6. 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?

Q7. 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?

Q8. 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?

Q9. 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)?

Q10. 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?

Q15. What will be the impacts of climate change and ocean acidification on marine ecosystems, biodiversity, resource management, and coastal communities?

Q20. 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?

Q21. 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?

Q22. 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?

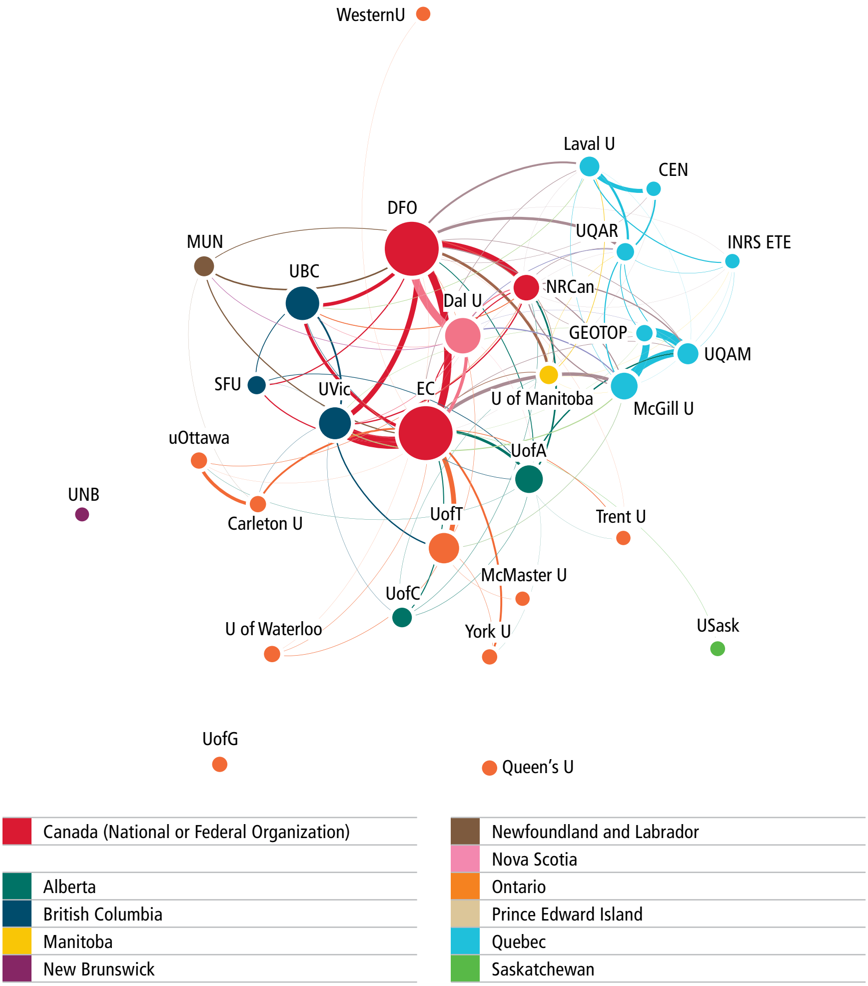
4.1.1 Research Output and Collaboration

Bibliometric analysis suggests that Canada's research output in ocean-climate interactions (4,544 papers) is lower among leading countries than in most other themes, with 6.1 per cent of world publications and a rank of seventh globally (Table 4.1). The scientific impact of Canadian papers (ARC = 1.28) in this theme remains above the world average, but is not as high as in most other themes or as high as that of many other countries in this theme. The theme is also not growing as quickly as other fields at the world level (GI = 0.97) or in Canada (GI = 0.96).

Figure 4.2 shows that DFO and Environment Canada are major hubs of publication and collaboration on ocean-climate interactions, followed by NRCan and five universities with similar output. One of the main centres for climate research, the Canadian Centre for Climate Modelling and Analysis (CCCma), is an Environment Canada centre located on the University of Victoria campus. The shared location explains the high level of co-publication of these organizations. In general, research capacity outside DFO and Environment Canada is fairly well distributed across Canadian institutions. Several regional/provincial clusters of collaboration emerge from the bibliometric data: McGill University, Université du Québec à Montréal, Geotop, and Ouranos, as well as a network consisting of Université Laval, Université du Québec à Rimouski, and the Centre d'études nordiques, in Quebec; collaboration between University of British Columbia, University of Victoria, and Simon Fraser University in British Columbia; and a strong link between the University of Ottawa and Carleton University in Ottawa, Ontario.

4.1.2 Research Seascape

Climate modelling uses data from past and present conditions to inform and test models of ocean-atmosphere interactions that further understanding of observed processes such as heat uptake, exchange of gases with the atmosphere, currents, thermohaline circulation, and many others. Models are also used to forecast future conditions and inform policy decisions (Johannessen *et al.*, 2004; IPCC, 2007). Canada is making several contributions to improving global and regional climate models. The CCCma, the Pacific Climate Impacts Consortium (University of Victoria), and other centres develop regional and global climate models to understand both past and predicted climate. These centres also contribute to international modelling efforts, including the Intergovernmental Panel on Climate Change (IPCC). From 1990 to 2007, six per cent of IPCC authors had Canadian affiliations, making it the fourth most common affiliation (Ho-Lem *et al.*, 2011).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.2

Collaboration Network of Top 30 Canadian Organizations Producing Papers on Ocean-Climate Interactions, 2003–2011

DFO and Environment Canada are the most productive organizations in this theme, closely followed by the University of British Columbia, Dalhousie University, University of Victoria, University of Toronto, University of Alberta, McGill University, and NRCan.

Note: Only links representing five or more collaborations between organizations are displayed, to improve readability.

Although global models benefit from improved representation of ocean-climate interactions, regional-scale models are also needed to forecast climate change impacts on ecosystems and coastal communities at finer resolutions (Foreman & Yamanaka, 2011). Several institutions and networks are working to improve regional climate modelling, addressing challenges such as the parameterization of global models at the regional scale. These include, for example, the Ouranos Consortium on Regional Climatology and Adaptation to Climate Change, focusing on Quebec and North American regional modelling; the Pacific Institute for Climate Solutions (PICS), a provincially funded knowledge network initiated by universities in British Columbia; and the Pacific Climate Impacts Consortium at the University of Victoria. ArcticNet and the new MEOPAR NCE also promote collaboration among Canadian ocean and climate modelling experts. Part of ArcticNet's focus includes climate change impacts in the Arctic, and the NCE has actively promoted research on more accurate regional-scale models that incorporate the role of the ocean and sea ice (ArcticNet, 2011, 2012). MEOPAR's research plan includes projects on marine modelling and prediction related to human activities in the ocean, including extreme events associated with climate change (MEOPAR, 2013).

While Canada has considerable capacity in climate model development and related information infrastructure, both global and regional modelling efforts suffer from a lack of ocean observation data, in particular the resolution of observation data required to parameterize regional climate models (Arritt & Rummukainen, 2011). Canadian contributions addressing this gap include unique remote sensing data from platforms such as the RADARSAT series of satellites, which provides observations of ocean, ice, land, and atmosphere to Canadian and international users (CSA, 2012a). Canadian ocean scientists also lead the development of remote sensing platforms, automated systems, and sensors for recording climate-related ocean data, such as profiling systems for use under mobile ice cover (Fowler *et al.*, 2004; Kaminski *et al.*, 2010; Send *et al.*, 2012).

The length of Canada's coastline and its dispersed infrastructure and population make it especially challenging to monitor climate-related ocean conditions *in situ* at the required spatial and temporal scales and resolutions. For example, the lack of available data limits the development of accurate regional models that reflect the rapid and complex changes occurring in the Arctic (Johannessen *et al.*, 2004; Huntington *et al.*, 2005). A 2008 Council of Canadian Academies report found that Canada was lagging behind other countries in the density and continuity of environmental monitoring in the Arctic (CCA, 2008). As Section 4.6 shows, upcoming investments such as the Canadian High Arctic Research Station

(CHARS) may increase capacities in some areas. At the same time, sustaining unique elements of observation capacity is challenging. For example, the Polar Environment Atmospheric Research Laboratory (PEARL), which is equipped with a number of highly specialized instruments, ceased year-round operation in 2012 due to lack of funding (CANDAC, 2013a). At the time of writing, a grant from NSERC was awarded for "Probing the Atmosphere of the High Arctic" (PAHA), which will allow limited winter data collection from 2013 to 2018 (CANDAC, 2013b).

Climatically relevant ocean observation is an increasingly global endeavour (Hall *et al.*, 2009; Roemmich *et al.*, 2009). Gaps in observation of climate-related ocean variables also affect Canada's ability to contribute to and benefit from international observation programs such as the IOC/WMO Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), the Global Ocean Observing System (GOOS), and the Global Climate Observing System (GCOS) (Nichols, 2005). Canada currently participates in GOOS and GCOS by providing data from several national observing systems, such as weather stations, tide gauges, moored and drifting buoys, Argo floats, and sensors mounted on voluntary ships.

Improving the representation of the ocean, ice, and snow are key challenges in climate modelling (Weller *et al.*, 2005; Jahn *et al.*, 2011). Canada is in a strong position to contribute to the understanding of sea ice through the Canadian Ice Service, which collects and maintains comprehensive data sets on sea ice extent, concentration, and type throughout Canadian waters (Nichols, 2005). Although these charts are produced primarily in support of marine transportation, the data can be a valuable addition to global climate monitoring and modelling.

Aside from observing and monitoring present conditions, understanding ocean-climate interactions also requires data on past climates from paleo-oceanographic records acquired through the analysis of sediments and ice cores, as well as other methods. This type of research is an essential part of the mandate of the International Ocean Drilling Program (IODP). Canada currently accesses IODP drilling capacity via a junior membership as a participant in the European Consortium for Ocean Drilling, which provides only limited access to the necessary specialized drilling capacity.

4.1.3 Opportunities and Challenges

Many of the research questions in this theme require improving climate models or better understanding the processes of ocean-climate interaction that feed into new models. Research in this area can benefit from capacities for related observation and monitoring activities, in which Canada has considerable strength (e.g., computation capacity, remote sensing). In addition, new flagship projects in ocean observation and upcoming investments in Arctic research capacity provide opportunities to improve the integration of ocean processes, sea ice, and ocean-atmosphere interactions in global and regional climate models.

The main challenges limiting Canada's potential in this theme relate to the need for sustained observation and monitoring of climate-related ocean phenomena, particularly in the Arctic. Due to Canada's vast coastline and exposure to the Arctic, relative to its population, this challenge is substantial. Such observations and resulting improvements in modelling and prediction, however, would benefit not only Canadian society, but also the global community. Canada's participation in international observation systems is contingent on the data and services that it contributes. Participation provides access to global data sets, other infrastructure, and opportunities to contribute to international capacity development for mutual benefit (see Westermeyer, 2010). This underscores the importance of international collaboration as well as the need for national-level coordination of observation and monitoring efforts.

4.2 BIOLOGICAL, MINERAL, AND ENERGY RESOURCES

The ocean contains a wealth of resources that support human well-being and economic activity (see Table 4.2 for examples). As human populations continue to grow and develop, the demand for these resources will likely increase (IOC/UNESCO *et al.*, 2011). There are limits to the ocean's apparent bounty, and resources are not evenly distributed throughout the ocean. Fish and other marine animals frequently move across borders. Ecosystem health determines the availability and quality of biological resources. The exploration and extraction of mineral and energy resources on or below the sea-floor pose technical and environmental challenges. Understanding the distribution, dynamics, and interdependencies of these resources is essential to their sustainable use and conservation in the face of increasing pressures from human activities and other types of global change.

Table 4.2

Examples of Marine-Derived Biological, Mineral, and Energy Resources

Biological	Mineral	Energy
Marine organisms: fish, marine mammals, algae **Genetic resources** **Marine natural substances:** nutraceuticals, pharmaceuticals	**Polymetallic massive sulfides** **Manganese nodules** **Manganese-cobalt crusts** **Phosphorites** **Heavy minerals**	**Non-Renewables:** oil and gas, gas hydrate deposits **Renewables:** offshore wind, in-stream tidal, wave energy

The biological, mineral, and energy resources theme combines research questions on the fundamental understanding of living and non-living resources. A number of questions concern the response of species and ecosystems to global change or other stresses, and the implications for living resources. Several questions that focus on understanding the impacts of mineral and energy resource exploitation (Q26, Q29) are addressed directly in the next theme: human impacts on marine and coastal ecosystems (see Section 4.3). This section deals with the research necessary to understand the nature and distribution of mineral and energy resources, and the dynamics and interdependencies of biological resource systems. In other words, the theme encompasses the more fundamental research required to further the understanding of ocean resources. This research serves as the basis for more applied research in development of extraction technologies and approaches to sustainable management.

Major Research Questions Related to Biological, Mineral, and Energy Resources

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q11. How do changes in species interactions affect food web structure within and across ecosystems?

Q12. How will changes in biodiversity affect the functioning of ocean ecosystems?

Q13. 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?

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Q14. How do management practices and natural variability influence how pathogens and parasites affect the abundance of marine species?

Q16. 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?

Q17. How are the movements and survival of marine organisms, including invasive species, being affected by environmental change, and what are the socio-ecological impacts?

Q19. 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?

Q21. 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?

Q26. 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?

Q27. What are the impacts of oil spills in cold and deep oceans, and under sea ice, and the appropriate strategies and technologies for prevention and mitigation?

Q28. 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?

Q29. 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?

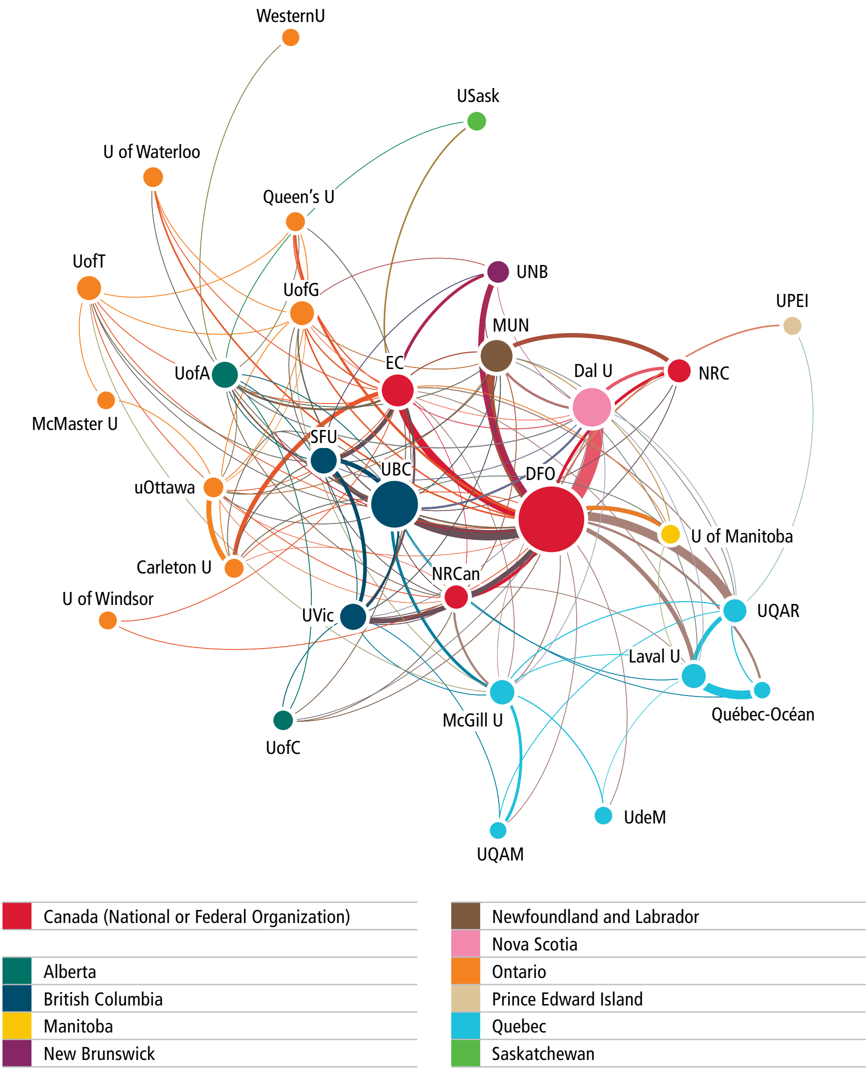
Q37. How are areas and/or species of special vulnerability, such as "hotspots" of relatively high diversity or function, identified, monitored and protected under conditions of uncertainty and in the context of global change? How can the related capacities to carry out these activities be improved?

4.2.1 Research Output and Collaboration

The theme of biological, mineral, and energy resources has the highest overall global publication output of the six themes, and the highest Canadian output. Canada ranked fourth in the world, with 6.7 per cent of world publications (13,782 papers) (Table 4.1). Canada is highly specialized in this theme (SI = 1.64), with impact above the world average (ARC = 1.33). World growth in this theme (GI = 1.06) is slightly above world growth in other fields, but the theme is losing ground to other areas of research in Canada (GI = 0.94), and Canada ranks last among of the top 25 countries by GI. Although an area of traditional strength in Canada, other countries may be catching up in research output.

The most productive organizations in Canada in research on this theme include DFO (over 2,400 papers), and the University of British Columbia and Dalhousie University, each with over 1,000 papers from 2003 to 2011 (Figure 4.3). Federal government departments also publish much of the research in this theme as reports, many of which are also peer-reviewed; however, these are not included in the bibliometric data analyzed for this report. Many publications in DFO's CSAS database present research on living resources, consistent with DFO's historical focus on fisheries management and current transition to ecosystem-based management under the *Oceans Act* (DFO, 2008b, 2008a).

Canada's network of collaborations in living and non-living resources is highly connected, comprising several decentralized hubs that include federal organizations, such as DFO and Environment Canada, in addition to universities that collaborate strongly across Canada, such as Dalhousie University, the University of British Columbia, the University of Victoria, Memorial University, and the University of Alberta. A cluster of Quebec universities suggests higher collaborations in this region than others, centred on Université Laval. International collaboration in fisheries research takes place in numerous international and regional fora, such as the FAO Fisheries Committee, the Northwest Atlantic Fisheries Organization (NAFO), and the North Atlantic Salmon Conservation Organization (NASCO) (Lutgen, 2010).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.3

Collaboration Network of Top 30 Canadian Organizations Producing Papers on Biological, Mineral, and Energy Resources, 2003–2011

The Canadian collaboration network in this theme is highly connected, comprising several decentralized hubs that include federal organizations, such as DFO and Environment Canada, in addition to universities that collaborate strongly across Canada, such as Dalhousie University, University of British Columbia, University of Victoria, Memorial University, and University of Alberta.

