

State-of-the-Ocean Report for the Gulf of St. Lawrence Integrated Management (GOSLIM) Area

Hugues P. Benoît, Jacques A. Gagné, Claude Savenkoff,
Patrick Ouellet, and Marie-Noëlle Bourassa, editors

Fisheries and Oceans Canada
Gulf Fisheries Centre
343 Université Ave.
Moncton, New Brunswick
Canada E1C 9B6

Pêches et Océans Canada
Institut Maurice-Lamontagne
850, route de la Mer
Mont-Joli, Québec
Canada G5H 3Z4

2012

**Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2986**



Fisheries and Oceans
Canada

Pêches et Océans
Canada

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2986

2012

State-of-the-Ocean Report for the Gulf of St. Lawrence
Integrated Management (GOSLIM) Area

Hugues P. Benoît¹, Jacques A. Gagné², Claude Savenkoff²,
Patrick Ouellet², and Marie-Noëlle Bourassa², editors

¹ Gulf Fisheries Centre
343 Université Ave.
Moncton, New Brunswick
E1C 9B6

² Institut Maurice-Lamontagne
C.P. 1000, 850, route de la Mer
Mont-Joli, Québec
G5H 3Z4

© Her Majesty the Queen in Right of Canada, 2012
Cat. No. Fs 97-4/2986E-PDF ISSN 1488-5387

Correct citation for this publication:

Benoît, H. P., Gagné, J. A., Savenkoff, C., Ouellet, P., and Bourassa M.-N. (eds.). 2012. State-of-the-Ocean Report for the Gulf of St. Lawrence Integrated Management (GOSLIM) Area. Can. Manusc. Rep. Fish. Aquat. Sci. 2986: viii + 73 pp.

TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	v
LIST OF APPENDICES	vi
ABSTRACT / RÉSUMÉ	vii
LIST OF CONTRIBUTORS	ix
1. Introduction.....	1
2. The Estuary and Gulf of St. Lawrence ecosystem	2
3. Existing literature on structure, status, and trends for the St. Lawrence ecosystem	4
3.1 Reports on ecosystem structure and status	4
3.2 Reports on trends.....	6
4. Purpose and structure of this report.....	6
4.1 State of the environmental effects.....	7
4.2 Driver pressure state impact response (DPSIR) framework	9
5. Status and trends for some important themes pertinent to the St. Lawrence ecosystem.....	10
5.1 Hypoxia in the Estuary and Gulf of St. Lawrence	10
5.1.1 Overview	10
5.1.2 Drivers and pressures	11
5.1.2.1 Hypoxia in the deep channels of the Gulf of St. Lawrence.....	11
5.1.2.2 Shallow-water hypoxia.....	12
5.1.3 Impacts of hypoxia on marine resources	13
5.1.4 Key directions in management response development	14
5.2 Ocean acidification impacts in the Gulf of St. Lawrence	15
5.2.1 Drivers of ocean acidification	15
5.2.2 Current state of acidification in the Estuary and Gulf of St. Lawrence	16
5.2.3 Impacts of acidification in the Estuary and Gulf of St. Lawrence	19
5.2.3.1 Calcification	20
5.2.3.2 Physiological effects, including non-calcifying species.....	21
5.2.3.3 Biogeochemistry.....	22
5.2.3.4 Interaction of acidification with others variables	23
5.2.4 Key directions in management response development	24
5.3 Changes in seasonal sea-ice cover and its effects on marine mammals	24
5.3.1 Drivers and pressures	24
5.3.2 Overview of variability in ice cover, impact, and expected changes	25
5.3.3 Status and trends in marine mammals found in the Estuary and Gulf of St. Lawrence and impact of environmental effects.....	28
5.3.4 Key directions in management response development and its implications	30

5.4 Aquatic invasive species	31
5.4.1 Overview	31
5.4.2 Drivers and pressures	31
5.4.3 State and impacts	32
5.4.4 Key directions in management response development for AIS introduction and establishment.....	36
5.5 Impacts of fishing and climate-driven changes in exploited marine populations and communities, with implications for management	36
5.5.1 Overview	36
5.5.2 Drivers and pressures – changes in natural and anthropogenic forcings.....	37
5.5.3 Impact – status and trends in marine species found in the Gulf of St. Lawrence	42
5.5.4 Key directions in management response development to future temperature changes and their implications	49
5.6. Potential impacts of grey seal predation on groundfish populations in the southern Gulf	50
5.6.1 Overview	50
5.6.2 Drivers and pressures – changes in the abundance of seals and the vulnerability of fish	51
5.6.3 Impact – evidence for elevated mortality and resulting enhanced risk of extirpations in large demersal fish	52
5.6.4 Key directions in management response development and their implications.....	55
6. Conclusion	56
7. Acknowledgements	57
8. References	58

LIST OF TABLES

Table 5.2-1.	Experiments suggests that marine organisms respond differently to ocean acidification depending on their physiology and habitat	20
Table 5.4-1.	List of non-indigenous species known to have established populations in marine and brackish waters of the Gulf of St. Lawrence.	32

LIST OF FIGURES

Figure 2-1.	Map of the Lower Estuary and Gulf of St. Lawrence showing the main channels and straits in this Large Ocean Management Area (LOMA)	3
Figure 5.1-1.	Oxygen saturation measured near the bottom at trawl stations during summer groundfish surveys in the Gulf of St. Lawrence, 2004 and 2005.....	12
Figure 5.2-1.	Historical pH measurements in the deep water of the St. Lawrence Estuary with 95% confidence intervals.....	17
Figure 5.2-2.	Average measurements from the August 2006 and July 2007 ship surveys of <i>in situ</i> pH (measured on the total proton scale) and calculated calcite and aragonite saturation states (Ω) throughout the Lower St. Lawrence Estuary and western Gulf of St. Lawrence.....	18
Figure 5.3-1.	Maximum sea-ice area occurring each year (red line) and in early March, and winter air temperature anomaly over the Gulf.....	25
Figure 5.3-2.	Seasonal maximum sea-ice distribution in 2003 (A) and 2010 (B). These are the extremes in volume within the 1969–2011 ice chart record from the Canadian Ice Service.....	26
Figure 5.4-1.	Distribution of six aquatic invasive species in the Gulf of St. Lawrence as of February 2012.....	34
Figure 5.5-1.	Water temperatures in the Gulf of St. Lawrence. May–November SST averaged over the Gulf (1985–2010), completed by a proxy based on April–November air temperature (1945–1984)	38
Figure 5.5-2.	Distribution of landings by functional groups in Northwest Atlantic Fisheries Organization (NAFO) divisions 4RS (northern Gulf) (A) and 4T (southern Gulf including the Estuary) (B)	40
Figure 5.5-3.	Main panel: Southern Gulf of St. Lawrence cod fishing mortality by gear type. Inset panel: total fishing effort for mobile gear (1000 hours) and fixed gear (100 trips) in the southern Gulf.....	41
Figure 5.5-4.	Northern Gulf of St. Lawrence cod fishing mortality by gear type	42
Figure 5.5-5.	Trends in the proportion by number of fish captured in the annual September survey of the southern Gulf that are from species associated with Arctic waters and changes in the September bottom-water temperature for depths 60–120 m	45

Figure 5.5-6.	St. Lawrence system divided into for oceanographic regions	46
Figure 5.5-7.	Illustration of dominant trends revealed by the dynamic factorial analysis (DFA) in the time series of demersal fish species abundance data for the four regions of the GSL	47
Figure 5.5-8.	Sea-surface temperature averaged over one week in 2001, from 8 to 14 August, corresponding to the warmest week recorded over the Magdalen Shallows between 1985 and 2010.....	49
Figure 5.6-1.	Trajectories (mean \pm 95% confidence interval) of the total population for the three grey seal herds in Eastern Canada.....	52
Figure 5.6-2.	Age- or stage-dependent trends in mortality for three southern Gulf of St. Lawrence marine fishes.....	54

LIST OF APPENDICES

Appendix 1.	List of acronyms.....	73
-------------	-----------------------	----

ABSTRACT

Benoît, H. P., Gagné, J. A., Savenkoff, C., Ouellet, P., and Bourassa M.-N. (eds.). 2012. State-of-the-Ocean Report for the Gulf of St. Lawrence Integrated Management (GOSLIM) Area. *Can. Manusc. Rep. Fish. Aquat. Sci.* 2986: ix + 73 pp.

This document is part of an initiative conducted by the Canadian Department of Fisheries and Oceans to report on the ecological “State of the Oceans” (SOTO). It concisely summarizes the most recent scientific information relevant to six key issues that have a considerable impact on the ecosystems of the Estuary and Gulf of St. Lawrence Large Ocean Management Area (LOMA): (1) hypoxia in the deep waters, (2) ocean acidification, (3) changes in seasonal sea-ice cover and its effect on marine mammals, (4) aquatic invasive species, (5) impacts of fishing and climate-driven changes in exploited marine populations and communities, and (6) potential impacts of grey seal predation on groundfish populations. The information is presented following the Drivers Pressures State Impacts and Responses approach (DPSIR) to the identification and management of the environmental effects. Existing reports on the structure, state, and management of the Estuary and Gulf of St. Lawrence LOMA are also reviewed with the aim to highlight the manner in which the present report complements that information. Furthermore, a brief discussion on what should constitute the structure and content of a more effective SOTO report is presented as an explanation for the nature of the present report and as a guide for future SOTO reporting in the LOMA. The report results from a collaboration between ocean scientists and managers in support of integrated management in the St. Lawrence LOMA.

RÉSUMÉ

Benoît, H. P., Gagné, J. A., Savenkoff, C., Ouellet, P., and Bourassa M.-N. (eds.). 2012. State-of-the-Ocean Report for the Gulf of St. Lawrence Integrated Management (GOSLIM) Area. Can. Manuscr. Rep. Fish. Aquat. Sci. 2986: ix + 73 pp.

Ce document s'insère dans une initiative du ministère canadien des Pêches et des Océans visant à décrire la situation écologique de ses océans bordant les côtes canadiennes («State of the Oceans» ou SOTO). Il résume brièvement l'information scientifique la plus récente et pertinente aux six enjeux suivants qui ont une influence considérable sur les écosystèmes de la Zone Étendue de Gestion des Océans (ZEGO) de l'estuaire et du golfe du Saint-Laurent : (1) hypoxie des eaux profondes, (2) l'acidification des océans, (3) changements dans la couverture saisonnière de glace et leurs effets sur les mammifères marins, (4) espèces aquatiques envahissantes, (5) impact de la pêche commerciale et du climat sur les populations et communautés marines et (6) impacts potentiels de la prédation par le phoque gris sur les populations de poissons démersaux. L'information est présentée selon le modèle Force motrice - Pression - État - Impact - Réponse (connu sous l'acronyme anglais « DPSIR ») appliqué à l'identification et à la gestion des impacts environnementaux. Nous discutons également de rapports existants sur la structure, l'état et la gestion de la ZEGO du Saint-Laurent afin de préciser comment le présent rapport les complète. En expliquant l'organisation et le contenu de ce document, nous suggérons brièvement comment de prochains rapports SOTO pourraient être réalisés pour en accroître leur utilité. Ce rapport est le fruit d'une collaboration entre scientifiques et gestionnaires des océans en appui à la gestion intégrée de la ZEGO du Saint-Laurent.

LIST OF CONTRIBUTORS

Maurice Lamontagne Institut (MLI)	Gulf Fisheries Center (GFC)
Chabot, Denis	Benoît, Hugues P.
Chassé, Joël	Cormier, Roland
Fréchet, Alain	Landry, Thomas
Gagné, Jacques A.	Locke, Andrea
Galbraith, Peter S.	Ouellette, Marc
Gilbert, Denis	
Hammill, Mike O.	
Ouellet, Patrick	
Savenkoff, Claude	
Scarratt, Michael	
Starr, Michel	

1. INTRODUCTION

Marine ecosystems worldwide are undergoing changes in their physical, chemical, and biological components. Awareness of these changes has increased dramatically both in the scientific and public spheres. Though broad-scale changes are becoming increasingly publicized, ecosystem-level changes are often not well communicated outside the scientific community. This leaves many people wondering about the present status and changes in the oceans that surround them. What is driving environmental changes? What are the impacts of human activities on particular marine ecosystems? What is the status of these ecosystems, how have they changed, and how are they projected to change? What are our responses to the changes and what are the expected outcomes of the responses? Jointly these questions form the framework of a well structured state-of-the-ocean (SOTO) report.

The Gulf of St. Lawrence is a semi-enclosed basin of the Northwest Atlantic Ocean and is one of five priority Large Ocean Management Areas (LOMA) in Canada. The planning and implementation of the integrated management of human activities within the Gulf ecosystem is undertaken under the Gulf of St. Lawrence Integrated Management (GOSLIM) initiative. As part of this planning process, several reports have been written describing the structure of the Gulf ecosystem as well as general trends in ecosystem components and possible drivers of change (see section 3). Together they serve to answer some, but not all, of the questions posed above. They nonetheless form a firm basis for SOTO reporting, by providing pertinent information in much more detail than would be possible here. Building from this existing published information, this report focusses on particular themes of concern for the Gulf of St. Lawrence, especially in light of the questions that may not have been addressed adequately in the previous reports. These questions concern the drivers of ecosystem changes, projected changes, and examples of consequences for different management responses to these changes.

The report begins with an overview of the Gulf of St. Lawrence ecosystem structure and a presentation of its principal and unique features (section 2).

Section 3 orients the reader to the most relevant sources of information by presenting the recent publications on the status and trends in the Gulf ecosystem and demonstrating how they fit together to provide an understanding of the system and support for integrated management. This section helps to set the context for the current report, which aims to minimize redundancy with existing information.

Section 4 presents the rationale and a description of the structure for SOTO reporting used in this report and proposed for similar future reports. An emphasis is made on reporting concerning issues that touch particular adverse environmental effects that are of interest for integrated oceans management. Likewise, it is argued that reporting should follow a well-established framework for environmental management planning that considers the drivers of changes through to the possible outcomes of alternate responses to the changes.

Finally, in section 5, several themes of particular importance to the state of the Estuary and Gulf ecosystem (EGSL) are explored in some detail following the framework outlined in section 4. The themes considered are hypoxia in the deep waters of the St. Lawrence Estuary, ocean acidification, changes in seasonal sea-ice cover, invasive aquatic species in estuaries and coastal lagoons, climate-driven changes in exploited marine populations and communities, and potential impacts of grey seal predation on groundfish populations. While these do not form an exhaustive list of issues of concern for the Gulf of St. Lawrence, they constitute a tractable list of key issues for which full-cycle reporting (i.e., from drivers to responses) is possible for this report. Furthermore, these themes are important elements of the contextual background to take into consideration while implementing integrated management not only in the Gulf of St. Lawrence, but also in numerous ecosystems worldwide. Additional themes, identified as priority areas in a management plan for GOSLIM, could be added to subsequent reports. These might include important topics for the coastal zone that are also of great management interest but that are not covered here due to current limitations in the nature and amount of compiled information available, the expertise of the authors, or the length of the report. These topics include changes in nutrient loading, water level increase, sedimentation and sediment movement, shoreline development, and the introduction of toxic chemicals.

2. THE ESTUARY AND GULF OF ST. LAWRENCE ECOSYSTEM

With a surface area of over 240 000 km², the Estuary and Gulf of St. Lawrence system represents one of the largest estuarine/marine ecosystems in Canada and in the world (Therriault 1991; see Fig. 2-1). Given a drainage basin that includes the Great Lakes, the St. Lawrence marine ecosystem receives more than half of the freshwater inputs from the Atlantic Coast of North America. The ecosystem is also strongly influenced by ocean and climate variability in the North Atlantic of both Arctic (Labrador Current) and tropical (Gulf Stream) origins. It has the furthest regular annual extension of sea ice in the North Atlantic during winter, yet largely the warmest surface water temperatures in Atlantic Canada during the summer. This unique setting provides the physical and chemical conditions for a highly diverse and productive biological community that is composed of a mixture of estuarine, marine, and sub-tropical to arctic species.

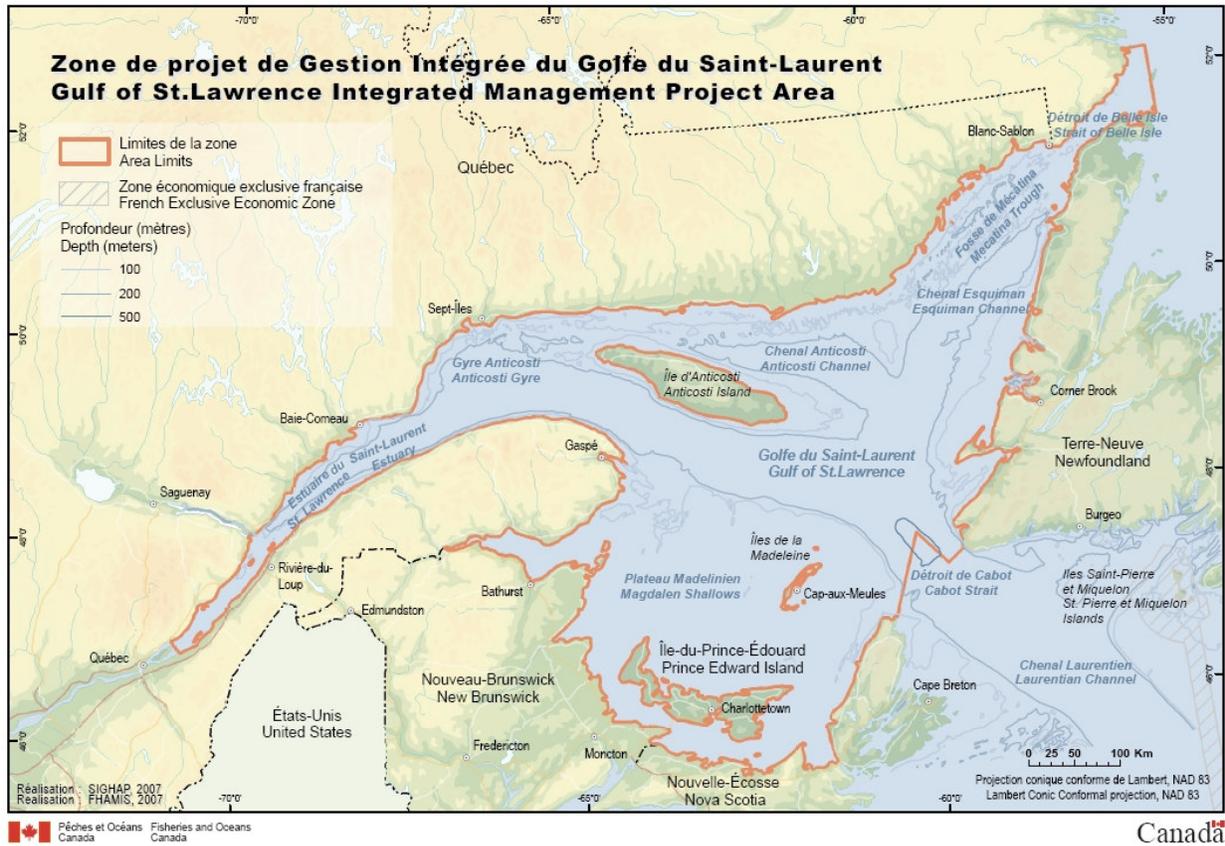


Figure 2-1. Map of the Lower Estuary and Gulf of St. Lawrence showing the main channels and straits in this Large Ocean Management Area (LOMA).

The Estuary and Gulf of St. Lawrence are subjected to a wide variety of human uses and related stressors that can cause adverse environmental effects on physical, chemical, and biological processes occurring in this region. These include but are not limited to:

- Advection and accumulation of contaminants resulting from industry and agriculture, originating from the Great Lakes region and within the St. Lawrence watershed;
- Hypoxic conditions in the deep waters and acidification throughout the water column that have been increasing since the 1930s as a result of climate change and eutrophication in the St. Lawrence Estuary;
- Increasing commercial, ecotouristic, and recreational navigation causing marine mammal disturbance and propagation of aquatic invasive species;
- Hydroelectric development and freshwater input modulations in the Estuary;
- Shoreline development and associated nutrient and sediment loading;
- Biomass removal, ghost fishing, entanglement, and habitat alteration resulting from fisheries;
- A large and expanding shellfish aquaculture industry that has transformed large portions of estuarine and lagoon waters into farms;
- Recent growing interest in oil and gas exploration (seismic surveys) and oceanic energy development (e.g., tides, currents).

The interactions between these different uses or stressors are poorly studied and their cumulative effects on local or global production are not known.

3. EXISTING LITERATURE ON STRUCTURE, STATUS, AND TRENDS FOR THE ST. LAWRENCE ECOSYSTEM

Existing reports on the Gulf of St. Lawrence ecosystem produced in the last 15 years fall broadly into two categories. Reports in the first category generally present a detailed account of the structure of the physical, chemical, and biological components of the system. Emphasis is occasionally placed on processes or components believed to be particularly ecologically or biologically significant. Reports falling into the second category generally present findings on trends in the various ecosystem components based on available monitoring. In both cases, threats to the system are occasionally identified and briefly described, but there is little detailed presentation of evidence for the role of different threats or detailed discussion of possible human responses.

3.1 Reports on ecosystem structure and status

The 2007 report *Estuary and Gulf of St. Lawrence marine ecosystem overview and assessment report* (Dufour and Ouellet 2007) provided arguably one of the most complete and up-to-date overviews of the components, structure, and functioning of the Estuary and Gulf of St. Lawrence ecosystem. The report also provided a preliminary evaluation of the main pressures exerted by

human activities at the ecosystem level and identified populations, species, and geographical areas that are of concern as a result. This report is broadly available; however, the level of technical detail is consistent with a target audience composed largely of experts in marine science and management.

An earlier, slightly less technical yet equally complete overview of components, structure, and functioning of the Estuary and Gulf of St. Lawrence ecosystem was presented in the 1997 report *Marine Environmental Assessment of the Estuary and Gulf of St. Lawrence* (White and Johns 1997). This report also presented a summary of the trends and impacts of chemicals introduced into the ecosystem. With the exception of discussions on trends, the general description of the structure and functioning of the ecosystem remains current. A further simplified summary for the Gulf, targeted at an informed public, was presented in *The Gulf of St. Lawrence – A Unique Ecosystem: The stage for the Gulf of St. Lawrence Integrated Management* (DFO 2005).

As part of the ocean planning process for the Gulf, areas considered to be particularly ecologically and biologically significant were identified (DFO 2007) as were prioritized conservation objectives for integrated management activities within the areas (DFO 2009a). Criteria to identify significant areas included their uniqueness, the degree of aggregation of biota or important ecological processes, and the impacts that constituent features have on species' fitness or success (DFO 2004). The process of identifying the 10 ecologically and biologically significant areas (EBSA) required the compilation of Gulf-scale information on the spatio-temporal distribution and occurrence of concentrations of physical and biological processes and data on biota ranging from phytoplankton to marine mammals (Savenkoff et al. 2007a and references therein). This allowed for the identification of key areas within the Gulf that serve to distinguish the ecosystem from others and that are also prime candidates for an enhanced application of caution in integrated management. Also, the identification process generated various data compilations that represent the state of knowledge for the various ecosystem components. These compilations are readily available from the Canadian Science Advisory Secretariat (<http://www.dfo-mpo.gc.ca/csas-sccs/index.htm>) (see DFO 2007 for the complete list). Because of limits on the compiled information available at the time, the identified ecologically and biologically significant areas were generally limited to mid- and offshore areas (generally deeper than 25-40 m), and there are efforts underway to identify coastal areas that meet the criteria for designation.

As for EBSAs, consistent criteria and guidance for their application have been developed for the identification of ecologically significant species and community properties for which protection should be enhanced (DFO 2006a). These are species whose loss following perturbation would result in ecological consequences that are substantially greater than an equal perturbation of most other species associated with the community in question. Eelgrass *Zostera marina* has been found to meet the criteria for an ecologically significant species (ESS) in the Gulf of St. Lawrence and in other parts of its range (DFO 2009b).

Assessing and managing human impacts on the biological and physical components of the Gulf of St. Lawrence also require a clear understanding of the human dimension in the system. This includes the governance structures, human settlement patterns, and human activities occurring within both the system's watershed and the marine environment. A four-volume social, economic, and cultural overview of the Gulf contains detailed reports for three subregions of the

Gulf—Quebec, Gulf, and Newfoundland and Labrador—as well as a synopsis document (DFO 2011a, b, c, Gaudet and Leger 2011). A 2010 report entitled *Gulf of St. Lawrence: Human Systems Overview Report* provides a similar summary of the region's socio-economic profile but also provides a detailed summary of the governance structure (Alexander et al. 2010).

3.2 Reports on trends

An Ecosystem Status and Trends Report (ESTR) for 25 Canadian ecozones (15 terrestrial, 1 freshwater, and 9 marine) was completed in 2010 as part of Canadian domestic and international commitments (Federal, Provincial and Territorial Governments of Canada 2010). The Estuary and Gulf of St. Lawrence ecosystem was one of the marine ecozones for which there was reporting on condition, trends, drivers, and stressors (DFO 2010). Based on long-term monitoring of various sorts, a detailed report was produced for the ecosystem that presented the most up-to-date information on changes in its physical, chemical, and biological components (Dufour et al. 2010). Because this monitoring has often tended to occur in offshore waters, trends in nearshore waters and in the coastal zone figured less prominently in the report.

Fisheries and Oceans Canada also provides regular reporting on the status and trends of certain ecosystem components via the Canadian Science Advisory Secretariat (CSAS; <http://www.dfo-mpo.gc.ca/csas-sccs/index.htm>). Overview reports on physical, chemical, and biological oceanographic conditions are produced by the Atlantic Zonal Monitoring Program (Pepin et al. 2005) on a regular basis (e.g., Harrison et al. 2006, Harvey and Devine 2009, Galbraith et al. 2010a). Reports on trends in the abundance, distribution, and size composition of populations of various ecosystem components (e.g., fish, invertebrates) based on surveys are produced regularly (e.g., Bourdages et al. 2010, Hurlbut et al. 2010). A number of these species as well as marine mammal species are subject to regular stock/population assessments, which provide a detailed account of trends along with present and projected status (e.g., seals, Atlantic cod, herring, snow crab; all available on the CSAS website).

4. PURPOSE AND STRUCTURE OF THIS REPORT

A state of the oceans report is a key tool in support of the development and evaluation of management strategies as they pertain to Fisheries and Oceans Canada's Strategic Outcome of Sustainable Aquatic Ecosystems, which aims for a management of oceans activities that preserves the ecological health of the oceans while allowing for sustainable use. The nature of state of the oceans (SOTO) reports is evolving worldwide, and Canada is no exception. As we describe in more detail below, this report aims to review the state of our knowledge on the past, current, and anticipated future states of important components or aspects of the Estuary and Gulf of St. Lawrence ecosystem, on the possible causes of ecosystem changes, and, where possible, on the implications of possible alternate management actions. In this respect, this report is largely forward-looking, identifying themes where closer attention or management action may be required.

Management of any environmental issue requires the application of measures (e.g., regulations, policies, programs, best management practices, and stewardship) that are mostly designed to eliminate, control, or mitigate human activities that have the potential of causing negative environmental effects. In some cases, the chosen management measures will be influenced by a need to adapt to broad-scale anthropogenic changes, such as climate change. Good scientific understanding of the probable causes of ecosystem changes through monitoring and scientific investigation of processes as well as a risk-based evaluation of the possible consequences of different management actions are required before effective actions can be undertaken. With time, the implementation of new management actions and accumulation of scientific knowledge will mean that future SOTO reports will increasingly emphasize an important additional dimension to those mentioned above: a review of indicators of how well existing (i.e., EBSA, ESS) and future ecosystem-based management objectives are being achieved.

Below we briefly describe the nature of the questions that motivated the contents of this SOTO report as well as how the remainder of the report will be structured. How this report differs from its predecessors is also briefly examined.

4.1 State of the environmental effects

Section 5 of this report addresses issues that were not fully discussed by earlier reporting for the Estuary and Gulf of St. Lawrence ecosystem. Rather than concentrate on describing status and trends for a suite of indicators for the mid- and offshore portions of the ecosystem, as is already available in Dufour et al. (2010), this report focusses on a limited number of environmental effects (themes) of importance and for which it is possible to address the following questions at least to some extent:

- What is happening (i.e., what are the environmental conditions and trends)?
- Why is the environmental effect happening (i.e., how are human activities and other stressors linked to the issue in question; Can anthropogenic impacts be distinguished from natural variation and processes)?
- Why is the environmental effect significant (i.e., what are the ecological and socioeconomic consequences, is it affecting an ecologically significant area or species)?
- Is the environmental effect sustainable (i.e., are human actions depleting environmental capital and causing deterioration of the ecosystem)?
- What is being done or could be done to mitigate these impacts?
- What are the anticipated direct and indirect effects of possible management actions?

