1.8 The Arctic cod (Boreogadus saida) ecosystem under the double pressure of climate change and industrialization (Arctic Cod)

**Project Leader**

Louis Fortier (Université Laval)

**Project Team**

**Network Investigators**

Yves Gratton (Institut national de la recherche scientifique - Eau, Terre et Environnement); Yvan Simard (Université du Québec à Rimouski); Jean-Eric Tremblay (Université Laval)

**Collaborators and Research Associates**

Shani Rousseau (ArcticNet Inc.); Dominique Robert (Québec-Océan); Alexandre Forest, Maxime Geoffroy, Makoto Sampei (Université Laval)

**Postdoctoral Fellows**

Keita Suzuki (Université Laval)

**PhD Students**

Delphine Benoit, Caroline Bouchard, Gerald Darnis, Jordan Grigor, Stephane Thanassekos (Université Laval)

**MSc Students**

Marie-Claude Perreault (Université Laval)

**Undergraduate Students**

Solemn Mordret (Université Laval)

**Technical and Project Staff**

Hélen Cloutier, Louis Letourneau (Université Laval)
ABSTRACT

The Arctic cod (Boreogadus saida), also known as the polar cod in Europe, is a key component of the Arctic Ocean pelagic ecosystem that effects up to 75% of the energy transfer between the plankton and the vertebrate fauna (fish, seals, whales and marine birds). Being an hyper-specialist adapted to life in ice-covered seas, Arctic cod is likely to be displaced by southern generalists such as the capelin and the sandlance as the ice regime becomes less severe. This project collaborates closely with “Hotspots”, “Moorings” and “Sea-ice” to map the distribution and migrations of Arctic cod populations in the Canadian Arctic, and to measure variations in hatching season and early growth in relation to annual changes in ice regime, surface temperature, and zooplankton prey abundance. In partnership with the Oil Exploration sector and the Department of Aboriginal Affairs and Northern Development (Beaufort Regional Environmental Assessment program), we assess the general distribution and reproduction of Arctic cod in the Beaufort Sea and the potential environmental risks of exploratory drilling on its ecology.

KEY MESSAGES

1. Seasonally migrating zooplankton assimilate carbon in the surface layer and respire it at depth. A first ever measurement of this vertical respiratory flux over an annual cycle shows that this process contributes significantly to the sequestration of atmospheric carbon dioxide by the Arctic Ocean;

• Since 2002, reduced ice cover and increased upwelling in the Beaufort Sea have boosted the population levels of the copepod Calanus glacialis, a major prey of the juvenile and adult stages of Arctic cod;

• The hatching season of Arctic cod extends from January to July in Arctic seas influenced by large rivers (Beaufort, Laptev, Hudson Bay) and is limited to May-July in other regions;

• An Individual-Based Model (IBM) of Arctic cod bioenergetics successfully reproduced the observed growth and survival (0-45 d) of juveniles in the Northeast Water in 1993 and in the North Water in 1998, opening the way to modelling the response of Arctic cod to a decline in ice cover and the warming of the surface layer;

• Starting in 2010 and again in 2011, significant numbers of Pacific sand lance (Amodytes pacificus) juveniles were detected for the first time in the offshore distribution area of Arctic cod juveniles, indicating that sand lance could have started displacing Arctic cod as the sea-ice regime becomes less severe;

• In the Amundsen Gulf, spawning Arctic cod start aggregating at depth precisely when the ice cover consolidate in early December, and disperse with the ice breakup in April. Aggregations move to deeper areas as the photoperiod lengthens.

• Contrary to expectations, Arctic cod does not seems to form dense schools in the surface layer of the offshore Beaufort Sea in late summer;

• The acoustic signatures (target strengths) of different marine mammals in a 1.5 km radius around the Amundsen have been measured in August-September 2011 with a SX90 fisheries sonar. These will help identify, monitor, and avoid marine mammals during scientific and seismic operations.

OBJECTIVES

• Describe decadal variations (2002-2016) in the late-summer absolute and relative abundance of the main arctic copepods and their predators (Arctic cod, chaetognaths, and the hyperiid amphipod Themisto libellula) in the Beaufort Sea;

• Track with unprecedented vertical resolution the seasonal migration at depth of the large calanoid copepods Calanus glacialis and C. hyperboreus and their lipid reserves using the new LOKI in-situ image profiler;
• Quantify with greater accuracy the role of copepod respiration and migration in the export of biogenic carbon from the surface Arctic layer to the deep Atlantic layer;

• Assess regional and interannual (2002-2016) variations in the prey field and food intake of larval and juvenile Arctic cod in the Beaufort Sea and North Water;