Note: Only links representing two or more collaborations between organizations are displayed, to improve readability.

4.2.2 Research Seascape

This theme encompasses fundamental research on a range of resource types, which the Panel examined separately to identify challenges and opportunities facing ocean science in Canada.

Biological Resources

Marine biological resources have long been a focus of DFO's mandate, which may account for an accumulation of significant capacity and strong performance as measured by bibliometric indicators for this theme. Biological resources remain prominent throughout the priorities outlined in *Fisheries and Oceans Canada Five-Year Research Agenda 2007–2012* (DFO, 2007, 2008b) (see Box 4.1).

Box 4.1
Science Priorities of Fisheries and Oceans Canada

1. Fish population and community productivity
2. Habitat and population linkages
3. Climate change and variability
4. Ecosystem assessment and management strategies
5. Aquatic invasive species
6. Aquatic animal health
7. Sustainability of aquaculture
8. Ecosystem effects of energy production
9. Operational oceanography
10. Emerging and enabling technologies for regulatory responsibilities

(DFO, 2007, 2008b)*

* At the time of writing, it was not known whether the priorities outlined remain active beyond 2013.

As mentioned in Chapter 2, DFO houses significant human and physical capacity in its regional institutes and laboratories. These facilities are the major hubs for research on biological resources, and provide much of the capacity necessary to address the research questions in this theme. DFO also maintains a total of 13 centres of expertise (see Table 4.3). Most of these are "virtual" centres that function as collaborative networks of scientists within and outside of DFO, while others are organized as physical institutes around local or regional infrastructure. Some centres focus on specific human impacts, but the majority conduct research that also contributes to the fundamental understanding of biological resources and ecosystems. From 2007 to 2012, consistent with its evolving ecosystem focus, DFO conducted seven pilot ecosystem research initiatives across Canada. The overarching goals were to understand ecosystem processes and the impacts of environmental and climate variability, and to develop tools to support DFO's ecosystem approach to management (DFO, 2013h). With research under these initiatives now completed, the findings are expected to inform DFO's operational activities, although many questions for further research remain (DFO, 2013b).

Table 4.3

DFO Science Centres of Expertise (COEs)

Centre	Research Priorities
Centre for Aquatic Animal Health Research and Diagnostics	Infectious diseases in wild or farmed aquatic animals.
Centre for Aquatic Biotechnology Regulatory Research	Regulatory research and risk assessment regarding fish with novel traits.
Centre for Aquatic Habitat Research	Habitat-population linkages regarding productive capacity, population productivity, ecosystem resilience, and management implications.
Centre for Aquatic Risk Assessment	Prioritization, coordination, and standardization of risk assessments of aquatic invasive species.
Centre for Cold-Water Corals and Sponge Reefs	Approaches for coral sponge conservation, including support for and coordination of international efforts.
Centre for Marine Mammalogy	Dynamics, ecology, habitat, migration, and health of marine mammals.
Centre for Environmental Research on Pesticides	Environmental consequences of pesticide use, including advice for pest management and regulation.
Centre for Traditional Ecological Knowledge (TEK)	Acquisition and integration of TEK with scientific data to improve decision-making; engagement of TEK holders in ocean and coastal management.
Centre on Hydropower Impacts on Fish and Fish Habitat	Impacts of hydroelectric energy development on fish and fish habitat.
Centre for Ocean Model Development for Applications	Development of ocean models and application to departmental priorities.
Centre for Offshore Oil, Gas, and Energy Research	Environmental and oceanographic impacts of offshore petroleum exploration, production, and transportation.
National Centre for Arctic Aquatic Research Excellence	Arctic marine and freshwater environments, including advice to Arctic legislation development.
Centre of State of the Ocean Reporting	Summarize analyses of marine data on trends and changes in Canada's ocean basins.

(DFO, 2012a)

The University of British Columbia Fisheries Centre is the largest university research institute for marine biological resources. It includes units performing multidisciplinary research on many aspects of fisheries, such as policy and ecosystem restoration in fisheries, marine mammals, quantitative modelling, fisheries economics, aboriginal fisheries, aquatic conservation sciences, and global ocean modelling. The Fisheries and Marine Institute and researchers in other departments of Memorial University perform research on a similar range of issues, whereas capacity in fisheries and related research at Dalhousie University is spread over several departments and institutes. Simon Fraser University, the University of Victoria, and the University of Alberta host important capacity within their biology departments and related research units.

In addition to these physical and virtual research institutions, scientists from universities, government departments, and others have formed several national networks focused on various aspects of marine biological resources:

- Canadian Fisheries Research Network (CFRN): a collaboration between academic and government researchers and the fishing industry. It aims to improve the basis for an ecosystem approach to fisheries management to achieve ecological sustainability and operational efficiency (CFRN, 2012b).
- Ocean Management Research Network (OMRN): originally created as a tool to manage DFO outreach activities by translating and mobilizing ocean science knowledge for use by different communities. It has evolved into a large pan-Canadian network with more than 800 members (OMRN, 2012).
- Canadian Healthy Oceans Network (CHONe): focuses on biodiversity science for the sustainability of Canada's ocean ecosystems, including marine biodiversity, ecosystem function, and population connectivity (CHONe, 2009).
- Atlantic Reference Centre: a research museum for aquatic organisms from Atlantic Canada. Maintained by DFO and the Huntsman Marine Science Centre, its collections are available for research and education purposes (HMSC, n.d.).
- Centre for Marine Biodiversity (CMB): a virtual institute aiming to enhance scientific capacity in support of the protection of marine biodiversity, with a focus on the Northwest Atlantic. It provides access to data sets of the Ocean Biogeographic Information System (OBIS) via the Canadian OBIS node, the Canadian Register of Marine Species (CRAMS), and the RAM Legacy Stock Assessment Database (CMB, 2013).

Over the past few years, Canada has been building important capacities in genomic analysis and its application to research on marine biodiversity, catalyzed and supported by Genome Canada. Flagship projects include the Marine Barcode of Life (MarBOL), hosted by the Biodiversity Institute of Ontario (MarBOL, 2013);

and FISH-BOL, hosted by the University of Guelph — a related project aiming to develop a specific reference library of genetic barcodes for all fish species (FISH-BOL, 2012). Genetic barcoding has made substantial contributions to the Census of Marine Life by enabling rapid and inexpensive identification of marine species.

Some of the infrastructure funded by Genome Canada is stimulating growth in the emerging field of marine biotechnology, with a particular focus on marine animal health by the Centre for Microbial Diversity and Evolution (University of British Columbia), the Canada Research Chair in Marine Biotechnology (Memorial University), and the Centre for Biomedical Research (University of Victoria) (Genome Prairie *et al.*, 2008). Biodiversity genomics is also increasingly used to assess the status of species at risk of extinction (Johnstone *et al.*, 2007). Advances in genomics raise a number of societal issues such as ethical, environmental, economic, legal, and social aspects of technologies and products based on genomic analysis. To facilitate their integration, Genome Canada incorporates these aspects into its funding program and requires that all applications address such issues (Genome Canada, 2013).

The rise of genomics is also leading to the emergence of new technologies and research that are currently not pursued at a significant scale in Canada, including the development of technologies for *in situ* remote genomic measurements of biodiversity, as well as the application of genomics to the broader range of marine biotechnology (McLean, 2013). Marine organisms are often cited as a potential basis of a new generation of products such as pharmaceuticals, cosmetics, or novel compounds and enzymes for biological processes. Although Canada hosted the 2nd Annual World Congress of Marine Biotechnology in 2012 and the 4th BioMarine International Business Convention in September 2013, the Panel could find no dedicated research network for marine biotechnology.

Despite advances in genomics, taxonomy remains the foundation for biodiversity science — a circumstance that often leads to tensions in decisions about investments in different areas of biodiversity science. A 2010 Council of Canadian Academies report found that Canada has outdated facilities and significant gaps in species description and geographic distribution data, digitization of collections, and systematic contributions to international biodiversity data-sharing efforts (CCA, 2010). In addition, the number of young taxonomists who remain in Canada is outpaced by the number of taxonomists retiring. The consequences of these gaps in taxonomic capacity include a risk of losing traditional and community knowledge; limited capacity to respond to emerging risks, such as impacts of global change, invasive species, and new pathogens; and decreasing support for other areas of biodiversity science. The lack of a sound basis in taxonomy could hamper Canada's ability to understand and protect its biodiversity resources, and sustainably manage associated ecological goods and services, in particular in aquaculture and fisheries, but also with regard to human health, nutrition, and well-being.

Mineral Resources

Several of the research questions in this theme aim at improving fundamental understanding of mineral resource deposits on the ocean floor. The sea-floor contains valuable mineral resources, the mining of which becomes more economical as demand for them increases. Deposits in deep ocean basins include ferromanganese crusts, manganese nodules, and sea-floor massive sulfides (SMS) (Scott, 2012). SMS deposits have attracted interest in recent years because they contain large quantities of base metals (copper, zinc, lead) and precious metals (silver, gold). SMS deposits form around hydrothermal vents on the deep sea-floor. More than 165 sites of active hydrothermal venting with significant SMS accumulation have been found worldwide, with several sites situated along the Juan de Fuca fault off Canada's Pacific coast and within Canada's EEZ (Hannington *et al.*, 2010; Hannington *et al.*, 2011). Current activities are led by three international companies, including Canada-based Nautilus Minerals (Scott, 2012).

The experience with current exploration sites has shown that collaboration between industry geologists and research scientists can greatly expand the knowledge about the deep sea-floor, both for scientific purposes and discovery of valuable resources (Hoagland *et al.*, 2010; Scott, 2012). Seabed mining also offers opportunities for technology development and transfer in international collaborative research and exploration projects, in line with the objective of the International Seabed Authority to support collaborative marine scientific research (Glasby, 2000; ISA, n.d.). The prospect of mining the sea-floor, however, is creating concerns about potential damage to sea-floor biodiversity, which is currently largely unexplored and unprotected by international law (Halfar & Fujita, 2007).

While industry does much of the exploration of actual sites, Canadian marine geoscience plays an important role in providing the basis for mineral exploration. NRCan, including the Geological Survey of Canada, is the lead federal department in this area of research, but collaboration is also common with DFO, the U.S. Geological Survey, NOAA, and many North American universities. In 2002 DFO and NRCan initiated the Geosciences for Oceans Management Program (GOM) to provide a comprehensive geoscience knowledge base of Canada's ocean sea-floor and coasts. Mineral exploration has been carried out using a range of specialized sensors and platforms, from magnetic remote sensing to ROVs and AUVs. Observation platforms such as NEPTUNE Canada allow for continuous monitoring of specific hydrothermal vents off the Pacific Coast, but understanding the larger-scale distribution of mineral resources requires more dispersed and mobile capacities.

Energy Resources

Canada is endowed with rich offshore oil and gas reserves, located in several sedimentary basins off the east and west coasts as well as in the Arctic. The production of these resources is an important driver of several ocean science themes. The discovery and exploration of offshore oil and gas fields require sophisticated techniques and instruments for two- and three-dimensional seismic testing, data processing, and visualization (CCEI, 2007). Calgary has become a major hub for R&D related to these services for the entire oil and gas industry, including offshore operations, as well as particular research needs for offshore drilling in the Arctic.

The offshore oil and gas industry has been an economic engine on Canada's East Coast, driving the growth of an ocean technology cluster in St. John's, Newfoundland and in Labrador. The unique challenges of accessing oil and gas deposits in areas covered in sea ice led to the creation of the Centre for Cold Ocean Resource Engineering (C-CORE) by the oil and gas industry in 1975 (C-CORE, 2005). Research on the potential benefits and risks of developing oil and gas resources in the Beaufort Sea is conducted by a collaboration between ArcticNet and several oil and gas companies, which has enabled a significant expansion of the collection of environmental data for energy exploration as well as other research purposes (ArcticNet, 2013).

Oil and gas companies collect large amounts of data and sample cores during exploration. Canadian regulations require that these be made available to the public for research purposes. Most of these resources are held by the geoscience centres of the Offshore Petroleum Boards of Newfoundland and Labrador and Nova Scotia, and the Frontier Information Office of the National Energy Board (for the Arctic). These institutions provide access to several thousand metres of drill cores, sidewall cores, drill-cutting samples, and geochemistry samples retrieved from several hundred offshore wells, as well as an enormous repository of two- and three-dimensional seismic data. These resources substantially contribute to research in geophysics and geological history, and to improving models of paleoclimate, paleocurrents, and plate tectonics (CNLOPB, 2013; CNSOPB, n.d.).

Ocean renewable energy could become a similar driver of ocean science in Canada. A recent inventory of Canada's R&D capacity in marine renewable energy commissioned by NRCan concludes that Canadian technologies and research facilities are on the leading edge in several areas, with strong potential for growth in R&D, manufacturing, deployment, and generation (Devine Tarbell & Associates, 2008). The report highlights world-class infrastructure such as the Bay of Fundy Research Centre for Energy (FORCE), which hosts an important test centre and observation facility for the development of in-stream tidal energy. FORCE is a not-for-profit corporation supported by the Government of Canada, the Government of Nova Scotia, Encana Corporation, and participating developers. Marine Renewables Canada, an alignment of industry, academia, and governments, has published Canada's Marine Renewable Energy Technology Roadmap, which lays out a vision for renewable ocean development building on these and other capacities, such as Canada's strength in technology-based research (MRN, 2012). The roadmap suggests supporting activities such as technology incubators, cross-sector technology transfer, and enhancement of engineering, procurement, and construction capacities to build international leadership, develop markets, and increase opportunities for technology transfer.

Offshore activities relating to energy and mineral resource development also create new research needs in potential impacts of energy resource extraction on the marine environment such as underwater noise and oil spills in cold-water environments (see, for example, OAG, 2012), human health and safety, and social-ecological impacts on the communities affected by drilling operations (both positive and negative). Some of this research is supported by the Environmental Studies Research Funds, financed through levies on oil and gas companies active in Canada's frontier lands (ESRF, 2013).

4.2.3 Opportunities and Challenges

This theme highlights the broad range of fundamental, discovery-based ocean research needed for sustainable development of marine resources. Advancing research in these areas has direct societal impacts by increasing the benefits derived from ocean resources. At the same time, the research questions point to a need for better integration of research on resource development and on potential impacts of the associated human activities (see Section 4.3). Bibliometric indicators demonstrate Canada's traditional strength in many related areas of fundamental research, which could contribute to addressing the research questions in this theme.

Research on marine biological resources can build on a firm capacity base located in DFO and several large university institutes and departments. If expertise in taxonomy can be maintained, Canada's capacity in new and emerging areas of biodiversity research will provide opportunities when addressing questions relating to marine biodiversity and ecosystem dynamics. Research on fisheries and fish populations can benefit from the nation's long history of research conducted by DFO and major university centres. Addressing some of the questions would require adopting a social-ecological approach, which may prove to be an important challenge in the coming years.

Canadian marine geoscience experts and mining companies are well positioned to play a leading role in performing the R&D needed to develop sub-sea mineral resources. Capacity in marine energy resources is strongest in the private sector, but partnerships with government departments and universities have great potential. The benefits to all these sectors of society will be greatest when they share information about the sea-floor.

Ocean monitoring and observation efforts considerably improve understanding of the distribution and dynamics of biological, mineral, and energy resources. As shown in Chapter 2, Canada is home to several leading initiatives in ocean observation, but there are also challenges in developing coordinated observation systems that provide adequate coverage of Canada's extensive ocean resources.

4.3 HUMAN IMPACTS ON MARINE AND COASTAL ECOSYSTEMS

Human impacts on the ocean will inevitably increase as a result of rising demand for ocean-based goods and services. Fishing, energy, mineral resource development, and tourism all affect the ocean in physical, ecological, or aesthetic ways that also affect its other human uses. Some aspects of the research questions listed here are captured in other themes: biological, mineral, and energy resources; and coastal communities. This theme focuses on aspects that further the understanding of how ocean systems are affected by human activities, and how they respond to impacts.

Several research questions in the theme go beyond mere understanding of impacts by asking what management approaches can be used to minimize impacts and achieve sustainable management. Q32 addresses the need for a holistic approach to studying human-ocean interactions by conceptualizing the ocean as a social-ecological system — a paradigm shift that will create new research needs and data requirements (Berkes *et al.*, 2001; Ommer & The Coasts Under Stress Research Project Team, 2007; Ommer *et al.*, 2011) (see Box 4.4 and CUS, 2006 for other example publications).

Among other advantages, this framing allows the investigation of complex feedback systems and secondary effects, such as the factors impeding fish stock recovery, or the influence of management practices on pathogen and parasite activity and their impacts on species abundance. It also highlights that it is not only essential to combine capacities in biological, chemical, and physical sciences to detect human impacts, but these efforts must also be embedded in a broader framework that includes research on the social and natural drivers of activities and impacts, building on natural and social sciences. Furthermore, this approach emphasizes the development of problem-specific and localized methodologies. It requires integration of qualitative and quantitative data, as well as sophisticated means of knowledge integration across disciplines and inclusion of non-scientific knowledge (see also Section 4.5).

Major Research Questions Related to Human Impacts on Marine and Coastal Ecosystems

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q10. 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 be the impacts on coastal ecosystems as well as broader impacts in human societies on global and regional scales?

Q12. How will changes in biodiversity affect the functioning of ocean ecosystems?

Q14. How do management practices and natural variability influence how pathogens and parasites affect the abundance of marine species?

Q15. What will be the impacts of climate change and ocean acidification on marine ecosystems, biodiversity, resource management, and coastal communities?

Q16. 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?

Q17. How are the movements and survival of marine organisms, including invasive species, being affected by environmental change, and what are the socio-ecological impacts?

Q25. 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?

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Q26. 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?

Q27. What are the impacts of oil spills in cold and deep oceans, and under sea ice, and the appropriate strategies and technologies for prevention and mitigation?

Q28. 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?

Q29. 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?

Q30. 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)?

Q31. What are the fates and impacts of plastics, nanomaterials, and emerging synthetic contaminants in the ocean?