These questions constitute, at least in part, some of the considerations identified by the European Environment Agency and others as being important in guiding the preparation of environmental status reports (EU EEA 2000, Cardoso et al. 2010). Though it was not possible to address at length each of these general questions in each of the themes presented here, these questions were nonetheless important in the selection of themes. The questions can also help identify gaps in our

understanding that could be filled with additional research and study, though this is only briefly discussed in the presentation of the themes.

The choice of themes for this report and the evaluation of adverse environmental effects were guided by the general elements considered by DFO's Ecosystems Management sector when setting management objectives (DFO 2002, DFO 2009c, EU 2010). These elements are the following:

1. Populations of all commercially exploited macroalgae, shellfish, fish, and marine mammals are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.
2. Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
3. Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing geographic and climate conditions.
4. Non-indigenous invasive species introduced by human activities are at levels that do not adversely alter the ecosystem.
5. Human-induced eutrophication is minimized, especially the adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms, and oxygen deficiency in bottom waters.
6. Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.
7. Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.
8. All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity, and at levels capable of ensuring the long-term abundance of the species within the bounds of natural variability and with the retention of their full reproductive capacity.
9. Concentrations of contaminants are at levels not giving rise to adverse pollution effects.
10. Contaminants in fish and other seafood for direct or indirect human consumption do not exceed levels established by legislation or other relevant standards.
11. Properties and quantities of marine litter do not cause harm to the coastal and marine environment.

A characteristic of the report is the focus on specific adverse environmental effects and their possible mitigation, rather than a general discussion on a description of the ecosystem and the intensity of human activities affecting it. It is in this respect that the report builds on the existing literature. The adverse environmental effects considered fall into one or more of six broadly defined classes, though not all of these classes are covered in the present report:

- Alteration or disruption of physical and chemical oceanographic regimes (e.g., shoreline modification, change in the coastal area and current regimes, acidification);
- Alteration, disruption, or destruction of habitat (e.g., loss or fragmentation of physical habitat, hypoxia);

- Alteration, disruption, or destruction of biota (e.g., biomass removals, introduced species);
- Alteration or disruption of nutrient regimes (e.g., eutrophication);
- Alteration or disruption of sediment regimes (e.g., turbidity and smothering of habitat).

Efforts were made in the selection of themes for section 5 such that collectively they cover a broad range of the adverse environmental effects. Though themes related to contaminants and to sediment regimes are not covered here, these would be logical candidates for subsequent reports.

4.2 Driver pressure state impact response (DPSIR) framework

A well-defined and structured analytical framework is desirable when undertaking an integrated environmental assessment as part of a SOTO report given the complexity of the ecosystem and its interactions with society. Several international scientific and development agencies have adopted a driver pressure state impact response (DPSIR) framework for integrated management planning (e.g., Elliott 2002). DPSIR is a general framework for organizing and defining information about the state of the environment and the human uses of it. It guides the assessment from general concepts towards details and helps establish cause–effect relationships between interacting components of social, economic, and ecological systems based on data and indicators. The framework also provides a communication tool for engaging a diverse group of participants in the management response process. The DPSIR framework is used to structure this report and is based on the following elaboration of the definitions and their application (UNEP/GRID-Arendal 2002):

- **Drivers** (or driving forces) are the social, cultural, economic, and regulatory human influences that contribute **pressures** on the environment, such as population growth, marine transportation, agricultural production, fisheries, or tourism. Natural conditions that drive environmental change are also included in the definition.
- **Pressures** are stresses that human activities and natural conditions place on the environment, including the number or load of physical, chemical, or biological products or changes resulting from or produced by the **drivers**. Examples include waste water, sediment and fertilizer runoff, fish catches, aggregate extraction, and the introduction of non-native species.
- The **state** of the environment is considered in terms of contaminant, sediment, nutrient, or hydrographical regimes as well as the condition or health of habitat and biota. Past, present, and anticipated conditions (i.e., trends) are typically of great interest. A key issue when discussing states and trends is establishing cause–effect relationships with the pressures based on the best available science. This includes distinguishing human-induced change from that resulting from natural processes.
- **Impacts** are the biological, economic, and social effects of environmental change. Examples may include algal blooms or adverse changes in marine plants or macro-algal,

water-related human health problems, changes in long-term species distribution and abundance, flooding, seabed destruction, loss in habitats, or genetic disturbances.

- **Responses** are considered as the management measures implemented via regulations, policies, best management practices, standards, or stewardship strategies in response to the environmental situation. Developed and implemented to achieve ecosystem-based management objectives, these may have international, national, or regional applications.

For an integrated assessment to be effective, the relative likelihood of success of different responses at addressing the impacts ultimately needs to be evaluated, though that is not necessarily presented here. The same is true of the risks associated with generating additional impacts on other ecosystem processes or components, or of unintentionally enhancing impacts on the state of the property in question. The degree to which likelihoods of success and risks can be evaluated differs greatly among the themes considered in this report, depending on the available science.

5. STATUS AND TRENDS FOR SOME IMPORTANT THEMES PERTINENT TO THE ST. LAWRENCE ECOSYSTEM

5.1 Hypoxia in the Estuary and Gulf of St. Lawrence (*M. Scarratt MLI, D. Chabot MLI, and D. Gilbert MLI*)

5.1.1 Overview

Hypoxia in marine waters, as in other environments, is most simply described as a shortage of dissolved oxygen (DO). This condition may occur naturally or be exacerbated or even caused by human influences, but in all cases, the processes involved and the resulting environmental stresses are essentially similar. Hypoxia occurs when respiration (including microbial processes) removes oxygen (O₂) from the water faster than it is replenished from the atmosphere or by photosynthesis. This situation may arise as a result of high microbial respiration in deep water and sediments, and may be stimulated by an increased supply of organic material from the surface waters (Levin et al. 2009). Hypoxia is most common in regions where strong stratification of the water column limits vertical mixing and hence reduces the penetration of oxygen into deeper water (Rabalais et al. 2002). Hypoxia is often stimulated by eutrophication that is caused by agricultural runoff or sewage inputs that transport nutrients from the land into the coastal zone (Diaz 2001). Hypoxia may be transient, seasonal, or permanent, depending on the forcing factors (such as eutrophication) and local oceanographic conditions (Rabalais et al. 2010).

Marine waters are considered to be severely hypoxic when the concentration of DO falls below 2 mg L⁻¹ (62.5 µmol L⁻¹) (Diaz 2001), or approximately 20 to 30% of full oxygen saturation, which depends upon the temperature and salinity (Rabalais et al. 2010). The resulting stress imposed on

living organisms depends not only on the actual concentration of DO, but also on the tolerance of each species for low DO levels. In hypoxic waters, marine fauna suffer a variety of impairments, including reduced growth rates, lower reproductive success, and increased mortality, and some of these effects can be observed even under mild hypoxia (30–50% saturation). Severely hypoxic waters have been referred to as “dead zones,” where few macroscopic organisms can exist and commercial species are essentially absent (Rabalais et al. 2002). Marine hypoxia is a growing problem worldwide, with increasing areas of coastal ocean becoming hypoxic in recent decades (Rabalais et al. 2010). In a recent compilation of the literature, Diaz and Rosenberg (2008) estimated that 245,000 km² of the world’s coastal ocean are now affected by severe hypoxia induced by eutrophication.

5.1.2 Drivers and pressures

5.1.2.1 Hypoxia in the deep channels of the Gulf of St. Lawrence

The causes of hypoxia in the deep waters of Estuary and Gulf of St. Lawrence (EGSL) have been described in detail by Gilbert et al. (2005, 2007). Briefly, deep water that is a mix of the oxygen-rich Labrador Current water and of warm and oxygen-poor North Atlantic Central Water (NACW) enters the mouth of the Laurentian Channel. DO levels are already low at the entrance of the Gulf of St. Lawrence (55–65% saturation below 150 m in Cabot Strait). Respiration (bacteria, invertebrates, fishes) further decreases DO levels as the water progresses slowly toward the head of the three main channels: the Laurentian Channel (its head is in the Estuary), the Esquiman Channel, and the Anticosti Channel. Historical and recent data indicate a trend of progressive worsening of hypoxia in the deep waters of the Gulf of St. Lawrence, especially at the heads of the Laurentian, Anticosti, and Esquiman channels (Fig. 5.1-1). The Laurentian Channel shows the lowest oxygen concentrations, generally in the range of 20% saturation (65 $\mu\text{mol L}^{-1}$) in recent years. This level of hypoxia culminates a long decline since the earliest available data (1932), when the bottom waters of the St. Lawrence Estuary averaged 38% oxygen saturation (125 $\mu\text{mol L}^{-1}$). Since the mid 1980s, oxygen saturations appear to have stabilized, with small fluctuations around the 20% level being observed each year (DFO 2008a, Galbraith et al. 2011). Most (up to two-thirds) of the decline in O₂ concentrations since 1932 can be explained by reduced input of water from the Labrador Current and an increase in the contribution of NACW, but the remainder appears to have been caused by increased O₂ demand in the deep water and sediments. This may be the result of increased supply of organic material from the surface, correlated with increased nitrate inputs from agricultural sources via the St. Lawrence River (Gilbert et al. 2007). Increased bacterial respiration associated with a nearly 2°C increase in temperature relative to the 1930s (Genovesi et al. 2011) probably also contributes to the higher O₂ demand.

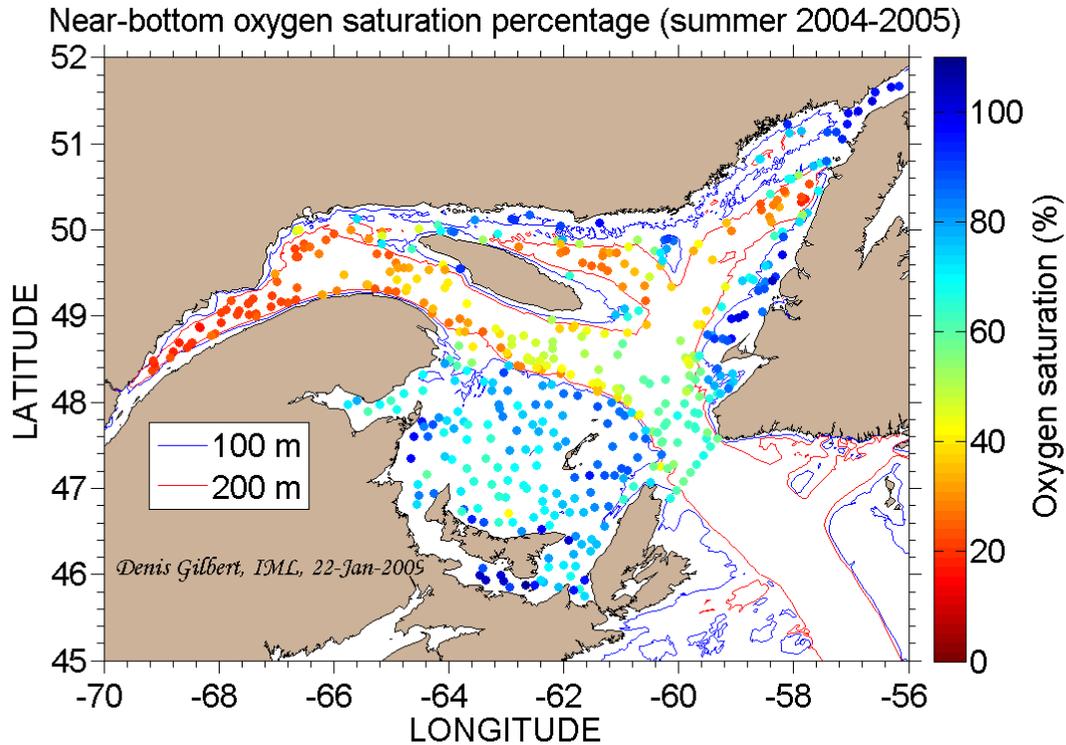


Figure 5.1-1. Oxygen saturation measured near the bottom at trawl stations during summer groundfish surveys in the Gulf of St. Lawrence, 2004 (south and north) and 2005 (northern Gulf only).

5.1.2.2 Shallow-water hypoxia

In addition to the deep-water hypoxia described above, certain shallow-water areas can also be impacted, especially where large nutrient or organic inputs are present. Plante and Courtenay (2008) described severe anoxia in Lamèque Bay in northern New Brunswick, where high nutrient inputs from the effluent water of a seafood processing plant led to excessive macrophyte growth in the bay. The subsequent decay of this organic material led to a seasonal depletion in O_2 concentrations in the water column and sediments, and release of hydrogen sulfide gas (H_2S) that compromised air quality. Similar episodes of seasonal anoxia have been noted in a number of small estuaries in the southern Gulf of St. Lawrence, often as a result of nutrient loading from agricultural runoff (AMEC Earth and Environmental 2007). For the most part, these incidents are confined to limited areas directly affected by the nutrient inputs, and the hypoxia can be reversed if those effluents are controlled and/or treated. This phenomenon was the subject of a DFO regional science workshop organized in Charlottetown by the Canadian Scientific Advisory Secretariat in March 2011 (Workshop on Approaches to Define Nutrient Enrichment Criteria in Southern Gulf of St. Lawrence Estuaries: http://www.dfo-mpo.gc.ca/csas-sccs/Schedule-Horraire/2011/03_08-09-eng.html). The proceedings of this workshop has not yet been published as of 27 Feb 2012.

5.1.3 Impacts of hypoxia on marine resources

Numerous impacts of hypoxia have been documented in a variety of environments including the St. Lawrence system. Responses to hypoxia at molecular, organism, and ecosystem scales have been reviewed in detail by Gray et al. (2002) and Wu (2002). A review by Chabot and Claireaux (2008) focussed on the impacts on fish and used Atlantic cod *Gadus morhua* as a model. Plante et al. (1998) have shown that half of cod die within 96 h of exposure to 21% O₂ saturation. They also found that 5% of cod die within 96 h when exposed to 28% O₂ saturation. Chabot and Dutil (1999) examined the effects of mild hypoxia in cod raised at O₂ saturations varying from 45 to 93%. When DO levels fell below 70% saturation, they found evidence for reduced feeding as well as a reduction in growth rate (both for length and mass) of the fish compared with normoxic controls, in addition to the perturbation of a number of physiological variables.

The main mechanism which affects organisms exposed to mild hypoxia is a reduction of the aerobic scope, that is, the difference between the maximum rate of energy expenditure a fish can produce through aerobic metabolism and the standard metabolic rate, which is the minimal amount of energy a fish must expend to maintain homeostasis (constant physiological state). Oxygen is a limiting factor for metabolism (Fry 1971): the maximum rate of energy expenditure progressively decreases as DO level decreases, whereas the standard metabolic rate remains stable as long as DO is above the critical level for survival. As a result, the difference between the maximum rate and the standard rate (the scope) becomes smaller and the fish must cut energy-demanding activities such as swimming and digestion. Indeed, swimming performance is reduced when cod are exposed to mild hypoxia (Schurmann and Steffensen 1997, Chabot and Dutil 1999, Herbert and Steffensen 2005, Dutil et al. 2007). Declining swimming performance may reduce the ability of fish to capture prey, avoid predators, and escape mobile fishing gear. Chabot and Dutil (1999) suggested that cod may deliberately avoid prolonged exposure to O₂ saturation levels less than 70% and cod avoid almost completely the areas of the EGSL where near-bottom levels of DO are lower than 30% saturation (D'Amours 1993, Chabot 2004, Gilbert et al. 2007). Field data confirmed this, as cod density is directly related to DO in the EGSL (Chabot 2004). The expansion of the hypoxic environment in the St. Lawrence Estuary could thus represent a loss of habitat, depending on seasonal movements of the stock.

Work in progress aims to assess the impact of present levels of near-bottom DO in the EGSL on two other important commercial species, the Greenland halibut *Reinhardtius hippoglossoides* and the northern shrimp *Pandalus borealis*, both of which inhabit deep waters and are therefore exposed to hypoxia. Preliminary work on snow crab *Chionoecetes opilio* suggests that they are quite tolerant of hypoxia (D. Chabot, unpub. data), but in general, very little is known about hypoxic effects on crustacean species in the EGSL. A literature review has shown that overall, crustaceans are as sensitive or more sensitive to hypoxia than fish (Vaquer-Sunyer and Duarte 2008). However both crustaceans and fishes are mobile and they will usually move to avoid hypoxic waters, as long as more oxygenated waters are available within a reasonable range. Vaquer-Sunyer and Duarte (2008) classified molluscs, polychaetes, echinoderms, and cnidarians as generally more hypoxia tolerant. Diaz and Rosenberg (1995) also found polychaetes to be generally hypoxia-tolerant. In the EGSL, Bourque (2009) found that some small polychaetes from the families Spionidae, Oweniidae, and Ampharetidae were more abundant in the Estuary (the most severely hypoxic stations), whereas polychaetes of the family Maldanidae were absent there but were well represented at better oxygenated stations in the EGSL. Even less is known of

the relative hypoxia tolerance of planktonic species in the EGSL. Some plankton species that also inhabit the deep waters of the EGSL have been found in the oxygen minimum zone off British Columbia (< 10% saturation) and can be categorized as hypoxia tolerant, including copepods *Metridia lucens* and chaetognaths *Parasagitta elegans* (Hoos 1970). Gelatinous zooplankton have low oxygen consumption rates and many species are hypoxia tolerant (for a review, see Ekau et al. 2010). The depth distribution of gelatinous zooplankton, their competitors, and their prey in the EGSL will have to be examined to assess to what extent they may outcompete more sensitive planktivorous species or increase the predation rate upon hypoxia-sensitive prey. Copepods spend the winter in deep water as hypoxia-tolerant cysts but otherwise are usually found in normoxic water in the EGSL (Plourde et al. 2002, Descroix et al. 2005).

No published study of the impact of seasonal hypoxia on the fauna of small estuaries in the southern Gulf of St. Lawrence is available. However, studies in other areas have shown that some coastal invertebrates are hypoxia tolerant, including the blue mussel *Mytilus edulis* and softshell clam *Mya arenaria* (Hoos 1973), while others are hypoxia sensitive, such as lobster *Homarus americanus*, rock crab *Cancer irroratus*, and sand shrimp *Crangon septemspinosa* (Miller et al. 2002, Vaquer-Sunyer and Duarte 2008).

Hypoxia also has ecosystem-level effects, including direct loss of habitat or habitat compression, altered trophic relationships, changes in migration patterns, and changes in biodiversity (Wu 2002). For example, based on a photographic survey (Belley et al. 2010), macrobenthic faunal community structure does vary between hypoxic and normoxic areas, with low-O₂-tolerant species dominating in low-O₂ waters. However, macrobenthic species richness is as high in hypoxic as in normoxic regions of the St. Lawrence Estuary, presumably because the oxygen levels are not sufficiently low to exclude many species. In coastal areas, severe shallow-water anoxia can have impacts on human populations, as illustrated in Lamèque Bay, New Brunswick (Plante and Courtenay 2008).

Possible synergisms exist between hypoxia and other stressors such as acidification (Whiteley 2011). Since pH can affect respiration efficiency in fish, the acidic, high carbon dioxide (CO₂) conditions observed in the bottom waters of the Lower St. Lawrence Estuary (see Section 5.2) could compound the effects of hypoxia for a number of species. The predicted long-term decrease in ocean pH due to anthropogenic CO₂ emissions in coming decades could also exacerbate the impact of hypoxia. There have been major changes in ecosystems dynamics in the Lower St. Lawrence Estuary, including abundance, diversity, and activity of benthic organisms (Bourque 2009). The relative contribution of hypoxia, acidification, and other factors remains an open question.

5.1.4 Key directions in management response development

In deep waters, the options for a management response are necessarily limited since deep-water hypoxia in the St. Lawrence is largely a natural phenomenon (Gilbert et al. 2005, 2007). However, efforts to address and limit eutrophication of rivers would help mitigate the risk by reducing the anthropogenic forcing on the system, although the effectiveness of these measures is hard to assess (Stigebrandt and Gustafsson 2007, Kemp et al. 2009). Continued monitoring of ecosystem variables (chemical and physical conditions, primary productivity, trophic web

interactions) as well as potentially vulnerable commercial species should be maintained and ideally enhanced to better understand the impacts of hypoxia before significant changes in the environment occur. In terms of fisheries resources, management practices should be modified to take into account reduced growth rates and possibly reduced survival through direct effects (hypoxia-induced mortality) and indirect effects (e.g., vulnerability to predators and mobile fishing gear) of hypoxia on commercial species. Management of mobile fishing gear should also be adapted to account for the effects of hypoxia on fish distribution, migration, swimming speeds, and possible loss of habitat.

Where hypoxia is clearly caused by excessive nutrient loading, key management responses are more clearly defined and remediation (removing or reducing the source of nutrient loading) has been shown to be effective (Kemp et al. 2009). In the Lamèque Bay case, improved wastewater treatment at the fish processing plant and mechanical removal of macrophyte overgrowth in the bay helped improve oxygenation of the sediment and water column (Plante and Courtenay 2008).

The increasing world population could result in greater nutrient inputs in to coastal waters in the future, and a worsening of eutrophication-driven hypoxia (Kennedy 1990, Justic et al. 1997, Wu 2002), both in the deep channels of the EGSL and in smaller estuaries. Climate warming would have negative impacts on the oxygen budget of both deep and coastal water in the EGSL because of the reduction in oxygen solubility (García and Gordon 1992) and increased respiration rate with increasing temperature (Fry 1971). Factors that affect circulation in the Atlantic Ocean, such as the North Atlantic Oscillation, as well as climate warming may also influence the proportion of Labrador Current water and NACW entering the Laurentian Channel and influence the DO level in the three main channels of the EGSL. Management responses will need to be adapted as new information becomes available and in response to these changing conditions.

5.2 Ocean acidification impacts in the Gulf of St. Lawrence (*M. Scarratt MLI and M. Starr MLI*)

5.2.1 Drivers of ocean acidification

Often referred to as “the other CO₂ problem” (Doney et al. 2009), acidification of marine waters has received considerable attention since the seminal paper of Feely et al. (2004). The phenomenon arises from the dissolution of anthropogenic CO₂ in marine waters, which forces the carbonate equilibrium system to a more acidic state, thus increasing the concentration of hydrogen ions (H⁺) in solution and lowering the pH (Feely et al. 2004). Although large changes in atmospheric CO₂ and ocean pH have occurred naturally throughout geologic history, in the present-day context this process is driven mostly by anthropogenic CO₂ emissions. It is estimated that since pre-industrial times, the ocean has absorbed approximately one third of the CO₂ added to the atmosphere by human industry (Sabine et al. 2004), and the average pH of ocean surface waters has fallen by 0.1 units from its pre-industrial value of about 8.3. Due to the logarithmic scale, this apparently minor change actually represents approximately a 30% increase in acidity. If global emission of CO₂ continues in its present rate, a further drop of at least 0.3 units (100% increase in acidity) is anticipated by the year 2100 (Caldeira and Wickett 2005). Changes of this magnitude and rapidity are unprecedented in at least the past 20 million years (Feely et al. 2004) and possibly since the Paleocene-Eocene Thermal Maximum (PETM), 55 million years ago; this

raises serious concerns about the ability of species and populations to adapt, in turn causing potentially dramatic changes in the structure and function of marine ecosystems.

Ocean acidification is a global threat; however, our cold coastal waters may be particularly affected because of the greater solubility of calcium carbonate and CO₂ at low temperatures. In addition to atmospheric inputs, ocean acidification can also be exacerbated in coastal waters by freshwater inputs, the supply of both organic matter and nutrients from land, and processes in the underlying sediments. Freshwater runoff tends to have higher dissolved CO₂ concentrations and lower pH than ocean water. In waters with no or less frequent contact with the atmosphere, the decomposition of organic matter, contributed from land or from local production, increases CO₂ and decreases pH. In coastal areas, a number of anthropogenic activities can exacerbate acidification, principally those that result in inputs of organic waste or nutrients, or that lead to the formation of acid precipitation (Doney et al. 2007). The impact of acidification is thus expected to be felt first at high latitudes and in hypoxic/anoxic waters, with heightened impact in certain susceptible coastal regions. As a result of these concerns, substantial research effort has been expended in recent years to better understand ocean acidification and its impacts on marine ecosystems.

In the St. Lawrence Estuary, recent oxygen depletion in the bottom waters has been caused by changes in the properties of water masses entering the Gulf and, to some extent, by an increase in respiration associated with the remineralization of organic matter in the water column and sediments. This phenomenon is discussed more thoroughly in section 5.1. The CO₂ produced by respiration accumulates in the deep water, causing it to acidify. Thus the deep waters of the Estuary are acidifying faster than the surface as a result of *in situ* processes not directly related to anthropogenic CO₂ emissions. Similar effects have been described in other coastal areas, for example in the recent paper of Cai et al. (2011).

5.2.2 *Current state of acidification in the Estuary and Gulf of St. Lawrence*

Relatively few published pH data exist for the Estuary and Gulf of St. Lawrence. Mucci et al. (2011) summarized the current state of knowledge using three data sets from 1934–1935, 1979–1980, and 2006–2007. While pH at the surface has not changed significantly since 1934, the pH of bottom waters (170–335 m) has decreased by 0.2 to 0.3 units over 73 years (Fig. 5.2-1), which is similar to the pH change predicted in the open ocean over the next century (Orr et al. 2005). It is important to note, however, that the pH decrease in the St. Lawrence Estuary is not due to atmospheric CO₂ uptake, but also to the effects of CO₂ increase related to the progressive hypoxia of the Estuary (Gilbert et al. 2005, 2007). The most acidic waters of the Estuary are in the deeper layers, where the concentration of oxygen is at a minimum. These low-O₂, high-CO₂ (high acidity) waters have been isolated from the atmosphere for several years, during which time respiration associated with organic matter remineralization has reduced O₂ and increased CO₂.

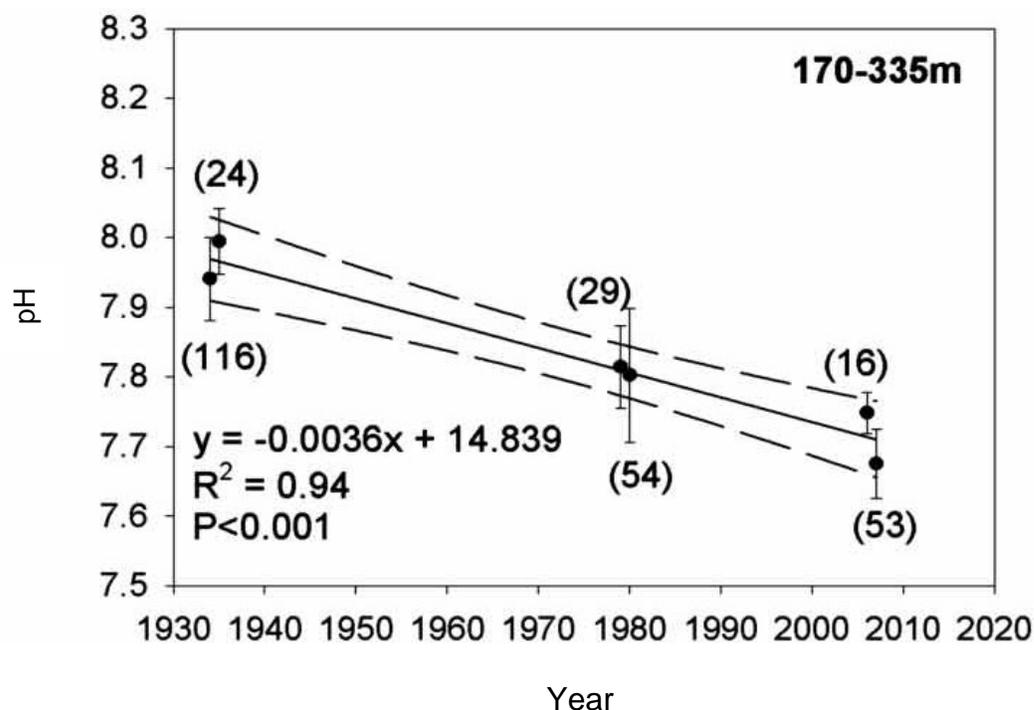


Figure 5.2-1. Historical pH measurements in the deep water of the St. Lawrence Estuary (circles) with 95% confidence intervals. Numbers in parentheses correspond to the number of data points grouped for each year and depth interval. The trend over time and associated uncertainty are shown by the solid and dashed lines, respectively. Data are from May to September measurements averaged for each separate year (from Mucci et al. 2011).