• Correlate decadal variations (2002-2016) in the hatch date frequency distribution of Arctic cod to variations in sea ice cover and surface temperature in the Beaufort Sea;

• Apply our IBM of Arctic cod early growth to model and explain seasonal and interannual differences in the growth trajectory of juveniles captured in late summer in the Beaufort Sea from 2002 to 2012;

• Determine the summer distribution of adult and juvenile Arctic cod and their marine mammal predators in southeastern Beaufort Sea;

• Detect regional variations in the population genetics of Arctic cod using microsatellite markers;

• Document the vertical and horizontal distribution of Arctic cod and zooplankton under the ice cover of the Canadian Arctic Ocean using sonars carried by an Autonomous Underwater Vehicle (AUV).

INTRODUCTION

The pelagic ecosystem of the Arctic Ocean provides local communities with many goods and services that include waterways in summer and ice-ways in winter, traditional food (fish, marine mammals and birds), “traditional” health (omega-3, selenium, etc.), furs and leather, heating oil, substrates for sculpture (e.g. bones and ivory), inspiration for the arts, social cohesion, intergenerational bonding, spiritual comfort, and life fulfilling. As the sea-ice cover of Arctic seas declines and their surface layer warms up, signs of the expected replacement of the unique Arctic pelagic ecosystem by North-Atlantic and North-Pacific ecosystem types are increasingly detected (e.g. Tynan and DeMaster 1997; Gaston et al. 2003, Grebmeier et al. 2006). The atlantification/pacification of the Arctic pelagic ecosystem threatens the services rendered to northern communities, and harbingers a shift to different ecosystem services that will benefit primarily southern industries: for instance, access to oil and other mineral resources, new shipping lanes, fish stocks of commercial interest, and ecotourism.

The objective of ArcticNet Integrated Regional Impact Studies (IRISes) is to provide Inuit communities, the private sector, and governments with the relevant scientific information to formulate the policies, adaptation strategies, and decisions that will shape the response of Canada to climate change and modernization in the Arctic. As far as marine ecosystem services are concerned, anticipating the rate and timing of the expected transformation of the pelagic Arctic ecosystem is a crucial element for all four IRISes. The Arctic cod (Boreogadus saida) is a key component of the relatively simple Arctic Ocean pelagic ecosystem. This small forage fish channels up to 75% of the energy transfer between the plankton and the vertebrates such as fish, seals, whales and marine birds that supply many ecosystem services (Welch et al. 1992). A hyper-specialist adapted to life in ice-covered seas, Arctic cod is likely to be rapidly displaced by southern generalists as the ice regime becomes less severe. In northern Hudson Bay where ice decline is intense, capelin (Mallotus villosus) and sand lance (Ammodytes spp.) have replaced Arctic cod as the main prey brought back to the nest to feed young thick-billed murres (Gaston et al. 2003). Similarly, in the Beaufort Sea where ice retreat is also severe, our own studies of the ichthyoplankton assemblage indicate the recent intrusion of the Pacific sand lance in the offshore distribution area of juvenile Arctic cod. We believe that changes in the ecology of Arctic cod, including its displacement by boreal forage fishes, are among the most powerful indicators of the transition of the Arctic Ocean pelagic ecosystem to a new equilibrium.

The Arctic Cod project collaborates closely with the “Hotspots”, “Moorings” and “Sea-ice” projects to map the distribution of Arctic cod in the Canadian Arctic, to measure variations in its hatching season and early growth in relation to annual changes in ice regime, sur-
face temperature, and zooplankton prey abundance, and to monitor changes in the ichthyoplankton assemblage to which it belongs. We also focus on numerical models of the early growth and survival of the juveniles. In partnership with the Oil Exploration sector and the Department of Aboriginal Affairs and Northern Development (Beaufort Regional Environmental Assessment program), we contrast the abundance and reproduction of Arctic cod among different regions of the Beaufort Sea, including the edge of the continental shelf where oil exploration rights have been awarded, so as to assess the potential risks of exploration drilling on the Arctic cod ecosystem. Starting in 2011, our team has initiated collaborations with the Nunavut Department of Environment, Fisheries and Sealing, to coordinate operations between the Amundsen and the research trawler Nuliajuk with the objective of documenting the invasion of Cumberland Sound by capelin.