Q32. 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?

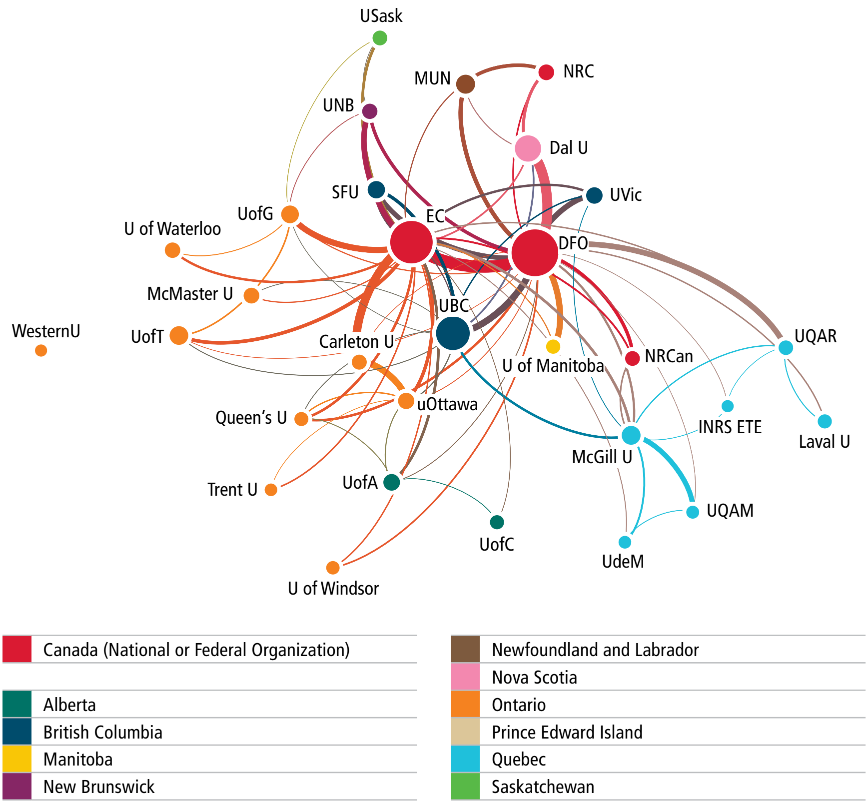
Q39. What technologies and strategies are needed to develop and deliver ocean-based renewable and non-renewable energy and minerals to society with minimal harm to the ocean environment?

4.3.1 Research Output and Collaboration

The theme of human impacts on marine and coastal ecosystems is the second largest theme by Canada's publication output (7,437 papers), after biological, mineral, and energy resources (Table 4.1). Canada's high rank in output (fourth in the world, with 6.3 per cent of the world total) reflects the historical strengths of Canadian research on the impacts of human activities such as fishing. Nevertheless, this area of research is losing ground to other fields in Canada (GI = 0.95), but is keeping pace with other fields at the world level (GI = 1.03).

The most productive Canadian organizations in research related to this theme include DFO (over 1,000 papers), Environment Canada (985), the University of British Columbia (730), and Dalhousie University (over 500) (Figure 4.4). While DFO's publications and collaboration with Environment Canada and

NRCan dominate the biological, mineral, and energy resources theme, both DFO and Environment Canada are major hubs for collaboration in this theme. Several regional clusters are evident in Quebec and Ontario.



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.4

Collaboration Network of Top 30 Canadian Organizations Producing Papers on Human Impacts on Marine and Coastal Ecosystems, 2003–2011

Canadian collaboration in this theme is centred on DFO and Environment Canada. The University of British Columbia and Dalhousie University are also prominent due to high publication output and high levels of collaboration with federal organizations and other universities.

Note: Only links representing two or more collaborations between organizations are displayed, to improve readability.

4.3.2 Research Seascape

In accordance with its mandate, DFO conducts research on the impacts of many human activities, including general assessments of the state of the ocean, as well as research on specific impacts of climate change and climate variability, invasive species, energy production, and pesticide use, for example. These activities are reflected in DFO's science priorities (see Box 4.1) and the mandates of the 13 DFO virtual Science Centres (see Table 4.3). Many of these centres involve collaborations with academia and other partners. The Centre for Offshore Oil, Gas and Energy Research, for example, conducts research on a broad range of impacts of oil and gas development, including in cold water and sea-ice conditions (Q27) in collaboration with partners from other departments, universities, and industry (DFO, 2013h).

Additional university-government collaborations take place with individual stock assessments, in which faculty and students participate with DFO staff, and with large directed research networks. Two of the latter are the Canadian Aquatic Invasive Species Network (CAISN) and the Canadian Healthy Oceans Network (CHONe). From 2006 to 2011, CAISN, a partnership involving 13 universities and 6 DFO laboratories, investigated the vectors and pathways by which aquatic invasive species enter Canada. CAISN II, funded from 2011 to 2016, will provide a comprehensive profile of aquatic invasive species in Canadian waters, and develop tools for their early detection and rapid management responses. CHONe was a five-year partnership between 15 Canadian universities, DFO, and other government laboratories focused on the biodiversity of ocean life in Canada (CHONe, 2009).

Canadian ocean scientists have also been closely involved and often play leading roles in international and intergovernmental marine science organizations focusing on the study of human impacts, such as the International Geosphere-Biosphere Program (IGBP), the Intergovernmental Oceanographic Commission of UNESCO (IOC), the International Council for the Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), the FAO Fisheries Committee, the Convention on Biological Diversity, and UNEP. Of the 89 authors of the synthesis volume on *Marine Ecosystems and Global Change* (Barange *et al.*, 2010), which resulted from the IGBP Global Ocean Ecosystem Dynamics core program, 12 per cent have Canadian affiliations. In addition, the current executive secretary of the IOC, the immediate past president of the ICES, the current chair of PICES, and the president-elect of the International Council for Science (ICSU) are all Canadian scientists.

As noted in Q25, research in this theme is particularly dependent on observation and monitoring data. Long-term observation and monitoring produce data sets that enable comparisons of ecosystem attributes before and after some human impact, providing insight into how ecosystems are affected and the length of time to recovery. Many facilities manage such data, and most are operated by the federal government, with specific mandates for these purposes. The DFO Integrated Science Data Management (ISDM) unit and other DFO units hold data related to physical, chemical, and biological observations collected by DFO and other organizations within and outside of Canada. ISDM also provides access to ocean databases housed by other organizations internationally, including:

- physical, chemical, and biological data provided by DFO's research institutes (Ocean Profiles);
- global temperature and salinity profiles provided through the Global Temperature-Salinity Profile Programme (GTSPP);
- data gathered by surface drifters and ocean profile data from Canadian and international programs such as the Climate Variability programme (CLIVAR);
- biological and chemical oceanographic data (BioChem);
- information on toxic chemicals in fish, other aquatic life, and their habitats from the National Contaminants Information System (NCIS); and
- Canada's portion of the Ocean Biogeographic Information System (OBIS).

(DFO, 2013g)

Non-governmental centres in Canada hold additional data sets, such as the RAM Legacy Stock Assessment Database (named after Ransom A. Myers, who compiled the original database) for more than 300 commercially exploited marine populations worldwide (Ricard *et al.*, 2011). Moreover, non-governmental organizations (NGOs) are increasingly conducting their own research and analyses of human impacts, particularly relating to marine spatial planning and marine protected areas (Hastings, 2011; Calado *et al.*, 2012; CEC, 2012).

In all three of Canada's ocean basins, DFO conducts annual, and sometimes seasonal, surveys to assess the abundance and other characteristics of fish and marine mammal populations. While these tend to focus on populations of commercial or charismatic interest, the evolution towards more holistic ecosystem approaches has led to increased attention to species of non-commercial interest (DFO, 2012d). Research on the collapse and recovery of fish stocks also shows the need for more integrated approaches (see Box 4.2). In the Canadian Atlantic, a region-wide physical and biological monitoring program has been in place since 1999 (Pepin *et al.*, 2005), but nothing similar has yet been established in the Pacific or Arctic.

Box 4.2
The Collapse of Atlantic Cod and the Scientific Challenges of Fisheries Management

The collapse of the northwest Atlantic cod fishery in the early 1990s, and its subsequent failure to recover to date, has motivated research in many disciplines, including marine biology, ecology, fisheries science, engineering, economics, sociology, and law: see, for example literature cited in Hutchings (1999), and other research conducted under the Eco-Research Program at Memorial University (MUN, 1997). While the combined knowledge from these disciplines can explain many of the factors that contributed to the initial collapse, there is still disagreement over the reasons for the unexpected long recovery time (Fu *et al.*, 2001; Hutchings & Rangeley, 2011). Understanding stock dynamics is, however, only one aspect of the broader challenge to develop approaches for sustainable fisheries management, which also requires addressing issues such as economic and legal aspects of access regimes, impacts of subsidies and international trade, and broader socio-economic factors driving fishing activities (Hammer *et al*., 2010; Sumaila, 2012).

Environment Canada operates many contaminant monitoring programs across Canada, contributing data and research on related human impacts on marine ecosystems. These programs include marine water quality and sanitary wastewater monitoring for the Canadian Shellfish Sanitation Program, as well as the Canadian Aquatic Biomonitoring Network (EC, 2013). Environment Canada also coordinates contaminant monitoring in Canada's Arctic, including in marine mammals and fish, through the Northern Contaminants Program, and contributes to the Arctic Council's Arctic Monitoring and Assessment Program (EC, 2001).

Research on the impacts of human activities faces several challenges. Long-term research and monitoring that could support ecosystem-based management can be constrained by the limited-term, three- to five-year federal science funding model (Cohen, 2012a). In addition, the mandates for research on human impacts in marine and coastal ecosystems are sometimes not clearly divided among government departments. Environment Canada monitors contaminant levels in marine organisms but not their effects on fish *populations*, which Environment Canada considers to be part of DFO's responsibility (Cohen, 2012a). Such disagreements show that coordination is an ongoing challenge in complex areas such as contaminant monitoring. In the long run, if the need to coordinate mandates and activities cannot be resolved, there is a risk of being unaware of gaps in the monitoring and analysis of contaminants and their impacts.

Responding to emerging needs for research and monitoring is another challenge. For instance, DFO's Aquaculture Collaborative Research and Development Program has a mandate to increase the scientific capacity of the Canadian aquaculture industry for essential research and development (Martell *et al.*, 2011). Nonetheless, the environmental impacts of aquaculture are subject to contentious debate (Cohen, 2012b; Hutchings *et al.*, 2012). Additional information is also needed on the abundance and pathways for introduction of invasive species (Sutherland & Levings, 2013) — a gap that CAISN II aims to fill. Other concerns about threats to marine biodiversity in Canadian waters include climate change and fishing (Hutchings *et al.*, 2012). A baseline of marine biodiversity is required to assess the influence of each of these threats as well as their cumulative impacts. The Atlantic Reference Centre, co-supported by DFO and the Huntsman Marine Science Centre, provides a unique resource of taxonomic expertise and biodiversity information for the Atlantic, but no similar facilities exist for the Pacific or Arctic. Another emerging need is research on the potential impacts of deep-sea mining as mining operations may be scaled up significantly in the near future. Existing studies indicate that the environmental impacts could be substantial (Halfar & Fujita, 2007) (see Section 4.2.2).

Contaminant monitoring is increasingly challenged by the need to be able to detect new contaminants such as novel pharmaceuticals, endocrine disruptors, personal care products, new persistent organic pollutants, and nanomaterials. Legal regulations in Canada are already vague in defining acceptable levels of many existing and new contaminants (Ross *et al.*, 2013). The capacity to develop contaminant-specific molecular signatures to monitor existing and new chemicals will be an important enhancement to assess and monitor the risks and impacts of human activities on marine systems (Veldhoen *et al.*, 2012).

With increased interest and practical requirements to move towards marine spatial planning, integrated coastal zone management, and ecosystem-based approaches, there is an increasing need for more detailed data, as well as enhanced integration of disparate data sets. The ability to smoothly and quickly link such dispersed data is being improved, for example by the IOC's Ocean Biogeographic Information System (OBIS), whose Canadian portal is hosted by DFO's ISDM, but further and faster connections are needed. There is also a lack of knowledge of the cumulative effects of multiple stressors on marine systems, an issue featured in the conclusions of the *Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River* (Cohen, 2012b).

4.3.3 Opportunities and Challenges

The information reviewed here suggests that ocean science in Canada is in a strong position to continue performing research on human impacts on marine and coastal ecosystems. Much of this strength can be attributed to the historical role of federal government organizations, as well as the substantial research performed by Canadian universities. However, the research questions also point to challenges arising from the changing context of research on human impacts. One challenge is to adapt capacities and expertise to the transition towards more holistic approaches, which use ecosystem-based or social-ecological frameworks. For biological resources, this challenge is in part addressed by DFO's transition to ecosystem-based research and management; however, challenges remain in interdisciplinary training of researchers and other highly qualified personnel needed to meet the needs of such an approach.

Another challenge is to ensure that capacity development keeps pace with the evolution of human activities, such as the ability to monitor environmental impacts of aquaculture or the fate of contaminants, including emerging nanomaterials. This also includes the ability to assess and monitor impacts of the expansion of resource development into new areas with sensitive ecosystems or those already affected by rapid global change.

Research on invasive species is an emerging gap that will most likely be addressed by the CAISN II network. Other networks, such as those in genomic methods for assessing aquatic animal health, illustrate both the opportunities that can be created through networks and the challenges of maintaining collaboration beyond the initial funding term. Emerging capacities of NGOs and other actors provide opportunities for new forms of collaboration and sharing of resources for conservation and integrated management.

4.4 PLATE TECTONICS AND NATURAL HAZARDS

Tectonic activity on the ocean floor is a source of significant natural hazards, such as earthquakes, volcanic eruptions, submarine slides, and resulting tsunamis. These threats are particularly relevant to Canada's Pacific Coast, where the sea-floor is spreading along the Juan de Fuca fault and converging along the nearby Cascadia subduction zone (Clague *et al.*, 2003; Leonard *et al.*, 2012). Seven of the ten largest earthquakes in Canada have occurred off the Pacific Coast (NRCan, 2011a). Such local events are the cause of most major tsunamis along this coastline (Leonard *et al.*, 2012).

The largest tsunami to hit Canada, however, was caused by an underwater landslide, triggered by an earthquake in the Grand Banks of the Atlantic Ocean in 1929 (Clague *et al.*, 2003). The tsunami hazard on Canada's Atlantic coastline is otherwise dominated by far-field sources, and coastal topography can amplify tsunami waves, causing greater than expected impacts (Leonard *et al.*, 2012). Canada's Arctic coastline has few active fault lines and is relatively sheltered from far-field sources, leading to lower tsunami hazards than Canada's other coasts.

The research questions in this theme focus on the need to understand earthquakes, tsunamis, and other hazards to reduce risks to human lives and infrastructure. An improved understanding allows better forecasting and development of warning systems. Research on plate tectonics builds on and contributes to geological and hydrographic research, as part of the broader field of geosciences. Geological and hydrographic surveying contribute to knowledge of plate tectonics, but also support safe navigation and the exploration of mineral and energy resources (see Section 4.2).

Major Research Questions Related to Plate Tectonics and Natural Hazards

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q4. 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?

Q5. 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?

Q19. 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?

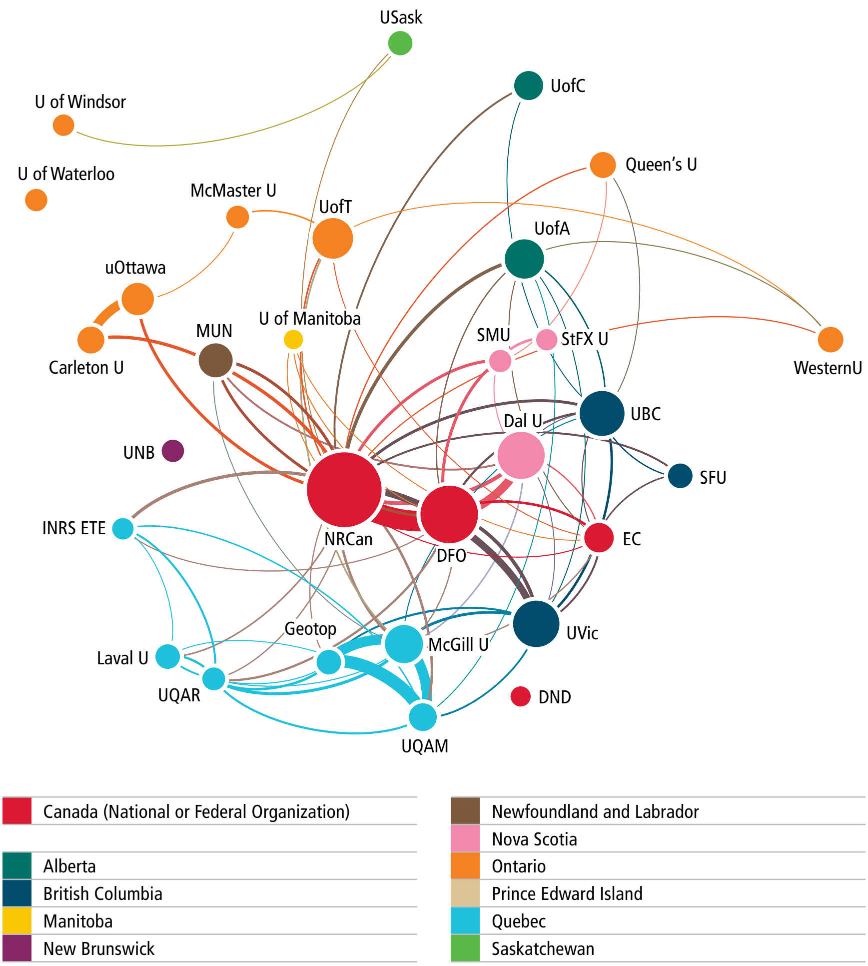
4.4.1 Research Output and Collaboration

Canada's share of world publications (5.5 per cent) is lowest in this theme (eighth in the world), compared with output in other themes (Table 4.1). While the impact of Canada's 4,546 papers on plate tectonics and natural hazards (ARC = 1.25) is above the world average, it is lower than in most other themes. This theme is growing as fast as other fields at the world level (GI = 0.99), but at a lower rate than other areas of research in Canada (GI = 0.90).