In terms of carbonate chemistry, the net result of acidification in the Estuary is that calcite (the less soluble form of calcium carbonate, found particularly in planktonic coccolithophorids and foraminifera) is now only slightly supersaturated while aragonite (the more soluble form, found particularly in molluscs and corals) is highly undersaturated in the waters below 150 m (Mucci et al. 2011) (Fig. 5.2-2). Complete “saturation” is the maximum concentration of a material, in this case calcium carbonate (calcite or aragonite), which can be dissolved in water under given conditions of temperature, pressure, and salinity. The “saturation state”, or omega (Ω), is the degree to which the water is saturated with calcium carbonate. When $\Omega > 1$, the water is supersaturated and calcium carbonate will precipitate to form a solid. When $\Omega < 1$, the water is undersaturated and solid calcium carbonate will dissolve.

Persistent zones of acidified bottom waters were also recently found at the heads of the Esquiman and Anticosti channels (M. Starr, MLI, unpub. data). These zones also correspond to the hypoxic waters previously documented by Gilbert et al. (2005, 2007). Acidified waters were also found in the shallow southern Gulf of St. Lawrence, but this phenomenon is likely intermittent (M. Starr, MLI, unpub. data). In this latter region, waters undersaturated with respect to aragonite are very close to the surface (40 m). The decomposition of organic matter and nutrient supply from the St. Lawrence Estuary may explain the presence of these CO_2 -rich waters in the shallow southern Gulf.

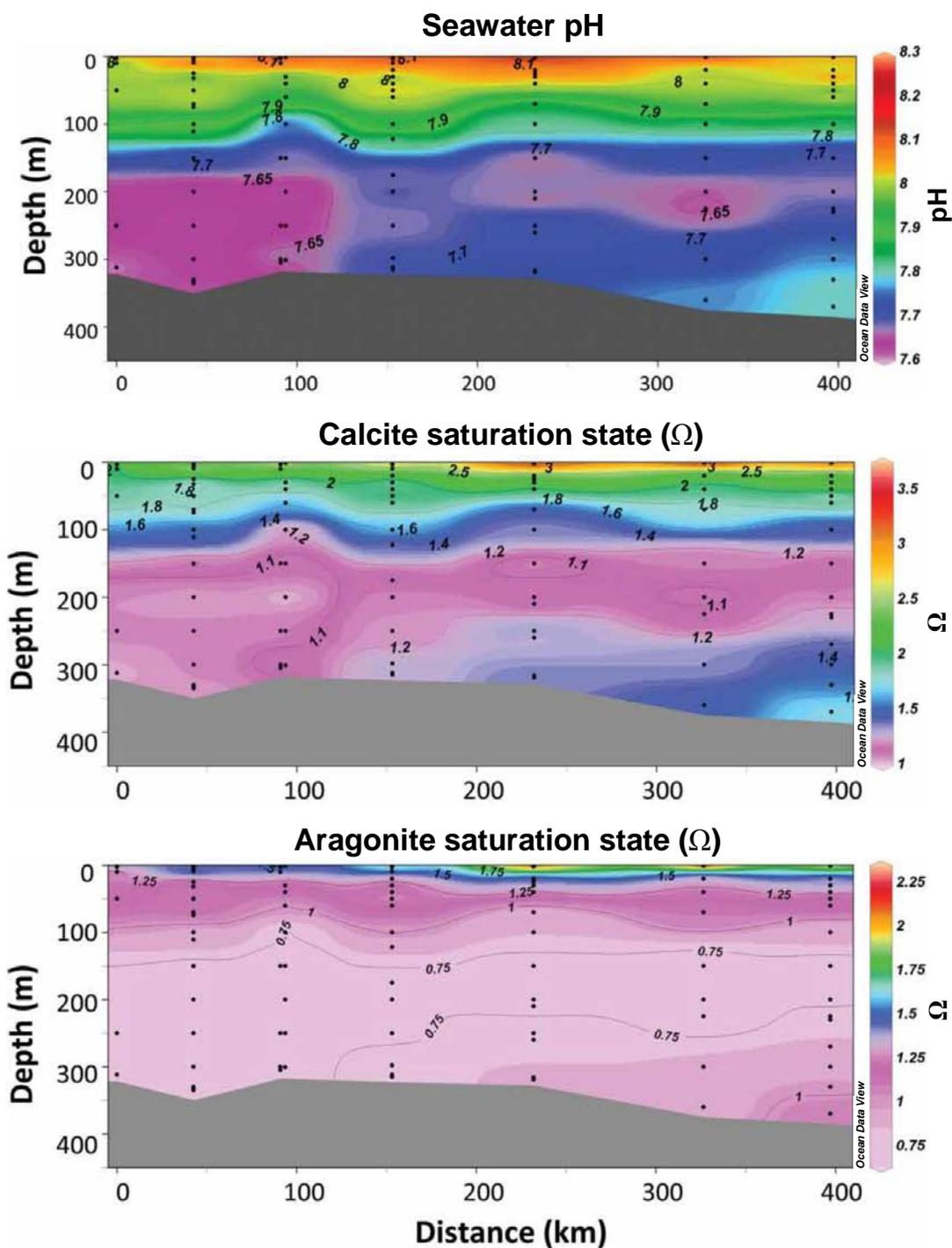


Figure 5.2-2. Average measurements from the August 2006 and July 2007 ship surveys of *in situ* pH (measured on the total proton scale) and calculated calcite and aragonite saturation states (Ω) throughout the Lower St. Lawrence Estuary and western Gulf of St. Lawrence. The two years of observations were merged to produce single contour plots. The horizontal scale indicates distance eastward from the head of the Laurentian Channel towards the Gulf. Values of $\Omega < 1$ indicate that dissolution of calcite or aragonite will occur. See text for explanation. (Fig. adapted from Mucci et al. 2011.)

5.2.3 Impacts of acidification in the Estuary and Gulf of St. Lawrence

The most direct impact of acidification is to organisms that form calcium carbonate shells and skeletons, because acidity increases the solubility of calcium carbonate. These organisms include phytoplankton such as coccolithophores, zooplankton such as pteropods and foraminifera (Riebesell et al. 2000), and other invertebrates (both deep- and shallow- water species) including several species of commercial and ecological importance, such as bivalve molluscs (Riebesell et al. 2000, Miller et al. 2009, Beniash et al. 2010), crustaceans (Kurihara 2008, Whiteley 2011), gastropods, echinoderms (Dupont et al. 2008), and corals (Kleypas and Yates 2009). Differences in the response of these organisms to reduced pH could have a considerable impact on biodiversity and on ecosystem goods and services. Increasing acidity may also alter the chemistry of marine waters, potentially affecting nutrient availability and water toxicity. Impacts may also extend to all marine organisms because pH plays a critical role in mediating physiological processes, including enzymatic and other biochemical reactions (Fabry et al. 2008). Indeed, laboratory experiments have shown that organisms such as dinoflagellates (including toxic or harmful phytoplankton species; Hallegraeff 2010), copepods (Kurihara 2008), and fish species (Ishimatsu et al. 2008), none of which have calcium carbonate shells or skeletons, are also affected by declining pH.

With the exception of the transient presence of acidified waters in the shallow Southern Gulf, acidified waters generally remain deeper than 100 m in the Gulf of St. Lawrence. The St. Lawrence system supports a wealth of bottom-dwelling calcifiers (molluscs, foraminifera, crustaceans, echinoderms, and cnidarians). Many of these are of direct economic importance (e.g., snow crab *Chionoecetes opilio*, northern shrimp *Pandalus borealis*), while others provide food for fish (e.g., pteropods) and marine mammals or contribute to the maintenance of the ecosystem. To date, no direct studies have examined the effects of acidification in the St. Lawrence system, but laboratory and microcosm experiments conducted throughout the world show that many calcifying species exhibit reduced rates of net calcification and even dissolution under conditions such as those currently encountered in the St. Lawrence hypoxic waters (Table 5.2-1). Early developmental stages of many faunal groups appear to be particularly vulnerable to acidified waters (Fabry et al. 2008). Nevertheless, the effects of ocean acidification on marine organisms are more variable and complex than previously thought, as some organisms seem to benefit from acidified conditions (Ries et al. 2009, Fabricius et al. 2011; Table 5.2-1). These effects vary among species and even within species depending on genetics, pre-adaptive mechanisms, and synergistic environmental factors (Doney et al. 2009).

Table 5.2-1. Experiments suggest that marine organisms respond differently to ocean acidification depending on their physiology and habitat (table based on Fig. 3 of Turley et al. 2010, with additional information from Riebesell et al. 1993, Fabry et al. 2008, Iglesias-Rodrigues et al. 2008, Fu et al. 2010, Sun et al. 2011). Pre-industrial ocean pH was about 8.3.

pH	Organisms	Impacts
8.03	Cold-water corals	Reduced calcification
<8.0	Diatoms	Increased growth rate
7.98	Brittlestars	Reduced larval development, growth, and survival
7.94	Toxic diatoms and dinoflagellates	Increased toxicity (domoic acid and karlotoxin)
7.93	Benthic gasteropods and mussels	Reduced growth
7.90	Foraminifera and coccolithophores	Reduced / increased calcification (species-dependent response)
7.90	Sea urchin adults	Reduced growth and survival rates
7.88	Oysters	Reduced growth
7.83	Pteropods	Shell dissolution
7.78	Sea urchin larvae	Reduced development and survival
7.73	Brittlestars	Muscle wastage
7.68	Coral reef fishes	Reduced olfaction

5.2.3.1 Calcification

The undersaturation of aragonite evident in the data of Mucci et al. (2011) suggests that acidification impacts on the biota may already be present in the St. Lawrence system, especially in deeper waters. A number of indigenous taxa produce skeletal structures of aragonite, and there is evidence in the literature of reduced calcification in these and other related species when exposed to acidification.

Such negative effects have been observed in a variety of bivalve species, including *Crassostrea virginica* (Beniash et al. 2010) and *Mytilus edulis* (Gazeau et al. 2007). Acidification may affect larval stages of certain species more seriously than adults since the former contain predominantly aragonite (Gazeau et al. 2010). While anthropogenic acidification is not yet severe enough to have significant effects on a global scale, environments exist where acidification has been demonstrated to limit bivalve reproduction and survival. Feely et al. (2010) reported low pH and consequent aragonite undersaturation as possible contributors to mass mortalities of cultured Pacific oyster *Crassostrea gigas* larvae in Puget Sound. This phenomenon arises when deeper, acidic water rich in CO₂ upwells to the surface in the fjords where the oyster hatcheries are located. The transient acidification observed in the relatively shallow waters of the southern Gulf

of St. Lawrence could lead to an analogous situation, although there are as yet no reports of acidification impacts in that region.

Some crustaceans also produce calcified exoskeletons and are thus susceptible to the dissolution effects caused by ocean acidification. A recent, comprehensive review (Whiteley 2011) compiled evidence for reduced calcification rates in several species including blue crab *Callinectes sapidus*, particularly during the post-moult period, when exposed to CO₂ concentrations 2–10 times higher than pre-industrial levels. The period required for calcification doubled and the carapace was more brittle than normal, which may leave the animals more vulnerable to predation. Similar responses have been observed in intertidal crustaceans including barnacles. Whiteley (2011) also noted that cumulative environmental effects (i.e., acidification combined with hypoxia or high temperature) may be more significant than that of acidification alone.

Coccolithophorid phytoplankton, which occur in the northeastern Gulf of St. Lawrence (Brown and Yoder 1994), produce calcareous skeletons (coccoliths) of calcite. Although calcite is less soluble than aragonite, the coccoliths do not develop properly at sufficiently low pH and may even dissolve. The calcification rate of a natural coccolithophorid assemblage has been shown to decline by up to 83% under high-CO₂ conditions (Riebesell et al. 2000), although the response varies among species (Iglesias-Rodriguez et al. 2008) and within species (Fabry et al. 2008). It has been hypothesized that, given sufficient time, evolutionary pressures may cause coccolithophorid populations to increase their calcification rates to compensate for acidification (Irie et al. 2010), but it is unknown whether such adaptation would occur fast enough to mitigate the anticipated changes and what the additional energetic costs would be. Tyrrell et al. (2008) propose that low calcite saturation states could explain the absence of coccolithophorids from the Baltic Sea compared with other waters at similar latitudes. At present, calcite is still slightly supersaturated in the St. Lawrence (Mucci et al. 2011).

5.2.3.2 Physiological effects, including non-calcifying species

Coccolithophorids may not be the only phytoplankton influenced by acidification. Non-calcifying taxa such as diatoms and dinoflagellates can also be affected, in part due to the increased concentration of CO₂. Riebesell et al. (1993) found that growth rates of large diatoms can be limited by CO₂ availability and speculated that rising atmospheric CO₂ may in fact stimulate diatom production. However, later studies have shown that smaller diatoms can compensate for low CO₂ availability by using biochemical mechanisms to concentrate inorganic carbon (Burkhardt et al. 2001, Rost et al. 2003), and thus their growth rate does not change as a function of CO₂ concentration (Tortell et al. 2006, Rost et al. 2008). In addition, CO₂ availability has been shown in field studies to affect phytoplankton community composition (Tortell et al. 2008) by stimulating overall productivity and favouring the growth of larger chain-forming diatoms over other species.

One factor of potential importance to the Estuary and Gulf of St. Lawrence is the effect of pH on the growth and toxicity of toxic phytoplankton species. In most years, the region is affected by blooms of various toxic species, including dinoflagellates *Alexandrium tamarense* and *Dinophysis* spp. and diatoms *Pseudo-nitzschia* spp., with major blooms occurring on roughly decadal scales. There is at present very little information concerning pH effects on toxic species.

Fu et al. (2010) and Sun et al. (2011) explored the combined effects of CO₂ concentration and phosphate availability on the dinoflagellate *Karlodinium veneficum* and the diatom *Pseudo-nitzschia multiseries*, respectively (note that the latter species occurs in the Southern Gulf of St. Lawrence). In both cases, increased CO₂ concentration stimulated growth and toxin production, especially under conditions of phosphate limitation, although the mechanism behind this is not clear. While the stimulation is not necessarily a direct effect of pH, the toxicity of these species could be enhanced under acidified conditions. In addition to the direct or indirect effects of pH or CO₂ on toxicity, the growth of toxic phytoplankton may become favoured as a result of pH impacts on other species. Hallegraeff (2010) speculated that since most harmful algal species including dinoflagellates (which comprise the majority of known toxic phytoplankton species) lack cellular mechanisms for concentrating CO₂, their growth may be presently limited by CO₂ availability. In future high-CO₂ and low-pH waters, the growth of these toxic species may be stimulated to a greater degree than that of normally more abundant species such as diatoms, which can better regulate their CO₂ uptake.

In contrast with the extensive freshwater literature regarding the impact of acid precipitation on freshwater fish, very little attention has been paid to the effects of acidification on marine fish. In general, marine fishes are thought to be relatively tolerant of increased CO₂ and reduced pH because they have relatively well-developed physiological mechanisms for internal acid–base regulation. Nevertheless, the metabolic cost of this internal regulation remains largely unknown. Extracellular pH can affect oxygen transport and respiration efficiency due to the reduced oxygen affinity with haemoglobin at lower pH (Seibel and Walsh 2003). Furthermore, recent studies have also demonstrated dramatic effects of elevated CO₂ concentrations on sensory and behavioural attributes of some fish species. For example, coral reef fish larvae exposed to CO₂ concentrations anticipated by the year 2100 exhibit impaired ability to identify chemical and olfactory cues that help them locate suitable adult habitat and avoid predators at the end of their pelagic phase (Munday et al. 2009). Juvenile fish also exhibited riskier behaviour in a natural coral-reef habitat, leading to markedly higher rates of mortality. These changes appear to result from disruption of the olfactory mechanism, causing fish to ignore favourable signals and in some cases be attracted to normally unfavourable ones.

Non-calcifying invertebrates may also suffer physiological stress due to acidification, leading to problems including reduced reproductive success. In a review of acidification impacts on a range of invertebrate species, Kurihara (2008) noted effects such as decreased egg production and reduced hatching success in several planktonic crustaceans, including *Acartia* spp., *Calanus finnmarchicus*, *Palaemon pacificus*, and *Euphausia superba* at pH levels ranging from 7.0 to 7.9.

5.2.3.3 Biogeochemistry

Acidification also impacts microbial and geochemical processes, with important consequences for the cycling of nutrients and trace elements in marine waters and sediments. Fundamental processes including carbon and nitrogen cycling are mediated by organisms that are susceptible to the effects of acidification. Exactly how biogeochemical cycles will change in response to acidification is unknown, but potential impacts have been experimentally demonstrated in various environments.

Since phytoplankton are clearly known to be affected by ocean acidification (see above), the carbon cycle is perhaps the most obvious biogeochemical process likely to be impacted. Acidification effects on carbon cycling may occur in several ways, including direct stimulation of carbon fixation (photosynthesis) by higher CO₂ concentrations (Riebesell et al. 1993), reduced export of carbon to deep water by the inhibition of coccolithophorids (Armstrong et al. 2002), or reduced CO₂ efflux from surface waters due to lower calcification rates (Barker et al. 2003). The full implications of acidification on the carbon cycle are not presently clear and are likely to involve contradictory and unanticipated effects (Rost et al. 2008, Riebesell et al. 2009).

The nitrogen cycle is another process that is vulnerable to the effects of acidification. Recent evidence shows that nitrification in natural marine bacterial assemblages is reduced by as much as 38% at pH levels anticipated within a century in the global ocean (Beman et al. 2011) but already present in the St. Lawrence Estuary. Over time, this will slow the nitrogen cycle and reduce the supply of nitrate (a nutrient essential for new primary production) to the surface waters, potentially limiting the productivity of marine ecosystems. In addition, marine nitrification is a major source of the natural greenhouse gas nitrous oxide (N₂O), which plays a significant role in global climate regulation (Nevison et al. 2003). Its production may be limited by acidification but stimulated by other climate changes such as increased temperature and hypoxia, leading to complex interactions and feedback effects. The full implications of these are the subject of current research and modelling efforts (e.g., Schmittner et al. 2008).

5.2.3.4 Interaction of acidification with other variables

Although acidification at the present time is still relatively weak at the surface, it may act synergistically with other factors. For example, upwellings of deep waters at the head of the Laurentian Channel may be increasing the intensity and areal extent of acidified waters. Increased temperature due to climate change is another stressor that is likely to interact with acidification to disrupt oyster reproduction by hindering fertilization and promoting abnormal larval development (Parker et al. 2009). Another example of a potential synergism is the interaction between acidification and low oxygen (hypoxia). Because extracellular pH can adversely affect respiration efficiency in fish, the low oxygen levels and high CO₂ observed in the bottom waters of the Lower St. Lawrence Estuary could act in concert to make respiration more difficult for a number of aerobic organisms including fish (e.g., cod). The abundance of several groups of benthic species (echinoderms, crustaceans) in the deep waters of the Lower St. Lawrence Estuary has declined substantially since the 1970s (Bourque 2009). Whether these major changes in ecosystem dynamics in the Lower St. Lawrence Estuary, including the abundance, community structure, and activity of benthic organisms, are due to hypoxia, acidification, other stressors such as eutrophication and contaminants, or a normal manifestation of foodweb dynamics remains an open question. Integrated, multidisciplinary efforts will be required to quantify the synergistic effects of warming, hypoxia, and acidification on marine fauna and ecosystem structure and function in the St. Lawrence Estuary.

5.2.4 *Key directions in management response development*

In support of global action to reduce CO₂ emissions, there is also a range of regional and local measures that should be undertaken to maintain the health of the St. Lawrence and to reduce the impacts of ocean acidification. The severity of ocean acidification impacts depends and will depend, in part, on the interaction of acidification with other environmental stresses such as over-fishing and land-based sources of pollution (contaminants, inputs of organic waste and nutrients). Recent investigations have already identified regions of the Gulf of St. Lawrence system that are sensitive to acidification, and a special attention to human activities within these areas is one of a possible range of direct management options. In particular, regional efforts to address and limit the eutrophication of rivers and coastal waters that increase the susceptibility of waters to acidification in the St. Lawrence estuarine system, would help mitigate the risk. Continued monitoring of ecosystem variables (chemical and physical conditions, primary productivity, trophic web interactions, species-specific pH sensitivity) as well as potentially vulnerable commercial species should be maintained and ideally enhanced to better understand the impacts of acidification before significant changes in the environment occur.

5.3 **Changes in seasonal sea-ice cover and its effect on marine mammals** (*M.O. Hammill MLI and P. S. Galbraith MLI*)

5.3.1 *Drivers and pressures*

The St. Lawrence Estuary (Estuary) and Gulf (Gulf) represent the most southerly extent of seasonal sea-ice cover in the North Atlantic. Sea ice is typically produced in shallow bays and the northern parts of the Gulf, and drifts towards the Îles-de-la-Madeleine and Cabot Strait during the ice season. Thicker sea ice from the Labrador Shelf also enters the Gulf through the Strait of Belle Isle. Formation begins in the late fall (early to late December depending on the year), and ice cover reaches its greatest extent and volume by early March, sometimes earlier in mild winters.

Winter air temperatures over the Gulf of St. Lawrence are important in driving the formation of the sea-ice cover (Fig. 5.3-1, blue line) and account for 57% of the interannual variability of the seasonal maximum of thicker ice cover area. To form sea ice, the oceanic surface mixed layer must first be cooled to the freezing point (around -1.7°C). Thus a fine balance must exist in atmospheric forcing conditions. Strong winds combined with cold air are required to extract heat from the ocean surface. Yet strong winds may also deepen the mixed layer, increasing the heat content to be removed through the air–water interface in order to cool this now thicker layer to the freezing point. This latter scenario appears to be what occurred during the winter of 2010, resulting in temperatures within the Gulf mixed layer that were about 1°C above freezing. Consequently the mixed layer never reached the freezing point in most parts of the Gulf, preventing the formation of sea ice (Galbraith et al. 2011). The winter air temperature anomaly from Charlottetown, Prince Edward Island, can be used as a proxy for ice cover with some degree of success. At Charlottetown, a winter air temperature warming trend of 1.2°C per century was observed between 1873 and 2009 (Galbraith et al. 2010b), showing that winters have been getting milder over this time scale. However, this proxy loses some of its predictive ability for the area of thicker ice available in early March. Winter average air temperature thus helps to predict the best

possible conditions that the ice cover could reach in the absence of early breakup from storms or thaws.

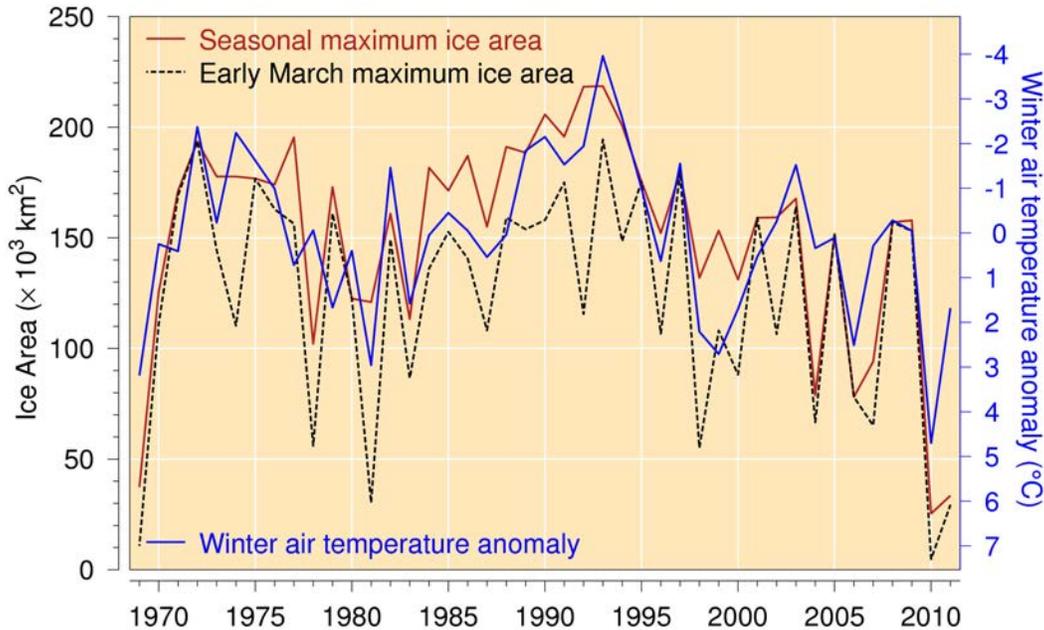


Figure 5.3-1. Maximum sea-ice area occurring each year (red line) and in early March (dashed line) and winter air temperature anomaly over the Gulf (blue line). Thin ice (< 15 cm) and small floes (< 100 m) are excluded from the computed areas. The winter air temperature anomaly is the January–March average at nine stations around the Gulf (adapted from Galbraith et al. 2011). Note the reverse scale for air temperature anomaly.

During the early growth period, the ice cover is fragile and any number of anomalous events such as storms or thaws can prevent the ice cover from reaching its full thickness and coverage potential for the season; it becomes more resilient to breakup as the ice expands and thickens, leaving less open water where waves may build up from wind forcing. This fragility, combined with the variability of winter air temperatures, leads to high interannual variability in the volume of ice formed and in the quality of the ice cover (thickness, floe size, and resilience to weather). In addition to the longer-term trend, shorter-term variability has been observed.

5.3.2 Overview of variability in ice cover, impact and expected changes

Ice cover in the Gulf can be extremely variable. In some years, it may reach thicknesses exceeding 2 m from ice floes rafting one on top of the other, while at other times, particularly in recent years, ice cover may be minimal. For example, Fig. 5.3-2 shows the sea-ice cover distribution on the day when the maximum seasonal volume was reached in 2003 and 2010—the extremes of the 1969–2011 ice chart record from the Canadian Ice Service. In 2003, the

maximum ice extent was reached in March as is typical, and the cover was almost complete, much of it more than 30 cm thick, with a considerable portion more than 50 cm thick. In contrast, ice cover reached its maximum more than a month earlier in 2010, with a cover that was not as extensive and ice that was very thin. These variable conditions have a major impact on human activity in the region, such as the transport of goods from the Atlantic to the continent interior, which requires ice-breaker support to allow safe passage of ships.

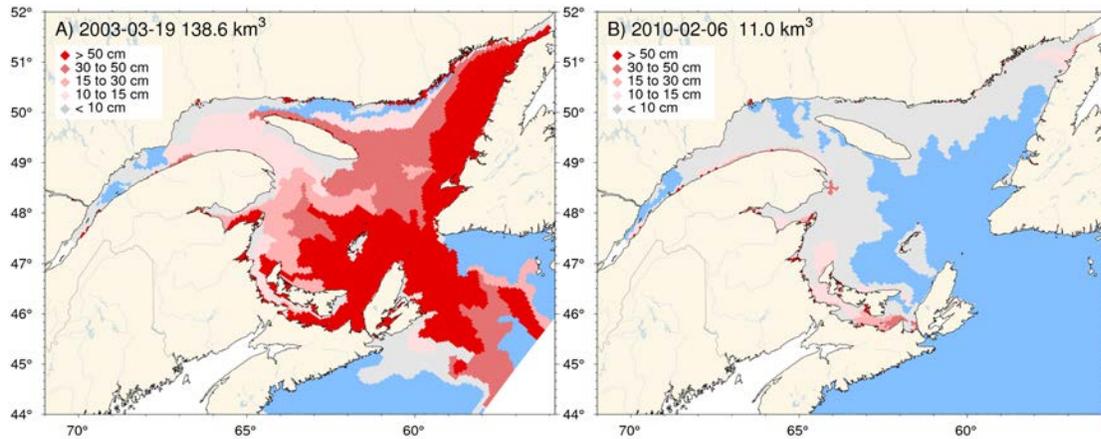


Figure 5.3-2. Seasonal maximum sea-ice distribution in 2003 (A) and 2010 (B). These are the extremes in volume within the 1969–2011 ice chart record from the Canadian Ice Service.

Ice cover could also have an effect on biological activity and especially on marine mammal behaviour or survival. Marine mammals actively dive to forage, but must return to the surface to breathe. Ice cover acts as a physical barrier, which in turn affects seasonal productivity of food resources, limits access to the surface for breathing, and consequently can reduce the available foraging habitat; but it may also provide a platform for resting or reproduction. As many as 16 species of whales (cetaceans) and seven species of seals (pinnipeds) may occur within the Gulf either seasonally or throughout the year (Lesage et al. 2007). Eleven whale species are seasonal residents, but they are largely absent from the Gulf and Estuary during the ice-covered winter months. Among the cetaceans, only the beluga whale *Delphinapterus leucas* is a year-round resident.