ACTIVITIES

Time frame and study area. In 2011-2012, the team pursued the monitoring of zooplankton, larval fish, and adult Arctic cod based on the annual ArcticNet mission to the Canadian Arctic on board the CCGS Amundsen. Since 2002, we have collected zooplankton samples annually and measured the taxonomic composition of the zooplankton assemblage, species abundance, and developmental stages frequency of the main copepod species at the end of the summer in different regions of the Canadian Arctic with emphasis on the Beaufort Sea. The abundance and vertical distribution of juvenile and adult fish (mainly Arctic cod) was assessed for the 15 m to bottom layer along the track of the ship using the EK60 fish finder. In 2011-2012, much effort was invested in the successful installation and deployment of the SX90 fisheries sonar for the detection of fish schools and marine mammals in a 1-2 km radius around the ship, including the insonification of the surface layer (0-15 m) which until now we could not study.

Research activities in 2011-2012

- Installation on the Amundsen and preliminary test at sea of the new SX90 fisheries sonar;
- Extensive test of the SX90 in the Gulf of St. Lawrence, the Labrador Sea, Baffin Bay and Lancaster Sound with the successful detection of fish school and the acquisition of target strength for marine mammals including ringed seals, minke whales and right whales;
- Joint survey of fish distribution in Cumberland Sound combining SX90 and EK60 acoustic surveys by the Amundsen with experimental trawling by the new Nunavut research trawler Nuliajuk;
- Sampling of zooplankton and ichthyoplankton at all basic stations along the ship track from Baffin Bay to the Beaufort Sea and return via the North Water;
- Extensive acoustic surveys (EK60 and SX90) of fish and marine mammal distributions in the Beaufort Sea as part of the Beaufort Region Environmental Assessment (BREA);
- The completion and publication of our Individual Based Model of juvenile (0-45 d) Arctic cod growth and survival for the North Water and Northeast Water;
- First ever assessment of the flux of carbon linked to the annual cycle of vertical migration and respiration of zooplankton in the Arctic Ocean (Beaufort Sea);
- Analysis of interannual variations (2002-2009) in the abundance of copepod species in relation to sea-ice cover and upwelling in the Beaufort Sea;
- First acoustic description and publication of the offshore winter distribution and aggregation behaviour of Arctic cod in the Arctic Ocean (Amundsen Gulf);
- Successful completion of major research partnerships with IOL and BP on the ecological importance of the offshore exploration claims relative to the overall Beaufort Sea;
- Successful completion of two doctoral theses, respectively on the IBM modeling of Arctic cod early bioenergetics (Thanassekos) and the acoustic study of Arctic cod distribution (Benoit);
• Analysis of zooplankton collections for the Nunatsiavut Fjords project;

RESULTS

In the relatively simple ecosystem of the Arctic Ocean, copepods and the Arctic cod channel most of the carbon and energy from ice algae and phytoplankton (the primary producers) to the vertebrate fauna (fish, marine mammals, marine birds) that provide services to communities. The magnitude and efficiency of this trophic flux of carbon is strongly influenced by physical conditions such as sea-ice regime, temperature, wind mixing, and the upwelling of nutrients. The “Moorings” and “Hotspots” projects examine how ocean climate control primary production and the vertical flux of carbon (the fraction of primary production that ends up sequestered at depth). In close collaboration with these projects, the Arctic Cod project focuses in addition on the trophic flux of carbon that underpins ecosystem services.

Zooplankton respiration and the transfer at depth of atmospheric carbon (Darnis et al. in press)

In Arctic seas, lipids accumulated by zooplankton migrants in the surface layer in spring-summer are respired at depth during the winter. The resulting active downward transport of carbon by the 200-1000 and >1000 μm mesozooplankton fractions was quantified based on 41 biomass and respiration profiles from October 2007 to July 2008 in the Amundsen Gulf (Canadian Arctic Ocean). The small fraction, dominated by CII-CIII of the copepod Calanus glacialis, represented on average 12% of the overall zooplankton biomass and contributed little to the active transport of carbon by respiration. From April to July, total zooplankton ingested 17-28% of the estimated gross primary production (GPP) in the surface 100 m, and 36-59% of GPP over the entire water column. The large fraction, comprised mainly of CIV, CV and adults Calanus hyperboreus and C. glacialis that accumulate large lipid reserves, was responsible for 89% of grazing. The downward migration of large zooplankton in late summer (Figure 1) coincided with a sharp decline in specific respiration rates signalling the start of diapause and the endogenous fueling of metabolism. From October to April, Calanus

![Figure 1. Time-depth section of community respiration as carbon loss for the >1000 μm zooplankton size fraction in southeastern Beaufort Sea from October 2007 to July 2008 (CFL program). Vertical lines correspond to the date of biomass and respiration profiles. White surfaces indicate missing data. From Darnis and Fortier 2012.](image1)

![Figure 2. Active respiratory flux and gravitational POC fluxes below 100 m depth in 2007-2008 (a) and below 200 m depth in the Amundsen Gulf (b). CA08, CA16 and CA18 are the mooring stations in the Amundsen Gulf where the gravitational POC fluxes were measured.](image2)
migration-respiration actively transported 3.1 g C m\(^{-2}\) beyond 100 m, a flux that represented 85 to 132% of the gravitational POC fluxes at 100 m from October to July (Figure 2). Our results stress the importance of including active transport by large zooplankton migrants in carbon budgets of the Arctic Ocean.