The most productive Canadian organizations in this theme are NRCan and DFO (Figure 4.5), supported by important expertise within the Canadian Hydrographic Service (CHS) at DFO, and the Geological Survey of Canada (GSC) at NRCan. High rates of collaboration between NRCan and DFO result from the co-location of the GSC's principal marine geoscience centres with DFO facilities: GSC Atlantic at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia (NRCan, 2008); and the Pacific Geoscience Centre at the Institute of Ocean Sciences in Sidney, British Columbia (NRCan, 2010). Other than a few local exceptions, most collaboration between Canadian organizations in this theme includes NRCan, DFO, or both, with lower rates of direct collaboration between universities (Figure 4.5).

4.4.2 Research Seascape

The Geological Survey of Canada and Canadian Hydrographic Service are the main providers of data on the characteristics of the sea-floor and the bathymetry of Canada's ocean basins. The Bedford Institute of Oceanography includes an Informatics Branch that supports the CHS, GSC, and the Department of National Defence and the Canadian Forces in analyzing and mapping survey data (BIO, 2013). These are used to produce hydrographic and navigational maps that identify hazards such as areas with sensitive bottom features that could be harmed by certain types of fishing gear. Fine-resolution bathymetry and land topography are needed for models to assess potential runup from tsunamis. The lack of such data and models currently limits the assessment of tsunami hazard for Canada's extensive coastline (Leonard *et al.*, 2012). Gaps in hydrographic data and the resulting lack of accurate charts across the Arctic pose a navigational hazard, given the anticipated increase in ship traffic in the area as sea ice recedes due to climate change (Arctic Council, 2009). These gaps also represent a constraint for research on interactions between the ocean, land, and sea-floor in the Arctic (as illustrated by Q4).



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.5

Collaboration Network of Top 30 Canadian Organizations Producing Papers on Plate Tectonics and Natural Hazards, 2003–2011

NRCan is the main collaborative hub in the Canadian network for this theme. The University of Victoria and Dalhousie University show strong collaboration with DFO, while several other universities with similar output collaborate less with the federal agencies. There is little collaboration among universities, with the exceptions of a cluster formed by McGill University, UQAM, and Geotop; and collaboration between the University of Ottawa and Carleton University.

Note: Only links representing four or more collaborations between organizations are displayed, to improve readability.

Seismic detection and monitoring systems provide long-term data about tectonic activity in areas that are of key interest to tectonic research. NRCan maintains the Canadian National Seismograph Network, comprising more than 100 land-based instruments, which are used to determine the size and location of earthquakes (NRCan, 2011b). For individual studies, the network can be complemented by ocean-bottom seismometers, which are designed for short-term use rather than long-term monitoring (Hunter, 2012). The CHS maintains a network of permanent tide gauges, which are also used to monitor tsunamis and storm surges (DFO, 2013c, 2013a). Canada participates in the Pacific Tsunami Warning System coordinated by the IOC (EMBC, n.d.), and has recently established a warning system for the Atlantic coast in partnership with the five Atlantic Provinces and NOAA (GC, 2007). DFO also applies its expertise and experience in marine natural hazards, including tsunamis and storm surge events, to provide science advice to Canadian and international decision-makers (DFO, 2006, 2013e).

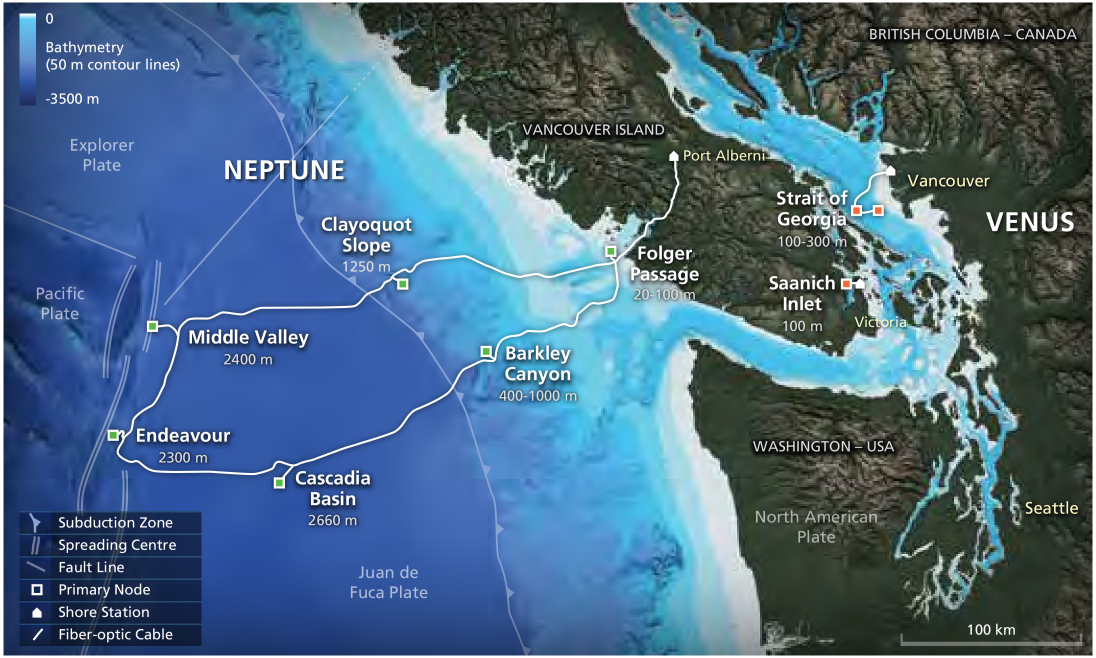
A substantial constraint in research on plate tectonics has been the lack of live observations of underwater volcanic eruptions, earthquakes, or events around hydrothermal vents. Canada has taken the lead globally in filling this gap by building the first regional-scale cabled observatory (NEPTUNE), with others expected to be built in the United States, Japan, Taiwan, and the European Union in coming years (Taylor, 2009). NEPTUNE (see Box 4.3) comprises five networked instrument nodes on the sea-floor off the coast of Vancouver Island, linked by 800 kilometres of powered electro-optic cable across the Juan de Fuca tectonic plate (Barnes *et al.*, 2008). The network's location enables unprecedented research on plate tectonics by allowing continuous observation of a seismically active region (including hydrothermal vents) and accelerated deployment of additional instruments when required. NEPTUNE is also poised to break new ground in international collaboration, as it will be fully interoperable with similar platforms to be built as part of the U.S. Ocean Observatory Initiative (OOI) (Taylor, 2009). This planned collaboration was one of several reasons NEPTUNE was funded through CFI's International Access Fund. Together, NEPTUNE and the OOI regional science nodes will provide a long-term and large-scale observation network covering the entire Cascadia subduction zone.

While NEPTUNE and OOI represent a tremendous breakthrough in ocean observation, the size and technical sophistication of these networks create new challenges. Building and operating cabled networks require specialized ships and equipment for cable-laying and deployment, and for servicing of nodes and instruments. These needs increase the demand for limited capacity that could also be used for other purposes. For example, from 2009 to 2012 almost all Canadian charters of the Remotely Operated Platform for Ocean Sciences (ROPOS), a highly versatile remotely operated vehicle (ROV) system capable of operating in depths up to 5,000 metres, were dedicated to working on NEPTUNE and VENUS (CSSF, 2013). Operating, servicing, and management costs for these cabled observatories are substantial, requiring ONC to secure additional sources of long-term funding to support continued operation (Barnes *et al.*, 2011). A related challenge for the scientific community is to mobilize resources to ensure that cabled networks are being used to their full scientific capacity (Taylor, 2009).

Box 4.3
The Ocean Networks Canada Observatory

Ocean Networks Canada (ONC) is a not-for-profit subsidiary of the University of Victoria, which manages NEPTUNE, the VENUS coastal observation network, and the ONC Centre for Enterprise and Engagement (ONCCEE). NEPTUNE and VENUS are powered cabled observatories that link nodes of instruments to the internet, continuously collecting and transmitting data on a variety of ocean processes, including tectonic and seismic activity, physical and chemical ocean processes, and marine biodiversity (Figure 4.6). In 2012 ONC expanded its activities to the Arctic by installing a pilot cabled system in Cambridge Bay (ONC, 2012). NEPTUNE is a collaborative endeavour, owned and operated by a consortium of 12 Canadian universities led by the University of Victoria, with over 250 scientists who have contributed to its design and operation (Barnes *et al.*, 2008). As well as providing governance and management for NEPTUNE and VENUS, ONC and ONCCEE also create opportunities for the Canadian marine science and technology sector to develop commercial technologies and promote knowledge translation for science policy, commercialization, outreach, and engagement (ONC, 2013).

ONC is also pioneering a Data Management and Archiving System (DMAS), based at the University of Victoria, to process the large amounts of data collected by the ONC observatory, and making it available to a wide range of users (Barnes *et al.*, 2008). NEPTUNE and ONC are funded by the Government of British Columbia; the Government of Canada, including through the Canada Foundation of Innovation (CFI), Canada’s Advanced Research and Innovation Network (CANARIE), and the Networks of Centres of Excellence (NCE) program; and in-kind support from industry (Barnes *et al.*, 2008; Taylor, 2009; CANARIE, 2012; NCE, 2012).



Adapted and reproduced with permission from Ocean Networks Canada (ONC). Bathymetry Data Sources: Saanich Inlet and Strait of Georgia bathymetry from Canadian Hydrographic Service; USGS Cascadia DEM report 99-369; University of Washington (UW), School of Oceanography, R/V Thomas G. Thompson, Multibeam cruise data — funding provided by KECK Foundation and UW; Plate Boundaries: Adapted from Dragert, *et al.* Science May 2001. Map Creation: Center for Environmental Visualization UW School of Oceanography.

Figure 4.6

The Ocean Networks Canada Observatory

The ONC observatory includes the Victoria Experimental Network Under the Sea (VENUS) and the North-East Pacific Time-series Undersea Networked Experiments (NEPTUNE) cabled observatories off Canada's Pacific coast. Both link nodes of instruments by electro-optic cable, which provide power and transmit data to onshore centres that process and manage data, as well as link the observatory to the internet. NEPTUNE is located over the northern Juan de Fuca tectonic plate, offering real-time monitoring of tectonic activity and hydrothermal vents.

Note: The green nodes in the figure belong to NEPTUNE while the orange nodes belong to VENUS.

4.4.3 Opportunities and Challenges

With the past and present contributions of the GSC and CHS, the various detection and warning systems, and the ONC observatories, ocean science in Canada has the opportunity to become a global leader in research on plate tectonics and related marine hazards. As with research on climate change, however, a key challenge is to provide comprehensive mapping of geological conditions in Canada's vast coastal and marine areas, in particular in the Arctic. Wide-ranging coverage of geological, bathymetric, and hydrographic mapping of Canada's three ocean basins are essential to address the research questions in this theme, along with many of the other questions. New challenges have emerged in ensuring long-term managerial stability and financial sustainability for the operation of VENUS and NEPTUNE to maintain Canada's leadership position, assumed by the establishment of these facilities, and further developing them as hubs for world-class international research.

4.5 COASTAL COMMUNITIES

Coastal areas are transition zones between land and sea. Bordering on continental shelves, these are some of the most resource-rich areas of the ocean. Coastal areas consist of complex, diverse, and rapidly changing social-ecologies that are often poorly understood. In 2011, 11.5 million Canadians (38.3 per cent) lived within 20 kilometres of a coast. By 2015 this number is projected to increase to 16.75 million (Manson, 2005, as cited in Ricketts & Harrison, 2007). The Canadian coastal population includes small, remote communities on all three coasts, as well as urban centres such as Victoria and Vancouver in British Columbia; Halifax, Saint John, St. John's, and Charlottetown in the Atlantic provinces; and Quebec City near the mouth of the St. Lawrence estuary.

Several of the questions in this theme focus on the impacts of change on coastal communities, including climate change, ocean acidification, and other types of global change, as well as more direct impacts of human uses of the ocean. Small and large coastal communities are affected by change in different ways. Small coastal communities are often isolated, sometimes transient, and reliant on one or two resource industries. Many are home to indigenous people and located on indigenous lands. People in small coastal communities have little or no control over the causes of change, and are highly vulnerable to change that affects their social and physical infrastructure, livelihoods, and culture. Urban livelihoods are impacted more indirectly when global change leads to the loss of economic opportunities if, for example, fisheries collapse or touristic landscapes are destroyed. Urban infrastructure is often directly exposed to damage by storm surges and other natural hazards.

Research on effective coastal governance and adaptation to change must therefore take place at multiple scales, and include historical perspectives and an understanding of the needs and rights of diverse groups (Ommer & The Coasts Under Stress Research Project Team, 2007). It is inherently multidisciplinary and requires the integration of expertise from the natural and social sciences. Fieldwork requires researchers trained in respectful and informed engagement with diverse communities, and possessing the necessary linguistic skills, as well as knowledge of methods for accessing and using traditional knowledge. While this kind of research is less dependent on physical infrastructure than some other themes, it does require resources to access remote communities. Information infrastructure such as high-bandwidth internet is essential to maintain communication as well as for data collection and processing.

Major Research Questions Related to Coastal Communities

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q10. 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?

Q15. What will be the impacts of climate change and ocean acidification on marine ecosystems, biodiversity, resource management, and coastal communities?

Q17. How are the movements and survival of marine organisms, including invasive species, being affected by environmental change, and what are the socio-ecological impacts?

Q26. 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?

Q32. 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?

Q35. What measures are required to ensure appropriate and effective participation of diverse coastal communities in ocean and coastal management and governance?

4.5.1 Research Output and Collaboration

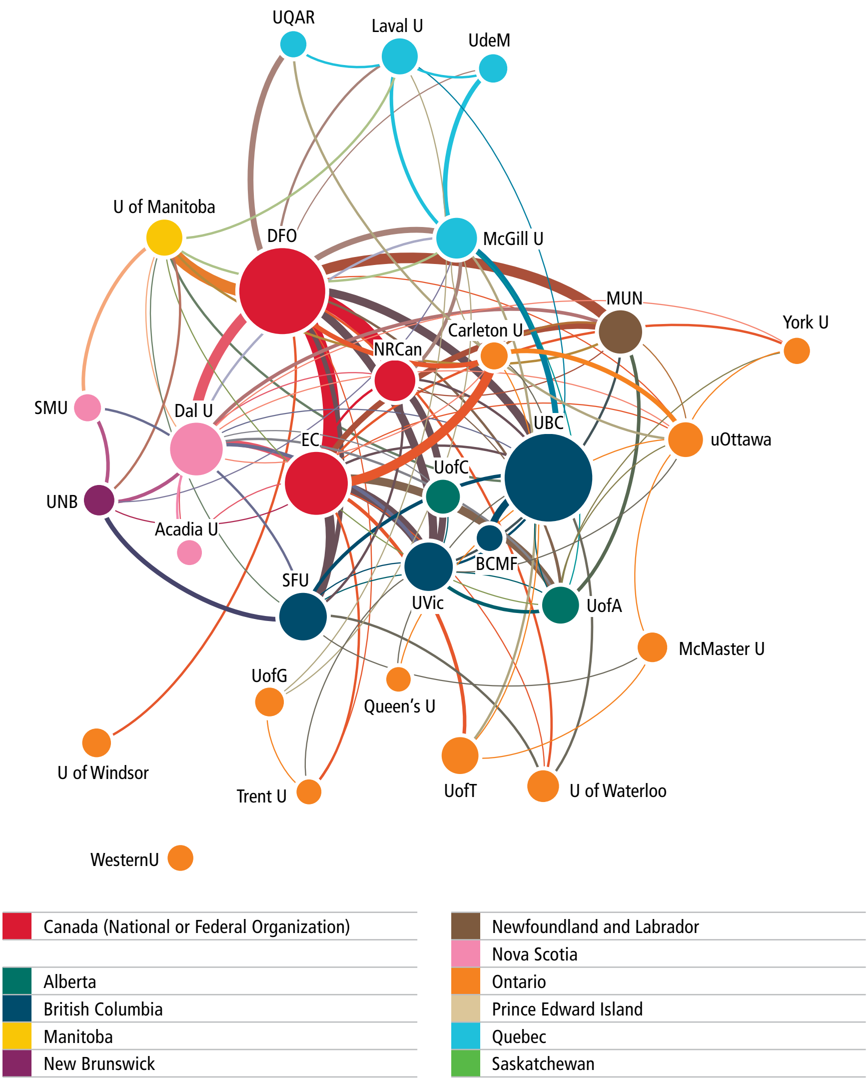
Canadian papers (1,282) on coastal communities account for a large proportion of world publications (6.5 per cent) and have scientific impact above the world average (ARC = 1.23), but at a lower rank among leading countries (14^{th}) than in other themes. This is the only research theme in which the output of peer-reviewed articles is growing relative to other fields in Canada (GI = 1.14), though it is growing more slowly than at the world level (GI = 1.22) (see Table 4.1).

For the outputs included, the most productive organizations in Canada include the University of British Columbia, DFO, and Environment Canada, with over 100 papers each from 2003 to 2011 (Figure 4.7). Major hubs for collaboration include federal organizations such as DFO and Environment Canada, in addition to Dalhousie University, the University of Victoria, and the University of British Columbia. Organizations in Quebec form a regional cluster, suggesting higher rates of collaboration within this province than with other organizations.

4.5.2 Research Seascape

Because of the theme's interdisciplinary nature, collaborative research projects and networks are an important element of capacity. Since the 1990s, much research on coastal communities has been carried out by multidisciplinary teams, starting with Eco-Research funding and continuing with more recent joint initiatives of Canada's three granting councils (NSERC, SSHRC, and CIHR), such as Coasts Under Stress; the NCEs AquaNet, ArcticNet, and MEOPAR; the Ocean Management Research Network (OMRN); and Community-University Research Alliances (CURAs). Coasts Under Stress was an example of a national network with a strong focus on multidisciplinary research in coastal areas with balanced engagement by researchers in the social, natural, and health sciences (see Box 4.4).

> ***Box 4.4***
> **Coasts Under Stress**
>
> Coasts Under Stress was a Major Collaborative Research Initiative jointly funded by NSERC and SSHRC for five years (2000–2005), with additional funding from partners that included universities, government, businesses, and non-government organizations (CUS, 2004). As the largest multidisciplinary network of this type in Canada, Coasts Under Stress conducted case studies on the East and West coasts, resulting in several hundred publications, including books synthesizing research outputs (CUS, 2006; Ommer & The Coasts Under Stress Research Project Team, 2007). Attempts to develop a follow-up project were unsuccessful because opportunities to apply for joint funding from multiple granting councils were limited at the time.