Seal life-history strategies are characterized by marine foraging with the requirement for a solid platform for breeding, moulting, and resting. Of the seven species of pinnipeds that occur in the Estuary or Gulf of St. Lawrence, ringed *Phoca hispida* and bearded *Erignathus barbatus* seals are primarily Arctic species. Harbour seal *Phoca vitulina concolor* colonies are found in several areas of the Estuary and Gulf and reside there throughout the year (Boulva and McLaren 1979). Harp *Pagophilus groenlandicus*, hooded *Cystophora cristata*, and to a lesser extent grey *Halichoerus grypus* seals are seasonal visitors to the Gulf / Estuary area. Harp and hooded seals arrive in the Gulf in December from their Arctic summering areas, breed on the pack-ice normally around the Îles-de-la-Madeleine during February–March (harp seals) or in March

(hooded seals), and then most individuals leave the area in April–May (Sergeant 1991). The harp seal is the most abundant pinniped in the North Atlantic, with an estimated population of approximately 8 million animals, which represents a 4.5-fold increase from less than 2 million animals in the early 1970s (Hammill et al. 2011). Hooded seal number around 600,000 animals and do not appear to have changed much since the early 1980s. However, this may reflect in part the fact that monitoring of this stock has been limited. Grey seals are generally associated with the Estuary and Gulf during the summer, with animals exiting the Gulf altogether or moving to the southern Gulf in the fall. Breeding occurs on the pack-ice between Prince Edward Island and Nova Scotia or on small isolated islands in the southern Gulf from December to February (Mansfield and Beck 1977, Lavigne and Hammill 1993, Hammill and Stenson 2011). After the breeding season, animals normally exit the Gulf moving onto the Scotian Shelf during spring. Grey seal abundance has increased considerably, from less than 30,000 animals in eastern Canada in the 1970s to over 350,000 animals in 2010 (Thomas et al. 2011).

The two decades beginning in the mid-1980s and continuing until the late 1990s were characterized by more severe than normal winters of above-average stable ice suitable for pup development and low mortality (Fig. 5.3-1). However, since 1998, the frequency of below-average ice conditions similar to conditions observed during the 1960s and 1970s has increased (Bajzak et al. 2011).

By how much sea-ice cover will be reduced with climate change is unclear. In a recent study, Senneville and Saucier (2007) estimated using numerical modelling that a 2°C increase in air temperature could translate to a decrease of up to 28% in ice cover and 55% in ice volume. While such winter temperature increases might seem far off into the future, the current interannual variability is already of this magnitude (Galbraith et al. 2011). While the much larger anomaly of 4.7°C observed in the winter of 2010 coincided with the almost complete absence of ice in the Gulf (Fig 5.3-2; Galbraith et al. 2011), the anomaly during winter 2011 was only 1.7°C and a similar very low ice cover occurred, much lower than foretold by such models. Dynamics of the fall and early winter mixed layer need to be investigated to fully understand why. Conversely, while climate change can be expected to bring many ice-free winters, interannual variability will likely ensure that ice will be present during at least some of the winters in coming decades.

Ice is used by seals, but the maximum ice extent as an index of quality habitat can be misleading for two reasons. Both the type of ice and the timing of ice formation are important. Generally, animals are associated with relatively thick ice (>30 cm), consisting of medium-sized floes that resist breakup from wave and storm activity (Bajzak et al. 2011). Harp seal pups are on the ice after birth in late February until late March, which should coincide with an ice habitat for pupping. In 2010, there was very little of the thicker “suitable” ice present in the Gulf, as shown by the red area in Fig 5.3-2B. With respect to the timing of suitable ice formation, the maximum cover occurred in early February 2010, about one month earlier than the typical period of maximum cover. By the first week of March 2010 (Fig. 5.3-1, dashed line), the area occupied by the thicker sea ice was much smaller than the seasonal maximum for that year. Since these records began in 1969, the maximum seasonal thick ice cover has been very low in 1969, 2010, and 2011 (Fig. 5.3-1) (Stenson and Hammill 2011). In some other years, in spite of a suitable maximum ice cover, its timing did not coincide with early March, at which time the cover was low and inappropriate as pup habitat. This occurred in 1978 and 1998, but most remarkably in 1981.

5.3.3 *Status and trends in marine mammals found in the Estuary and Gulf of St. Lawrence and impact of environmental effects*

With the exception of St. Lawrence beluga, there is little information available on abundance and trends of whales in the St. Lawrence. Beluga are an Arctic ice-adapted species. Their white colour, absence of a dorsal fin, and thick skin are thought to be adaptations to an ice-covered environment. In other species, the dorsal fin and thinner skin are thought to be more sensitive to ice damage. As outlined above, ice acts as a physical barrier to many marine mammals because they must access the surface to breathe. In the Arctic, bowhead whales *Balaena mysticetus* are able to push up against ice up to 60 cm thick and break it to provide access to the surface. Other cetaceans (e.g., blue *Balaenoptera musculus* and fin *Balaenoptera physalus* whales) are presumably large enough to be capable of breaking relatively thick ice, but their dorsal fins and thin skin are easily damaged by ice, and this weakness would act as a constraint to this behaviour. Many seasonal residents (e.g., fin, blue, and minke *Balaenoptera acutorostrata* whales) remain in the Gulf until December and maybe longer in the ice-free regions over the northern part of the Laurentian Channel as they forage. However, sudden changes in temperature and wind direction can result in ice being pushed against the west coast of Newfoundland and has resulted in fatal blue whale entrapments (Lien et al. 1989). The warming of winter temperatures and decline in ice cover are less likely to create conditions resulting in whale entrapments, which are often fatal. Instead, an increase in winter open-water conditions resulting from the decline in ice-cover will open up new habitat to the whales, increasing the potential for competition for food resources. During the mild, largely ice-free winter of 2011, a large baleen whale was observed in March, off the north coast of Prince Edward Island (M.O. Hammil, personal observation). Other cetaceans may begin to overwinter in the southern Gulf, but this will also be affected by the response of food resources to changing temperature conditions. The reduction of ice cover may also increase exposure to potential predation from killer whales.

All seals in the Gulf make use of ice as a platform for haul out. For harp and hooded seals, ice is an obligate platform, whereas some grey seals may breed on the ice while others breed on land. The more detailed discussion that follows is limited to harp and grey seals, for which we have the best information. These two species may respond to declining ice conditions in one or a combination of five possible ways: (1) breeding females may utilize the ice that is available, even if not preferred or suitable; (2) seals may abandon their normal ice habitat and pup on beaches; (3) seals may move northwards, but remain within the traditional whelping area (e.g., a shift to the northern Gulf) or further north; (4) whelping harp seals may give birth outside of the traditional areas; or (5) the timing of pupping may change as females seek suitable ice.

Harp seal abundance has increased since the 1970s and this is likely due to a combination of reduced hunting and favourable ice-conditions from the early 1970s until the mid-1990s. However, since the mid-1990s, there has been an increase in the frequency of poor ice winters (Fig. 5.3-1), and the population may even have declined slightly due to increased mortality among young of the year (YOY) and also a decline in herd productivity (Bajzak et al. 2011, Hammill et al. 2011). Field observations suggest that whelping normally occurs on ice pans that are extensive and thick enough to persist for some time and resist destruction from storm activity, but at the same time, not so extensive as to prevent adults from entering the water during the

lactation period. Areas preferred by harp seals appear to occur in zones where the ice is retained, or the drift to the open ocean is at least slowed (Bajzak et al. 2011). The YOY need stable ice during nursing as they develop insulative blubber reserves and as a platform for resting for several weeks as they make the physiological transition from a “terrestrial” animal to a marine mammal (Burns et al. 2010). Thus the stability of the ice platform until breakup is also important (Bajzak et al. 2011). During this period, if suitable conditions are not available, then mortality of the YOY is quite high. Harp seals rarely haul out on land. Extremely poor early-March ice conditions have been observed in 1969, 1981, 2010, and 2011 (e.g., Fig. 5.3-1). Conditions in 1969 and 2010 were similar: there was very little ice, and the ice that did form was not suitable for pupping. In both of these years, it appears that most animals, but not all, probably left the Gulf, resulting in a shift in pupping towards the northern limit of their normal breeding range off the Labrador coast. Consequently, although pup mortality was higher than normal, it was perhaps not as severe as initially considered, because fewer animals were born in the Gulf (Sergeant 1991, Stenson and Hammill 2011). However, in 1981 and 2011, apparently good ice was available early in the season, around the time that females would be looking for pupping sites and hauling out on the ice to give birth. Unfortunately, ice-forming conditions did not continue, so suitable thick and stable ice did not develop (Fig. 5.3-1). Consequently, there was considerable ice destruction. Thus in 1981 and 2011, females had their pups in the traditional areas, albeit perhaps a few days later than normal. Mortality appears to have been extremely high in 1981, and we expect that pup mortality was extremely high in 2011 as well (Sergeant 1991, Stenson and Hammill 2011). Therefore, from a harp seal perspective, receding ice cover is likely to result in a shift in the distribution of the breeding population towards the northern Gulf or even outside of the Gulf, with a shift to the Labrador coast or further north. There have been recent reports of harp seals pupping along the west Greenland coast (Rosing-Asvid 2008), but it is not clear if these are not from another herd, the Northwest Atlantic harp seal herd that breeds along the east Greenland coast. Harp seals may continue to feed in the Gulf during early winter, but this region may no longer support a significant breeding colony. As mentioned above, ice cover is likely to be quite variable, and winters with good ice conditions can still be expected, interceded with winters with very little to no ice cover. If harp seals spend less time in the Gulf, this will reduce predation pressure on zooplankton and fish populations (See section 5.6) and help to limit potential competition between harp seals and overwintering cetaceans that may increase their presence in the Gulf.

Grey seal abundance has also increased markedly since the 1970s, but much of this increase has occurred among grey seals breeding on land at Sable Island, while there has been less change in the abundance of grey seals breeding in the Gulf (Thomas et al. 2011). The lower rate of growth of the Gulf component is likely due to several factors including higher mortality rates among animals born on the pack ice and greater removals through government bounty and sampling programs (Hammill and Stenson 2011). Ice-breeding grey seals use the drifting ice in Northumberland Strait between Prince Edward Island and Nova Scotia, where ice drift is slow, particularly in the southeastern portion of the Strait. However, the ice used by grey seals is also thinner and less stable in January–February than is the ice normally preferred by harp seals. Grey seals have their young on land and on the pack-ice in the southern Gulf, but they are not as well adapted as harp seals to an ice-breeding environment, with a weaker mother–pup bond, a greater sensitivity of the young to cold winter temperatures, and greater energy loss when forced to spend time in the water instead of on land during the post-weaning fast (Hansen and Lavigne 1997, Worthy and Lavigne 1987).

For grey seals, ice quality conditions have been much more variable since the early 1980s than they have for harp seals. A strong positive relationship has been observed between pup production estimates and ice conditions, with an increase in mortality related to poor ice conditions (Hammill and Stenson 2011). However, in years where there is no ice, animals will have their young only on land, which may reduce YOY mortality. With an increase in relatively mild winters, we have seen new colonies develop on islands in the southern and the northern Gulf (Anticosti Island; Hammill and Stenson 2011) as well. The milder winters and associated reduction in ice cover will likely allow a northward expansion of breeding animals due to improved survival of pups, warmer temperatures, and increased access to new isolated beaches and islands that were formerly not accessible because of heavy ice conditions. An increase in grey seals will obviously raise their potential impact on groundfish fisheries. This increased impact can be direct through predation, parasites, or damage to catch or fishing gear. Such impacts may limit recovery of groundfish stocks, as has been reported in the southern Gulf (DFO 2011d), or result in additional costs to industry as parasites must be removed from landed fish and gear repaired. Indirect impacts include changes in fish distribution to minimize predation by seals (Harvey et al. 2010).

5.3.4 Key direction in management response development and its implications

The reduction in ice cover will likely increase the amount of time spent in the Gulf and Estuary by seasonally resident cetaceans. Expanding seal and whale populations may increase marine mammal observation opportunities as well. This may require additional management intervention to limit disturbance on marine mammals, particularly those listed under the Species at Risk legislation. There will be increased potential for whale–fishing gear interactions, which may require more intervention to free entrapped whales, as well as changes in gear types and possible modifications to fishery opening–closure dates to reduce interactions. The loss of ice will likely lead to shifts in the distribution of breeding harp seals favouring a shift to the Labrador coast or further north at the expense of breeding in the Gulf. This will have a negative impact on the seal hunting industry in the Gulf. Although harp seals may decline, an expansion in distribution and abundance of grey seals throughout the Gulf can be expected, with an associated increase in fisheries interactions and parasite transmission. Unfortunately, the loss of markets for seal products has limited opportunities to make greater use of this renewable resource. Management actions to reduce seal–fisheries interactions might include gear modifications, culling, and sterility programs if seal numbers are to be reduced. If not, then losses due to predation will have to be considered when setting fishing quotas (see section 5.6).

5.4 Aquatic invasive species (*T. Landry GFC and A. Locke GFC*)

5.4.1 Overview

Non-indigenous, alien, introduced, or exotic are equivalent terms for “species intentionally or accidentally transported and released by humans into an environment or facility with effluent access to open-water or flow-through system outside its present range.” Within this group of species, a non-indigenous species is considered *invasive* when its introduction into an ecosystem may cause harm to the economy, environment, human health, recreation, or public welfare (CCFAM 2004).

Invasion of alien species is considered to be a leading cause of biodiversity loss and a major threat to livelihoods in aquatic ecosystems worldwide (Simberloff and Rejmánek 2011). Increasing trends in the numbers of aquatic invasive species (AIS) have been documented throughout the world in recent decades and are attributed to human activities and environmental changes (Carlton and Geller 1993).

5.4.2 Drivers and pressures

To be considered non-indigenous, a species must be transported by human intervention across a natural barrier to dispersal (e.g., an ocean), and its subsequent dispersal must be either by anthropogenic or natural vectors. The number of introduced species in an ecosystem is a function of both the supply of potential invaders and the susceptibility of the ecosystem to invasion (Crooks et al. 2011). Thus, the drivers and pressures that contribute to the spread of AIS are either (1) human activities that provide vectors (pathways) that increase the probability of AIS propagules being inoculated into an ecosystem, or (2) environmental factors that increase the probability of successful establishment.

Potential vectors related to marine transport in the Gulf of St. Lawrence include international and local commercial shipping and recreational boating. The globalization of trade is one of the main factors associated with the increased introduction of marine AIS worldwide, particularly through shipping vectors (Carlton and Geller 1993, McNeely et al. 2001). More than 80% of global trade is transported by ship (UNCTAD 2011). Faster ships, larger ships, and changes in the pattern of trade have all contributed to increase the risk of species inoculations into new regions. Commercial shipping between ports within the Gulf of St. Lawrence as well as intra- and inter-provincial movements of recreational and fishing vessels can expedite local dispersal of non-indigenous species once inoculated into the Gulf of St. Lawrence by international vectors (Darbyson et al. 2009).

The development of aquaculture is also an important pathway for AIS, with both intentional and unintentional introduction of alien species (McKindsey et al. 2007; see also Table 5.4-1). In the Gulf of St. Lawrence, the mussel aquaculture industry played a pivotal role in the local spread of these AIS before the development of management strategies to reduce the transport of AIS with the movements of seed stock between water bodies and of harvested products to processing plants (Locke et al. 2009).

Invasive species are often generalist species well adapted to fluctuating environmental conditions and rapid colonization of new habitat (Simberloff and Rejmánek 2011). Thus, environmental stressors such as climate change and anthropogenic disturbance of habitat are two factors that can contribute to the successful establishment of AIS. Introduced species may even be more successful in polluted habitats than in unpolluted habitats because of reduced competition by native species (Crooks et al. 2011). Climate change enhances the establishment of non-indigenous species in two ways: by providing suitable environmental conditions and by destabilizing conditions for native species. Range distributions of species associated with climate change may represent expansions of either native or non-indigenous species.

5.4.3 State and impacts

In the Gulf of St. Lawrence, it is estimated that at least 20 non-indigenous aquatic species have become established, and half of these have arrived since 1994 (Table 5.4-1).

If harm was caused to the ecosystem or economy by the earlier arrivals, it was not documented and is now virtually impossible to determine. However, harm has been documented for at least six of the recently arrived species, several of which have become widespread especially in the southern Gulf of St. Lawrence (Fig. 5.4-1).

Table 5.4-1. List of non-indigenous species known to have established populations in marine and brackish waters of the Gulf of St. Lawrence. (Source, A. Locke and J.M. Hanson, unpub. ms.)

Taxonomic name	Common name	Year of first report	Location of first report	Reference
<i>Ostracoblabe</i> sp. (fungus)	European oyster disease	1969	Ellerslie PEI	Newkirk et al. 1995
<i>Fucus serratus</i> (brown alga)		1869	Pictou NS	Edelstein et al. 1973
<i>Stictyosiphon soriferus</i> (brown alga)		1976	West shore of Newfoundland	South and Hooper 1976
<i>Furcellaria lumbricalis</i> (red alga)		1931	Northumberland Strait and PEI	Bell and MacFarlane 1933
<i>Bonnemaisonia hamifera</i> (red alga)	Hookweed or Featherweed	1948	Souris PEI, Bayfield NS	Stephenson and Stephenson 1954; Erskine 1955
<i>Codium fragile fragile</i> (green alga)	Oyster thief	1996	Caribou NS, Malpeque PEI	Garbary et al. 1997

Table 5.4-1. Cont.

Taxonomic name	Common name	Year of first report	Location of first report	Reference
<i>Littorina littorea</i> (gastropod)	Common periwinkle	1840	Pictou NS	Bequaert 1943
<i>Argopecten irradians</i> (bivalve)	Bay scallop	1982 (intentional)	Ellerslie PEI	Townshend and Worms 1983
<i>Penilia avirostris</i> (branchiopod)		2001	Souris PEI	Bernier and Locke 2006
<i>Caprella mutica</i> (amphipod)	Japanese skeleton shrimp	1998	Brudenell PEI	Locke et al. 2007
<i>Carcinus maenas</i> (crab)	European green crab	1994	Aulds Cove NS	Klassen and Locke 2007
<i>Membranipora membranacea</i> (bryozoan)	Coffin box bryozoan	2002	West shore of Newfoundland	C. McKenzie, pers. comm. IML
<i>Styela clava</i> (tunicate)	Clubbed tunicate	1998	Georgetown PEI	ICES 1999
<i>Ciona intestinalis</i> (tunicate)	Vase tunicate	2004	Georgetown PEI	Locke et al. 2007
<i>Botryllus schlosseri</i> (tunicate)	Golden star tunicate	2001 (Note: there were a few occurrences that did not establish permanent populations in the GSL about a century ago; Brunel et al. 1999)	St. Peters PEI	Locke et al. 2007
<i>Botrylloides violaceus</i> (tunicate)	Violet tunicate	2002	Savage Harbour PEI	Locke et al. 2007
<i>Diplosoma listerianum</i> (tunicate)	Compound sea squirt	2009?	Magdalen I., QC	Willis et al. 2011
<i>Salmo trutta</i> (fish)	Brown trout	1930s (intentional introduction)	Pictou County NS	Crossman 1984
<i>Onchorhynchus mykiss</i> (fish)	Rainbow trout	1924 (intentional introduction)	Northumberland Strait PEI	MacCrimmon 1971
Unidentified disease agent	Malpeque disease	1915	Malpeque PEI	Needler 1931



Figure 5.4-1. Distribution of six aquatic invasive species in the Gulf of St. Lawrence as of February 2012. (Source: R. Bernier and DFO National Aquatic Invasive Species Database).

Since 1998, four new tunicate species have become established in the Gulf of St. Lawrence: clubbed tunicate *Styela clava*, vase tunicate *Ciona intestinalis*, violet tunicate *Botrylloides violaceus*, and golden star tunicate *Botryllus schlosseri* (Fig. 5.4-1). Another tunicate species was recently reported from the Îles-de-la-Madeleine: the compound sea squirt, *Diplosoma listerianum*. The full and long-term ecosystem impacts of tunicate infestations have yet to be determined. The most commonly reported impact in the Gulf of St. Lawrence is an economic one resulting from the increased weight of tunicates growing on mussel socks, farm structures, and equipment used in mussel aquaculture, which in turn leads to increased handling costs and loss of mussels that fall off the socks (Locke et al. 2007, Ramsay et al. 2009).

The green crab *Carcinus maenas* is another important AIS that has recently invaded the Gulf of St. Lawrence (Fig. 5.4-1e). This omnivorous species is an ecosystem engineer, known worldwide for its severe impacts on a wide variety of prey, especially mollusc species. Virtually all nearshore benthic biota may be affected through predation or competition, and habitat may be damaged and modified while the crab is digging for prey (Klassen and Locke 2007). The recent invasion of the green crab in the marine protected area of Basin Head, PEI, is being investigated as a possible cause of the decline of a unique type of Irish moss that is found nowhere else in the world.

The algae *Codium fragile fragile* has a more widespread impact in the marine ecosystem, affecting both coastal and deep-water habitats (Garbary et al. 1997). In the coastal waters, *Codium* (commonly known as the oyster thief) can have a significant impact on shellfish beds and their key ecological roles in pelagic–benthic coupling and habitat structure. In some coastal areas, however, this invasive alga has been reported to increase productivity, both in terms of diversity and abundance (Drouin et al. 2011). In deeper waters, its impact is mainly as a competitor to the native kelp forests, which are important habitats for juvenile fish and invertebrates because they provide food and shelter from predators. These kelp forests are commonly grazed by sea urchins, leaving the sea floor barrens for eventual re-colonization and re-growth by native kelp species. However, the introduction of *Codium* can lead to the invasion of these urchin barrens, replacing the kelp beds.

The estimates of non-indigenous species in the Gulf of St. Lawrence are very conservative because the investigation of non-indigenous species has been focussed primarily in very shallow coastal environments and estuaries. Which non-indigenous species may have become established in deep benthic habitats, and the role that they may play in ongoing community changes (see section 5.2) relative to other stressors, is difficult to assess given our current lack of knowledge of benthic diversity.

AIS are sometimes described as “biological pollution,” but unlike chemical contaminants, the pollution worsens over time without additional inputs as AIS reproduce and disperse from the original point of introduction (Simberloff and Rejmánek 2011). AIS are therefore considered a major threat to ecosystem health and the sustainability of the aquaculture and fishing industries around the world. In coastal ecosystems, the negative impact of AIS on keystone species, such as oysters and eelgrass, has the potential to lead to significant loss in productivity through the disruption of microscale and mesoscale spatial patterns in trophic relationships. By disturbing the ecosystem, an initial AIS infestation can also facilitate the establishment of subsequent new AIS (Locke et al. 2007).

5.4.4 *Key directions in management response development for AIS introduction and establishment*

Management strategies for the prevention of invasive species should address both the propagule pressure of species via vectors and the conditions of establishment (Crooks et al. 2011).

In 2005, DFO launched its national aquatic invasive species program based on “a Canadian Action Plan to Address the Threat of Aquatic Invasive Species.” The program has two main goals: (1) to control the pathways by which AIS enter into Canadian waters and (2) to control the spread of existing AIS along the Canadian coast. More specifically, the three main objectives of the program are:

1. Prevention – Management of invasion pathways through the development of policies and regulations based on research and risk assessments.
2. Early detection – Development and coordination of national surveillance and monitoring networks for high-risk locations and pathways of introduction.
3. Rapid response – Development of regulatory programs, including the supporting policy framework, for the collaborative management of AIS with the provinces and territories.

Rapid response may include eradication, containing the AIS within a given area, suppressing population abundance of the AIS to slow its spread, suppressing population abundance below an economic or ecological threshold, or learning to live with the problems caused by the species (Locke et al. 2010). Since the establishment of the AIS program, an increased awareness of the risk and impact of introducing or spreading alien invasive species has contributed to the development of regulatory and management programs to control and mitigate the effect of existing and potential AIS. For example, Canada’s National Code on Introductions and Transfers of Aquatic Organisms (2003) has been adapted to minimize dispersal of tunicates with aquaculture and fisheries products (Locke et al. 2009).

Policies and programs to support management of AIS in Canada are currently under development. Pathways and high-risk AIS have been identified, and monitoring efforts provide critical information for the management of AIS. Risk assessments led by the Centre of Expertise for Aquatic Risk Assessment (Fisheries and Oceans Canada, Burlington, ON) help to identify potential threats to the Gulf of St. Lawrence and other water bodies.

5.5 Impacts of fishing and climate-driven changes in exploited marine populations and communities, with implications for management (*H.P. Benoît GFC, C. Savenkoff MLI, P. Ouellet MLI, P. S. Galbraith MLI, J. Chassé MLI, and A. Fréchet MLI*)

5.5.1 *Overview*

Fishing is generally considered a major contributor to changes in the structure and functioning of exploited marine communities (Sinclair and Murawski 1997, Jackson et al. 2001, Mullan et al. 2005). Fishing impacts can be direct, such as the reduction of targeted and incidentally captured populations and truncations in their age and size composition, or indirect via the alteration of foodweb structure (e.g., Bianchi et al. 2000, Link and Garrison 2002, Frank et al. 2005). Changes

in ocean climate also contribute to changes in marine populations and communities, both directly and indirectly. For example, ocean temperatures can impact survival and growth rates (e.g., Attrill and Power 2002, Beaugrand et al. 2003) as well as the availability of preferred and tolerated thermal habitats (e.g., Marsh et al. 1999, Perry et al. 2005, Dulvy et al. 2008). As such, the harvest rates that are sustainable may vary with changes in climate and therefore stock productivity (e.g., Bennett et al. 2004, Rose 2004). Furthermore, the effects of fishing can exacerbate effects of temperature changes by decreasing stock resilience or by increasing variability in abundance and therefore the risks of collapse (Hsieh et al. 2006, Mora et al. 2007, Anderson et al. 2008).

Much of the above description typifies our understanding of the changes that have occurred in the Gulf over the past decades, as is described below. Both north and south of the Laurentian Channel, fisheries aimed mainly on groundfish have led to the collapse of a number of fish stocks, many of which have failed to recover despite decades of considerably reduced fishing. Decreased stock productivity, in some instances climate-related, contributed to worsening these trends. Yet for other species, mostly invertebrates, favourable environmental conditions have contributed to strong stock productivity. Periods of sustained temperature changes led to shifts in species distribution and fish assemblage composition. Looking forward, there is a pressing need to understand how changes in ocean climate affect the exploited marine taxa of the Gulf and their ecological interactions, so that fisheries may be undertaken sustainably as ocean climate conditions change as part of a warming world.

5.5.2 Drivers and pressures – changes in natural and anthropogenic forcings

In the North Atlantic, large-scale spatial patterns of oceanographic variability (temperature and salinity) are related to sustained periods of weak and strong meteorological forcing represented by the winter North Atlantic Oscillation (NAO) index (Hurrell et al. 2003, Petrie 2007). The NAO is an index of the relative strengths of atmospheric pressures over Iceland and the Azores. During periods of negative NAO anomalies, warm, salty conditions prevail in the bottom waters of the Gulf of St. Lawrence, though these sorts of relationships appear to be changing (Polyakova et al. 2006). Nonetheless, changes in the NAO and other local climatic forcing during the past four decades have led to profound changes in water temperatures in the Gulf.