**Sea-ice decline, upwelling and copepod abundance in the Beaufort Sea (Suzuki et al. ms)**

Interannual time series correlating physical and biological processes to measure the response of Arctic Ocean ecosystems to climate variability are few. From 2002 to 2007, a progressive reduction in the summer ice cover of the Beaufort Sea favoured the upwelling of nutrients from depth. We assessed the potential response of copepod populations to upwelling by tracking the abundance and developmental composition of the main copepod species from September to November of each year on the Mackenzie Shelf and in the offshore Beaufort Sea. An index of cumulated potential wind-driven upwelling over the spring-summer season was calculated for each year based on sea ice concentration and dominant wind forcing. The upwelling potential is a dimensionless index of the probability of wind-driven upwelling prior to the sampling of zooplankton in a given year. In 2005, 2006 and 2007, upwelling-favourable winds dominated during ice-free periods. Beyond the shelf break, total copepod density increased significantly from 2004 (annual mean: 60000 copepods m\(^{-2}\)) to 2007 (170000 copepods m\(^{-2}\)), primarily due to increased abundance of small omnivorous copepods such as *Oithona similis*, *Microcalanus*, *Oncaea parila*, and *Triconia borealis* (Figure 3). Both the abundance and biomass of the large herbivore *Calanus glacialis* increased with the upwelling index (Figure 3 and 4). However, the other large herbivore *Calanus hyperboreus* and the abundant omnivore *Metridia longa* presented no obvious trend in abundance. Accordingly, total copepod biomass was uncorrelated to upwelling. No copepod taxon appeared

![Figure 3](image_url)

*Figure 3. Mean (+ 1 SD) annual density of copepods (a) and *Calanus glacialis* developmental stages (b) from 2002 to 2007 in the offshore Beaufort Sea.*

![Figure 4](image_url)

*Figure 4. Mean annual density (+ SD) of *Calanus glacialis* (a) and dominant small copepods (b) in relation to upwelling potential in offshore southeastern Beaufort Sea from 2002 to 2007. The upwelling potential is a dimensionless index of the probability of wind-driven upwelling prior to the sampling period in a given year, assuming threshold sea ice concentration (SIC) of 5, 10, and 20% on the Mackenzie Shelf. rs is Spearman’s correlation coefficient.*
negatively impacted by increased upwelling. Our observations may represent the first signs of the general increase in secondary production predicted to result from a reduction of ice cover, a warming of the surface layer, and an intensification of wind-induced upwelling in Arctic seas. Continued annual monitoring of zooplankton dynamics is crucial to anticipate the future services provided by pelagic ecosystems in the Arctic Ocean.

**A pan-Arctic synthesis of the hatching season of Arctic cod (Bouchard and Fortier 2011)**

Our understanding of how Arctic marine ecosystems will respond to climate change is often hampered by a want of circumpolar syntheses to contrast key ecological processes for the different environmental regimes that prevail in different seas. Here, the hypothesis that salt-related differences in winter sea surface temperature dictate regional differences in the hatching season of Arctic cod is tested by contrasting hatch date frequency distributions among six oceanographic regions of the Arctic Ocean characterized by different freshwater input (Figure 5). Consistent with the hypothesis, hatching started as early as January and extended to July in seas receiving large river discharge (Laptev/East Siberian Seas, Hudson Bay, and Beaufort Sea). By contrast, hatching was restricted to April-July in regions with little freshwater input (Canadian Archipelago, North Baffin Bay, and Northeast Water). Length (weight) in late summer (14 August) varied from <10 mm (<0.01 g) in July hatchers to 50 mm (0.91 g) in January hatchers. Hence, a large size at the end of the summer, which is believed to provide an advantage to survive the first winter, is clearly linked to an earlier hatchdate (Figure 6). An earlier ice break-up, more frequent winter polynyas, a warmer surface layer, and increased river discharge linked to climate warming could enhance the survival of juvenile 0+ polar cod by enabling a larger fraction of the annual cohort to hatch earlier and reach a larger size before the fall migration to the deep overwintering grounds. A further test of the hypothesis would require the verification that the early winter hatching of polar cod actually occurs in the thermal refuge provided by under-ice river plumes.