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.7

Collaboration Network of Top 30 Canadian Organizations Producing Papers on Coastal Communities, 2003–2011

Although DFO collaborates broadly on research in this theme, it is not as central as in other themes. Universities contribute a larger proportion of papers in this theme than in others, and are more prominent in the collaboration network than federal organizations, such as DFO, Environment Canada, and NRCan.

Note: All links are displayed on the network.

Among the NCEs, ArcticNet stands out with its series of regional impact studies that aim to inform decision-making and governance at multiple levels. These could serve as models for other coastal impact studies in Canada that aim to incorporate a broader range of disciplinary perspectives and improve their relevance for decision-making. Other networks or projects focusing on impacts of climate change on, and adaptation of, coastal communities include the Coastal Communities Challenges project, the Canada-Caribbean Coastal Climate Adaptation Strategies project, and the Ouranos program on Impacts and Adaptation in the Maritime Environment. Several provinces and territories engage in adaptation research, through organizations such as the Nunavut Climate Change Centre. At the federal level, NRCan's Climate Change Impacts and Adaptation Division (CCIAD) liaises with provincial and territorial governments to develop information resources and tools for adaptation in coastal zones.

The Panel identified a gap in research on urban communities and coastal cities. A keyword search of the publications of Coasts Under Stress and papers presented at the biannual conferences of Coastal Zone Canada revealed very little ongoing research in this area. The Coastal Cities at Risk: Building Adaptive Capacity for Managing Climate Change in Coastal Megacities Program, launched in 2011, is likely to build important capacity in this area. The project aims to develop the knowledge base and capacities of mega-cities to adapt to climate change, using the city of Vancouver as one of several international study sites; develop integrated knowledge and interdisciplinary simulation models; and increase the number of highly qualified personnel through knowledge mobilization and translation (Coastal Cities at Risk, n.d.).

With regard to the management of fisheries and other aquatic resources, the Canadian Fisheries Research Network (CFRN) is an NSERC-funded network focusing on collaborating with the fishing industry to improve fisheries science and management in Canada (CFRN, 2012a). The Province of British Columbia has recently provided funding to the B.C. Foods and Resources Society and Vancouver Island University for the Aquatic Foods Initiative. Its goals are to increase economic, cultural, social, and ecological values of the province's aquatic food resources through activities in seafood security, seafood governance, and the meaning of seafood (VIU, 2013).

Since 2012, SSHRC's new Partnership Grants Program has funded the following ocean-related seven-year partnerships:

- "Community conservation research network: exploring local-level environmental stewardship across land and sea" (Saint Mary's University);
- "Too big to ignore: global partnership for small-scale fisheries research" (Memorial University); and
- "Exploring distinct indigenous knowledge systems to inform fisheries governance and management on Canada's coasts" (Dalhousie University).

Another form of collaboration between researchers and coastal communities is found in co-management organizations that bring together local stakeholder groups, such as hunter and fisher organizations, with government agencies, NGOs, and public management boards to share management responsibility for natural resources (DFO, 2010a). Such organizations can become important mechanisms for knowledge mobilization and knowledge co-production: "a collaborative process of bringing a plurality of knowledge sources and types together [including traditional knowledge] to address a defined problem and build an integrated or systems-oriented understanding of that problem" (Dale & Armitage, 2011) (see Box 5.3). The knowledge produced by these processes is essential for addressing research questions on the sustainable management of resource systems, understanding social-ecological impacts, and developing adaptation strategies. At the same time, the process of knowledge co-production is itself an emerging area of research (Armitage *et al.*, 2011). Among other benefits, this research contributes to the development of social-ecological approaches to change (Q32) and co-management (Q35).

The importance of interdisciplinary training, cultural and linguistic skills, and experience with processes such as knowledge co-production, makes human capacity a very important indicator of overall research capacity related to coastal communities. Human capacity, however, is difficult to estimate in this area. Although researchers from many disciplines carry out coastal community research, their research is not easily captured using ocean science keyword searches. In the absence of other sources, funding data from SSHRC, and the number of participants at conferences and symposia of Coastal Zone Canada, can be used as proxies for research activity (see Box 4.5). These indicate that substantial research is taking place, in particular in areas such as fisheries, aboriginal issues, aquaculture, coastal development, physical safety related to coastal erosion and other ocean changes, and coastal governance issues.

Box 4.5
Coastal Zone Canada Association (CZCA)

CZCA is a Canadian not-for-profit society that supports Integrated Coastal Zone Management (ICZM) in Canada and abroad (CZCA, 2013). CZCA sponsors biannual conferences on ICZM, which attract between 300 and 600 participants, to present research and practical experiences on ICZM. Each conference publishes a conference statement articulating research findings and key messages to policy-makers and practitioners. Through its conferences and outreach activities, CZCA has successfully established Canada as a major venue for international dialogue on coastal and ocean management (Ricketts *et al.*, 2004).

Aside from human capacity and interdisciplinary networks, an important asset for addressing the research questions in this theme is high-quality data sets on human activities, demographics, economies, health and cultures in coastal areas, which can be linked to spatial data sets on the distribution of resources, weather, wave height, coastal structure, etc. Long-term data sets have traditionally been generated by federal and provincial government departments, including DFO (e.g., research vessel survey data, tagging data, fisheries data such as landed and export value, logbook data, and costs and earnings data); Statistics Canada (e.g., census data, the Labour Force Survey, tax filer data, and Employment Insurance data); Environment Canada (meteorological data); and NRCan (e.g., data on coastal ice cover, coastal erosion, and sea-level rise). Continuity in some of these data-gathering services may be at risk due to recent policy changes such as the replacement of the compulsory long-form census survey (which has served as a benchmark for other surveys) with the voluntary National Household Survey (Green & Milligan, 2010).

Increases in coastal populations, changes in their distributions, and increasingly intense and diversified marine and coastal activities highlight emerging social-ecological challenges in coastal areas and the related need for accurate, fine-scale, and up-to-date data on coastal and nearshore areas. These data are essential for monitoring emerging opportunities and challenges for coastal communities, and for the development of effective integrated coastal zone management. Unfortunately, data on nearshore fish assemblages and habitat, and on the changing socio-economic face of coastal communities, are limited and variable, as are the resources to monitor what is happening at local and regional scales on an ongoing basis. For instance, coastal resource inventories based on local knowledge have been carried out, but only once, and findings were not confirmed (O'Brien *et al.*, 1998).

4.5.3 Opportunities and Challenges

The information reviewed by the Panel indicates that a large group of researchers is working on issues relating to coastal communities in Canada. It also suggests that these researchers have substantial expertise and access to capacity to address research questions on coastal communities, including on impacts of climate change and adaptation, community-based management of coastal and fisheries resources and co-management arrangements. The information reviewed also underlines the importance of large interdisciplinary networks to support the development of understanding of the drivers and consequences of change in coastal communities at multiple scales. Such networks are also essential for mobilizing this knowledge, and providing the opportunity and training to conduct interdisciplinary research. The experience with large-scale, multidisciplinary and multi-year programs such as Coasts Under Stress suggests that these initiatives are unlikely to last beyond the initial funding period. A key challenge is therefore to establish a mechanism for continued interdisciplinary training, and collaboration and integration of research on coastal communities, so as to maintain and mobilize the knowledge and skills accumulated.

Challenges also exist in ensuring continuity in collecting data on human activities and their integration with relevant spatial and environmental data. The low level of research activity on coastal cities indicates challenges in addressing important research related to coastal urbanization.

4.6 THE ARCTIC OCEAN

The Arctic is one of the fastest-changing areas of the ocean, physically, ecologically, and socially. Sea ice and cold temperatures pose challenges for research, leading to many important knowledge gaps, while the distinct and dynamic social-ecological context also presents many research opportunities. The retreat of sea ice due to warmer temperatures is opening access to new energy and mineral resource deposits, shipping routes, and fisheries. The growing global demand for these resources creates new opportunities for economic development in the region, but new research is also needed to ensure that the development of these resources is socially, environmentally, and economically sustainable. As a consequence, the Arctic is receiving greater federal attention through policy instruments such as *Canada's Northern Strategy* (GC, 2009).

Research priorities in the Arctic cut across all dimensions of ocean science, with a particular focus on the impacts of climate change. Several of the research questions in this theme relate closely to questions on ocean-climate interactions (Section 4.1), and plate tectonics and natural hazards (Section 4.4). The last question (Q36) recognizes the importance of northern coastal communities as active participants in research and management of Arctic ecosystems.

4.6.1 Research Output and Collaboration

The Arctic Ocean is one of the smallest themes by international research output (Table 4.1). Canada is highly specialized in this theme (SI = 3.15), and contributes a much larger proportion of world publications than in any other research theme (13 per cent), second only to the United States. The scientific impact of Canadian papers related to the Arctic Ocean (ARC = 1.26) is above the world average, but Canada's rank by ARC score is lower in this theme (13^{th}) than in most other themes. Canada has a growth index (GI = 0.95) higher than the world average (GI = 0.91) in output related to the Arctic Ocean, in contrast to other themes where Canada's growth index tends to be lower. With a growth index of less than 1.0, however, research on the Arctic Ocean is not growing as quickly as other fields, either in Canada or at the world level. These results suggest that while Canadian papers on the Arctic Ocean have had low scientific impact relative to other countries, Canada's high level of research activity could be a basis for raising its international profile.

DFO and Environment Canada, the most productive organizations in Arctic Ocean research, function as major hubs of research collaboration (Figure 4.8). Most universities collaborate more with DFO, Environment Canada, or NRCan than with each other, with the exception of universities in Quebec. In Quebec, collaboration centres on provincial networks such as Québec-Océan and the Centre for Northern Studies (Centre d'études nordiques; CEN). In addition to the coastal universities, the universities of Toronto, Alberta, Calgary, and Manitoba are among the top-publishing institutions, with strong collaborative links with federal departments. The prominence of institutions from across Canada indicates that physical location may be less relevant for research on the Arctic Ocean than for other themes.

4.6.2 Research Seascape

Several federal government departments contribute to research on the Arctic Ocean. NRCan's Polar Continental Shelf Program, for example, which coordinates field logistics in support of advancing scientific knowledge and management of Canada's Arctic lands and natural resources, has collaborated with Foreign Affairs and International Trade Canada and DRDC on autonomous underwater vehicles (AUVs) for Arctic exploration (DFAIT, 2011). Environment Canada and DFO also act in partnership to monitor ice conditions (EC, 2011, 2012). Canada also collaborates with the United States, other Arctic countries, and international organizations to harmonize information gathering and use for the UNCLOS survey to delineate the limits of Canada's continental shelf and ice services (CCG, 2011; EC, 2011).

Major Research Questions Related to the Arctic Ocean

The following questions are numbered and ordered according to the *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q1. 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?

Q2. 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?

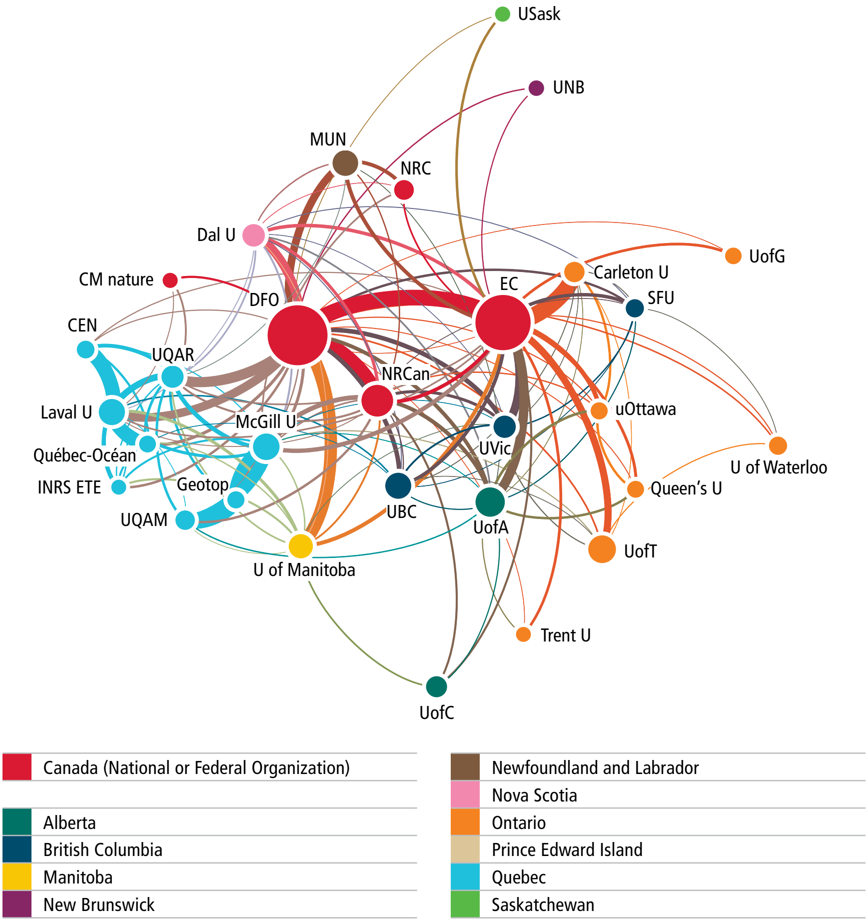
Q3. How will ocean-ice-atmosphere interactions in the Arctic Ocean and surrounding seas be affected by and affect climate change, and how will the productivity, biodiversity, and services of Arctic benthic, pelagic, and sea-ice ecosystems respond?

Q4. 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?

Q27. What are the impacts of oil spills in cold and deep oceans, and under sea ice, and the appropriate strategies and technologies for prevention and mitigation?

Q36. 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?

Research collaboration in the Arctic is supported by the Canadian Polar Commission (CPC) and its Canadian Polar Information Network, which includes a roster of polar experts and an inventory of northern research facilities that can be accessed via an interactive online map (POLAR, 2012). Together with Aboriginal Affairs and Northern Development Canada, the CPC supports the Canadian Network of Northern Research Operators (CNNRO), which provides a forum for the operators of research facilities in the Canadian Arctic and Subarctic.



Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 4.8

Collaboration Network of Top 30 Canadian Organizations Producing Papers on the Arctic Ocean, 2003–2011

DFO and Environment Canada are both major hubs of collaboration, although a cluster of universities and other organizations in Quebec also show high levels of collaboration.
Note: Only links representing five or more collaborations between organizations are displayed, to improve readability.

The international Arctic research community has committed to sharing research data and enhancing knowledge sharing, to build a common baseline of knowledge. The Polar Data Catalogue, for instance, is a repository that describes and provides access to diverse Arctic and Antarctic data sets (ArcticNet, 2011). ArcticNet has become an important collaborative network to enable research on a diversity of issues, including engaging Arctic communities, industry, and other national and international partners (see Box 4.6).

Box 4.6
ArcticNet and *CCGS Amundsen*

In 2002 a consortium of Canadian universities and federal agencies leveraged a CFI grant of $27.4 million and additional funding from other sources to retrofit and transform a decommissioned icebreaker into a state-of-the-art Arctic research vessel. *CCGS Amundsen* performs Coast Guard functions most winters, and serves as a dedicated research vessel during the summer months. During its first mission, the *Amundsen* remained in the Canadian Arctic for over a year without returning to port. It also carried research staff to 14 remote communities in northern Quebec for the *Qanuippitaa*? (How are we?) health survey (CCGSAS, 2013c).

CCGS Amundsen is owned and operated by the Canadian Coast Guard, which manages its missions collaboratively with a committee of universities and research institutions (CCGSAS, 2013a). This arrangement has allowed the Canadian scientific community to collaboratively leverage funding from a variety of sources to provide shared access to a critical piece of infrastructure. ArcticNet, an NCE established in 2004, uses *CCGS Amundsen* as its primary mobile research platform (CCGSAS, 2013b). The network brings together hundreds of researchers from universities and government organizations, who work with over 100 partner organizations from 15 countries. ArcticNet and the *Amundsen* have transformed Arctic research, and contributed to improving collaboration at the national level, as well as between academia, the private sector, and local communities. In recognition of its contributions to Arctic science, the *Amundsen* was selected as the theme of the Canadian $50 bill (CCGSAS, 2013c).

A criticism aimed at past Arctic research has been that scientists arrive in the North without the social science skills needed to gather and incorporate local knowledge into ocean science and to engage with Arctic communities (Dale & Armitage, 2011). This research also needs to respect the communities' rights to maintain, control, protect, and develop their knowledge in line with international agreements such as the UN Declaration on the Rights of Indigenous Peoples and the Convention on Biological Diversity. There is an unmet need for understanding how to share or co-produce, integrate, and apply knowledge from different traditions to enable co-management (Armitage *et al.*, 2011). Other countries have established models to fill this gap, such as the Alaska Native Knowledge Network at the University of Alaska Fairbanks, or the Sami Research Centre at the University of Lapland. In Canada, the Inuit Knowledge Centre, Inuit Qaujisarvingat, was established in 2010 (Inuit Qaujisarvingat, 2013).

At the international level, Canada participates in several collaborative projects that emerged from the International Polar Year, or were initiated by the Arctic Council, such as the Sustaining Arctic Observing Network (AANDC & CPC, 2011; Lockwood *et al.*, 2012). Canada's current chairmanship of the Arctic Council from 2013 to 2016 provides an opportunity to further strengthen international collaboration and leadership.

Infrastructure

Ice-going vessels are essential for most research activities in the Arctic, as mobile research platforms as well as a means to access research stations and Arctic communities. The CCG currently operates six icebreakers, three of which are used for Arctic research regularly. *CCGS Louis S. St-Laurent* (1968, 120 m, 20142 kW) has lab facilities and special equipment such as scientific winches. The medium-sized *CCGS Amundsen* (1979, 98 m, 11155 kW) is dedicated to research during the summer months and carries a substantial pool of scientific equipment, making it a versatile platform for ocean research (see Box 4.6) (ArcticNet, 2011). The smaller *CCGS Laurier* (1986, 83 m, 5250 kW) conducts science operations in the western Arctic (CCG, 2010, 2012a). In addition, DRDC's research vessel *CFAV Quest* occasionally performs military research in the Arctic in light ice conditions (DRDC, 2012).