During the summer, the Gulf is typified by three depth-dependent water temperature layers: a warm relatively fresh surface layer, a cold intermediate layer (CIL) ranging roughly between 50 and 150 m with temperatures ranging from $<0^{\circ}\text{C}$ – 2°C (e.g., found on the bottom of the Magdalen Shallows), and a warmer salty layer (4°C – 6°C) covering areas deeper than 200 m (i.e., the main Laurentian Channel and branching Esquiman and Anticosti channels of the northern Gulf). The exception concerning the deeper layer is Mécatina Trough, where much colder (-1.8°C to 1.6°C), fresher (32.2 to 33.2), well-oxygenated waters occupy the bottom (Galbraith et al. 2011) after winter inflows of Labrador Shelf waters through the Strait of Belle Isle (Galbraith 2006). During the fall and winter, the surface layer cools and merges with the CIL, renewing it for the following summer with what are, by the end of winter, near-freezing waters ($< -1^{\circ}\text{C}$) that cover the shallower areas of the Gulf including most of the Magdalen Shallows. Based on water depth and their intersection with the sea floor, these water layers contribute greatly to defining ecologically distinct regions within the Gulf ecosystem (Fig. 2-1). There have been divergent trends in water

temperatures in these layers since monitoring began in the mid 20th century (Fig. 5.5-1). Surface water temperatures during ice-free months have followed a strong warming trend of 1.5°C since 1985 (Fig. 5.5-1, red line; Drinkwater and Gilbert 2004, Galbraith et al. 2011); this is part of a weaker long-term trend correlated with spring-to-fall air temperatures that have increased by 0.8°C per century since 1873 (Galbraith et al. 2011). In contrast, temperatures in the CIL went from being exceptionally warm during the late 1960s and early 1980s, to very cold from 1986 to 1998 (Fig. 5.5-1, blue line). Recent conditions have been closer to normal. The temperature of deep water masses in the main channels of the Gulf are not affected by local atmospheric conditions or exchanges with the surface layer within the Gulf. Rather, conditions found at the mouth of the Laurentian Channel are slowly advected into the Gulf towards the St. Lawrence Estuary (and the heads of Esquiman and Anticosti channels) by estuarine circulation. Temperatures at 200 to 300 m depth were relatively cold from at least the mid 1940s until the 1970s, and generally warmer thereafter except for short periods such as the early 1990s (Fig. 5.5-1, green lines).

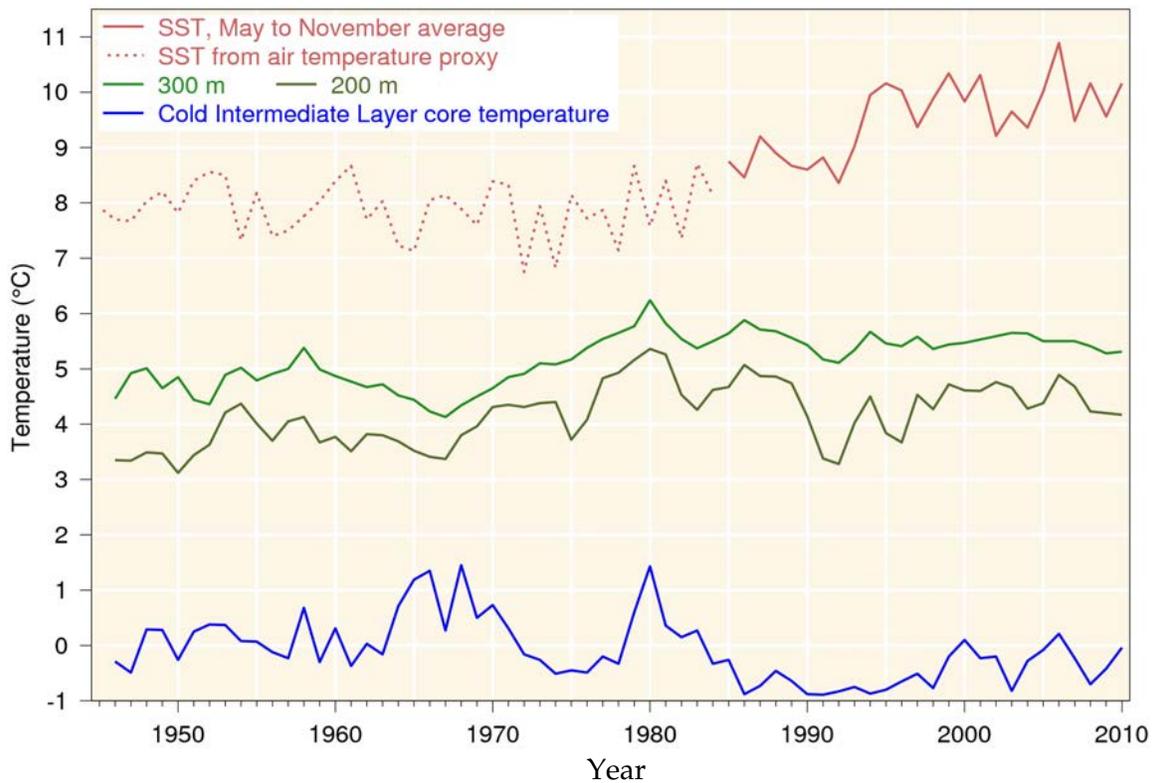


Figure 5.5-1. Water temperatures in the Gulf of St. Lawrence. May–November SST averaged over the Gulf (1985–2010, red line), completed by a proxy based on April–November air temperature (1945–1984, red dashed line). Layer-averaged temperature for the Gulf of St. Lawrence at 200 and 300 m (green lines). Cold intermediate layer minimum temperature index in the Gulf of St. Lawrence (blue line). SST from Galbraith et al. (2012) and other time series from Galbraith et al. (2011).

The main economic activity in the Gulf affecting ecosystem trophic structure is the commercial fishery. Historically, the largest fisheries were directed to groundfish: cod *Gadus morhua*, redfish *Sebastes* spp., witch flounder *Glyptocephalus cynoglossus*, Greenland halibut *Reinhardtius hippoglossoides*, and Atlantic halibut *Hippoglossus hippoglossus* in the northern Gulf; cod, American plaice *Hippoglossoides platessoides*, white hake *Urophycis tenuis*, and Atlantic halibut in the south (Fig. 5.5-2). There have also been important fisheries for pelagic fish, most notably Atlantic herring *Clupea harengus* but also Atlantic mackerel *Scomber scombrus*. Landings of groundfish in the Gulf during the 1970s–1980s were around 180,000 tonnes (t) annually. Following the collapse of northern and southern Gulf cod stocks as well as redfish, white hake, and other demersal fish in the early to mid 1990s, fishing effort and groundfish landings have declined dramatically. In recent years, annual landings of groundfish in the Gulf have varied around 14,000 t and have been composed largely of cod, Greenland halibut, and witch flounder. Concurrent with these declines has been an increase in landings of numerous high value invertebrate fisheries such as snow crab *Chionoecetes opilio*, northern shrimp *Pandalus borealis*, and lobster *Homarus americanus*. Invertebrate landings increased from 48,000 t in the 1970s–1980s to around 123,000 t in the 2000s. For snow crab, there is ongoing debate about the relative roles of population change and increased fishing effort in explaining increased catches. For shrimp, it is clearer that increases in landings have largely been driven by increases in abundance, though fishing effort has also increased. While the inverse pattern in groundfish and invertebrate landings may reflect, in part, release from predation by groundfish in the case of shrimp (Worm and Myers 2003), there is less support for this hypothesis for snow crab and lobster (e.g., Hanson and Lanteigne 2000, Chabot et al. 2008). Since the mid 1980s, landings of pelagic fish have varied around an average of 109,000 t.

Leading up to the groundfish collapse, fishing effort and therefore mortality reached record highs (Fig. 5.5-3). Fishing is widely considered the principal factor leading to the collapse or serious decline of the many groundfish species of the Gulf. However, the high exploitation occurred at a time of low stock productivity (e.g., cod; see below), which likely precipitated the declines from which no population has fully recovered and some continue to decline (e.g., southern Gulf groundfish; see section 5.6). For the northern Gulf cod (NAFO divisions 3Pn, 4RS), there were two moratorium periods, a first one from 1994 to 1996 and a second in 2003 (Fig. 5.5-4). Aside from the very high values of fishing mortality in 1992 and 1993, the average fishing mortality of the series has been around twice the target fishing mortality for long-term sustainability. During the past two decades, this has occurred despite the fact that the mature biomass has been well below the limit reference point for the stock, i.e., the level considered to be undesirable and which management action should try to avoid having the stock fall below (Duplisea and Fréchet 2011). The dominant fishing method used in the northern Gulf cod fishery before the moratorium of 1994 was mobile gear (side and stern trawlers and seines). Since the reopening in 1997, this stock is the only cod stock in eastern Canada to be caught by fixed gear only (hand lines, longlines, and gillnets). Because of the small quotas, the mobile gear fleet has been redirected to other fisheries, mostly shrimp. In contrast, population abundance and landings of invertebrate species have increased. As discussed below, a number of these changes in productivity may have had an environmental influence.

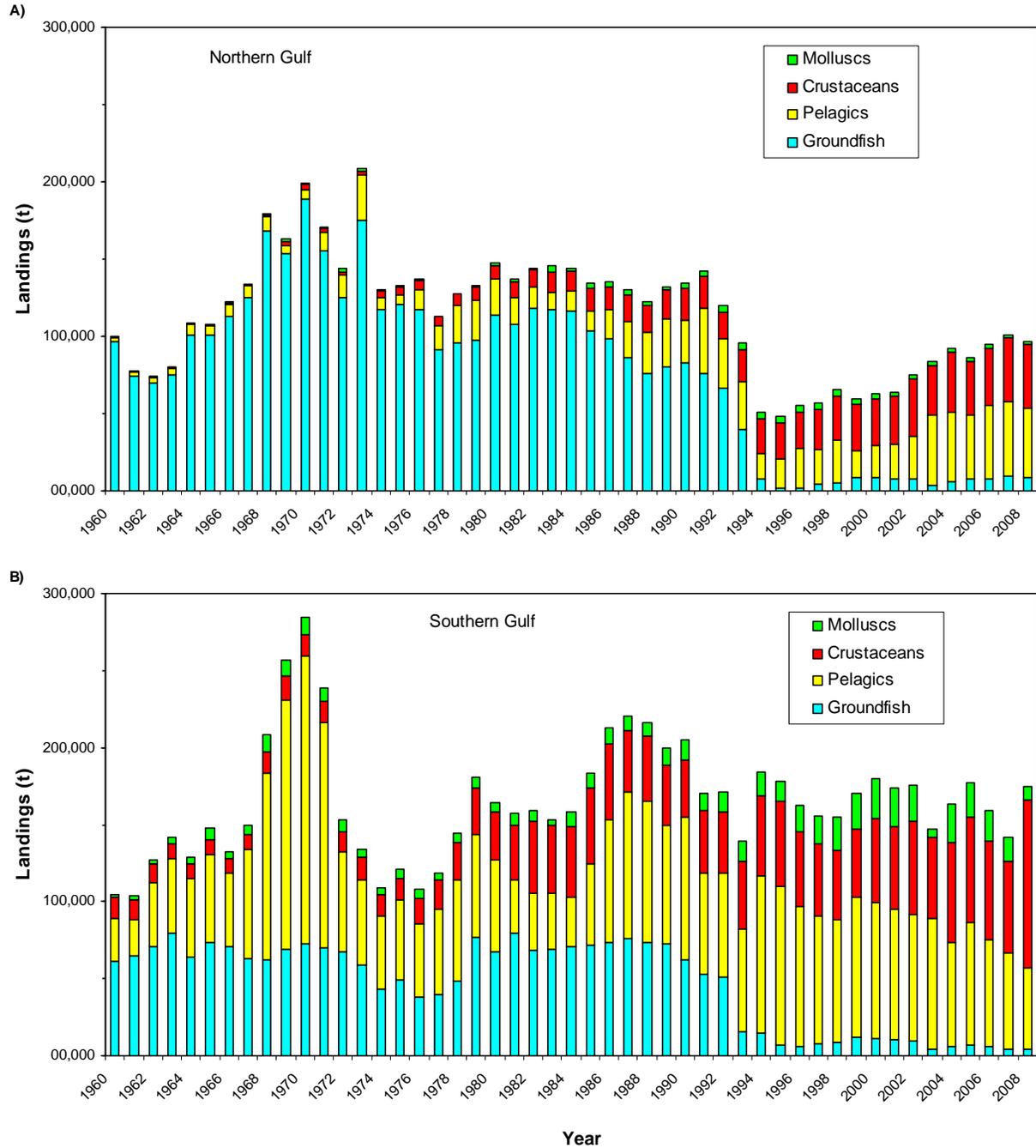


Figure 5.5-2. Distribution of landings by functional groups in the Northwest Atlantic Fisheries Organization (NAFO) divisions 4RS (northern Gulf) (A) and 4T (southern Gulf including the Estuary) (B). NAFO divisions 4RS and 4T are used to compile statistics and regulate fisheries in the Northwest Atlantic.

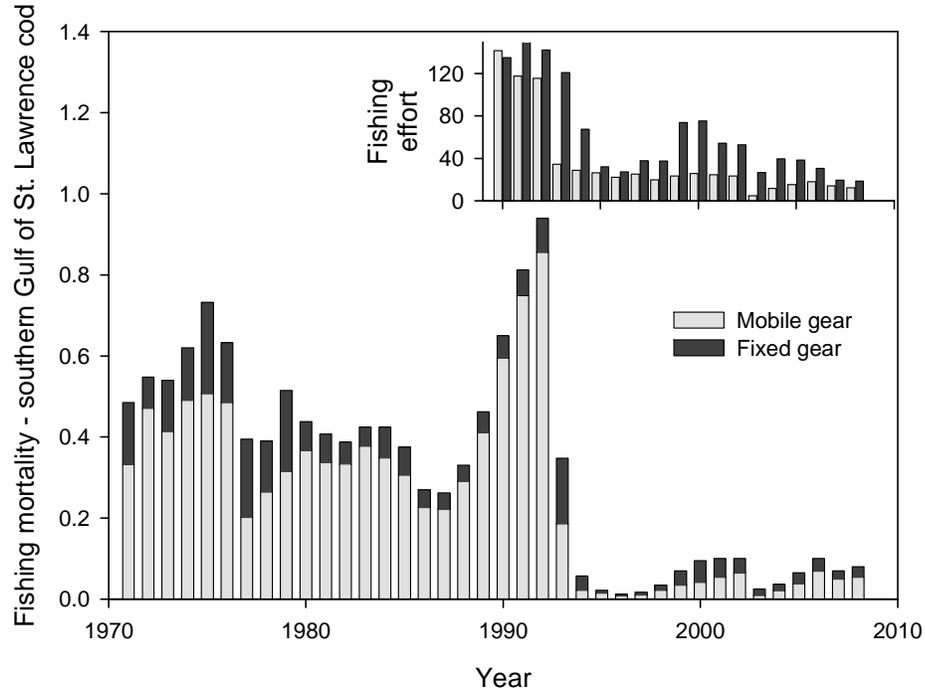


Figure 5.5-3. Main panel: Southern Gulf of St. Lawrence cod fishing mortality rate by gear type. Fishing mortality (F) is dimensionless (instantaneous mortality rate) and can be used to calculate annual mortality rate (as $1 - e^{-F}$, according to Ricker 1980). Inset panel: total fishing effort for mobile gear (1000 hours) and fixed gear (100 trips) in the southern Gulf. Because cod is the principal groundfish species fished, trends in fishing mortality provide an index for fishing effort in the area.

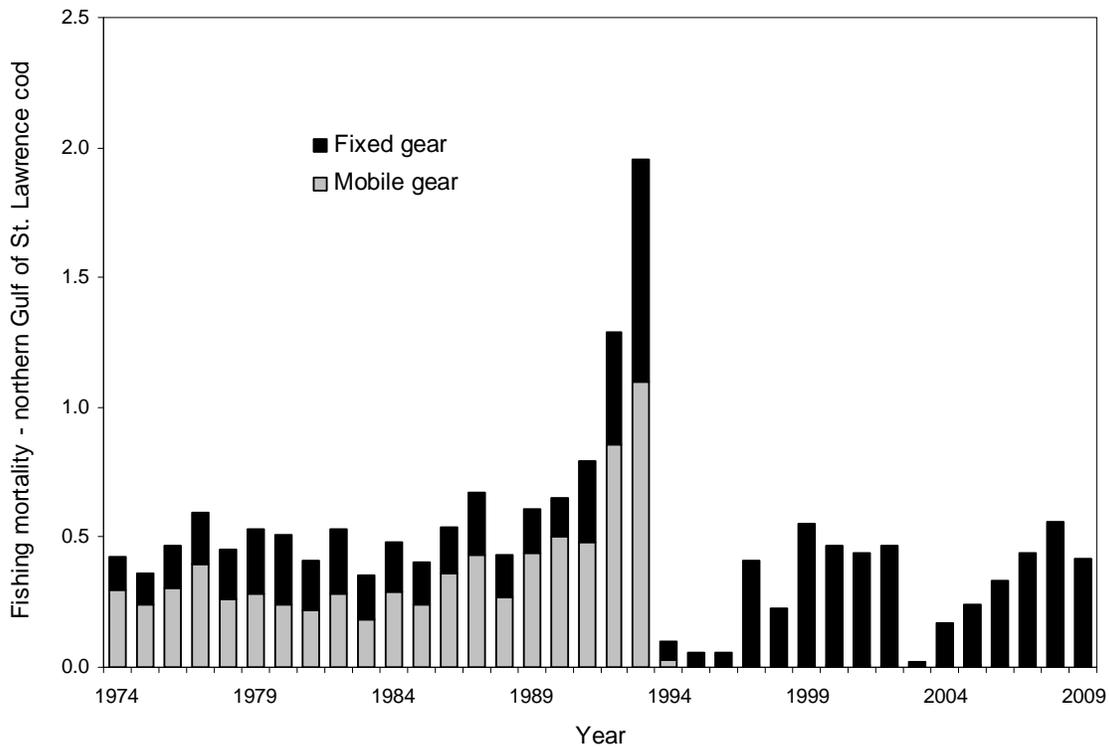


Figure 5.5-4. Northern Gulf of St. Lawrence cod fishing mortality rate by gear type.

5.5.3 Impact - status and trends in marine species found in the Gulf of St. Lawrence

The biomass structures of both the northern and southern Gulf ecosystems shifted dramatically from one dominated by large groundfish predators (e.g., Atlantic cod, redfish, white hake) and small-bodied forage species (capelin *Mallotus villosus*, mackerel, herring, northern shrimp) in the 1980s to one now dominated only by small-bodied forage species (Savenkoff et al. 2007b, c, Benoît and Swain 2008). Following the collapse of larger groundfish and the ensuing predation release, several small-bodied forage species increased considerably in abundance (e.g., daubed shanny *Leptoclinus maculate*, hookear sculpins *Artediellus* ssp., northern shrimp in the northern Gulf) while others clearly showed a significant expansion in their geographical distribution (horizontal) in the entire Gulf of St. Lawrence (capelin: Gregoire et al. 2005; herring: DFO 2006b, c) or a deepening of their vertical distribution (capelin: Mowbray 2002; herring: McQuinn 2009). Since the mid-1990s, there has been little or no fishing on the large groundfish populations (with the exception of northern Gulf cod, where there has been a moderate fishery during most of the past decade); hence, factors other than the direct impacts of fishing must be responsible for the lack of recovery or ongoing declines in many groundfish populations.

A dominant feature of climatic influence on groundfish and other bottom-living fauna has been the decadal-scale changes that occurred in the CIL and the deeper waters. At the population level, the most prominent effect has arguably been on cod, mainly in the northern Gulf. During the periods of cold water, the average condition of cod, measured as body weight as a function of length, declined to very low levels there (Dutil et al. 1999, Dutil and Lambert 2000). In laboratory studies, condition levels observed in the northern Gulf led to increased mortality of adult cod. Poor condition is therefore believed to have contributed to elevated natural mortality of northern Gulf cod during the early to mid 1990s, precipitating fishery-induced declines and greatly moderating post-moratorium recovery. As temperatures have increased, condition has improved and its contribution to mortality appears to have decreased. However, continued exploitation of the stock has prevented recovery to levels observed prior to the 1990s (Shelton et al. 2006). The contribution of poor condition to elevated natural mortality of southern Gulf cod, if it occurred, is believed to be considerably smaller (Swain et al. 2011a). Despite improvements in September condition since the mid 1980s, the natural mortality of southern Gulf cod has remained high and is leading to continued stock decline in the absence of fishing. There is mounting evidence that predation may be the cause (see section 5.6).

Bottom temperatures are one component that defines the preferred habitat of species. Long-term changes in the CIL thickness and core temperature affect the bottom temperature on the Magdalen Shallows of the southern Gulf. In some years, no waters colder than 0°C are found on the bottom by September, whereas in other years they can cover as much as 25,000 km² of the bottom (Galbraith et al. 2011). This variability affects the distribution and perhaps the abundance of a number of species. For example, snow crab prefer cool waters (-1 to 3°C). The cooling and areal expansion of the CIL during the late 1980s to early 1990s may have led to an extended distribution of the stock and may have contributed to high abundances during and following that period (Chassé and Pettipas 2009, Hébert et al. 2010), though a conclusive link has yet to be made due to the complex relationship between snow crab distribution and productivity and temperature (Sainte-Marie et al. 2008, Burmeister and Sainte-Marie 2010). As an alternate example, a negative relationship between the area of bottom water below 1°C and the probability to capture capelin in the trawl survey of the southern Gulf suggest that warming conditions are linked either to an increase of the Gulf capelin population, a shift in distribution, or both (Grégoire et al. 2004, F. Grégoire, MLI, unpub. data).

At the community level, the prolonged run of summers having cold CIL (bottom) waters beginning in the mid 1980s led to an increased dominance of species of arctic and boreal origin in the southern Gulf (Benoît and Swain 2008) (Fig. 5.5-5). In general, the relative proportion (by number) of fish belonging to species associated with arctic waters captured in the annual survey has varied inversely with average bottom temperatures for the southern Gulf. The inferred effect of temperature change on community composition was distinct from prominent inferred effects of fishing and predation by grey seals. For some species, such as polar sculpin *Cottunculus microps*, Arctic sculpin *Myoxocephalus scorpioides*, and Arctic cod *Boreogadus saida*, their sudden appearance as waters cooled in the 1990s—and disappearance as they warmed—is consistent with a distributional shift. For others, such as Atlantic and Greenland halibut, cooler waters have corresponded to an increased abundance of young fish (e.g., Benoît et al. 2003). This improved recruitment, possibly related to the environmental conditions, has led to population increases beginning in the late 1990s. In the northern Gulf, the increase in abundance of Greenland halibut juveniles since the early 1990s was concomitant with a rise in the biomass of the northern

shrimp, one of its most important prey species (Savenkoff et al. 2007b). Greenland halibut progressively replaced cod and redfish as the main shrimp predators. The increase in Greenland halibut may nonetheless reflect, at least in part, an indirect effect of climate, as increases in shrimp have been linked to favourable oceanographic conditions. This is discussed later in this section (Ouellet et al. 2011).

Analyses have recently been undertaken to examine the major trends in demersal (bottom) fish community composition for four distinct ecological regions of the Gulf (Fig. 5.5-6) using a technique called dynamic factor analysis (Zuur et al. 2003). The analyses are based on long-term monitoring of the Gulf using data from bottom-trawl surveys (since 1990 in the north and 1971 in the south). Preliminary results suggest that, for all regions of the northern Gulf, the overall pattern of variability in species abundance (and biomass) can be summarized by two dominant trends: (1) species associated with a largely increasing trend over time from the early 1990s to the present and (2) species associated with a rapid decline in the early 1990s followed by a more or less stable period and increasing values in recent years (Fig. 5.5-7). Though patterns of variability in the southern Gulf are best described by three trends, together they correspond to the trends for the northern Gulf for the period since 1990. Correlations between the original species-specific time series and the dominant trends were carried out to identify which species contribute the most to the overall variability in the communities. For northern GSL regions, there were the obvious cases, such as the collapses of Atlantic cod and redfish populations for the declining trends and the increase in Greenland halibut population for the increasing trends. In addition, non-commercial species such as thorny *Raja radiata* and smooth *Raja senta* skates were associated with the increasing trend while marlin spike *Nezumia bairdi* and longfin hake *Urophycis chesteri* were significantly related to the declining trend in the northern Gulf regions. Similarly, for the southern GSL, various non-commercial species were associated with the different trends, e.g., ascending trend: daubed shanny, shorthorn sculpin *Myoxocephalus scorpius*, snakeblenny *Lumpenus lamprataeformis*; declining trend: oceanpout *Zoarces americanus* and sea raven *Hemitripterus americanus*. Thus, it would seem that fishery pressure is not the only factor (or at least not directly), and other environmental forcings must be involved to explain the overall patterns of variability in GSL fish communities. The coherence in trends among regions suggests the possible role of similar factors, and further analyses are underway to establish the likely factors. The regions are united by a common exploitation history and some correspondence in changes in bottom water temperatures that occurred in the CIL and in deeper waters.

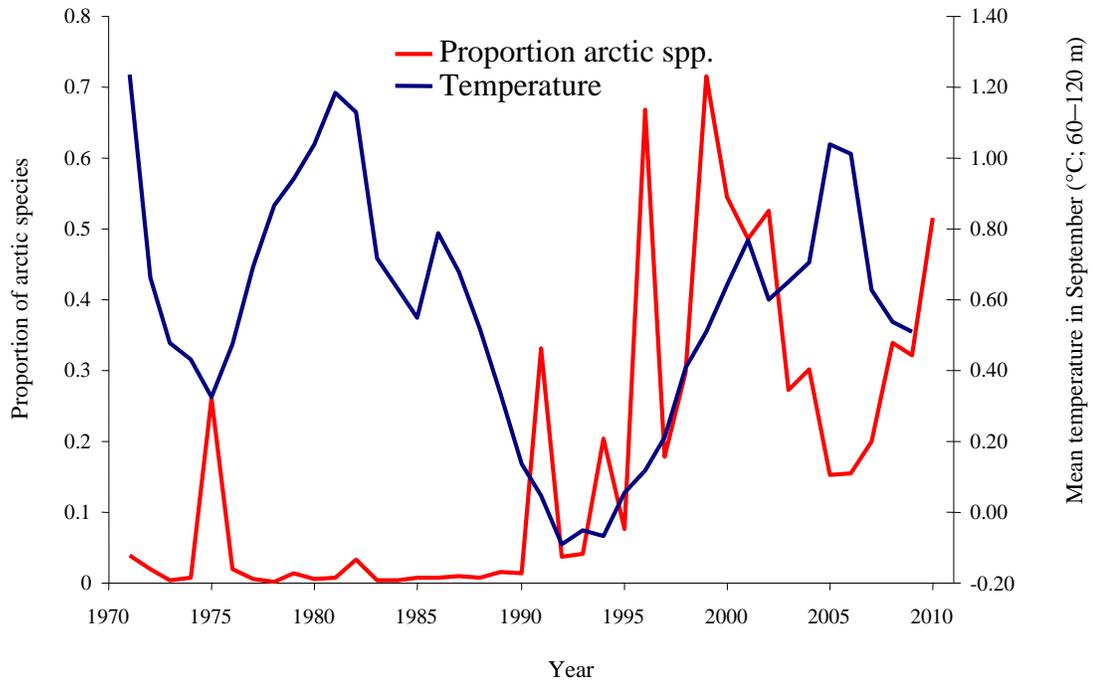


Figure 5.5-5. Trends in the proportion by number of fish captured in the annual September survey of the southern Gulf that are from species associated with Arctic waters and changes in the September bottom-water temperature for depths 60–120 m (in °C). Short-term fluctuations in the temperature series were smoothed prior to plotting using a three-year running average.

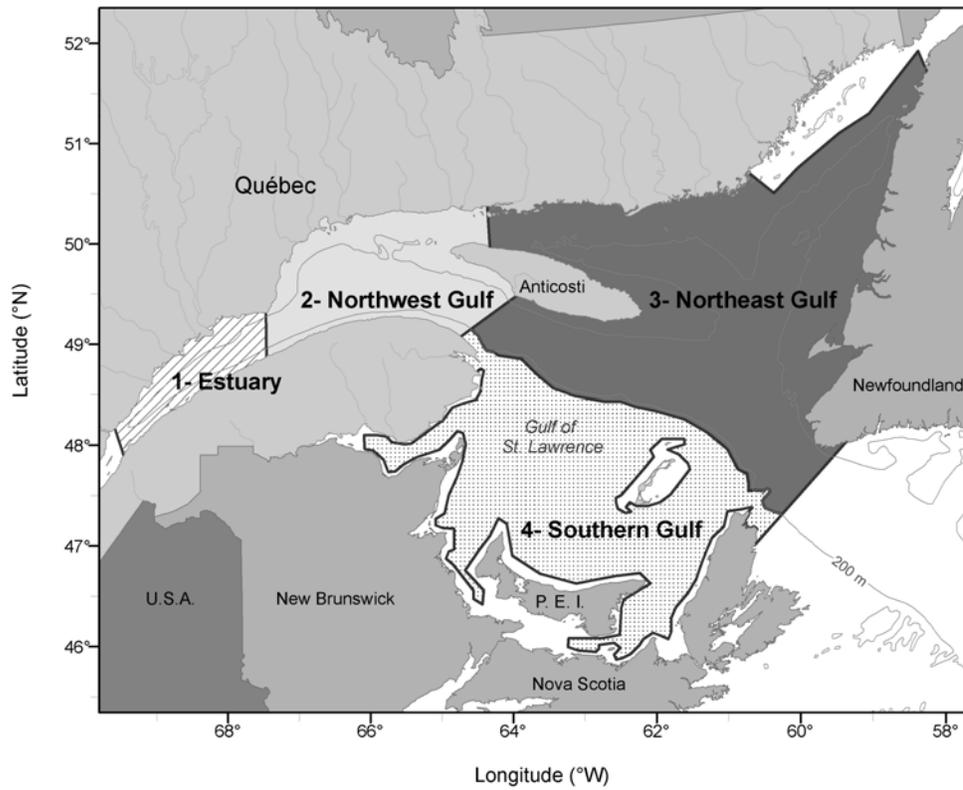


Figure 5.5-6. St. Lawrence system divided into four oceanographic regions.