Figure 5. Average hatch date frequency distribution and mean hatch date (HD) of polar cod in six regions of the Arctic Ocean ordered by decreasing freshwater input. The monthly salinities in the 0-10 m layer were extracted from the World Ocean Atlas. From Bouchard et Fortier 2011.
Modelling the early (0-45 d) growth and survival of Arctic cod larvae in the North Water and Northeast Water Polynyas (Thanassekos and Fortier 2012; Thanassekos et al. 2012).

Actual observations from a ship invariably provide a very limited picture of the population dynamics of planktonic organisms, a fortiori in ice-covered seas where sampling coverage is limited both in time and in space. Hence, studying and predicting the response of key components of the Arctic plankton community to climate variability and change will increasingly rely on numerical simulations. In such computer models, a virtual population of organisms is released in a virtual representation of its environment. The goal is to generate a complete picture of its dynamics, over a given time interval, that reproduces and completes the partial picture provided by sampling at sea.

We developed an Individual-Based Model (IBM) of Arctic cod bioenergetics that successfully reproduced the observed growth and survival (0-43 d) of juveniles of Arctic cod hatched from mid-May to mid-July in the Northeast Water (NEW, a) and the North Water (NOW, d). Mean length at age of each daily cohort color-coded by its hatch date (circles) with maximum (downward pointing triangles) and minimum (upward pointing triangles) lengths-at-age among all cohorts for the NEW (b) and the NOW (e).

Figure 6. Regression of standard length on 14 August (SL) on hatch date (HD) for polar cod collected in late summer and early fall in regions characterized by strong river discharge (full circles, Laptev Sea, Hudson Bay and Beaufort Sea) or weak river discharge (open circles, Northwest Passage and Baffin Bay). SL = 49.87 - 0.203 HD, r² = 0.906, n = 1075, p < 0.0001. From Bouchard et Fortier 2012.

Figure 7. Observed length-at-age of individual Arctic cod larvae color-coded by their hatch date in the Northeast Water (NEW, a) and the North Water (NOW, d). Mean length at age of each daily cohort color-coded by its hatch date (circles) with maximum (downward pointing triangles) and minimum (upward pointing triangles) lengths-at-age among all cohorts for the NEW (b) and the NOW (e).
growth and increased the match between simulated and observed variances in length-at-age. The IBM nevertheless underestimated the observed exceptional growth during match events.

This first effort opens the way to modelling the response of Arctic cod to a decline in ice cover and the warming of the surface layer.

Are we witnessing the first signs of a displacement of Arctic cod by sand lance in the offshore Beaufort Sea?

Fish respond rapidly to changes in the geographical position of isotherms in the Ocean. A general prediction of fisheries ecology is that, with climate warming, the distribution of fish populations in the Northern Hemisphere will shift northward. Southern species of fish and their copepod prey have been observed moving to temperate areas, and temperate species have been seen expanding north in response to a shift in ocean climate (Beaugrand et al. 2002, Perry et al. 2005). Indications are that boreal species from the North Pacific and the North Atlantic are invading the Arctic Basin (Gaston et al. 2003, Babaluk et al. 2000). In particular, capelin (Mallotus villosus) and sand lance (Ammodortes spp.) are two small forage fishes that could soon displace the Arctic cod on the continental shelves of the Arctic Ocean (Hunt and Megrey 2005, Barber et al. 2008, Stephenson and Hartwig 2010). Already, capelin and sand lance are increasingly replacing Arctic cod in the diet of thick-bill murres as the ice regresses in northern Hudson Bay (Gaston et al. 2003). A replacement of Arctic cod by capelin and/or sand lance would harbinge a profound shift in the structure of the pelagic ecosystem and in the ecosystem services provided by the Arctic Ocean.

Starting in 2010, significant numbers of Pacific sand lance (Ammodortes hexapterus) juveniles were detected for the first time in the offshore distribution area of Arctic cod juveniles. For example, in the exploration claim for oil at the edge of the continental shelf, sand lance juveniles were captured at none of 21 stations in 2009, 2 of 18 stations in 2010, and 9 of 13 stations in 2011 (Figure 8). Since the presence of juveniles necessarily implies successful reproduction in the area, this progression suggests that sand lance could have started displacing Arctic cod as the sea-ice regime becomes less severe and the summer surface layer warms up in the Beaufort Sea. In addition to continued sampling in the coming years, the next step in verifying this hypothesis is to check for the presence of sand lance larvae and juveniles in our own ichthyoplankton collections in the area since 2002 and in inventory of fish larvae by other programs predating 2002.