As part of the National Shipbuilding Procurement Strategy (NSPS), Canada has committed to construct, by 2017, a polar icebreaker (*CCGS John G. Diefenbaker*), which is expected to have extensive science capability (CCG, 2012a, 2012d). The NSPS also provides for six Arctic/Offshore Patrol Ships (AOPS) designed as multi-purpose vessels with limited ice capability, which could be used for science. These procurements provide an opportunity to significantly expand Canada's physical infrastructure for research in the Arctic Ocean. With *CCGS Diefenbaker* and *CCGS Amundsen*, Canada will soon have two icebreakers available for year-round research in two-year and moderate multi-year sea ice conditions. Both icebreakers are, however, allocated to regular icebreaking services during winter, which can create allocation problems, particularly if seasonal icebreaking needs change due to climate change.

Canada also has extensive capacity for remote observation in the Arctic, including active satellite systems: SSM/I for records of sea-ice extent, and RADARSAT II to study sea-ice dynamics (CSA, 2012a). The RADARSAT Constellation platform is planned to launch in 2018, starting with three satellites. The PolarSat (Polar Communications and Weather-1) mission, also planned for 2018, will provide continuous meteorological observation and communication services to the Arctic, including ocean surface temperature, sea-ice extent and thickness, and an array of atmospheric variables (CSA, 2012b). Currently, different satellite-borne instruments such as MODIS and SeaWifs detect ocean colour from which phytoplankton biomass and other key variables are derived. However, the Arctic regions are often poorly resolved, and an ocean-colour detector on a polar orbiter is lacking (Gregg & Casey, 2007).

Autonomous platforms, such as AUVs, ocean gliders, and automated buoys, have great potential to facilitate and scale up research in the Arctic once they have been adapted to sea ice and extreme cold. Canada has made notable contributions to Arctic observation technology, such as the two Arctic Explorer AUVs that performed the bathymetric surveys for Canada's submission for the delineation of its outer continental shelf. One of these AUVs set a new record by operating continuously for 12 days under Arctic sea ice (Kaminski *et al.*, 2010; ISE, 2011).

Land-based infrastructure related to the study of ice-covered seas is found in various locations across Canada. The recently inaugurated Sea-ice Environmental Research Facility (SERF) at the University of Manitoba includes an outdoor seawater pool to study sea ice under controlled conditions (SERF, n.d.). The NRC operates several ice tanks that simulate Arctic environments that can be used for the testing of new vessel designs, and other research purposes (NRC, 2012c; Safer, 2012). Among DFO laboratories, the Bedford Institute of Oceanography, the Institute of Ocean Sciences, and the Freshwater Institute perform research in the Arctic Ocean. DFO's Arctic research program includes fish and marine mammal ecology and assessment, stock assessment, environment, and contaminants (DFO, 2010b). More than 80 research stations of various sizes and capacities are spread out across the Canadian Arctic, 33 of which are situated on the coast (POLAR, 2012). In 2017 these stations will be complemented by the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavut. CHARS is expected to become a year-round hub for Canadian and international Arctic science, and will include facilities for marine research (AANDC & CPC, 2011).

4.6.3 Opportunities and Challenges

The Arctic's key importance for Canada's future development is reflected in recent policy decisions and current and upcoming investments in physical infrastructure, such as icebreakers, research stations, networks, and large-scale research projects involving northern communities. Chairing the Arctic Council from 2013 to 2015 presents Canada with an opportunity to raise the international profile of Arctic research and take the lead in establishing new international collaborations. These conditions present outstanding opportunities to address the research questions on the Arctic Ocean, and, at the same time, to contribute to broader themes such as climate change, community-based resource management, Arctic marine biodiversity, and the establishment of a strategy for sustainable Arctic development.

The cross-cutting nature of research in the Arctic means, however, that scientists face the same challenges as in other regions. For example, research on climate change is constrained by limited data coverage for the Arctic. Similarly, research on northern coastal communities suffers from gaps in socio-economic and survey data (see Section 4.5). Another challenge is to ensure that research is adequately prioritized to keep pace with the policy decisions and human activities it aims to inform, such as research on the consequences of oil spills in Arctic environments. The Arctic presents numerous research opportunities, many of which require sizeable investments to pursue. The additional cost of addressing the research questions on the Arctic Ocean leads to trade-offs between investments in Arctic research capacity and in research capacity in other marine areas.

5

Opportunities and Challenges for Emerging and Future Areas of Ocean Science in Canada

- Ocean Technology
- Ocean Governance
- Human Health and Well-Being

5 Opportunities and Challenges for Emerging and Future Areas of Ocean Science in Canada

Key Findings

- Ocean technology development continually opens new opportunities for scientific research, which are often seized by alignments between governments, universities, and the private sector.
- Researchers working on ocean governance increasingly realize the need to address uncertainty in the dynamics of marine social-ecological systems, thereby challenging established scientific approaches and institutional structures.
- Canadian research on human health and well-being has been narrowly focused, and rarely includes multidimensional aspects of well-being that are increasingly recognized internationally.

The forward-looking nature of the process that produced *40 Priority Research Questions for Ocean Science in Canada* means that many of the questions transcend traditional research activities. The capacity required to address the research questions also relies on needs that have not yet been defined due to the emerging or dynamic nature of the research areas. While addressing some questions may require tools, methods, or approaches that have yet to be developed, others experiment with emerging tools, methods, and approaches with untested potential, which may become standard in the near future. In all cases, these activities are not well reflected in bibliometric analysis, due to (i) the emerging and multidisciplinary nature of the research and requirements; and (ii) the production of outputs such as technologies, policy advice, or reports, which are not captured in bibliometric data (see Section 3.2).

Ocean technology is a vibrant sector of Canada's economy. Ongoing research enables the creation of new technology, provides opportunities to apply existing tools and methods in new ways, and creates opportunities for innovation. As the ocean, and our relationships to it, changes, so will its contribution to the well-being of Canadians. Research into the many pathways linking the ocean to human health and well-being, however, is still an emerging area in Canada and the world.

The dynamic and interactive nature of marine social-ecological systems, as well as of the research itself, requires that governance systems adapt to changing circumstances. The final set of the 40 research questions challenges us to explore ways to improve ocean governance and examine how science informs the management of human activities in the ocean.

5.1 OCEAN TECHNOLOGY

Technology supports and enables many scientific and commercial activities in the ocean. Technology development is a pillar of *Canada's Oceans Action Plan* (DFO, 2005), and a priority for Canadian Arctic research. It has the potential to improve monitoring, telecommunications, safety, and other infrastructure (CCA, 2008). Science and technology are often associated for mutual benefit: research allows the development of new methods, processes, and tools, which in turn allow the collection of new data that contribute to scientific knowledge in sometimes unexpected ways. For example, magnetic and acoustic sensors developed during World War II to detect submarines opened up new opportunities for research into plate tectonics, mapping the ocean floor, and physical oceanography (Doel *et al.*, 2006). The global market for ocean technology creates competitive challenges at the international level, but can be an important arena for Canadian leadership and contributions to global-scale ocean observation and research programs.

Several of the 40 research questions highlight the need for new sensors, platforms, products, and other technologies to improve ocean observation and monitoring. New and emerging technologies will allow continuous access to more ocean areas than ever before, changing the view of the ocean from one consisting of "snapshots" across space to real-time data at finer spatial and temporal resolutions, as well as simultaneous measurements of multiple interacting processes (Delaney & Barga, 2009; Kintisch, 2013). Technology can also transform how information is exchanged between researchers or provided to users and decision-makers. Much of this technology is not exclusive to ocean science, coming from fields such as nanotechnology, biotechnology, information technology, robotics, and engineering (Delaney & Barga, 2009). Making use of new and existing technologies for effective observation is a challenge that requires coordination and alignment of stakeholders in the Canadian ocean science community.

Major Research Questions Related to Ocean Technology

The following questions are numbered and ordered according to the *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q18. What in-situ sensors and platforms need to be developed to expand observation capacity for biological, chemical, physical, and geological ocean properties?

Q19. 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?

Q21. 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?

Q23. How can autonomous and networked platform infrastructure and sensors be developed to deliver comparable ocean data and data products for observation, monitoring, analysis, and decision-making?

Q24. How can a network of Canadian ocean observations be established, operated, and maintained to identify environmental change and its impacts?

Q39. 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?

5.1.1 Research Seascape

Nearly all the research questions on ocean technology are related to ocean observations, which are fundamental to understanding and predicting events in the ocean. Q18 and Q19 focus on the need for new observation technologies. Other questions (Q21, Q23, and Q24) identify the need to design and deploy observation systems, which ultimately include questions of science governance and policy on how to manage limited resources. The final question (Q39) recognizes the need for a broad-based strategy for sustainably harnessing ocean resources while minimizing deleterious impacts. All these questions, which apply equally to the use of current and new technologies, may have to be re-examined as technology development changes the requirements, supply, and cost of observation systems, and as international agreements and partnerships governing global-scale ocean observation also change. The phrasing of many of the research questions in this theme suggests that the science and technology needs remain unknown, which makes an assessment of Canada's capacity in this area challenging.

Canada has a special interest in ocean observation, with its long coastline and partly ocean-based economy. Canada's many areas of sea ice, in particular the Arctic, continue to present a challenge for observation. Efforts to overcome this challenge, however, have provided Canada with internationally recognized experience and expertise, demonstrated in developments such as the Arctic Explorer AUV, the Icycler and SeaCycler moored profilers (see Box 5.1), and the many innovations developed by the Centre for Cold Ocean Resource Engineering (C-CORE) for offshore oil and gas extraction. Beyond the Arctic, Canadian researchers have also led international observation efforts including the Census of Marine Life, the Ocean Tracking Network, and cabled observatories such as VENUS and NEPTUNE.

After private-sector investments, government procurement can be an important driver of technology development (Jenkins *et al.*, 2013). As the examples in Box 5.1 show, the federal government is an important client of technology companies such as ISE, and MacDonald, Dettwiler and Associates Ltd. Another area in which procurement can have important impacts is the ongoing fleet renewal, particularly when government orders require custom-built ships or refits, such as the upcoming icebreaker *CCGS Diefenbaker* or the refit of *CCGS Amundsen* as a research icebreaker (see Section 4.6).

Canada's participation in global observation systems, such as GOOS (the Global Ocean Observing System), is contingent on committing resources and expertise, and in turn provides access to the resulting data, technology, and shared knowledge. Canada contributes data from several weather stations, tide gauges, moored buoys, and ships of opportunity to the Global Climate Observing System under the United Nations Framework Convention on Climate Change (GOOS & GCOS, 2005; Nichols, 2005). Novel approaches to observation systems, data processing, and delivery to users will benefit from collaboration between ocean and computer scientists with economists, sociologists, geographers, business researchers, and others (Baker & Chandler, 2008; Delaney & Barga, 2009; Ribes & Lee, 2010). As noted in Section 2.2.4, Canada has a strong and diverse ocean technology sector comprising more than 500 companies, including a few large and many small and medium-sized enterprises (SMEs) as well as regionally based R&D organizations (Industry Canada, 2012; Cinmaps, 2013).

Box 5.1
Examples of Canadian Ocean Observation Technology

International Submarine Engineering (ISE) is a world-renowned manufacturer of marine submersibles based in Port Coquitlam, British Columbia. Founded in 1974, ISE has been a leader in the development of submarines, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs). Several of ISE's innovations were developed in response to government requests. These innovations include the Remotely Operated Platform for Ocean Science (ROPOS), developed for DFO; the world's first fully autonomous AUV, built for the Canadian Hydrographic Survey; a large AUV for laying underwater cable, with the capability of deploying smaller AUVs, developed for the Department of National Defence and the Canadian Forces; and the Arctic Explorer AUVs used by NRCan to map Canada's continental shelf, one of which established a record for 12 days of continuous operation under sea ice (Kaminski *et al.*, 2010).

Engineers at DFO's **Bedford Institute of Oceanography** developed a moored profiling device designed to operate year-round under unstable sea ice, called Icycler (Fowler *et al.*, 2004). Icycler inspired a more general-purpose moored profiler, SeaCycler, which is being developed by researchers at DFO and international partners in the United States, United Kingdom, and Germany (Send *et al.*, 2012). Both Icycler and SeaCycler are designed to be energy-efficient, multi-purpose platforms, on which a variety of sensors can be mounted. They can be used for long-term frequent data collection along vertical profiles, linked to data centres by satellites. In contrast to the autonomous buoys used in the Argo program, for example, these platforms operate at a fixed location while avoiding the many hazards at the ocean surface, such as ships, ice, or debris (Fowler *et al.*, 2004; Send *et al.*, 2012).

Ocean Networks Canada operates the NEPTUNE and VENUS cabled ocean observatories off Canada's Pacific coast, providing interactive access to continuous data over the internet for a wide range of ocean variables (see Box 4.3). Not only are these projects forerunners of similar observatories around the world, they also contribute heavily to an ocean technology cluster on Canada's Pacific coast (see Box 5.2).

Much of Canada's capacity in satellite earth and ocean observation is also the product of collaboration between government and private sector firms. The RADARSAT satellites were developed and built primarily by **MacDonald, Dettwiler and Associates Ltd. (MDA)** for the Canadian Space Agency (CSA, 2006). Many instruments used on Canadian and international satellites are also produced by the Canadian-based company **ComDev**.

Internationally, Canadian technology firms have built a reputation in several niche markets for custom science-related products and services, including hydrographic services and products, coastal management technology, remote sensing and satellite data analysis, and harsh/cold ocean engineering. These are complemented by emerging strengths in data management systems for spatial data, hydro-acoustic data processing for advanced fish stock and biomass assessment, marine environmental monitoring and management systems, and sustainable management decision support (Industry Canada, 2012). The largest domestic consumer of ocean science and technology is the offshore oil and gas industry, which accounts for 43 per cent of domestic spending, primarily for technology goods and services required for exploration and development.

The Government of Canada uses incentives like the Scientific Research and Experimental Development (SR&ED) program to encourage R&D by Canadian firms in all sectors. Similarly, the Industrial Research Assistance Program (IRAP) provides innovation and funding services to support business growth. These programs target firms across all sectors, whereas policies in support of technology clusters are being used to target ocean science and technology firms specifically (see Box 5.2).

Recent research and debate have focused on the emergence of maritime technology clusters in several of Canada's coastal regions (Doloreux & Shearmur, 2009; Lepawsky, 2009). Although many definitions of *cluster* appear in the literature, a cluster is generally a group of related firms in the same geographical region, linked by supplying each other with specialized inputs, services, infrastructure, or other relationships (see Doloreux & Shearmur, 2009; Lepawsky, 2009). Many clusters also include government organizations and universities that provide knowledge and specialized training (Porter, 2003; Doloreux & Shearmur, 2009). While the positive impact of clusters on innovation is generally recognized, there is an ongoing debate on whether government policies can aid the formation of self-sustaining clusters (Doloreux & Shearmur, 2009). Nonetheless, even clusters dependent on government support can be effective vehicles for economic and technology development (Colbourne, 2006; Doloreux & Shearmur, 2009; Safer, 2012).

Box 5.2
Ocean Technology Clusters

The **St. John's Cluster (NL)** emerged from the need for technologies to explore and safely extract offshore oil and gas resources in conditions of sea ice and cold water (Doloreux & Shearmur, 2009; Safer, 2012), which motivated the foundation of the Centre for Cold Ocean Resource Engineering (C-CORE) in 1975. In 1985 the federal government established the NRC Institute for Ocean Technology (NRC-IOT), which provides unique capacities such as business expertise, incubation labs for start-up companies, and facilities such as the world's largest ice tank (Colbourne, 2006). The cluster also benefits from Memorial University's School of Ocean Technology, which contributes to a highly skilled workforce in the region (Safer, 2012). In 2005 OceansAdvance Inc. was established as an industry-led ocean technology cluster organization (OceansAdvance, n.d.). While the companies within the cluster initially focused on servicing the oil and gas industry with charting, remote sensing, data recording, and communication products, the creation of additional facilities such as the NRC-IOT provided opportunities for broader scientific and technological innovation. Recent growth in annual private profits suggests that the cluster could become self-sustaining in the near future (Doloreux & Shearmur, 2009).

Halifax (NS) supports a cluster of ocean technology firms, working in partnership with DFO, NRCan, NRC, and Dalhousie University (GC, 2010). Halifax firms have a particular strength in marine-derived nutraceuticals and food additives (Greater Halifax Partnership, n.d.), supported by the NRC Institute for Marine Biosciences (NRC-IMB). The presence of several Royal Canadian Navy facilities, and other branches of the Department of National Defence and the Canadian Forces, has supported the development of a marine defence and security industry in Halifax, in addition to a sizeable offshore oil and gas sector. The Halifax Marine Research Institute, launched in 2011, is expected to further strengthen the linkages between industry, government, universities, and other institutions.

The **Technopole Maritime du Québec (Quebec Marine Resource, Science and Technology Cluster; QC)** encompasses Quebec's sparsely populated coastal region along the St. Lawrence estuary. Federal and provincial governments have proposed stimulating technology and economic development through measures such as innovation-support organizations (Doloreux & Shearmur, 2009). However, firms in this cluster collaborate infrequently with each other and rely little on research centres

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and universities as sources of innovation (Doloreux & Melançon, 2008). Furthermore, the amount of economic activity in the region has yet to achieve a critical mass that can financially sustain the organizations meant to support innovation. Many innovation-support organizations in the region have therefore had to seek clients outside the cluster, leading to a mismatch between local supply and demand for ocean technology and innovation-support services (Doloreux & Melançon, 2009).

The **Pacific Ocean Technology Cluster (BC)** encompasses collaborative links between university research, spin-off companies, and commercial activities in Vancouver and Victoria. The cluster developed primarily around four large-scale projects, including the cabled observation networks VENUS and NEPTUNE (see Box 4.3), the Canadian Seabed Resource Mapping Program, and oil and gas exploration to support planned development of the industry in British Columbia (Doloreux & Shearmur, 2009). While the projects themselves rely on government funding, they have attracted some 50 SMEs in Victoria and Vancouver that produce navigation systems, ROVs, AUVs, marine communication technologies, aquaculture equipment, and marine environmental monitoring technologies for Canadian and international niche markets.