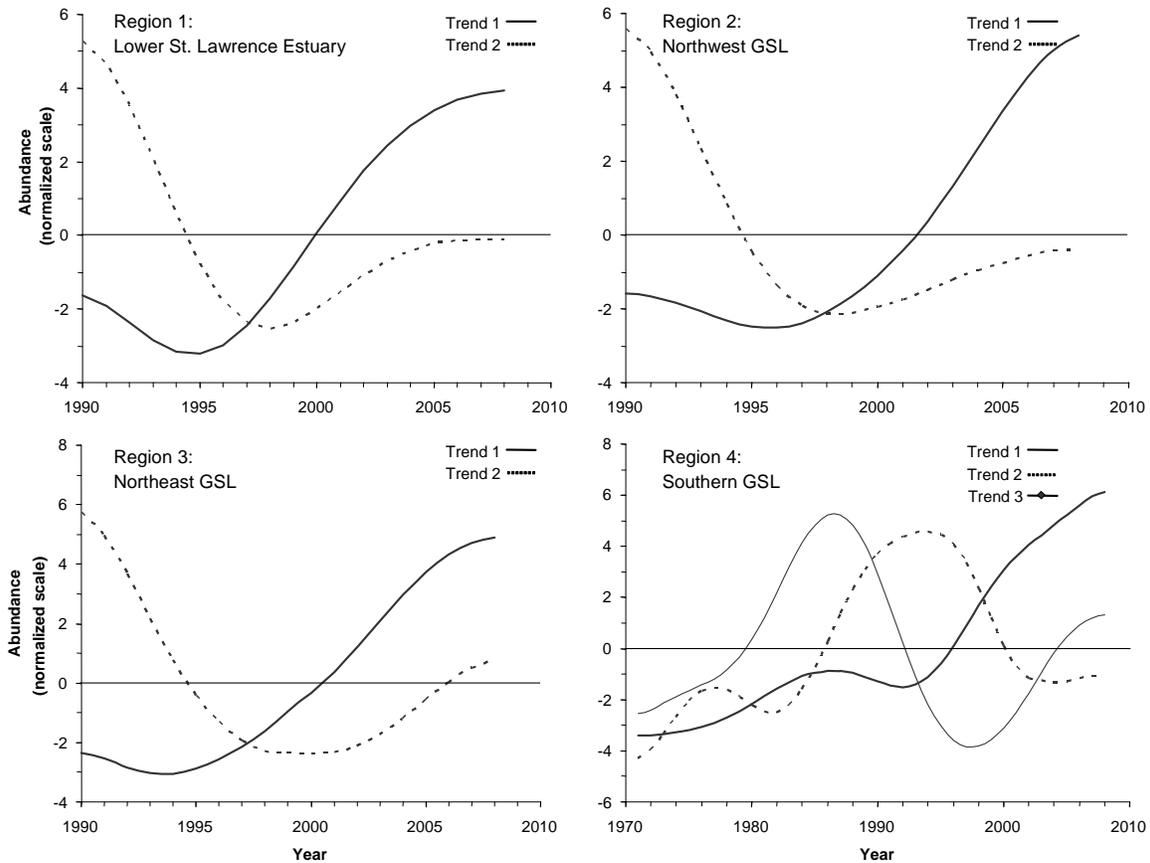


Figure 5.5-7. Illustration of dominant trends revealed by the dynamic factor analysis (DFA) in the time series of demersal fish species abundance data for the four regions of the GSL (similar trends were extracted from the time series of biomass data). Please refer to the text for a discussion of the contribution of particular species to these trends for each region.

Long-term changes in surface water temperature have also affected important fisheries resources for the Gulf, as described below. Because seasonal and interannual trends in surface layer temperatures affect the timing, duration, and intensity of plankton production, they in turn affect recruitment of key fisheries resources (e.g., Cushing 1990, Beaugrand et al. 2003, Platt et al. 2003). For example, spring oceanographic conditions (sea-surface water temperature and duration of the phytoplankton spring bloom) are important determinants of the recruitment success of northern shrimp in the northern Gulf (Ouellet et al. 2011). Similarly, Atlantic mackerel recruitment success and subsequent population abundance are correlated with species-specific copepod production in the southern Gulf (Castonguay et al. 2008) and ultimately to the regional climate (oceanographic) conditions. For instance, exceptionally warm surface conditions in 1999 resulted in the largest observed mackerel year class since at least 1982, when its monitoring began.

Observed and projected warming trends for Gulf surface waters will likely push certain temperature-sensitive species outside of the shallow waters they presently occupy. For example, temperatures over 23.5°C are lethal to giant scallop *Placopecten magellanicus* as are sudden increases to temperatures of 20°C (Dickie 1958). Furthermore, at higher temperatures that are not directly lethal to scallops, the risk of predation by crabs *Cancer irroratus* and sea stars *Asterias vulgaris* on scallops is increased (Barbeau and Scheibling 1994). Temperature-related mass mortalities of scallops have occurred frequently in the southwestern Gulf in the past (Dickie and Medcof 1963). With projected warming, mortalities may become more common in the areas where the warm surface layer reaches the bottom. As an example of extreme conditions, Fig. 5.5-8 shows the warmest weekly averaged sea-surface temperature (SST) recorded over the Magdalen Shallows between 1985 and 2010 and highlights the already-possible occurrence of surface waters above 20°C. This will likely result in a shift in giant scallop distribution towards deeper, cooler waters.

In contrast to the predicted shift in distribution for scallops, the habitat of warmer-water species that are currently limited to coastal waters in the Gulf, such as lobster, is likely to increase in areas with projected warming. Lobsters are likely to occur in deeper waters in the Gulf in the future, as is presently the case in more southerly areas of the NW Atlantic.

The anticipated changes in Gulf marine species and communities with projected global warming are difficult to predict. Conceptually, they are expected to include a combination of the following:

- (1) Direct effects of warming will likely include the loss of habitat for certain species currently residing in the southern Gulf (e.g., snow crab, capelin) and the creation of new habitat for southerly species currently at low abundance or not residing in the Gulf (Parmesan and Yohe 2003). Many benthic species are associated with specific bottom types and seafloor topography, and the conjunction with appropriate thermal conditions in the future will largely affect both distribution and abundance. For current southern Gulf residents that are acclimated to warmer temperatures, it may mean a shift to deeper waters (e.g., Dulvy et al. 2008) or northward (e.g., Perry et al. 2005).
- (2) A prediction of global warming is increased climate variability, which in turn is likely to increase the variability in vital rates (e.g., recruitment, mortality, growth) that are affected by water temperatures and thus variability in species abundance.
- (3) Differential changes in the habitats occupied by species seasonally and temperature-related species performances mean that ecological relationships among species (e.g., predator–prey) may also change (e.g., Petchey et al. 1999, 2010, Van der Putten et al. 2010).
- (4) Continued warming and reduction of the winter sea-ice cover can affect the timing of the spring phytoplankton bloom and the phenology (timing, duration, and intensity) of the biological production cycle, with consequences for the recruitment of species (e.g., northern shrimp). Such indirect effects of warming that are more difficult to predict may lead to some of the most profound changes to the marine communities.

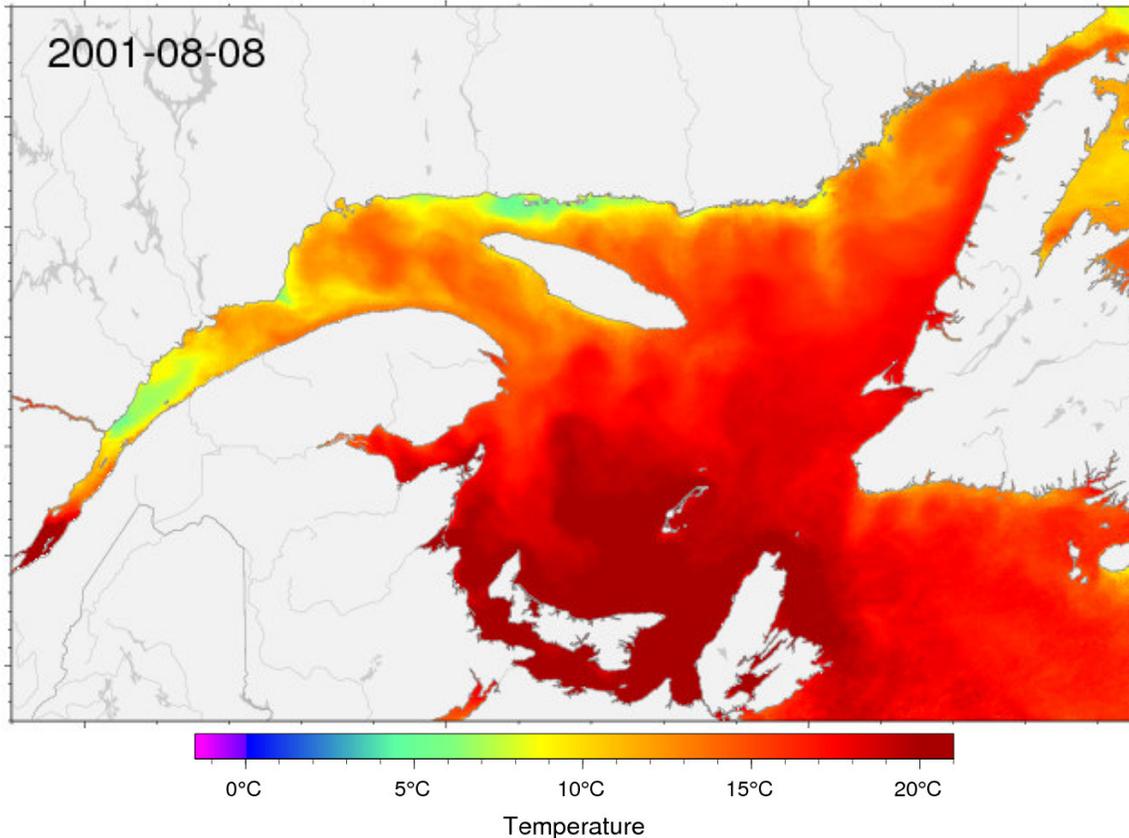


Figure 5.5-8. Sea-surface temperature averaged over one week in 2001, from 8 to 14 August, corresponding to the warmest week recorded over the Magdalen Shallows between 1985 and 2010. Note the presence of temperatures above 20°C. Data are courtesy of Pierre Larouche from the Maurice Lamontagne Institute remote sensing laboratory.

5.5.4 *Key directions in management response development to future temperature changes and their implications*

From a global perspective, the sensitivity of Canadian fisheries to climate change is considered moderate, and the nation's capacity to adapt is high relative to less developed countries that are more dependent on fisheries for sustenance and export (Allison et al. 2009). The projected impacts of climate change on exploited marine communities can be broadly summarized as changes in species productivities and enhanced population variability (Brander 2010, MacNeil et al. 2010). The mechanisms underlying these impacts will include a variety of direct and indirect effects on a number of physical and chemical factors, such as temperature, vertical mixing, oxygen, pH, and loss of sea ice. Consequences specific to a number of these mechanisms are discussed elsewhere in this report (see sections 5.1, 5.2, and 5.3).

With a changing climate, some harvesting opportunities may be lost while others created by northward movements of species into the Gulf might be gained. This is likely to raise questions concerning the allocation of fishing opportunities among communities within the Gulf (Brander

2010). More generally, though, establishing and implementing sustainable exploitation rates may be difficult depending on the rates of productivity change. This may be most difficult if the objective is to maximize the sustainable yield of individual species or of species assemblages. Strategies with more conservative objectives may therefore be required to keep pace with changes in productivity and to build resilience within the exploited population. A key to this resilience is the re-establishment of a diverse age structure in species that were formally much longer lived than they are today (e.g., cod, white hake, redfish) and a rebuilding of abundance. Both have known stabilizing effects on population abundance, which on one hand contributes to enhanced interannual predictability of yield and on the other reduces the risk of collapse or extinction resulting from sporadic mortality events or recruitment failures.

With increased ecological variability, strong research programs will be required to monitor and understand the changes. These monitoring and research activities will also need to be closely linked to flexible and responsive management systems.

5.6 Potential impacts of grey seal predation on groundfish populations in the southern Gulf (*H. Benoît GFC and C. Savenkoff MLI*)

5.6.1 Overview

During the early 1990s, several populations of large groundfish in the Gulf of St. Lawrence collapsed, with no signs of recovery even today (e.g., Atlantic cod *Gadus morhua*, white hake *Urophycis tenuis*, redfish *Sebastes* spp.). Other populations have been in continuous decline since the 1980s (e.g., American plaice *Hippoglossoides platessoides*, thorny skate *Raja radiata*, winter skate *Leucoraja ocellata*, black dogfish *Centroscyllium fabricii*). Ongoing declines in a number of these populations are such that the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed winter skate, Atlantic cod, and American plaice to be at an elevated risk of extirpation (<http://www.cosewic.gc.ca/>). Though overfishing during the 1980s and early 1990s is the main cause of the collapse of southern and northern Gulf cod stocks and a strong contributor to declines in the other species, there has been very little fishing on southern Gulf cod and other groundfish stocks since at least the mid-1990s (e.g., Fig. 5.5-3). With the possible exception of northern Gulf cod, factors other than the direct impacts of fishing and environmental change are therefore largely responsible for the lack of recovery or ongoing declines.

Predation by seals has been proposed as an important contributor to the lack of recovery of collapsed groundfish populations throughout the Northwest (NW) Atlantic (DFO 2008b, 2009d, Bundy et al. 2010). The evidence to support this hypothesis varies by region. Here, we focus specifically on the implications of a possible role of predation by grey seals on southern Gulf groundfish for two reasons. First, the evidence for and against this effect has recently been extensively reviewed, and there has been some exploration of the possible consequences of specific management actions (DFO 2011d). Second, the issue of elevated natural (i.e., non-fishing) mortality is particularly acute in southern Gulf groundfish.

5.6.2 Drivers and pressures – changes in the abundance of seals and the vulnerability of fish

As indicated in section 5.3.1, the four common species of pinnipeds that inhabit the Gulf at least part of the year are the harbour *Phoca vitulina*, grey *Halichoerus grypus*, harp *Pagophilus groenlandicus*, and hooded *Cystophora cristata* seals. The abundance of at least three of these species in the Northwest Atlantic has increased since the 1960s (trends for harbour seals are not available). Harp and hooded seals are in the southern Gulf only during the winter and early spring, and likely do not feed much in the area (Hammill and Stenson 2000). Harbour seals are year-round residents but are not very abundant and feed mainly on small fish in coastal areas; they are therefore not considered an important contributor to the elevated natural mortality of large groundfish.

Grey seals are by far the most common seal that feeds in the southern Gulf (Hammill and Stenson 2000). Their abundance in Atlantic Canada has increased over the last 50 years from around 13,000 in 1960 to over 350,000 individuals in 2010 (Fig. 5.6-1; DFO 2011d, Thomas et al. 2011). Approximately 60,000–70,000 NW Atlantic grey seals breed in the Gulf and readily move into and out of the Gulf, with an estimated 100,000 individuals that spend at least part of the year in the southern Gulf (Benoît et al. 2011a). Their diet consists almost exclusively of fish (Hammill et al. 2007), and on average, a grey seal can consume between 1.0 to over 2.5 t of prey per year, depending on the energy content of their prey (DFO 2011d). Although there is considerable uncertainty concerning the exact diet composition of grey seals in the southern Gulf, larger groundfish are certainly consumed and might be preferentially selected by grey seals (DFO 2011d).

The drivers of the NW Atlantic grey seal population increase are not well understood. During the 19th and early 20th centuries, grey seals were hunted to the point of being considered rare (Davies 1957, Chantraine 1980). Since the 1970s, grey seal numbers have increased considerably, and there may be several reasons for this. First, considerably reduced human presence on Sable Island and more recently on other small islands (e.g., due to lighthouse closures) may have resulted in less harassment and the opening up of prime beaches for pupping. Second, the abundance of grey seal predators such as sharks has declined to very low levels (Brodie and Beck 1983, Baum et al. 2003). The extirpation of Atlantic walrus during the 18th century has resulted in the absence of a former predator on young grey seals and a competitor for haul-out and pupping sites for adults (i.e., an open niche). Third, hunting pressure has been reduced with the elimination of bounty and culling programs for the seals.

An increase in the abundance of predators is not the only factor that contributes to the increased vulnerability of fish populations to predation. For a given density of predators, prey mortality rates generally increase as prey abundance declines (Gascoigne and Lipcius 2004). This is an important component of the predator pit phenomenon, whereby predation probability decreases above and below an intermediate level of prey abundance and where the level of predation (i.e., depth of the pit) also depends on predator abundance. Therefore fishery-driven stock collapses may have enhanced vulnerability by increasing the mortality rates imposed by predation. Furthermore, fisheries in the southern Gulf, as elsewhere, typically removed the largest fish in the populations, resulting in truncations in stock size composition. This likely resulted in a loss of an important size refuge for the oldest (often most fecund) fish in many populations and perhaps in a shift in size composition towards fish sizes preferred by grey seals. The apparent long-term

coexistence of seals and fish such as cod prior to the intensive exploitation of the past few centuries might be explained by lower predation rates resulting from larger fish stock size and the presence of size refuges (Chantraine 1980, Lear 1988, Lavigueur and Hammill 1993).

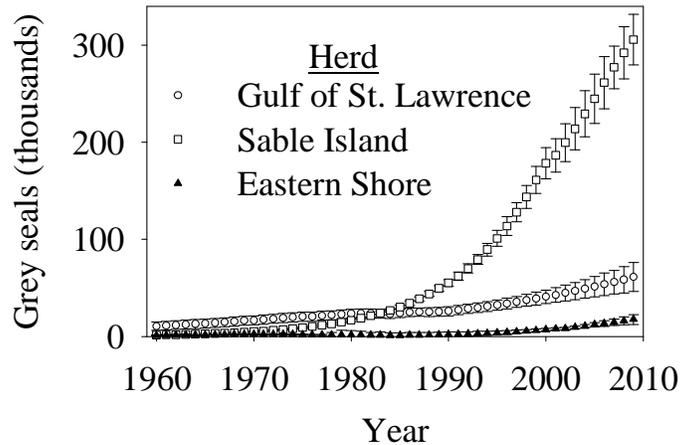


Figure 5.6-1. Trajectories (mean \pm 95% confidence interval) of the total population for the three grey seal herds in Eastern Canada (from DFO 2011d).

5.6.3 Impact – evidence for elevated mortality and resulting enhanced risk of extirpations in large demersal fish

Patterns in the mortality rates of marine fishes in the southern Gulf of St. Lawrence have been characterized by a decline for small fish and an increase for larger fish (generally >40 cm) since the 1980s (Fig. 5.6-2; Benoît and Swain 2011). The declines for small fish are true both for small-bodied species and for smaller individuals of large-bodied species. This pattern is consistent with a release from predation that occurred as the abundance of larger predatory groundfish declined (Savenkoff et al. 2007c, Benoît and Swain 2008). For the larger fish, the increases in natural (non-fishing) mortality rates have been large in magnitude and are apparent across a range of species (Benoît and Swain 2011). Since the early 1980s, the annual natural mortality rates of adult southern Gulf cod and white hake have increased approximately fivefold, while that of southern Gulf winter skate increased about eightfold (Fig. 5.6-2; Swain et al. 2009a, b, Benoît et al. 2011b). Since the 1970s, the total (fishing and natural) mortality rates of adult thorny and smooth skate have increased two- or threefold, despite declines in fishing-induced mortality due to decreasing groundfish fishing effort. These increases in mortality place the populations in question at considerably heightened risk of extirpation (local extinction) within a few decades even in the absence of fishing-induced mortality, unless the productivity of these populations improves (Swain and Chouinard 2008, Swain et al. 2009a, Benoît et al. 2011b). Winter skate in the southern Gulf may constitute a distinct species (see discussion in Benoît et al. 2011b), so their loss from the ecosystem could constitute extinction.

The causes of the elevated natural mortality of large demersal fish in the southern Gulf of St. Lawrence are not firmly established. The evidence concerning a number of hypotheses to explain the mortality, including disease, starvation, and predation, was examined for southern Gulf of St. Lawrence Atlantic cod, white hake, and winter skate (Benoît et al. 2011b, Swain et al. 2011b). Though not all hypotheses could be rigorously examined because of a lack of existing data, there is strong evidence in support of a large contribution of grey seal predation to elevated mortality (DFO 2011d). The evidence includes generally coincident trends in mortality rates and seal population increases, coincident population trends among most species that are prey to grey seals, shifts in fish distribution away from areas frequented by seals, and calculations that confirm there is sufficient feeding demand by seals and spatial and temporal overlap with prey to explain elevated natural mortality in at least three fish species.

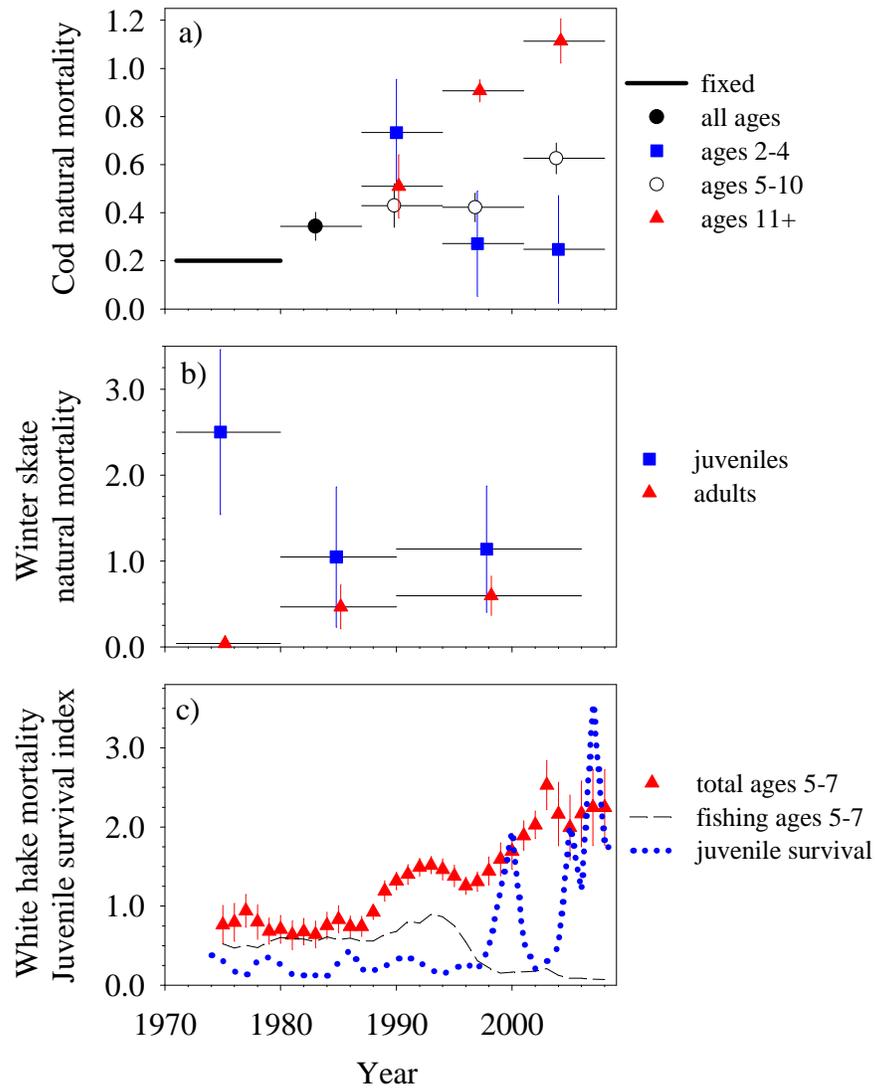


Figure 5.6-2. Age- or stage-dependent trends in mortality for three southern Gulf of St. Lawrence marine fishes. (A) Age-dependent trends in cod natural mortality (mean ± 2 SE; redrawn from Swain et al. 2009b). Natural mortality was estimated for blocks of years (denoted by the horizontal lines), assuming a fixed rate from 1971–1979 and estimating a common rate across ages for 1980–1986 (see Swain et al. 2009b for details). (B) Stage-dependent estimates of winter skate natural mortality (mean ± 95 percentile range) in approximately decadal blocks of years (horizontal lines) (Swain et al. 2009a). (C) Index of juvenile survival (dotted line) and age 5–7 total mortality (triangles: mean ± 2 SE) and fishing mortality (dashed line) for white hake (Benoît et al. unpubl. data).

5.6.4 *Key directions in management response development and its implications*

An informal risk analysis conducted as part of the 2010 advisory process on grey seal impacts concluded that risks concerning the possible extirpation of southern Gulf cod, white hake, and winter skate appear to be minimized by undertaking reductions in the number of grey seals that forage in the southern Gulf of St. Lawrence (DFO 2011d). These reductions are not expected to pose a conservation risk to the grey seal population itself, but are likely to generate strong responses in certain segments of society such as animal rights organizations. The risk analysis acknowledged the possibility that seal reductions can have unanticipated effects in the ecosystem. However, preliminary results of ongoing ecosystem modelling suggest that the risk and severity of unanticipated effects on cod or other groundfish would be small (Morissette and Hammill 2011). As cod recovers, it may regain its role as a key predator of fish in the system, which may then in turn affect the population dynamics of its prey and competitors.

There are two main options for controlling the size of the grey seal population: sterilization of adults and hunting. A third option, rebuilding the populations of natural seal predators such as sharks to a level at which they can control seal abundance, is arguably one of the more sustainable approaches for the long term but does not address the present risk of extirpation in fish populations (Lessard et al. 2005). A fourth option, rebuilding fish populations to a level and size composition that decreases their vulnerability to adverse impacts of predation, will only be viable if their productivity increases substantially over a prolonged period of time (i.e., sustained decrease in their natural mortality).

Sterilization was not considered as a favoured approach for controlling grey seal abundance during the 2010 advisory process because the possible benefits to fish populations may not materialize in time to reverse the population trends of those at risk of extirpation (since grey seals can live 40 years or more). However, sterilization is a viable option for stabilizing population size in a medium-term time horizon. Removals by hunting were therefore discussed as the main option for population control.

It is not possible to reliably determine the degree to which the grey seal population must be reduced to allow cod and other species to recover, largely because of large uncertainties in the diet composition of seals. Different models based on a variety of assumptions were therefore used (Benoît et al. 2011b, Swain et al. 2011c). Given a certain set of assumptions that are consistent with the weight of evidence that suggests a predominant effect of seal predation, reductions on the order of 70% (i.e., to 30,000 foraging seals in the Gulf) are required to allow recovery in southern Gulf cod, winter skate, and white hake (DFO 2011d). Furthermore, the annual production of pups needs to be curtailed to stabilize the abundance of grey seals. If particular seals specialize in predation of cod and these seals can be targeted for removal (e.g., male grey seals in areas of high overlap with cod, such as Cabot Strait in winter), then the required removals could be much lower. Likewise, targeting grey seals that feed in areas where winter skate or white hake aggregate (Northumberland Strait, Laurentian Channel) would likely require considerably less removal for comparable reductions in the mortality rates.

To be effective, a predator control program requires clear statements of objectives and the use of performance measures that provide a quantitative estimation of the extent to which objectives have been met and benefits realized. Guidelines to do so have been prepared (DFO 2011d,

Hammill and Swain 2011). Given the very large uncertainties in the Gulf food-web structure and dynamics, it is not possible to reliably predict the outcomes of such a program, and as such it should be conducted in an adaptive management framework. Furthermore, societal acceptability of a hunt would be enhanced substantially if it were undertaken as a sustainably managed harvest (DFO 2011d).