Sea ice cover and the winter aggregation of Arctic cod in the offshore Amundsen Gulf (Beaufort Sea) (Geoffroy et al. 2011)

During the Circumpolar Flaw Lead System Study (CFL, 2007–2008), aggregations of polar cod were detected in winter in the Amundsen Gulf (Western Canadian Arctic) using the EK60 echosounder of the CCGS Amundsen
research icebreaker. Biomass estimated over 10 months reached a maximum of 0.732 kg m\(^{-2}\) in February. Aggregations were encountered only in the presence of an ice cover from December to April. The vertical extent of the aggregations was dictated by temperature and zooplankton prey distribution (Figure 9). In winter, polar cod generally occupied the relatively warm deep Atlantic Layer (\(0^\circ\)C), but a fraction of the densest aggregations occasionally followed zooplankton prey up into the cold Pacific Halocline (-1.6 to 0°C). The diel vertical migration of polar cod was precisely synchronized with the seasonally increasing photoperiod. Throughout winter, polar cod aggregations migrated to progressively deeper regions (from 220 to 550 m bottom depths) in response to increasing light intensity, presumably to avoid predation by visual predators such as the ringed seal (Figure 9). Comparing Amundsen Gulf and Franklin Bay indicates that the entrapment of polar cod in embayments during winter is an important mechanism to provide marine mammal predators with dense concentrations of their main prey within their diving range.

**A new SX90 fisheries sonar for the detection of fish in the surface layer of the Arctic Ocean**

Large aggregations of Arctic cod form from December to April in the lower Pacific halocline (140 m to bottom) of central Franklin Bay (Benoit et al. 2008, 2010) and in the deep Atlantic layer of Amundsen Gulf (Geoffroy et al. 2011, Figure 9 above). These deep winter aggregations detected by the vertical EK60 sonar of the CCGS...
Amundsen re-invaded the surface layer starting in April and, for all purposes, disappeared from the EK60 records for the rest of the summer (Benoit et al. 2008, 2010, Geoffroy et al. 2011). This led to the hypothesis that, during the summer months, Arctic cod are located in the 0-20 m surface layer, above the insonification cone of the EK60. The 180° vertical fan sweep of the SX90 fisheries sonar can detect fish and marine mammals in the surface layer up to 2 km away on each side of the ship. Thanks to a partnership with BP and Kongsberg Maritime and funding from the Beaufort Regional Environmental Assessment (BREA), a SX90 fisheries sonar was successfully installed on the Amundsen in 2011 and tested in the Gulf of St. Lawrence, Baffin Bay, Cumberland Sound and Lancaster Sound during Leg 1 of the ArcticNet annual expedition to the Arctic (Figure 10). The sonar was then deployed in the Beaufort Sea during Leg 2 of the expedition, concurrently with the EK60 to map the summer distribution of Arctic cod and other fish species from the surface to the bottom, in relation to sea-ice and bathymetry.

Despite logging 291 hours of surveys in different bathymetric areas, no dense school of fish were detected in the surface layer of the offshore Beaufort Sea in September and October. Juvenile fish (mainly Arctic cod) were detected in the sub-surface layer (40-60 m) by the EK60 and sampled with the Rectangular Midwater Trawl. Schools of adult fish (presumably Arctic cod) were detected at depth on the slope by the EK60. Hence, contrary to the hypothesis, adult Arctic cod does not seem to form dense schools in the surface layer of

![Figure 10. Screenshot from the SX90 fisheries sonar of the Amundsen showing fish schools and whales echoes in the Gulf of St. Lawrence.](image-url)
the offshore Beaufort Sea in late summer. The acoustic signatures (target strengths) of different (visually identified) marine mammals in a 1.5 km radius around the Amundsen have been acquired with the SX90. These will help identify, monitor, and avoid marine mammals during scientific and seismic operations.

DISCUSSION

The long-term monitoring of the ecosystem of the Arctic cod is starting to reveal significant trends in the abundance, reproduction, and population dynamics of the main actors (e.g. Arctic cod and copepods). Although still weak, these trends are generally coherent with predictions based on the ecology of the species in a context of progressive sea-ice reduction, warming of the surface layer, and increased upwelling of nutrient by wind. In the Beaufort Sea, they include primarily (1) a multi-year increase in the abundance of some key members of the low-diversity guild of copepods that makes up the bulk of the mesozooplankton of Arctic seas; (2) a potential shift in the hatching season of Arctic cod towards the preferential survival of early hatchers; and (3) the invasion of the offshore dispersion area of Arctic cod juveniles by sand lance juveniles. Such observations are consistent with previous studies documenting higher nutrient availability, primary production in Arctic seas characterized by a longer ice-free season (e.g. Rysgaard et al. 1999, Tremblay et al. 2006, 2011); higher copepod standing stocks in polynyas relative to adjacent ice-covered regions (Ringuette et al. 2002); and a general (predicted and observed) northward expansion of the distribution of temperate/boreal zooplankton and fish into sub-arctic and arctic seas (Babaluk et al. 2000, Beaugrand et al. 2002, Gaston et al. 2003, Perry et al. 2005, Hunt and Megrey 2005, Barber et al. 2008, Stephenson and Hartwig 2010).