5.1.2 Opportunities and Challenges

Demand for resources and information continues to drive the development of new sensors, platforms, and infrastructure to deploy them. The convergence of new and existing technologies also creates opportunities for new ways of observing the ocean, sharing data and knowledge, and accessing resources under extreme conditions. Technology and innovation will continue to transform the way humans and societies interact with marine systems and to open up new possibilities for scientific research. Collaboration between ocean, computer, and social scientists may provide the tools to translate fast-paced changes in technology into better information for decision-makers and broader socio-economic benefits.

Canada has several internationally competitive firms in the ocean technology sector. This source of strength presents many opportunities for Canada to leverage domestic expertise to contribute to international observation initiatives. The domestic market, however, is not large enough to sustain many small and medium-sized ocean technology firms. Alignments between sectors (public, private, and academic) improve the application of basic science to technology development, and the uptake of new technology for new scientific approaches. Although alignments in Canada have sustained several active clusters of technology development, these have thus far been reliant on funding from resource industries or governments.

5.2 OCEAN GOVERNANCE

Management decisions are often only appropriate for a specific context, and can rarely be standardized, suggesting the need for a governance approach to dealing with people and the oceans. Whereas *management* constitutes a set of tools applied to concrete tasks with measurable outcomes, *governance* is an iterative, adaptive process involving interactions of stakeholders, as well as the ways in which goals are chosen and management decisions made (Jentoft & Chuenpagdee, 2009). Multiple conflicting uses, and complex and changing interactions between the ocean and societies at multiple spatial, temporal, and organizational scales, pose challenges for ocean governance (Perry & Ommer, 2003; Jentoft & Chuenpagdee, 2009; Sumaila, 2012; Miller *et al.*, 2013). Furthermore, recent research has revealed that the ways in which policy is developed and implemented can be just as important to the outcomes as the interventions themselves (Jentoft & Chuenpagdee, 2009; Ommer *et al.*, 2011; Charles, 2012). Given these issues, skilled, interdisciplinary research capacity is essential to inform not only specific policies, but also an understanding of entire governance systems that structure interactions between human societies and the ocean.

The research questions in this theme highlight the challenges associated with achieving sustainable ocean governance in the context of social and ecological diversity (Q33, Q35–37), uncertainty (Q34, Q37), multiple interacting effects of global change (Q34, Q37), and potential conflict between alternative uses of ocean resources and ecosystem services (Q38–40). Some of these research questions overlap with those addressed under the coastal communities theme. This reflects the role coastal communities have as major stakeholders in ocean governance and associated research needs (Section 4.5). Many of the research questions in this theme focus on alternative ways of applying and translating science into decision-making, and the consequences of management decisions. Addressing these research questions will require networking, comparative research in diverse contexts and at multiple scales, and continual re-examination of outcomes and adaptation of policies under changing social and ecological conditions.

5.2.1 Research Seascape

A substantial knowledge base has accumulated around various management tools in Canada, and different forms of fisheries and coastal governance. Some of this knowledge has been shared through mechanisms such as the Ocean Management Research Network and other collaborations between DFO, universities, NGOs, and the private sector (see Sections 2.2.6, 4.2, and 4.3).

Major Research Questions Related to Ocean Governance

The following questions are numbered and ordered according to the *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q33. 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?

Q34. What research, information, and tools are required to govern ocean use in the context of cumulative, interactive effects on socio-ecological systems?

Q35. What measures are required to ensure appropriate and effective participation of diverse coastal communities in ocean and coastal management and governance?

Q36. 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?

Q37. 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?

Q38. What strategic decision-making frameworks are required to establish a socially and ecologically sustainable balance between aquaculture and wild fisheries in marine ecosystems?

Q39. 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?

Q40. 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?

The nature of marine social-ecological systems poses several challenges to governance, including the common pool and transboundary character of marine resources (Sumaila, 2012); effects of multiple interacting pressures and global change, including climate change, ocean acidification (IOC/UNESCO *et al.*, 2011; Perry *et al.*, 2011; Miller *et al.*, 2013), and globalization of markets; and the multiple scales at which these changes occur and management decisions are made (Charles, 2012; Sumaila, 2012). Decisions can be made at different scales, from local to international, with consequences at other scales. Given the many ways in which Canada relies on the ocean, there is great potential for conflicting interests: one stakeholder's solution may create a problem for another (Jentoft & Chuenpagdee, 2009). Furthermore, unpredictable changes in a resource can disrupt governance arrangements (Perry *et al.*, 2011; Miller *et al.*, 2013).

Canada has a strong foundation of research and experience in ocean governance at a range of scales, though little work has been done to integrate knowledge from research on the many fisheries management successes and failures throughout Canadian history. Coasts Under Stress (see Box 4.4), one of the largest efforts to carry out and integrate research findings from several coastal communities on two Canadian coasts, acknowledged the many challenges in integrating research across disciplines and management "silos" (Ommer & The Coasts Under Stress Research Project Team, 2007). A social-ecological framework provides one possible approach to overcoming such challenges and addressing the inherent complexities and uncertainties of marine social-ecological systems.

Ocean governance research in Canada, and internationally, is placing increasing emphasis on cross-scale linkages, communication between different levels of decision-making, and identifying the appropriate level for certain types of decisions (Ommer & The Coasts Under Stress Research Project Team, 2007; Jentoft & Chuenpagdee, 2009; Charles, 2012; Sumaila, 2012). The challenges described above have led some to argue for more adaptive, participatory approaches to ocean governance (Jentoft & Chuenpagdee, 2009; CFRN, 2012c; Wilson *et al.*, 2013). Canada has experience in applying such approaches, including integrated coastal zone management (Ricketts & Hildebrand, 2011) and co-management agreements within larger land claim agreements between the Government of Canada and Aboriginal peoples (Dale & Armitage, 2011). Co-management arrangements have revealed the need to incorporate different sources of information in participatory governance processes, including Western scientific knowledge and traditional or local knowledge (Berkes *et al.*, 2001; Armitage *et al.*, 2011; Dale & Armitage, 2011).

Timely access to information about the systems being governed as well as governance dynamics are essential for more responsive governance (Wilson *et al.*, 2013). A Canadian Fisheries Research Network project aims to better identify the information needed for participatory ocean governance, as well as required training and capacity (CFRN, 2012c). Specialized skills and capacities are needed to translate scientific information into formats accessible to policy-makers, industry actors, and community leaders (see Box 5.3). Information technologies are also playing a growing role in providing data to users on-demand and in real-time (Taylor, 2009; Kintisch, 2013).

Box 5.3
Knowledge Mobilization

Knowledge mobilization in its broadest sense means moving knowledge from science to action: i.e., making the results of research available to policy-makers and other users of knowledge, such as industry and civil society organizations (see Levin, 2008 for a discussion of currently used definitions of knowledge mobilization). In interdisciplinary research, knowledge needs to be moved between disciplines to enable the development of common frameworks and the synthesis of findings across different approaches and methods. Research on ocean governance further requires the mobilization of different types of knowledge, including traditional ecological knowledge, to enable the co-generation of contextualized knowledge for specific problems and locations.

Knowledge mobilization occurs by creating multidirectional pathways for knowledge discovery and uptake, which may include activities such as knowledge translation (the adaptation of research results for specific audiences) and knowledge transfer (the marketing of such results to audiences) (Hawkins, 2011). Knowledge management is a proactive process that requires designated skills and resources on a sustained basis (Levin, 2008). Funding agencies are increasingly requiring, and providing support for, the integration of knowledge mobilization in research projects and networks, such as SSHRC's knowledge mobilization strategy (SSHRC, 2009), or NSERC strategic research networks (NSERC, 2010). Many Canadian universities have established offices for knowledge mobilization to enhance the uptake of research outputs in policy-making and to support commercialization of research findings (see, for example, the ResearchImpact network of knowledge mobilization centres; ResearchImpact, n.d.). A particular challenge for knowledge mobilization in ocean science is developing the capacity to translate and transfer knowledge among diverse user communities.

Canada has made several national and international commitments to adopt management approaches intended to sustain marine biodiversity, including ecosystem-based management, integrated coastal zone management, and a precautionary approach to fisheries management (VanderZwaag *et al.*, 2012). The governance implications of some of these goals have not been fully articulated, however, and Canadian organizations have sometimes struggled with fully achieving or operationalizing these commitments, leaving space for more research (Juda, 2003; Jessen, 2011; Ricketts & Hildebrand, 2011; Hutchings *et al.*, 2012; VanderZwaag *et al.*, 2012).

5.2.2 Opportunities and Challenges

Growing uncertainty in both ecological and social elements of social-ecological systems poses significant challenges to established approaches of governance, but also offers an opportunity to try new ones while learning from ongoing Canadian and international experiences (Ommer & The Coasts Under Stress Research Project Team, 2007; IOC/UNESCO *et al.*, 2011). Sustainable ocean governance requires dynamic decision-making approaches that can adapt to continual change based on rigorous, multidisciplinary research done at appropriate spatial, temporal, and organizational scales using information from multiple sources. Addressing the research questions in this theme may require novel scientific approaches and institutional structures that have yet to be described or evaluated.

5.3 HUMAN HEALTH AND WELL-BEING

Health is a multidimensional concept that encompasses positive aspects of physical and mental wellness, not merely the absence of disease (Coulthard, 2012). The broader concept of well-being recognizes the social, environmental, and cultural factors that contribute to the quality of life of a person or community. The study of well-being now incorporates objective and subjective measures, and views well-being as a process rather than an outcome — a process that can provide insight into people's interactions with the marine environment (Charles, 2012; Coulthard, 2012). Just as human activities have impacts on the ocean (see Section 4.3), resulting changes in the ocean can have consequences for human health and well-being, creating the potential for complex feedbacks.

The relationship between the ocean and human health and well-being is an emerging theme that is gaining increasing attention internationally. While none of the 40 research questions focuses directly on human health, several recognize the potential to improve the understanding of ocean-related determinants of human health and well-being. Although phrased in a general way, the questions reflect the complex relationships between human activities, environmental change, and human well-being (CCA, 2012a). Multiple uses of the ocean create feedbacks where one activity can have negative impacts on human health and well-being due to effects on other activities, such as when contaminants from human activities accumulate in species harvested for food.

Some of the research questions highlight other socio-economic consequences of global change, such as the disappearance of sea ice, sea-level change, and ocean acidification. Changing species distributions have implications for food security and commercial harvesting, as well as novel pathogens and parasites.

The final question (Q40) highlights the importance of sustainable ocean-based food production for local and global food security, and the health and well-being of coastal communities.

Major Research Questions Related to Human Health and Well-Being

The following questions are numbered and ordered as they appear in *40 Priority Research Questions for Ocean Science in Canada* (CCA, 2012a):

Q17. How are the movements and survival of marine organisms, including invasive species, being affected by environmental change, and what are the socio-ecological impacts?

Q26. 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?

Q32. 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?

Q40. 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?

Addressing the health-related aspects of these research questions requires approaches that go beyond a focus on an individual's health to include the determinants of the health of populations. The social-ecological perspective emphasizes the social and ecological determinants of the health outcomes related to the health of an entire population, rather than to individuals. Emerging theories in epidemiology are conceptualizing these determinants in various ways, such as ecosocial theory and eco-epidemiology (Krieger, 2011). These approaches recognize that determinants can have both positive and negative outcomes, and differentiate biologically driven pathways from those driven by cultural, social, economic, and psychological determinants. Table 5.1 illustrates some of the pathways through which the ocean affects human health and well-being.

Table 5.1

Pathways that Impact Human Health and Well-Being

Biological pathways affecting the health and well-being of *individuals* and *populations*:	**Environmental and social pathways affecting the health and well-being of *populations*:**
• Exposure to ocean pathogens, including through contaminated seafood • The ocean as a vector for bacterial and viral infections and epidemics • Exposure to marine biotoxins and ocean-borne pollutants • Marine bioproducts, therapeutics, and pharmaceuticals • Shifts in and emergence of biological pathways as a consequence of environmental change	• Ocean hazards and extreme events, including impacts of global change • Impacts of ocean-based industries and related policies on economic opportunity, social inequality, and community resilience • Occupational health risks in ocean and coastal-based employment • Impacts of ocean change and resource development on traditional cultures, especially in the Arctic • Benefits and risks of recreational ocean uses

This table lists examples of ocean-related pathways that affect human health and well-being, with a distinction between *biological* and *environmental and social* pathways. While biological pathways may have obvious direct impacts on the health of individuals and populations, many pathways also have implications for human well-being, by affecting food security, or economic well-being, or by changing the supply of resources (e.g., fisheries, marine bioproducts, etc.). Environmental and social pathways operate at larger scales, with more complex feedbacks to the health and well-being of human populations. Note that environmental and social pathways are not limited to coastal communities, although these are likely to feel the greatest impacts.

Research on biological pathways requires a system for recording and processing data on illness due to pathogens, biotoxins, and pollutants as part of an expanded environmental monitoring infrastructure covering both animal and human health data (NSTC, 2007). Shore-based lab facilities with specialized equipment and computational resources are required to apply new tools, such as genomics, proteomics, or bioinformatics, which will expand monitoring and screening capabilities.

The study of environmental and social pathways requires interdisciplinary approaches that combine various forms of data and knowledge to support integrated analyses of the social-ecological systems that shape human interactions with the ocean. Sustained interdisciplinary research institutes and collaborative networks with specific abilities to mobilize, translate, and integrate different kinds of knowledge are key to successful social-ecological research. Aside from biomedical data, such research groups require access to a wide array of social-ecological data, scientific and non-scientific forms of knowledge, and tools to collect, record, and process these kinds of data and knowledge.

5.3.1 Research Seascape

Current capacity in Canada appears to focus on biological pathways and well-established sub-fields focusing primarily on marine pathogens and human health, with contaminated seafood consumption being the primary pathway. Other sub-fields receive much less attention, especially studies of the environmental and social pathways related to health and well-being. Research on the ocean and well-being does not currently figure prominently in the programs and projects supported by the Canadian Institutes for Health Research and the Public Health Agency of Canada, or in the activities of the leading centres for population and public health. For example, CIHR contributions to ocean science have accounted for approximately 0.12 per cent of total CIHR funding and 3 per cent of total ocean science funding over the past 10 years (see Table 2.2). Similarly, links between the ocean and human health and well-being are currently not included in the funding priorities of the federal granting councils. The NCE program, however, encourages networks to engage experts across disciplines and sectors of society, which offers the opportunity, though not the requirement, to engage ocean and health researchers, as is the case within ArcticNet.

This situation contrasts with specifically targeted initiatives in the United States and Europe. For example, enhancing human health is one of six research priorities in a recently released report by the U.S. National Science and Technology Council (NSTC, 2013). The United States has also created four centres for oceans and human health, and three centres of excellence funded by NOAA's Oceans and Human Health Initiative. The ocean and human health is among the eight priority research topics identified in a recent European foresight report (European Marine Board, 2013a). The European Centre for Environment and Human Health, at the University of Exeter in the United Kingdom, includes several projects on the ocean and human health within a broader research program investigating the links between the environment and human well-being.

Federal departments and agencies in Canada maintain a network of labs that provide specialized equipment to monitor and analyze pathogens, biotoxins, and pollutants (NRC, 2012a, 2012b, 2012e, 2012d). These labs provide the infrastructure for several programs that perform monitoring and research services relevant to animal and human health, including the Canadian Shellfish Sanitation Program, administered jointly by CFIA, Environment Canada, and DFO (CFIA, 2013).

While CFIA is primarily responsible for monitoring pathogens and biotoxins at the federal level, DFO also collects data on species that carry, produce, or affect these health hazards. Monitoring of marine contaminants is carried out by Environment Canada, DFO, and other federal departments. Contaminant monitoring in the Arctic is coordinated under the Northern Contaminants Program, which includes participation by Aboriginal Affairs and Northern Development Canada, Environment Canada, Health Canada, DFO, and territorial governments, and contributions from university researchers (EC, 2001).

While still embryonic, there is substantial potential in Canada for research growth in marine bioproducts linked to the development of medical therapeutics and pharmaceuticals. This would build on Canada's strength in the application of new genomic technologies, in particular in medical and human heath applications. Several university chairs already perform genomic and marine biotechnological research on pathogens for aquatic species (see Section 4.2).

Some health and safety research programs focus on the marine setting. These include the Centre for Occupational Health and Safety Research at Memorial University (SafetyNet), where researchers have investigated health risks related to the physical and psychosocial aspects of marine and coastal work (SafetyNet, 2013). The Offshore Safety and Survival Centre at the Marine Institute of Memorial University offers safety and emergency response training, and also supports an applied research unit (MUN, n.d.). Other research on occupational health and safety in marine settings has been carried out through the Faculty of Engineering and Applied Sciences at Memorial University and the Faculty of Engineering at Dalhousie University. The Search and Rescue New Initiatives Fund (SAR NIF) is a Government of Canada program that provides up to $8 million for new projects in any sector to improve Canada's National Search and Rescue Program, including public education, consultation, and volunteer recognition (NSS, 2010). Explicit attention to population health issues in relation to the ocean has therefore been confined mostly to human health components within broader ocean-related projects and programs.

The Coasts Under Stress project (see Box 4.4) examined the effects of resource extraction activities on the health and well-being of residents in Canadian coastal communities, including fisheries and oil and gas resources (Ommer & The Coasts Under Stress Research Project Team, 2007). ArcticNet is studying the impacts of environmental change on the culture, lifestyles, livelihood, and health of aboriginal populations in northern Canada. The new MEOPAR network plans to incorporate studies of the risks of extreme marine events (e.g., tsunamis and storm surges) to people, infrastructure, and communities, and their relevance to the vulnerabilities of industries and coastal communities (MEOPAR, 2013).

Research on social pathways would be improved by data sets that track indicators of social determinants of individual and community well-being. The existing health information infrastructure focuses primarily on the provision of health services; some provincial health databases, such as the Manitoba Population Health Research Data Repository, integrate administrative, registry, survey, and other information on residents (MCHP, 2009). There is a need to establish population health data sources that cover social determinants of health in coastal regions and permit linkages to provide pan-Canadian analyses. The small sample sizes of existing data sources limit the opportunities to study coastal communities separately from others.