Successfully rebuilding populations of large groundfish to levels observed 30 or more years ago is likely to have important impacts in the ecosystem that are also important to the fishing industry. Prior to the 1990s, cod was a dominant predator in the Gulf ecosystem. The collapse of cod and other predatory groundfish such as white hake and redfish in the early 1990s resulted in predation release not only on smaller fish, as noted above, but also likely contributed to increases in commercially important invertebrates such as shrimp (Worm and Myers 2003; but see also section 5.5 in this report). It may not be possible to simultaneously and sustainably achieve high yields from groundfish, as occurred during the 1980s, and present-day yields of those invertebrate and fish species that are important groundfish prey. Such trade-offs must be explicitly recognized and must inform decisions on conservation objectives for harvest fisheries.

6. CONCLUSION

The Estuary and Gulf of St. Lawrence system is changing in response to environmental forcing but also as a result of human activities. Impacts of climate change exacerbate these changes but are still difficult to discriminate from natural interannual or long-term periodic variability. This report focusses on specific adverse effects and possible mitigation of selected environmental agents, identified in collaboration with DFO's Ocean sector. As indicated in section 5.0, some changes will improve ecosystem goods and services to society while others will be neutral or detrimental. For instance, new aquatic species entering the EGSL as a result of environmental change may fill niches that have been vacated by species that have been overharvested or that have themselves been displaced by environmental change, or may occupy new niches. Despite increasing regulation, human-facilitated unintentional introductions are also likely to continue. Control measures recently put in place may prevent some non-native species from becoming invasive and, although aquatic invasive species generally represent a threat to ecosystem health (section 5.4), some introduced species may constitute yet unforeseen exceptions. Some important commercially exploited species like scallops and snow crab are predicted to experience habitat shifts and possible degradation, but impacts on others such as lobster and mackerel are expected to be in the opposite direction (section 5.5). The case of Atlantic cod well illustrates the difficulties of predicting trends and developing mitigation measures. Although expected environmental conditions might be favourable for cod, they may also result in higher abundances of key predators such as seals (section 5.3), hence the recommendation for harvest strategies with more conservative objectives (section 5.5) and the need to develop an ecosystem approach to harvesting that explicitly accounts for trophic interactions (section 5.6). Enhanced precaution in resource extraction will further be necessary given the definitively adverse phenomena such as hypoxia (section 5.1) and acidification (section 5.2). Given the complexity of these interactions and the common obligation to manage ocean activities in a way that preserves the ecological health of the oceans while allowing for sustainable use, natural science and socio-economic

experts must join forces with managers to follow major ecosystem changes, assess their causes, and identify management measures to mitigate anticipated detrimental impacts.

This report results from work undertaken collaboratively by ocean scientists and managers towards improved management of the Gulf of St. Lawrence Large Ocean Marine Area. Future SOTO reports are likely to increasingly cover an important part of the EGSL that was largely not discussed here, the coastal zone. Important themes not covered in this report are also likely to attract more attention, such as contaminants and coastal erosion, and there is likely to be a greater discussion on the risks and vulnerabilities associated with human activities and ecosystem changes. Furthermore, once management measures have been implemented to address environmental effects such as those described here, and sufficient data are collected to allow scientists to distinguish between the possible effect of human interventions and natural variability, SOTO reporting will increasingly be the venue for documenting the effectiveness of the measures.

7. ACKNOWLEDGEMENTS

This work was supported by the Health of the Ocean (HOTO) program of the Department of Fisheries and Oceans. Roland Cormier and Marc Ouellette contributed to elaborating and drafting the text in section 4. We appreciate their insights regarding the structure, content, and purpose of effective state of the oceans reporting. We are grateful to colleagues who made data available for this manuscript. We wish to acknowledge Roland Cormier (GFC), Mark Hanson (GFC), Bernard Sainte-Marie (MLI), and Jacques Trottier (MLI) for their thoughtful comments on the manuscript. Our gratitude is extended to Laure Devine for reading and commenting on the manuscript.

8. REFERENCES

- Alexander, D.W., Sooley, D.R., Mullins, C.C., Chiasson, M.I., Cabana, A.M., Klvana, I. and Brennan, J.A. 2010. Gulf of St. Lawrence: Human systems overview report. Oceans, Habitat and Species at Risk Publication Series, Newfoundland and Labrador Region. 0002: xiv + 154 pp.
- Allison, E.H., Perry, A.L., Badjeck, M.-C., Neil Adger, W., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L. and Dulvy, N.K. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* 10: 173–196.
- AMEC Earth and Environmental. 2007. Northumberland Strait Ecosystem Overview Report, Fisheries and Oceans Canada, Moncton, NB. 252 pp.
- Anderson, C.N.K., Hsieh, C.-H., Sandin, S.A., Hewitt, R., Hollowed, A.B., Beddington, J.R., May, R.M. and Sugihara, G. 2008. Why fishing magnifies fluctuations in fish abundance. *Nature* 452: 835–839.
- Armstrong, R.A., Lee, C., Hedges, J.I., Honjo, S. and Wakeham, S.G. 2002. A new mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. *Deep-Sea Res. II* 49: 219–236.
- Attrill, M.J. and Power, M. 2002. Climatic influence on a marine fish assemblage. *Nature* 417: 275–278.
- Barbeau, M.A. and Scheibling, R.E. 1994. Temperature effects on predation of juvenile sea scallops (*Placopecten magellanicus* (Gmelin)) by sea stars (*Asterias vulgaris* Verrill) and crabs (*Cancer irroratus* Say). *J. Exp. Mar. Biol. Ecol.* 182: 27–47.
- Bajzak, C., Hammill, M.O., Stenson, G.B. and Prinsenberg, S. 2011. Drifting away: implications of changes in ice conditions for a packice-breeding phocid, the harp seal (*Pagophilus groenlandicus*). *Can. J. Zool.* 89: 1050–1062.
- Barker, S., Higgins, J.A. and Elderfield, H. 2003. The future of the carbon cycle: review, calcification response, ballast and feedback on atmospheric CO₂. *Philos. Trans. R. Soc. Lond. A* 361: 1977–1998.
- Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J. and Doherty, P.A. 2003. Collapse and conservation of shark populations in the Northwest Atlantic. *Science* 299: 389–392.
- Beaugrand, G., Brander, K.M., Lindley, J.A., Souissi, S. and Reid, P.C. 2003. Plankton effect on cod recruitment in the North Sea. *Nature* 426: 661–664.
- Bell, H.P. and MacFarlane, C.I. 1933. The marine algae of the Maritime Provinces of Canada. I. List of species with their distribution and prevalence. *Can. J. Res.* 9: 265–279.
- Belley, R., Archambault, P., Sundby, B., Gilbert, F. and Gagnon, J.-M. 2010. Effects of hypoxia on benthic macrofauna and bioturbation in the Estuary and Gulf of St. Lawrence, Canada. *Cont. Shelf Res.* 30: 1302–1313.
- Beman, J.M., Chow, C.-E., King, A.L., Feng, Y., Fuhrman, J.A., Andersson, A., Bates, N.R., Popp, B.N. and Hutchins, D.A. 2011. Global declines in oceanic nitrification rates as a consequence of ocean acidification. *Proc. Nat. Acad. Sci.* 108: 208–213.
- Beniash, E., Ivanina, A., Lieb, N.S., Kurochkin, I. and Sokolova, I.M. 2010. Elevated level of carbon dioxide affects metabolism and shell formation in oysters *Crassostrea virginica*. *Mar. Ecol. Prog. Ser.* 419: 95–108.

- Bennett, W.A., Roinestad, K., Rogers-Bennett, I., Kaufman, L., Wilson-Vandenberg, D. and Heneman, B. 2004. Inverse regional responses to climate change and fishing intensity by the recreational rockfish (*Sebastes* spp.) fishery in California. *Can. J. Fish. Aquat. Sci.* 61: 2499–2510.
- Benoît, H.P. and Swain, D.P. 2008. Impacts of environmental change and direct and indirect harvesting effects on the dynamics of a marine fish community. *Can. J. Fish. Aquat. Sci.* 65: 2088–2104.
- Benoît, H.P. and Swain, D.P. 2011. Changes in size-dependent mortality in the southern Gulf of St. Lawrence marine fish community. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/039: iv + 22 pp.
- Benoît, H.P., Abgrall, M.-J. and Swain, D.P. 2003. An assessment of the general status of marine and diadromous fish species in the southern Gulf of St. Lawrence based on annual bottom-trawl surveys (1971-2002). *Can. Tech. Rep. Fish. Aquat. Sci.* 2472: 183 pp.
- Benoît, H.P., Swain, D.P. and Hammill, M.O. 2011a. Seasonal patterns in the spatial overlap of southern Gulf cod and grey seals, with a discussion of sources of error and possible bias. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/018: iv + 16 pp.
- Benoît, H.P., Swain, D.P. and Hammill, M.O. 2011b. A risk analysis of the potential effects of selective and non-selective reductions in grey seal abundance on the population status of two species at risk of extirpation, white hake and winter skate in the southern Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/033: iv + 28 pp.
- Bernier, R. and Locke, A. 2006. New record of *Penilia avirostris* Dana, 1849 (Cladocera) in the Gulf of St. Lawrence. *Crustaceana* 79: 949–959.
- Bequaert, J. 1943. The genus *Littorina* in the Western Atlantic. *Johnsonia* 1: 1–28.
- Bianchi, G., Gislason, H., Graham, K., Hill, L., Jin, X., Koranteng, K., Manickchand-Heileman, S., Payá, I., Sainsbury, K.J., Sanchez, F. and Zwanenburg, K. 2000. Impacts of fishing on size composition and diversity of demersal fish communities. *ICES J. Mar. Sci.* 57: 558–571.
- Boulva, J. and McLaren, I.A. 1979. Biology of the harbor seals, *Phoca vitulina*, in eastern Canada. *Bull. Fish. Res. Board. Can.* 200: 1–24.
- Bourdages, H., Archambault, D., Bernier, B., Fréchet, A., Gauthier, J., Grégoire, F., Lambert, J. and Savard, L. 2010. Preliminary results from the groundfish and shrimp multidisciplinary survey in August 2010 in the northern Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2010/107: vi + 92 pp.
- Bourque, M. 2009. Variation spatio-temporelle de la macrofaune endobenthique dans la zone profonde du Saint-Laurent (Québec, Canada) en relation avec les conditions environnementales. Master's Thesis, Université du Québec à Rimouski, xi + 94 pp.
- Brander, K. 2010. Impacts of climate change on fisheries. *J. Mar. Syst.* 79: 389–402.
- Brodie, P. and Beck, B. 1983. Predation by sharks on the grey seal (*Halichoerus grypus*) in eastern Canada. *Can. J. Fish. Aquat. Sci.* 40: 267–271.
- Brown, C.W. and Yoder, J. A. 1994. Distribution pattern of coccolithophorid blooms in the western North Atlantic Ocean. *Cont. Shelf Res.* 14: 175–197.
- Bundy, A., Heymans, J.J., Morissette, L. and Savenkoff, C. 2010. Seals, cod and forage fish: A comparative exploration of variations in the theme of stock collapse and ecosystem change in four Northwest Atlantic ecosystems. *Prog. Oceanogr.* 81: 188–206.
- Burkhardt, S., Amoroso, G., Riebesell, U. and Sültemeyer, D. 2001. CO₂ and HCO₃⁻ uptake in marine diatoms acclimated to different CO₂ concentrations. *Limnol. Oceanogr.* 46: 1378–1391.

- Burmeister, A., and Sainte-Marie, B. 2010. Patterns and causes of a temperature-dependent gradient of size at terminal moult in snow crab (*Chionoecetes opilio*) along West Greenland. *Polar Biol.* 33: 775–788.
- Burns, J.M., Skomp, N., Bishop, N., Lestyk, K. and Hammill, M.O. 2010. Development of aerobic and anaerobic metabolism in cardiac and skeletal muscles from harp and hooded seals. *J. Exp. Biol.* 213: 740–748.
- Cai, W.-J., Hu, X., Huang, W.-J., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W.-C., Zhai, W., Hollibaugh, J.T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M. and Gong, G.-C. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience* 4: 766–770.
- Caldeira, K. and Wickett, M.E. 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res.* 110: C09S04.
- Cardoso, A.C., Cochrane, S., Doerner, H., Ferreira, J.G., Galgani, F., Hagebro, C., Hanke, G., Hoepffner, N., Keizer, P.D., Law, R., Olenin, S., Piet, G.J., Rice, J., Rogers, S.I., Swartenbroux, F., Tasker, M. and Van de Bund, W. 2010. Scientific support to the European Commission on the marine strategy framework directive - management group report. Office for Official Publications of the European Communities, Luxembourg. EUR - Scientific and Technical Research series - ISSN 1018-5593, ISBN 978-92-79-15649-6. 57 pp.
- Carlton, J.T. and Geller, J.B. 1993. Ecological roulette: the global transport of nonindigenous marine organisms. *Science* 261: 78–82.
- Castonguay, M., Plourde, S., Robert, D., Runge, J.A. and Fortier, L. 2008. Copepod production drives recruitment in a marine fish. *Can. J. Fish. Aquat. Sci.* 65: 1528–1531.
- CCFAM, Canadian Council of Fisheries and Aquaculture Ministers. 2004. A Canadian Action Plan to address the threat of aquatic invasive species. Aquatic Invasive Species Task Group, Canadian Council of Fisheries and Aquaculture Ministers. Sept. 2004. 26 pp.
- Chabot, D. 2004. Chronic non-lethal levels of hypoxia limit distribution and growth of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence, Canada. *In: Proceedings of the 7th International Symposium on Fish Physiology, Toxicology and Water Quality. Edited by G.L. Rupp and M.D. White.* Athens, GA:U.S. Environmental Protection Agency, Ecosystems Research Division. pp 183–205.
- Chabot, D. and Claireaux, G. 2008. Environmental hypoxia as a metabolic constraint on fish: The case of Atlantic cod, *Gadus morhua*. *Mar. Pollut. Bull.* 57: 287–294.
- Chabot, D. and Dutil, J.-D. 1999. Reduced growth of Atlantic cod in non-lethal hypoxic conditions. *J. Fish. Biol.* 55: 472–491.
- Chabot, D., Sainte-Marie, B., Briand, B., and Hanson, J.M. 2008. Atlantic cod and snow crab predator-prey relationship in the Gulf of St. Lawrence, Canada. *Mar. Ecol. Prog. Ser.* 363: 227–240.
- Chantraine, P. 1980. The living ice: the story of the seals and the men who hunt them in the Gulf of St. Lawrence. McClelland and Stewart Limited, Toronto, 238 pp.
- Chassé, J. and Pettipas, R.G. 2009. Temperature conditions in the southern Gulf of St. Lawrence during 2008 relevant to snow crab. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2009/087: vi + 24 pp.
- Crooks, J.A., Chang, A.L. and Ruiz, G.M. 2011. Aquatic pollution increases the relative success of invasive species. *Biol. Invasions* 13: 165–176.
- Crossman, E. J. 1984. Introduction of exotic fishes into Canada. *In Courtenay, W. R., and J. R. Stauffer (eds.). Distribution, biology, and management of exotic fishes.* Johns Hopkins University Press, Baltimore, Maryland. pp. 78-101.

- Cushing, D.H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. *Adv. Mar. Biol.* 26: 249–294.
- D'Amours, D. 1993. The distribution of cod (*Gadus morhua*) in relation to temperature and oxygen level in the Gulf of St. Lawrence. *Fish. Oceanogr.* 2: 24–29.
- Darbyson, E., Locke, A., Hanson, J.M. and Willison, J.H.M. 2009. Marine boating habits and the potential for spread of invasive species in the Gulf of St. Lawrence. *Aquatic Invasions* 4: 87–94.
- Davies, J.L. 1957. The geography of the gray seal. *J. Mammal.* 38: 297–310.
- Descroix, A., Harvey, M., Roy, S. and Galbraith, P.S. 2005. Macrozooplankton community patterns driven by water circulation in the St. Lawrence marine system, Canada. *Mar. Ecol. Prog. Ser.* 302: 103–119.
- DFO, Department of Fisheries and Oceans. 2002. Canada's Oceans Strategy: Our oceans, our future Oceans Act. Oceans Directorate, Ottawa. ISBN 0-662-32449-8. 36 pp.
- DFO, Department of Fisheries and Oceans. 2004. Identification of ecologically and biologically significant areas. *DFO Can. Sci. Advis. Sec. Ecosystem Status Rep.* 2004/006: 15 pp.
- DFO, Department of Fisheries and Oceans. 2005. The Gulf of St. Lawrence – A unique ecosystem: The stage for the Gulf of St. Lawrence integrated management. Oceans and Science Branch Report. <http://www.glf.dfo-mpo.gc.ca/e0006090> (accessed 21 September 2011).
- DFO, Department of Fisheries and Oceans. 2006a. Identification of ecologically significant species and community properties. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2006/041: 24 pp.
- DFO, Department of Fisheries and Oceans. 2006b. Assessment of the Quebec North Shore (Division 4S) herring stocks in 2005. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2006/020: 14 pp.
- DFO, Department of Fisheries and Oceans. 2006c. Assessment of the west coast of Newfoundland (Division 4R) herring stocks in 2005. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2006/021: 12 pp.
- DFO, Department of Fisheries and Oceans. 2007. Ecologically and biologically significant areas (EBSA) in the Estuary and Gulf of St. Lawrence: identification and characterization. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2007/016: 14 pp.
- DFO, Department of Fisheries and Oceans. 2008a. State of the ocean 2007: Physical oceanographic conditions in the Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2008/016: 19 pp.
- DFO, Department of Fisheries and Oceans. 2008b. Proceedings of the national workshop on the impacts of seals on fish populations in Eastern Canada (Part 1); 12-16 November 2007. *DFO Can. Sci. Advis. Sec. Proceed. Ser.* 2008/021: iv + 144 pp.
- DFO, Department of Fisheries and Oceans. 2009a. Conservation objectives for the ecologically and biologically significant areas (EBSA) of the Estuary and Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2009/049: 10 pp.
- DFO, Department of Fisheries and Oceans. 2009b. Does eelgrass (*Zostera marina*) meet the criteria as an ecologically significant species? *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2009/018: 11 pp.
- DFO, Department of Fisheries and Oceans. 2009c. Conservation objectives for the ecologically and biologically significant areas (EBSA) of the Estuary and Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.* 2009/049: 10 pp.

- DFO, Department of Fisheries and Oceans. 2009d. Proceedings of the national workshop on the impacts of seals on fish populations in Eastern Canada (Part 2); 24-28 November 2008. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2009/020: x + 126 pp.
- DFO, Department of Fisheries and Oceans. 2010. 2010 Canadian marine ecosystem status and trends report. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/030(Revised): 38 pp.
- DFO, Department of Fisheries and Oceans. 2011a. Social, economic, and cultural overview of the Quebec Region. OHSAR Pub. Ser. Rep. NL Region. No. 0007: xviii + 168 pp.
- DFO, Department of Fisheries and Oceans. 2011b. Social, economic and cultural overview of Western Newfoundland and Southern Labrador. OHSAR Pub. Ser. Rep. NL Region. No. 0008: xx + 173 pp.
- DFO, Department of Fisheries and Oceans. 2011c. Synopsis of the social, economic, and cultural overview of the Gulf of St. Lawrence. OHSAR Pub. Ser. Rep. NL Region. No. 0005: vi + 32 pp.
- DFO, Department of Fisheries and Oceans. 2011d. Impacts of grey seals on fish populations in Eastern Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/071: 48 pp.
- Diaz, R.J. 2001. Overview of hypoxia around the world. *J. Environ. Qual.* 30: 275–281.
- Diaz, R.J. and Rosenberg, R. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanogr. Mar. Biol. Annu. Rev.* 33: 245–303.
- Diaz, R.J. and Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.
- Dickie, L.M. 1958. Effects of high temperature on survival of the giant scallop. *J. Fish. Res. Board Can.* 15: 1189–1211.
- Dickie, L.M. and Medcof, J.C. 1963. Causes of mass mortalities of scallops (*Placopecten magellanicus*) in the southwestern Gulf of St. Lawrence. *J. Fish. Res. Board Can.* 20: 451–482.
- Doney, S.C., Mahowald, N., Lima, I., Feely, R.A., Mackenzie, F.T., Lamarque, J.-F. and Rasch, P.J. 2007. Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. *Proc. Nat. Acad. Sci.* 104: 14580–14585.
- Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A. 2009. Ocean acidification: the other CO₂ problem. *Annu. Rev. Mar. Sci.* 1: 169–192.
- Drinkwater, K.F. and Gilbert, D. 2004. Hydrographic variability in the waters of the Gulf of St. Lawrence, the Scotian Shelf and the Eastern Gulf of Maine (NAFO Subarea 4) during 1991–2000. *J. Northw. Atl. Fish. Sci.* 34: 85–101.
- Drouin, A., McKindsey, C.W. and Johnson, L.E. 2011. Higher abundance and diversity in faunal assemblages due to the invasion of *Codium fragile* ssp. *fragile* in eelgrass meadows. *Mar. Ecol. Prog. Ser.* 424: 105–117.
- Dufour, R. and Ouellet, P. 2007. Estuary and Gulf of St. Lawrence marine ecosystem overview and assessment report. *Can. Tech. Rep. Fish. Aquat. Sci.* 2744E: vii + 112 pp.
- Dufour, R., Benoît, H.P., Castonguay, M., Chassé, J., Devine, L., Galbraith, P.S., Harvey, M., Larouche, P., Lessard, S., Petrie, B.D., Savard, L., Savenkoff, C., St-Amand, L. and Starr, M. 2010. Ecosystem status and trends report: Estuary and Gulf of St. Lawrence ecozone. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/030: v + 187 pp.
- Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmaller, V., Dye, S.R. and Skjoldal, H.R. 2008. Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *J. Appl. Ecol.* 45: 1029–1039.

- Duplisea, D. and Fréchet, A. 2011. Updated reference point estimates for northern Gulf of St. Lawrence (3Pn4RS) cod (*Gadus morhua*) based on revised beginning of year weights at age. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/003: iv + 8 pp.
- Dupont, S., Havenhand, J., Thorndyke, W., Peck, L. and Thorndyke, M. 2008. Near-future level of CO₂-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. Mar. Ecol. Prog. Ser. 373: 285–294.
- Dutil, J.-D. and Lambert, Y. 2000. Natural mortality from poor condition in Atlantic cod (*Gadus morhua*). Can J. Fish. Aquat. Sci. 57: 826–836.
- Dutil, J.-D., Castonguay, M., Gilbert, D. and Gascon, D. 1999. Growth, condition, and environmental relationships in Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence and implications for management strategies in the Northwest Atlantic. Can J. Fish Aquat. Sci. 56: 1818–1831.
- Dutil, J.-D., Sylvestre, E.L., Gamache, L., Larocque, R. and Guderley, H. 2007. Burst and coast use, swimming performance and metabolism of Atlantic cod *Gadus morhua* in sub-lethal hypoxic conditions. J. Fish. Biol. 71: 363–375.
- Edelstein, T., Bird, C. and McLachlan, J. 1973. Investigation of the marine algae of Nova Scotia. XI. Additional species new or rare to Nova Scotia. Can. J. Botany 51: 1741–1746.
- Ekau, W., Auel, H., Pörtner, H.O. and Gilbert, D. 2010. Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). Biogeosci. 7: 1669–1699.
- Elliott, M. 2002. The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. Mar. Pollut. Bull. 44: iii–vii.
- Erskine, D. 1955. Two red algae new to Nova Scotia. Can. Field Nat. 69: 150–151.
- EU, European Union. 2010. Commission Decision of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters (notified under document C(2010) 5956) (Text with EEA relevance 2010/477/EU). Official Journal of the European Union L 232/14.
- EU EEA, European Union European Environment Agency. 2000. Questions to be answered by a state-of-the environment report: The first list. Technical Report No 47. 116 pp.
- Fabricius, K.E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M.S. and Lough, J.M. 2011. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. Nature Climate Change 1: 165–169.
- Fabry, V.J., Seibel, B.A., Feely, R.A. and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci. 65: 414–432.
- Federal, Provincial and Territorial Governments of Canada. 2010. Canadian biodiversity: ecosystem status and trends 2010 [online]. Canadian Councils of Resource Ministers. Ottawa, ON. <http://www.biodivcanada.ca/ecosystems> (accessed 21 September 2011).
- Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Millero, F.J. 2004. Impact of anthropogenic CO₂ on the CaCO₃ system in the oceans. Science 305: 362–366.
- Feely, R.A., Alin, S.R., Newton, J., Sabine, C. L., Warner, M., Devol, A., Krembs, C. and Maloy, C. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. Estuar. Coast. Shelf Sci. 88: 442–449.
- Frank, K.T., Petrie, B., Choi, J.S. and Leggett, W.C. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308: 1621–1623.
- Fry, F.E.J. 1971. The effect of environmental factors on the physiology of fish. In: Hoar, W. S., Randall, D. J. eds., Fish physiology, Academic Press, vol. 6, pp. 1–98.

- Fu, F.-X., Place, A.R., Garcia, N.S. and Hutchins, D.A. 2010. CO₂ and phosphate availability control the toxicity of the harmful bloom dinoflagellate *Karlodinium veneficum*. *Aquat. Microbial. Ecol.* 59: 55–65.
- Galbraith, P.S. 2006. Winter water masses in the Gulf of St. Lawrence. *J. Geophys. Res. (C Oceans)*, 111, C06022, 23 pp.
- Galbraith, P.S., Pettipas, R.G., Chassé, J., Gilbert, D., Larouche, P., Pettigrew, B., Gosselin, A., Devine, L. and Lafleur, C. 2010a. Physical oceanographic conditions in the Gulf of St. Lawrence in 2009. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2010/035: iv + 77 pp.
- Galbraith, P.S., Larouche, P., Gilbert, D., Chassé, J. and Petrie, B. 2010b. Trends in sea-surface and CIL temperatures in the Gulf of St. Lawrence in relation to air temperature. *Atlantic Zone Monitoring Program Bulletin*, Dept. of Fisheries and Oceans Canada, No. 9: 20–23.
- Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G. and Lafleur, C. 2011. Physical oceanographic conditions in the Gulf of St. Lawrence in 2010. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/045: iv + 82 pp.
- Galbraith, P.S., Larouche, P., Chassé, J. and Petrie, B. 2012. Sea-surface temperature in relation to air temperature in the Gulf of St. Lawrence: interdecadal variability and long term trends. *Deep Sea Res. II*, in press.
- Garbary, D.J., Vandermeulen, H. and Kim, K.Y. 1997. *Codium fragile* ssp. *tomentosoides* (Chlorophyta) invades the Gulf of St. Lawrence, Atlantic Canada. *Bot. Mar.* 40: 537–540.
- García, H.E. and Gordon, L.I. 1992. Oxygen solubility in seawater: better fitting equations. *Limnol. Oceanogr.* 37: 1307–1312.
- Gascoigne, J.C. and Lipcius, R.N. 2004. Allee effects driven by predation. *J. Anim. Ecol.* 41: 801–810.
- Gaudet, T. and S. Leger. 2011. Social, economic, and cultural overview of the Gulf Region. *OHSAR Pub. Ser. Rep. NL Region.* No. 0006: viii + 114 pp.
- Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J.-P., Middelburg, J.J. and Heip, C.H.R. 2007. Impact of elevated CO₂ on shellfish calcification. *Geophys. Res. Lett.* 34: L07603.
- Gazeau, F., Gattuso, J.P., Dawber, C., Pronker, A.E., Peene, F., Peene, J., Heip, C.H.R. and Middelburg, J.J. 2010. Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. *Biogeosciences* 7: 2051–2060.
- Genovesi, L., de Vernal, A., Hillaire-Marcel, C., Mucci, A. and Gilbert, D. 2011. Recent changes in bottom water oxygenation and temperature in the Gulf of St. Lawrence: Micropaleontological and geochemical evidence. *Limnol. Oceanogr.* 56: 1319–1329.
- Gilbert, D., Sundby, B., Gobeil, C., Mucci, A. and Tremblay G. H. 2005. A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence Estuary: The northwest Atlantic connection. *Limnol. Oceanogr.* 50: 1654–1666.
- Gilbert, D., Chabot, D., Archambault, P., Rondeau, B. and Hébert, S. 2007. Appauvrissement en oxygène dans les eaux profondes du Saint-Laurent marin: Causes possibles et impacts écologiques. *Nat. Can.* 131: 67–75.
- Gray, J.S., Wu, R.-S. and Or, Y.Y. 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. *Mar. Ecol. Prog. Ser.* 238: 249–279.
- Grégoire, F., Savenkoff, C., Benoît, H., Chabot, D., Lévesque, C., Hudon, J. and Lavers, J. 2004. Capelin (*Mallotus villosus*) fishery, biology and distribution in NAFO Divisions 4RST in 2003. *DFO Can. Sci. Adv. Sec. Res. Doc.* 2004/136: iv + 79 pp.
- Grégoire, F., Savenkoff, C. and Chabot, D. 2005. Capelin (*Mallotus villosus*) of the Estuary and Gulf of St. Lawrence (NAFO Divisions 4RST) in 2004. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2005/058: iv + 55 pp.

- Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *J. Phycol.* 46: 220–235.
- Hammill, M.O. and Stenson, G.B. 2000. Estimated prey consumption by harp seals (*Phoca groenlandica*), hooded seals (*Cystophora cristata*), grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) in Atlantic Canada. *J. Northw. Atl. Fish. Sci.* 26:1–23.
- Hammill, M.O. and Stenson, G.B. 2011. Modelling grey seal abundance in Canadian waters. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/014: iv + 27 pp.
- Hammill, M.O. and Swain, D.P. 2011. A controlled experiment (strawman draft) to test the impact of removals of grey seals on the mortality of southern Gulf cod. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/013: vi + 12 pp.
- Hammill, M.O., Stenson, G.B., Proust, F., Carter, P. and McKinnon, D. 2007. Feeding by grey seals in the Gulf of St. Lawrence and around Newfoundland. *NAMMCO Sci. Publ.* 6: 135–152.
- Hammill, M.O., Stenson, G.B., Doniol-Valcroze, T. and Mosnier, A. 2011. Northwest Atlantic harp seals population trends, 1952-2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/99. iv + 28 pp.
- Hansen, S. and Lavigne, D.M. 1997. Temperature effects on the breeding distribution of grey seals (*Halichoerus grypus*). *Physiol. Zool.* 70: 436–443.
- Hanson, J.M. and Lanteigne, M. 2000. Evaluation of Atlantic cod predation on American lobster in the southern Gulf of St. Lawrence, with comments on other potential fish predators. *Trans. Am. Fish. Soc.* 129:13–29.
- Harrison, G., Sameoto, D.D., Spry, J., Pauley, K., Maass, H., Kennedy, M.K. and Soukhovtsev, V.V. 2006. Optical, chemical and biological oceanographic conditions in the Maritimes/Gulf regions in 2005. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/081: iv + 50 pp.
- Harvey, M. and Devine, L. 2009. Oceanographic conditions in the Estuary and the Gulf of St. Lawrence during 2008: zooplankton. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/083: vi + 54 pp.
- Harvey, V., Hammill, M. and Swain, D.P. 2010. Summer overlap between a central-place forager and its prey in the southern Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/131: vi + 46 pp.
- Hébert, M., Wade, E., Biron, M., DeGrâce, P., Landry, J.-F. and Moriyasu, M. 2010. The 2009 assessment of snow crab, *Chionoecetes opilio*, stock in the southern Gulf of St. Lawrence (Areas 12, 19, 12E and 12F). DFO Can. Sci. Advis. Sec. Res. Doc. 2010/091: vi + 85 pp.
- Herbert, N.A. and Steffensen, J.F. 2005. The response of Atlantic cod, *Gadus morhua*, to progressive hypoxia: fish swimming speed and physiological stress. *Mar. Biol.* 147: 1403–1412.
- Hoos, L.M. 1973. A study of the benthos of an anoxic marine basin and factors affecting its distribution. M.Sc. Thesis. Dalhousie Univ., N.S. 149 pp.
- Hoos, R.A.W. 1970. Distribution and physiology of zooplankton in an oxygen minimum layer. M.Sc. Dissertation. Univ. Victoria, Victoria, B.C. 113 pp.
- Hsieh, C.-H., Reiss, C.S., Hunter, J.R., Beddington, J.R., May, R.M. and Sugihara, G. 2006. Fishing elevates variability in the abundance of exploited species. *Nature* 443: 859–862.
- Hurlbut, T., Morin, R., Surette, T., Swain, D.P., Benoît, H.P. and LeBlanc, C. 2010. Preliminary results from the September 2009 bottom-trawl survey of the southern Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/044. iv + 50 pp.

- Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M. 2003. The North Atlantic Oscillation: climatic significance and environmental impact. Geophysical Monograph 134. American Geophysical Union, Washington. 279 pp.
- ICES, International Council for the Exploration of the Sea. 1999. Introductions and transfers of marine organisms. *In* Report of the Advisory Committee on the Marine Environment, International Council for the Exploration of the Sea. pp 99-103.
- Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-Hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., Dassow, P., Rehm, E., Armbrust, E.V. and Boessenkool, K.P. 2008. Phytoplankton calcification in a high-CO₂ world. *Science* 320: 336–340.
- Ishimatsu, A., Hayashi, M. and Kikkawa, T. 2008. Fishes in high-CO₂, acidified oceans. *Mar. Ecol. Prog. Ser.* 373: 295–302.
- Irie, T., Bessho, K., Findlay, H.S. and Calosi, P. 2010. Increasing costs due to ocean acidification drives phytoplankton to be more heavily calcified: optimal growth strategy of coccolithophores. *PLoS ONE* 5: e13436.
- Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J. and Warner, R.R. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629–638.
- Justic, D., Rabalais, N.N. and Turner, R.E. 1997. Impacts of climate change on net productivity of coastal waters: implications for carbon budgets and hypoxia. *Climate Res.* 8: 225–237.
- Kemp, W.M., Testa, J.M., Conley, D.J., Gilbert, D. and Hagy, J.D. 2009. Temporal responses of coastal hypoxia to nutrient loading and physical controls. *Biogeosciences* 6: 2985–3008.
- Kennedy, V.S. 1990. Anticipated effects of climate change on estuarine and coastal fisheries. *Fisheries* 15: 16–24.
- Klassen, G. and Locke, A. 2007. A biological synopsis of the European green crab, *Carcinus maenas*. *Can. Manuscr. Rep. Fish. Aquat. Sci.* No. 2818: vii + 75 pp.
- Kleypas, J.A. and Yates, K.K. 2009. Coral reefs and ocean acidification. *Oceanography* 22: 108–117.
- Kurihara, H. 2008. Effects of CO₂-driven ocean acidification on the early developmental stages of invertebrates. *Mar. Ecol. Prog. Ser.* 373: 275–284.
- Lavigne, L., and Hammil, M.O. 1993. Distribution and seasonal movements of grey seals, *Halichoerus grypus*, born in the Gulf of St. Lawrence and eastern Nova Scotia shore. *Can. Field Nat.* 107: 329–340.
- Lear, W. 1988. History of fisheries in the Northwest Atlantic: The 500-year perspective. *J. Northw. Atl. Fish. Sci.* 23: 41–73.
- Lesage, V., Gosselin, J.-F., Hammill, M.O., Kingsley, M.C.S. and Lawson, J. 2007. Ecologically and biologically significant areas (EBSAs) in the Estuary and Gulf of St. Lawrence – A marine mammal perspective. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2007/046: iii + 92 pp.
- Lessard, R.B., Martell, S., Walters, C.J., Essington, T.E. and Kitchell, J.F.K. 2005. Should ecosystem management involve active control of species abundance? *Ecology and Society* 10 (2):1, [online]. <http://www.ecologyandsociety.org/vol10/iss2/art1/> (accessed 21 September 2011).
- Levin, L.A., Ekau, W., Gooday, A.J., Jorissen, F., Middelburg, J.J., Naqvi, S.W.A., Neira, C., Rabalais, N.N. and Zhang, J. 2009. Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosci.* 6: 2063–2098.

- Lien, J., Stenson, G.B. and Jones, P.W. 1989. A natural trap for blue whales *Balaenoptera-Musculus* - sightings and ice entrapments in Newfoundland (1979-1988). *Am. Zool.* 29: A44–A44.
- Link, J.S. and Garrison, L.P. 2002. Changes in piscivory associated with fishing induced changes to the finfish community on Georges Bank. *Fish. Res.* 55: 71–86.
- Locke, A., Hanson, J.M., Ellis, K.M., Thompson, J. and Rochette, R. 2007. Invasion of the southern Gulf of St. Lawrence by the clubbed tunicate (*Styela clava* Herdman): Why have estuaries in Prince Edward Island been more susceptible? *J. Exp. Mar. Biol. Ecol.* 342: 69–77.
- Locke, A., Hanson, J.M., MacNair, N.G. and Smith, A.H. 2009. Rapid response to non-indigenous species. 2. Case studies of invasive tunicates in Prince Edward Island. *Aquatic Invasions* 4: 249–258.
- Locke, A., Mandrak, N.E. and Therriault, T.W. 2010. A Canadian rapid response framework for aquatic invasive species. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2010/114: vi + 30 pp.
- MacCrimmon, H.R. 1971. World distribution of rainbow trout (*Salmo gairdneri*). *J. Fish. Res. Board Can.* 28: 663–704.
- MacNeil, M.A., Graham, N.A.J., Cinner, J.E., Dulvy, N.K., Loring, P.A., Jennings, S., Polunin, N.V.C., Fisk, A.T. and McClanahan, T.R. 2010. Transitional states in marine fisheries: adapting to predicted global change. *Philos. Trans. R. Soc. Lond. Ser. B.* 365: 3753–3763.
- Mansfield, A.W. and Beck, B. 1977. The grey seal in eastern Canada. *Dept. Environ., Fish. And Mar. Serv. Tech. Rep. No.* 704. 81 pp.
- Marsh, R., Petrie, B., Weidman, C.R., Dickson, R.R., Loder, J.W., Hannah, C.G., Frank, K.T. and Drinkwater, K. 1999. The 1882 tilefish kill - a cold event in the shelf waters off the north-eastern United States? *Fish. Oceanogr.* 8: 39–49.
- McLeod, B.A., Brown, M.W., Moore, M.J., Stevens, W., Barkham, S.H., Barkham, M. and White, B.N. 2008. Bowhead whales, and not right whales, were the primary target of 16th to 17th century Basque whalers in the western North Atlantic. *Arctic* 61: 61–75.
- McKindsey, C.W., Landry, T., O'Beirn, F.X. and Davies, I.M. 2007. Bivalve aquaculture and exotic species: a review of ecological considerations and management issues. *J. Shellfish Res.* 26: 281–294.
- McNeely, J.A., Mooney, H.A., Neville, L.E., Schei, P.J. and Waage, J.K. (eds). 2001. A global strategy on invasive alien species. Cambridge: IUCN Global Invasive Species Programme. 50 pp.
- McQuinn, I. H. 2009. Pelagic fish outburst or suprabenthic habitat occupation: legacy of the Atlantic cod (*Gadus morhua*) collapse in eastern Canada. *Can. J. Fish. Aquat. Sci.*, 66: 2256–2262.
- Miller, A.W., Reynolds, A.C., Sobrino, C. and Riedel, G.F. 2009. Shellfish face uncertain future in high CO₂ world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS. ONE* 4: e5661.
- Miller, D., Poucher, S. and Coiro, L. 2002. Determination of lethal dissolved oxygen levels for selected marine and estuarine fishes, crustaceans, and a bivalve. *Mar. Biol.* 140: 287–296.
- Mora, C., Metzger, R., Rollo, A. and Myers, R.A. 2007. Experimental simulations about the effects of overexploitation and habitat fragmentation on populations facing environmental warming. *Proc. R. Soc. B.* 274: 1023–1028.
- Morissette, L. and Hammill, M.O. 2011. A preliminary evaluation of the impacts of grey seal, *Halichoerus grypus*, predation on the 4T ecosystem and possible effects of their removal on cod recovery. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/016. iv + 27 pp.

- Mowbray, F.K. 2002. Changes in the vertical distribution of capelin (*Mallotus villosus*) off Newfoundland. ICES J. Mar. Sci. 59: 942–949.
- Mucci, A., Starr, M., Gilbert, D. and Sundby, B. 2011. Acidification of Lower St. Lawrence Estuary bottom waters. Atmos.-Ocean 49: 206–218.
- Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V. and Dowling, K.B. 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. Proc. Nat. Acad. Sci. 106: 1848–1852.
- Mullon, C., Fréon, P. and Cury, P. 2005. The dynamics of collapse in world fisheries. Fish Fish. 6: 111–120.
- Needler, A.W.H. 1931. A preliminary account of the oyster disease of 1915-1916 in Malpeque Bay. Fish. Res. Board Can., Manuscript Reports of the Biological Stations 287: 1–12.
- Nevison, C., Butler, J.H. and Elkins, J.W. 2003. Global distribution of N₂O and the deltaN₂O-AOU yield in the subsurface ocean. Global Biogeochem. Cycles 17: 1119.
- Newkirk, G.F., Muise, B.C. and Enright, C.E. 1995. Culture of the Belon oyster, *Ostrea edulis*, in Nova Scotia. In Cold-water aquaculture in Atlantic Canada. Edited by A.D. Boghen. Tribune Printing, Sackville, NB. pp 225-253.
- Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matar, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y. and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681–686.
- Ouellet, P., Fuentes-Yaco, C., Savard, L., Platt, T., Sathyendranath, S., Koeller, P., Orr, D. and Siegstad, H. 2011. Ocean surface characteristics influence recruitment variability of populations of northern shrimp (*Pandalus borealis*) in the Northwest Atlantic. ICES J. Mar. Sci. 68: 737–744.
- Parker, L.M., Ross, P.M. and O'Connor, W.A. 2009. The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster *Saccostrea glomerata* (Gould 1850). Global Change Biol. 15: 2123–2136.
- Parnesan, C. and Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37–60.
- Pepin, P., Petrie, B., Therriault, J.-C., Narayanan, S., Harrison, W.G., Frank, K.T., Chassé, J., Colbourne, E.B., Gilbert, D., Gregory, D., Harvey, M., Maillet, G.L., Mitchell, M. and Starr, M. 2005. The Atlantic Zone Monitoring Program (AZMP): Review of 1998-2003. Can. Tech. Rep. Hydrogr. Ocean Sci. 242: v + 87 pp.
- Perry, A.L., Low, P.J., Ellis, J.R., and Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. Science 308: 1912–1915.
- Petchey, O.L., McPhearson, P.T., Casey, T.M. and Morin, P.J. 1999. Environmental warming alters food-web structure and ecosystem function. Nature 402: 69–72.
- Petchey, O.L., Brose, U. and Rall, B.C. 2010. Predicting the effects of temperature on food web connectance. Philos. Trans. R. Soc. Lond. Ser. B. 365: 2081–2091.
- Petrie, B. 2007. Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmos.-Ocean 45: 141–151.
- Plante, F. and Courtenay, S.C. 2008. Increased oxygenation of sediment in Lamèque Bay (New Brunswick) following removal of algae and reduction of nutrient inputs from a seafood processing plant. Can. Tech. Rep. Fish. Aquat. Sci. 2805: v + 36 pp.

- Plante, S., Chabot, D. and Dutil, J.-D. 1998. Hypoxia tolerance in Atlantic cod. *J. Fish Biol.* 53: 1342–1356.
- Platt, T., Fuentes-Yaco, C. and Frank, K.T. 2003. Spring algal bloom and larval fish survival. *Nature* 423: 398–399.
- Plourde, S., Dodson, J.J., Runge, J.A. and Therriault, J.-C. 2002. Spatial and temporal variations in copepod community structure in the Lower St. Lawrence Estuary, Canada. *Mar. Ecol. Prog. Ser.* 230: 211–224.
- Polyakova, E., Journal, A., Polyakov, I. and Bhatt, U.S. 2006. Changing relationship between the North Atlantic Oscillation and key North Atlantic climate parameters. *Geophys. Res. Lett.* 33: L03711.
- Rabalais, N.N., Turner, R.E. and Wiseman, W.J. Jr. 2002. Gulf of Mexico hypoxia: a.k.a. "The dead zone." *Annu. Rev. Ecol. Evol. Syst.* 33: 235–235.
- Rabalais, N.N., Diaz, R.J., Levin, L.A., Turner, R.E., Gilbert, D. and Zhang, J. 2010. Dynamics and distribution of natural and human-caused hypoxia. *Biogeosci.* 7: 585–619.
- Ramsay, A., Davidson, J., Bourque, D. and Stryhn, H. 2009. Recruitment patterns and population development of the invasive ascidian *Ciona intestinalis* in Prince Edward Island, Canada. *Aquatic Invasions* 4: 169–176.
- Ricker, W. E. 1980. Calcul et interprétation des statistiques biologiques des populations de poissons. *Bull. Fish. Res. Board Can.* 191F: 409 pp.
- Riebesell, U., Wolf-Gladrow, D.A. and Smetacek, V. 1993. Carbon dioxide limitation of marine phytoplankton growth rates. *Nature* 361: 249–251.
- Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E. and Morel, F.M.M. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO₂. *Nature* 407: 364–367.
- Riebesell, U., Kortzinger, A. and Oschlies, A. 2009. Sensitivities of marine carbon fluxes to ocean change. *Proc. Nat. Acad. Sci.* 106: 20602–20609.
- Ries, J.B., Cohen, A.L. and McCorkle, D.C., 2009. Marine calcifiers exhibit mixed responses to CO₂-induced ocean acidification. *Geology* 37: 1131–1134.
- Rose, G.A. 2004. Reconciling overfishing and climate change with stock dynamics of Atlantic cod (*Gadus morhua*) over 500 years. *Can. J. Fish. Aquat. Sci.* 61: 1553–1557.
- Rosing-Asvid A. 2008. A new harp seal whelping ground near South Greenland. *Mar. Mammal. Sci.* 24: 730–736.
- Rost, B., Riebesell, U., Burkhardt, S. and Sültemeyer, D. 2003. Carbon acquisition of bloom-forming marine phytoplankton. *Limnol. Oceanogr.* 48: 55–67.
- Rost, B., Zondervan, I. and Wolf-Gladrow, D. 2008. Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Mar. Ecol. Prog. Ser.* 373: 227–237.
- Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.-H., Kozyr, A., Ono, T. and Rios, A.F. 2004. The oceanic sink for anthropogenic CO₂. *Science* 305: 367–371.
- Sainte-Marie, B., Gosselin, T., Sevigny, J.M., and Urbani, N. 2008. The snow crab mating system: Opportunity for natural and unnatural selection in a changing environment. *Bull. Mar. Sci.* 83:131–161.
- Savenkoff, C., Bourassa, M.-N., Baril, D. and Benoît, H.P. 2007a. Identification of ecologically and biologically significant areas for the Estuary and Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2007/015: iv + 49 pp.

- Savenkoff, C., Castonguay, M., Chabot, D., Hammill, M.O., Bourdages, H. and Morissette, L. 2007b. Changes in the northern Gulf of St. Lawrence ecosystem estimated by inverse modelling: Evidence of a fishery-induced regime shift? *Est. Coast. Shelf Sci.* 73: 711–724.
- Savenkoff, C., Swain, D.P., Hanson, J.M., Castonguay, M., Hammill, M.O., Bourdages, H., Morissette, L. and Chabot, D. 2007c. Effects of fishing and predation in a heavily exploited ecosystem: comparing periods before and after the collapse of groundfish in the southern Gulf of St. Lawrence (Canada). *Ecol. Model.* 204: 115–128.
- Schmittner, A., Oschlies, A., Matthews, H.D. and Galbraith, E.D. 2008. Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO₂ emission scenario until year 4000 AD. *Global Biogeochem. Cycles* 22: GB1013.
- Schurmann, H. and Steffensen, J.F. 1997. Effects of temperature, hypoxia and activity on the metabolism of juvenile Atlantic cod. *J. Fish Biol.* 50: 1166–1180.
- Seibel, B.A. and Walsh, P.J. 2003. Biological impacts of deep-sea carbon dioxide injection inferred from indices of physiological performance. *J. Exp. Biol.* 206: 641–650.
- Senneville, S., and Saucier, F. 2007. Étude de sensibilité de la glace de mer au réchauffement climatique dans le golfe et l'estuaire du Saint-Laurent. *Ouranos Report*. 30 pp.
- Sergeant, D.E. 1991. Harp seals, man and ice. *Can. Spec. Publ. Fish. Aquat. Sci.* 114: 153 pp.
- Shelton, P.A., Sinclair, A.F., Chouinard, G.A., Mohn, R. and Duplisea, D.E. 2006. Fishing under low productivity conditions is further delaying recovery of Northwest Atlantic cod (*Gadus morhua*). *Can. J. Fish. Aquat. Sci.* 63: 235–238.
- Simberloff, D. and Rejmánek, M. 2011. *Encyclopedia of biological invasions*. University of California Press. 760 pp.
- Sinclair, A.F. and Murawski, S.A. 1997. Why have groundfish stocks declined? *In* Northwest Atlantic groundfish: perspectives on a fishery collapse. *Edited by* J. Boreman, B.S. Nakashima, J.A. Wilson, and R.L. Kendall. American Fisheries Society, Bethesda, MD. pp 71–94.
- South, G.R. and Hooper, R.G. 1976. *Stictyosiphon soriferus* (Phaeophyta, Dictyosiphonales) from eastern North America. *J. of Phycol.* 12: 24–29.
- Stenson, G.B. and M.O. Hammill. 2011. Living on the edge: Observations of Northwest Atlantic harp seals in 2010 and 2011. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2011/108.
- Stephenson, T.A. and Stephenson, A. 1954. Life between tide-marks in North America. III. A. Nova Scotia and Prince Edward Island: description of the region. *J. Ecol.* 42: 14–45.
- Stigebrandt, A. and Gustafsson, B.G. 2007. Improvement of Baltic proper water quality using large-scale ecological engineering. *AMBIO* 36: 280–286.
- Sun, J., Hutchins, D.A., Feng, Y., Seubert, E.L., Caron, D.A. and Fu, F.-X. 2011. Effects of changing pCO₂ and phosphate availability on domoic acid production and physiology of the marine harmful bloom diatom *Pseudo-nitzschia multiseriata*. *Limnol. Oceanogr* 56: 829–840.
- Swain, D.P. and Chouinard, G.A. 2008. Predicted extirpation of the dominant demersal fish in a large marine ecosystem: Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. *Can. J. Fish. Aquat. Sci.* 65:2315–2319.
- Swain, D.P., Jonsen, I.D., Simon, J.E. and Myers, R.A. 2009a. A stage-structured state-space model to assess threats and management scenarios for data-deficient species-at-risk: Estimating mortality trends in winter skate (*Leucoraja ocellata*, Family Rajidae). *Ecol. Appl.* 19: 1347–1364.
- Swain, D.P., Savoie, L., Hurlbut, T., Surette, T. and Daigle, D. 2009b. Assessment of the southern Gulf of St. Lawrence cod stock, February 2009. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2009/037: vi + 129 pp.

- Swain, D.P., Benoît, H.P., Savoie, L., and Surette, T. 2011a. Can poor fish condition explain the elevated natural mortality of cod and other marine fish in the southern Gulf of St. Lawrence? DFO Can. Sci. Adv. Sec. Res. Doc. 2011/037. iv + 26 pp.
- Swain, D.P., Benoît, H.P., Hammill, M.O., McClelland, G., and Aubrey, É. 2011b. Alternative hypotheses for causes of the elevated natural mortality of southern Gulf cod: the weight of evidence. DFO Can. Sci. Adv. Sec. Res. Doc. 2011/036. iv + 33 pp.
- Swain, D.P., Benoît, H.P. and Hammill, M.O. 2011c. Grey seal reduction scenarios to restore the southern Gulf of St. Lawrence cod population. DFO Can. Sci. Adv. Sec. Res. Doc. 2011/035: iv + 8 pp.
- Therriault, J.-C. (ed.). 1991. The Gulf of St. Lawrence: small ocean or big estuary? Can. Spec. Publ. Fish. Aquat. Sci. 113, 359 pp.
- Thomas, L., Hammill, M.O. and Bowen, W.D. 2011. Estimated size of the Northwest Atlantic grey seal population 1977-2010. DFO Can. Sci. Adv. Sec. Res. Doc. 2011/017: iv + 23 pp.
- Tortell, P.D., Martin, C.L. and Corkum, M.E. 2006. Inorganic carbon uptake and intracellular assimilation by subarctic Pacific phytoplankton assemblages. *Limnol. Oceanogr.* 51: 2102–2110.
- Tortell, P.D., Payne, C.D., Li, Y., Trimborn, S., Rost, B., Smith, W.O., Riesselman, C., Dunbar, R.B., Sedwick, P. and DiTullio, G.R. 2008. CO₂ sensitivity of Southern Ocean phytoplankton. *Geophys. Res. Lett.* 35: L04605.
- Townshend, E.R. and Worms, J.M. 1983. Introduction of a new pectinid species *Argopecten irradians irradians* to the Gulf of St. Lawrence, Canada. ICES Council Meeting 1983 (Collected Papers), ICES, Copenhagen, Denmark, 13 pp.
- Turley, C., Eby, M., Ridgwell, A.J., Schmidt, D.N., Findlay, H.S., Brownlee, C., Riebesell, U., Fabry, V.J., Feely, R.A. and Gattuso, J.-P. 2010. Editorial: The societal challenge of ocean acidification. *Mar. Pollut. Bull.* 60: 787–792.
- Tyrrell, T., Schneider, B., Charalampopoulou, A. and Riebesell, U. 2008. Coccolithophores and calcite saturation state in the Baltic and Black Seas. *Biogeosci.* 5: 485–494.
- UNCTAD, United Nations Conference on Trade and Development. 2011. Review of maritime transport 2011. UNCTAD/RMT/2011. 229 pp.
- UNEP/GRID-Arendal. 2002. DPSIR framework for state of environment reporting. Maps and Graphics Library.
http://maps.grida.no/go/graphic/dpsir_framework_for_state_of_environment_reporting
(accessed 21 September 2011).
- Van der Putten, W.H., Macel, M. and Visser, M.E. 2010. Predicting species distribution and abundance responses to climate change: why it is essential to include biotic interactions across trophic levels. *Philos. Trans. R. Soc. Lond. Ser. B.* 365: 2025–2034.
- Vaquer-Sunyer, R. and Duarte, C.M. 2008. Thresholds of hypoxia for marine biodiversity. *Proc. Nat. Acad. Sci.* 105: 15452–15457.
- White, L. and Johns, F. 1997. Marine environmental assessment of the Estuary and Gulf of St. Lawrence. Programme d'étude des produits chimiques toxiques 1997. Fisheries and Oceans Canada. Dartmouth, Nova Scotia and Mont-Joli, Québec. 128 pp.
- Whiteley, N.M. 2011. Physiological and ecological responses of crustaceans to ocean acidification. *Mar. Ecol. Prog. Ser.* 430: 257–271.
- Willis, J.E., Stewart-Clark, S., Greenwood, S., Davidson, J. and Quijon, P. 2011. A PCR-based assay to facilitate early detection of *Diplosoma listerianum* in Prince Edward Island. *Aquatic Invasions* 6: 7–16.

- Worm, B. and Myers, R.A. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. *Ecology* 84: 162–173.
- Worthy, G.A.J. and Lavigne, D.M. 1987. Mass loss, metabolic rate and energy utilization by harp and gray seal pups during the postweaning fast. *Physiol. Zool.* 60: 352–364.
- Wu, R.S.S. 2002. Hypoxia: from molecular responses to ecosystem responses. *Mar. Pollut. Bull.* 45: 35–45.
- Zuur, A.F, Tuck, I.D. and Bailey, N. 2003. Dynamic factor analysis to estimate common trends in fisheries time series. *Can. J. Fish. Aquat. Sci.* 60: 542–552.

Appendix 1. List of acronyms.

AIS	Aquatic invasive species
CIL	Cold intermediate layer
CO ₂	Carbon dioxide
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CSAS	Canadian Science Advisory Secretariat
DFA	Dynamic factorial analysis
DFO	Department of Fisheries and Oceans
DO	Dissolved oxygen
DPSIR	Driver pressure state impact response
EBSA	Ecologically and biologically significant areas
EGSL	Estuary and Gulf of St. Lawrence
ESS	Ecologically significant species
ESTR	Ecosystem Status and Trends Report
GFC	Gulf Fisheries Center
GOSLIM	Gulf of St. Lawrence Integrated Management
GSL	Gulf of St. Lawrence
H ⁺	Hydrogen ions
H ₂ S	Hydrogen sulfide gas
HOTO	Health of the Ocean
ICES	International Council for the Exploration of the Sea
LOMA	Large Ocean Management Area
MLI	Maurice Lamontagne Institute
N ₂ O	Nitrous oxide
NACW	North Atlantic Central Water
NAFO	Northwest Atlantic Fisheries Organization
NAO	North Atlantic Oscillation
O ₂	Oxygen
PETM	Paleocene-Eocene Thermal Maximum
SE	Standard error
SOTO	State of the Oceans
Spp.	Species
SST	Sea surface temperature
YOY	Young of the year
ZEGO	Zone Étendue de Gestion des Océans