Although consistent with predictions, the observed trends remain statistically weak because of the shortness of the time series. Also, while records have accumulated and been analysed for the Beaufort Sea where ice cover reduction and surface warming have been intense, observations for other regions of the Canadian sector of the Arctic Ocean either have not been collected as extensively (e.g. Arctic Archipelago) and/or have not been analysed as completely (e.g. North Water, Hudson Bay). This regional imbalance in our monitoring effort can be attributed to the focus of several large initiatives on the Beaufort Sea (CASES, CFL, Malina, ArcticNet partnerships with the oil exploration sector, BREA, etc.), and to the relative success of the mooring program in this region compared to the North Water and Hudson Bay. Clearly, corroboration of the trends observed in the Beaufort Sea for other regions where climate warming has been intense (e.g. northern Hudson Bay), and their contradiction in other, more stable or cooling, regions (e.g. North Water) would be extremely informative. We conclude that, during Cycle II of ArcticNet, the successful monitoring of the Beaufort Sea must be expanded imperatively to Baffin Bay and Hudson Bay, so as to fully capture the potential awakening and response of the Arctic cod ecosystem to climate change and to provide baseline information for future generations of researchers.

CONCLUSION

Impacts of the proposed research. As with previous arctic work by my team, several components of the research help inform policy, decisions, and adaptation strategies of stakeholders (e.g. Inuit, Federal departments, Oil Exploration sector) in the rapidly changing and developing Canadian Arctic. Examples of the significance of the research include:

- Our work on the present and future services provided by pelagic arctic marine ecosystems is being incorporated into ArcticNet’s Integrated Regional Impact Assessments for the Canadian Western High Arctic, the Eastern High Arctic, and Hudson Bay;
- Our study of the summer offshore distribution of Arctic cod in southeastern Beaufort Sea is part of the Beaufort Regional Environmental Assessment (BREA) of Aboriginal Affairs and Northern Development Canada (formerly Indian and Northern Affairs Canada);
• The installation, adaptation and deployment of the new SX90 on the Amundsen is conducted in close collaboration with Simrad-Kongsberg and BP, two industrial partners that are interested in testing the capacity of the fisheries sonar to detect marine mammals as a mitigation measure for seismic studies;

• In addition to its contribution to the BREA, the annual survey of the southeastern Beaufort Sea pelagic ecosystem provides the regional background necessary to assess the ecological importance of the exploration claims acquired by Imperial Oil Limited and BP at the edge of the Mackenzie Shelf;

• As part of a building collaboration between my team and the Fisheries and Sealing Division of the Nunavut Department of Environment, the Amundsen and Nunavut’s scientific trawler MV Nuliajuk were deployed jointly in Cumberland Sound in August 2011 as a pilot attempt to assess pelagic fish stocks;

• All data sets generated by my arctic research program are integrated into the Polar Data Catalogue developed jointly by ArcticNet and the Canadian Cryospheric Information Network;

• The expertise of my team on arctic zooplankton and fish is increasingly in demand by other parties, for example the Oil Exploration sector (IOL, BP); the Nunatsiavut and Royal Military College joint program on the ecology of Labrador Fjords; the Institute of Marine Sciences at the University of Alaska, Fairbanks; and the Census of Marine Life;

Future Work

As discussed in the previous section, the long-term monitoring of the ecosystem of the Arctic cod is starting to yield significant trends in the abundance, reproduction and population dynamics of the main actors (e.g. Arctic cod and copepods), that are coherent with the general predictions based on the ecology of the species in a context of sea-ice reduction, warming of the surface layer, and increased upwelling of nutrient by wind. Accordingly, our priority in the coming years will be to maintain and expand the monitoring of the Arctic cod ecosystem in continued collaboration with the Hotspot and Mooring programs of ArcticNet, and in new partnership with the Remote-Sensing program (CERC on the Remote-sensing of Canada’s new Arctic frontier at Université Laval).