5.3.2 Opportunities and Challenges

Current ocean and health research capacity in Canada has been narrowly focused on selected biological determinants of human health, such as marine biotoxins and contaminants in food species. Moreover, this research is poorly integrated with research and initiatives focusing on broader well-being. Very few research projects supported by the major funding agencies address the relationship between the ocean and human health and well-being. Canadian research in medical applications of marine bioproducts is an example of an opportunity to contribute to globally emerging areas (see Section 4.2). Social-ecological research using a health lens has so far been largely limited to single projects (such as Coasts Under Stress) or to specific components of larger research networks (such as ArcticNet). These could serve as a foundation for more integrative research on the ocean and well-being, which is garnering increasing attention in international policy fora.

6

Conclusions

- Responding to the Charge
- Responding to the Sub-Questions
- Final Conclusions

6 Conclusions

This chapter synthesizes the main findings that emerged from the Panel's deliberations and analyses presented in the previous chapters and answers the main question and sub-questions that comprise the charge to the Panel.

To guide the assessment, the Panel used the 40 research questions developed by the Core Group on Canadian Ocean Science (see CCA, 2012a) as the "major research questions." As described in Chapter 1, the Panel chose not to conduct a detailed analysis of capacity with regard to each of the 40 research questions, but to assess Canada's capacity and output in ocean science in general (Chapters 2 and 3), followed by an analysis of opportunities and challenges in addressing questions in each of nine research themes representing groups of related research questions (Chapters 4 and 5). The findings of these analyses are presented under each of the sub-questions of the charge.

6.1 RESPONDING TO THE CHARGE

Main Question

What are Canada's needs and capacities with regard to the major research questions in ocean science that would enable it to address Canadian ocean issues and issues relating to Canada's coasts and enhance its leading role as an international partner in ocean science?

Canada is endowed with not only the longest coastline in the world, but also tremendous diversity of ocean systems, resources, and coastal cultures and communities. This endowment provides almost unlimited opportunities in fundamental research on understanding ocean processes, as well as applied research on sustainable ocean and coastal development and management for the benefit of Canadian society. At the same time, it bestows on Canada the responsibility to act as a steward of the global ocean. The 40 research questions reflect this diversity in opportunities and societal relevance by highlighting a complex set of key research concerns for the coming decades. The extent of these concerns relative to Canada's small population creates a key challenge for Canadian society: how to ensure that capacities for ocean science are comprehensive and adaptive (taking advantage of insights and input from multiple disciplines, sectors, and groups), appropriately designed, and efficiently deployed.

The overview presented in Section 2.2 shows that ocean science in Canada is organized as a networked system of regional clusters on the East Coast, West Coast, and in the centre of the country, with additional research stations in the Arctic. This organization reflects the tendency for collaboration to increase with geographic proximity, but it also avoids the risks associated with centralization, including focusing scarce resources and capacity on one geographical area or a narrow range of issues. With no single organization responsible for coordination of ocean research activities, however, challenges remain for effective collaboration, coordination, and integration at the national level.

The bibliometric analyses presented in Chapters 3 and 4 show the historical importance of federal government organizations (in particular, DFO, NRCan, Environment Canada, and the NRC) for collaboration, especially with universities, on peer-reviewed scientific articles. The decentralized structure of these organizations makes them important hubs for collaboration within regional clusters, which serve as points of access to their national networks of government scientists. In many cases, government research stations in the regions provide access to expertise, as well as essential infrastructure such as vessels and other platforms, specialized labs, databases, and computing infrastructure. Universities are also important hubs that collaborate with government departments, and increasingly with each other through NCEs or consortia, such as CCORU. While DFO is an important hub of collaboration in most research themes, the relative importance of other government departments varies by theme. A similar pattern can be observed for universities. The private sector has substantial research capacity in areas such as offshore oil and gas development, deep-sea mining, and ocean technology development. Ocean science capacity is thus not only geographically dispersed, but also distributed across a variety of organizations with diverse mandates and priorities. This adds another dimension to the challenge of coordinating activities and allocating resources for ocean science across the country.

The Panel found that the data and information needed to evaluate the different dimensions of capacity are held by a large number of institutions, recorded in formats that are not comparable, and often incomplete or not always accessible to the public. The multidisciplinary nature of ocean science also made it difficult to delineate the field within existing data sets. Finding good data on collaborations between researchers in the social and natural sciences, or information on the mobilization of scientific knowledge for applied research and institutional change, for example, was particularly problematic. The first conclusion drawn by the Panel is thus that there are several information gaps on key elements of capacity in ocean science in Canada. Table 6.1 displays the main gaps and explains their importance.

Table 6.1

Gaps in Data on Ocean Science Capacity in Canada

Data unavailable to the Panel	Importance
Number of researchers in ocean science	Due to the diversity of disciplines and fields contributing to ocean science, solid estimates of human capacity would require comprehensive information on the educational backgrounds of ocean scientists in universities, government departments, and private firms performing marine research. Such data would allow estimating trends in human capacity and identify current and future gaps in specialized fields or interdisciplinary training.
University research activities	Most universities record information on research activities by discipline, which does not allow for a thorough assessment of capacity in interdisciplinary fields such as ocean science. Future studies would benefit from more detailed information on research activities to identify the universities and departments that contribute to ocean science and their specific strengths in capacity.
Research conducted by the private sector	Private sector research is not captured by bibliometric analysis because industry does not usually report on its research activities in peer-reviewed journals. This makes it difficult to assess capacity in areas with high industry activity such as oil and gas development, mining, or renewable energy development. Alternative approaches (e.g., technometrics or webometrics) are still in their infancy.
Government research spending on ocean science	Publicly available reports and data do not clearly identify ocean science expenditures. Disaggregated data would be necessary to assess total funding available in ocean sciences and identify trends in government research capacity.
Inventories of research infrastructure and its use	These data would allow identification of physical infrastructure constraints and facilitate prioritization of infrastructure investments.
International research collaborations	More detailed information about the type, objectives, and governance of international scientific collaborations would allow a full analysis of Canadian contributions to international science and facilitate identification of areas of strength or weakness.
Social sciences and interdisciplinary research outputs	Bibliometric analysis does not capture a large proportion of output in the social sciences or interdisciplinary research. Such data would allow a better understanding of the need for interdisciplinary training and other complementary research skills.

6.2 RESPONDING TO THE SUB-QUESTIONS

Sub-question 1

How do these capacities and needs relate to the varied dimensions of ocean research, such as the technological, economic, environmental, social, policy and governance aspects of this kind of research?

The nine themes identified by the Panel reflect the broader research areas described by the 40 research questions. The Panel used bibliometric analysis and other available information to assess the capacity in each of the six themes that build on established approaches and methods in ocean science. Based on this assessment, the Panel then identified opportunities and challenges for ocean science in Canada to address the research questions within each theme.

- **Ocean-climate interactions**: Canada's capacity in remote sensing and climate modelling provides opportunities to advance research on ocean-climate interactions, particularly in addressing questions requiring better integration of ocean and sea ice in climate models. Realizing this opportunity, however, requires sustained observation and monitoring of climate-related ocean data. This is a challenge for Canada, primarily due to its vast and remote coastline, much of which is in the Arctic where observation and monitoring are inherently more costly. Addressing research questions in this theme also requires other means of experimentation and sampling that depend on the availability of various types of infrastructure, such as vessels, autonomous and remote platforms, and specialized instruments.
- **Biological, mineral, and energy resources**: Fundamental research on understanding these resources can build on a long tradition of government science, particularly fisheries science and marine geology, as well as fisheries research conducted by several top-publishing university research institutes. Emerging strengths in genomic analysis and biodiversity assessment open up new opportunities for research and collaboration to study the dynamics of marine biodiversity and ecosystems. The main challenges in this area are to prevent further loss of capacity in taxonomy and to continue the transition towards more holistic approaches such as ecosystem-based and social-ecological frameworks. Substantial research capacity in mineral and energy resources is located in the private sector, which supports applied research that provides direct societal benefits through resource development. This distribution of capacity creates challenges for integrating research conducted by private,

government, and academic institutions. Another challenge is to effectively integrate research on the environmental and societal impacts associated with ocean resource development.

- **Human impacts on marine and coastal ecosystems**: Similar to research on biological, energy, and mineral resources, Canadian research capacity in this theme benefits from historical strengths in government departments and universities. The challenge is to adapt existing capacity to the changing context and priorities of this research. Adjustments made to date have led to a gap in research on invasive species — a gap that may soon be filled through a new network project — as well as on monitoring and understanding the behaviour of contaminants, in particular novel contaminants and known contaminants under new and changing conditions. These emerging gaps represent key challenges in the context of the overlapping mandates of federal agencies.
- **Plate tectonics and natural hazards**: Major opportunities arise in this theme due to past achievements in geological and hydrographic surveying and recent investments in cutting-edge cabled observatories. These investments also create challenges in ensuring long-term coverage of operational costs and funds for research using these platforms. Addressing all the research questions in this theme requires comprehensive geological and bathymetric mapping of Canada's vast coastal and marine areas, leading to similar challenges as in other research themes that depend on comprehensive monitoring, surveying, and observation.
- **Coastal communities**: A large group of researchers from many disciplines contributes to research in this theme, which includes impacts of climate change on coastal communities and adaptation, community-based management of coastal fisheries and other resources, and co-management. The Panel found little evidence of research on coastal cities — an important gap in the light of growing urban coastal populations that are increasingly exposed to the impacts of global change. Interdisciplinary networks are very important for research on coastal communities, but tend to be short-lived. A key challenge is therefore to establish more permanent structures for continued interdisciplinary training, and integration and mobilization of knowledge.
- **The Arctic Ocean**: Recent and upcoming investments in icebreakers and research labs in the Arctic will create opportunities to address research questions on the Arctic Ocean. Some of these opportunities will be driven by the increasing strategic and economic importance of the Arctic region. As many of the questions relate to impacts of climate change, similar challenges arise in ensuring sustained observations. There are other challenges in prioritizing research on specific impacts of human activities in the Arctic to ensure that research keeps pace with development dynamics.

The remaining three themes comprise questions of a more forward-looking nature that describe future needs or anticipate paradigm shifts that cannot be captured by bibliometric analysis. The Panel therefore focused on emerging approaches in research, and the conditions that support their development and adoption. Using this approach, the Panel identified the following opportunities and challenges:

- **Ocean technology**: The research questions in this theme ask what measurements will be necessary in the future, what sensors will be needed to provide them, and how these can be integrated into national-scale observation networks. Addressing these questions enables new kinds of observations and experiments and lowers the cost of large-scale and long-term monitoring, which also contributes to reducing challenges in other research themes. Canada's diverse and dynamic ocean technology sector has ample capacity to develop tools and technologies for advancing ocean science in Canada and abroad. A key challenge is to better align the research-driven technology development in the science sector with opportunities for commercial technology development, and to improve access to international markets for science instruments so as to make such innovations economically viable.
- **Ocean governance**: Research on ocean governance faces growing uncertainty in both ecological and social elements of social-ecological systems, which require multidisciplinary research and inclusion of knowledge from different sources. The need to develop adaptive and participatory approaches to ocean governance opens up opportunities for developing innovative approaches to research as well as new alignments and collaborations between researchers, policy-makers, and practitioners.
- **Human health and well-being**: Research on the relationship between the ocean and human health and well-being is currently being redefined by a paradigm shift from a focus on contaminants and disease towards a more holistic understanding of the social and environmental determinants of health. Although several research questions allude to this shift, current research in Canada mostly addresses selected biological determinants such as pathogens and biotoxins. The main challenges relate to integrating research capacities in ocean-specific determinants of health with research framed by a broader social-ecological perspective.

Sub-question 2

What infrastructure does Canada have presently and what will it need to acquire in order to address the major ocean research questions with their varied dimensions?

Using a broad interpretation of this sub-question, the Panel identified several overarching areas of capacity that are essential to ocean science in general and therefore affect most research activities contributing to addressing the 40 research questions:

- **Human capacity**: The Panel noted with concern that overall human capacity in ocean science could not be determined because of data limitations. As Section 2.1 shows, the main limitation is that available statistical data sets do not take into account the multidisciplinary character of ocean science. Other reasons include the lack of consistent data from universities and government departments. Based on the available data, the Panel found a slight upward trend in the number of graduates (in natural sciences) with training relevant for ocean science at universities in Canada over the last decade. The number of professors receiving funding for ocean science increased from 2002 to 2008, but has declined since. Nevertheless, the Panel could not determine whether this trend reflects researchers leaving Canada, or focusing on fields other than ocean science, or receiving funding from other sources.
- **Ship time and fleet management**: The evidence presented in Section 2.3.1 suggests that maintaining research vessel capacity, including the age of the fleet and access for non-DFO researchers, is a key challenge for ocean science infrastructure in Canada. While the ongoing fleet renewal will address some of these issues, the paucity of information on availability and use of ship time is a problem for planning and determining future research needs. Other countries are addressing this problem through the establishment of consortia for the joint management of access to ship time for research and large scientific instruments. Improved information and management also facilitate international sharing of capacity, which can provide access to a broader range of equipment.

- **Ocean observation**: Canada has world-class capacity in certain observation activities, such as cabled networks, space-based observation, and tracking of marine species. But challenges exist in achieving geographical coverage, and data integration and management. As noted above, Canada's vast coastline and exposure to the rapidly changing Arctic present substantial challenges for providing the sustained observation and monitoring necessary to address many of the 40 research questions in a comprehensive manner. As a small country by population, Canada is unlikely to generate the necessary resources alone. In this context, prioritization and coordination are important to ensure that investments in observation infrastructure meet priority needs, and that the resources to operate and use them are available in the long run. International collaboration and exchange of instruments are another way to achieve better and more comprehensive observation with limited resources.

Sub-question 3

What are the arrangements and new innovative alignments among the stakeholders of ocean research (i.e., governments, universities, industries and communities) that could enable Canada to continue to address its ocean issues and enhance its leading role as an international partner in ocean science?

The Panel identified several types of innovative networks and alignments that are changing the way ocean scientists collaborate to address research questions in Canada. In particular, new types of funding opportunities through CFI, the NCE program, and other sources are enabling the development of new forms of collaborative investment in, and management of, major physical infrastructure. The most prominent examples are NCEs such as ArcticNet, which manages the research icebreaker *CCGS Amundsen*; and ONCEE, which supports partnerships between industry and researchers in the development and use of ocean observation technologies such as those applied in the NEPTUNE and VENUS cabled observatories. These funding opportunities also allow for the formation of new types of partnerships across disciplines and between researchers in government, universities, the private-sector, and civil society organizations. Other examples, such as the Ocean Tracking Network, show how such investments can catalyze effective international collaboration. On a smaller scale, NSERC strategic partnerships and other programs are leading the development of partnerships and networks of scientists and practitioners that focus on specific issues. Finally, emerging consortia of actors such as CCORU are creating momentum for further change in the ocean science seascape in Canada.

6.3 FINAL CONCLUSIONS

Bearing in mind that the charge is directed at ocean science capacity at the national level, the Panel identified the following gaps in the coordination and alignment of ocean science in Canada, which are currently not being addressed.

- **The vision gap**: In contrast to other countries, or other disciplines in Canada, no comprehensive national strategy or vision currently exists for ocean science in Canada. The Panel noted that DFO's 2008 science strategy does not cover important issues addressed by the 40 research questions, many of which fall outside DFO's mandate. The absence of such a vision or strategy makes it difficult to prioritize needs for ocean science, and plan investments in a comprehensive, forward-looking manner.
- **The coordination gap**: Addressing the 40 research questions requires enhanced collaboration at local, regional, national, and international levels. There are many instances of successful collaboration in Canada. Although the structure of regional clusters allows for addressing many of the complex, multi-scale challenges described by the 40 research questions, important challenges remain in coordination, e.g., aggregation of local- and regional-scale research findings in a macro-scale context, and sharing and communicating research insights internationally. A related challenge is to improve knowledge mobilization capacity, both across disciplines to support interdisciplinary research and co-generation of knowledge, and between the ocean science community and the users of ocean science in policy-making, industry, and civil society. Coordination challenges also exist in sustaining large-scale observation, effectively allocating resources, and planning, managing, and sharing infrastructure at the national level.
- **The information gap**: As noted in Table 6.1 above, limitations in access to, and availability and comparability of, information made it difficult to assess several categories of capacity. While many actors in ocean science maintain inventories for internal use, no existing mechanism or repository systematically collects and regularly updates information on essential key research activities, infrastructure, and other ocean science capacities for the entire country. Although gathering this information is a complex task worldwide, some countries, such as the United States, Germany, and the United Kingdom, have established institutions and processes to collect and make available such data. The information is then used not only to assess capacity, but also to inform development of national science strategies and plans on a regular basis, and to prioritize decision-making on research infrastructure investments (see Section 2.2.6). The absence of such inventories in Canada makes it difficult to identify capacity needs at the national level. Similarly, opportunities to address the 40 research questions through national or international collaboration are more difficult to identify.

Addressing these gaps is essential if Canada is to meet the growing needs of ocean science with limited resources, and make best possible use of existing capacities to unlock the opportunities of ocean science while fostering international collaboration. None of the current and emerging alignments, consortia, or networks can address these gaps singlehandedly. It requires a national effort involving the entire community of ocean scientists in Canada, as well as users of ocean science in government, the private sector, and civil society.

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- Vision for the Canadian Arctic Research Initiative: Assessing the Opportunities (2008)
- Energy from Gas Hydrates: Assessing the Opportunities and Challenges for Canada (2008)
- Small is Different: A Science Perspective on the Regulatory Challenges of the Nanoscale (2008)
- Influenza and the Role of Personal Protective Respiratory Equipment: An Assessment of the Evidence (2007)
- The State of Science and Technology in Canada (2006)

The assessments listed below are in the process of expert panel deliberation:

- Canadian Industry's Competitiveness in Terms of Energy Use
- The State of Knowledge of Food Security in the Canadian North
- Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction
- The Future of Canadian Policing Models
- The Potential for New and Innovative Uses of Information and Communication Technologies (ICTs) for Greening Canada
- The State of Canada's Science Culture
- Therapeutic Products for Infants, Children, and Youth
- Memory Institutions and the Digital Revolution

- STEM Skills for the Future
- RISK: Is the Message Getting Through?
- Wind Turbine Noise and Human Health
- Timely Access to Health and Social Data for Health Research and Health System Innovation

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Council of Canadian Academies
180 Elgin Street, Suite 1401
Ottawa, ON K2P 2K3
Tel: 613-567-5000
www.scienceadvice.ca