This year we added successfully the SX90 fisheries sonar to our arsenal. As part of the renewal of Fortier’s Tier 2 CRC, the LOKI (Lightframe On-sight Keyspecies Investigation System), an in-situ taxonomist robot for the determination of the fine-scale vertical distribution of mesozooplankton and fish larvae, will be developed over the next year. Finally, due to the acoustic tantrum generated when breaking ice, the many sonars of the Amundsen become useless in ice covers denser than 7/10th. As a result, the spatial distribution of fish and zooplankton under the ice remains poorly resolved. In partnership with Kongsberg Maritime and with financial support from the Quebec Government we are planning the acquisition of a Hugin 1000 Autonomous Underwater Vehicle (AUV) with under-ice navigation capability and a 80-km radius of operation to be deployed from the Amundsen. Carrying sonars like the EK60 and SX90, the ecological module of the AUV will enable us to document the vertical and horizontal distribution of Arctic cod and its zooplankton prey under the ice cover of the Canadian Arctic.

Six of the 8 engines and generators of the Amundsen must be replaced and the ship will not be available for science in 2012. With the agreement of AANDC, we are trying for 2012 to transfer our BREA program based on the SX90 to the trawler chartered by DFO (Jim Reist) before resuming operations on the Amundsen in 2013. This plan would allow a direct validation of the SX90 echoes with fish collections.

The non-availability of the Amundsen in 2012 will impact briefly the monitoring of the transformation of ecosystems in the Canadian Arctic Ocean by the Arctic cod, Hotspot, Mooring, and Remote-Sensing programs of ArcticNet. However, these 4 programs will use this
hiatus to regroup and refocus our highly successful and expanding efforts since 2002. We are proposing in 2012 a workshop gathering these and other ArcticNet programs using the Amundsen to (1) discuss and advance the analysis and hybridization of existing data sets that can consolidate and complete the emerging picture of the changing ecosystem of Canadian Arctic seas; (2) to refocus the scientific program of the ArcticNet annual mission on the Amundsen as our objectives change in response to the results obtained; (3) to re-organize the Mooring program to offset the retirement of its leader; and (4) to re-build, consolidate and expand the technical team in charge of the maintenance and deployment of the growing pool of scientific equipment of the Amundsen.

ACKNOWLEDGEMENTS

In addition to Canada’s Network of Centres of Excellence (NCE) program, the Arctic cod (Boreogadus saida) ecosystem under the double pressure of climate change and industrialization (Arctic Cod) program of ArcticNet is supported by several collateral funding sources. We thank the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chair program (CRC), the Canada Excellence Research Chair program (CERC), the Canada Foundation for Innovation (CFI), the Canadian International Polar Year, the Beaufort Regional Environmental Assessment (BREA) program of Aboriginal Affairs and Northern Development Canada, le Fonds québécois pour la recherche sur la nature et la technologie (FQRNT, volet Regroupements Stratégiques et volet Équipes), et le Comité national pour la recherche scientifique français (CNRS). Major industrial partners such as BP, Imperial Oil Limited and Kongsberg Maritime contribute to our program. We acknowledge fruitful collaborations with several researchers in the Departments of Fisheries and Oceans Canada, Environment Canada, and Natural Resources Canada. None of our achievements could be possible without the expertise and complicity of the personnel, officers and crew of the Canadian Coast Guard. We thank our numerous colleagues in and outside ArcticNet for their expertise and data, with emphasis on our friends at the Center for Observation Studies (U. Manitoba), the Norwegian Polar Institute (U. Tromsø) and the National Institute of Polar Research in Tokyo. The research results presented here are contributions to the programs of ArcticNet, Québec-Océan at Université Laval, the Canada Research Chair on the response of marine arctic ecosystems to climate warming, and the Fisheries and Oceans Canada Research Chair in marine acoustics applied to resources and ecosystems.

REFERENCES


2011-12 PUBLICATIONS

All ArcticNet refereed publications are available on the ASTIS website (http://www.aina.ucalgary.ca/arcticnet).


Darnis, G., Fortier, L., 2011, Respiration zooplanctonique et exportation du carbone en profondeur dans le golfe d’Amundsen (Océan Arctique), Annual General Meeting of Québec-Océan, Lac Delage, Québec, 17 November.

Darnis, G., Fortier, L., 2011, Zooplankton respiration and the export of carbon at depth in the Amundsen Gulf (Arctic Ocean), High latitude pelagic and ice ecosystems meeting, University of Tromso, Tromso, 31 October.


Geoffroy, M., Rousseau, S., Pyc, C., Fortier, L., 2011, Searching for the missing cod using hydroa-
Acoustic technology, Beaufort Regional Environmental Assessment (BREA) Day, Inuvik, 5 December.


Robert, D., Grant, C., Gagnon, J., 2011, Data from the environment and marine resources assessment of Imperial Oil/BP Exploration License Areas 446, 449, 451 and 453 (Beaufort Sea), in the summers of 2009, 2010 and 2011, Québec, Canada, 74 pp.
