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

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## 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 a hyper-specialist adapted to life in ice-covered seas, Arctic cod is likely to be displaced by southern generalists such as capelin and 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 Aboriginal Affairs and Northern Development Canada (AANDC - Beaufort Regional Environmental Assessment (BREA) 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

- The Lightframe On-sight Keyspecies Investigation System (LOKI), an *in situ* profiling mesozooplankton imager with sufficient optical resolution to identify major taxonomic groups was successfully deployed in Hudson Bay. By combining the imager with automated computer identification, we hope to achieve a sampling capacity and a spatio-temporal resolution for mesozooplankton similar to those provided by the CTD-rosette for phytoplankton studies;
- From 2002 to 2007, reduced ice cover and increased upwelling in the Beaufort Sea may have favoured small cyclopoid copepods and the large herbivorous copepod *Calanus glacialis*, a major prey of the juvenile and adult stages of Arctic cod;
- The seasonal vertical migrations of 7 dominant copepods over an annual cycle were described with unprecedented details revealing the life strategies of the different species in relation to the sea ice regime and microalgal production cycle in central Amundsen Gulf;
- By combining genetics and otolith analysis, a simple criteria based on the size of the nucleus of the lapillus was developed to discriminate the morphologically identical larval and juvenile stages of the Arctic cod (*Boreogadus saida*) and the Ice cod (*Arctogadus glacialis*);
- Sets of 19 and 16 microsatellite loci were developed for the study of the population genetics of Arctic cod and Ice cod, respectively. Determining population structure and distribution is fundamental to anticipate the response of the two fishes to environmental changes and human activities;
- In the Beaufort Sea, the hatching season of Ice cod coincided precisely with that of Arctic cod from mid-March to late June in both 2004 and 2008, suggesting (1) that the two species share what could be the only temporal window of potential larval survival, and (2) that competition could occur between the two very similar species;
- As part of BREA, acoustic surveys validated by trawling indicated that Arctic cod juveniles are distributed in the 0-100 m strata over the entire offshore region of the Beaufort Sea in summer, while adults aggregated in the 200-400 m depth range on the continental slope. These results are crucial to understanding and modeling the impacts of an eventual oil spill on the species;
- Pacific sand lance *Ammodytes hexapterus* larvae and juveniles are increasingly frequent in the offshore nursery areas of Arctic cod. Comparing the diet of the two species indicates a potential for competition between the two species;
- The poorly known role of chaetognaths in the trophic food web will be elucidated by looking at the diet of *Sagitta elegans* over an annual cycle in Svalbard fjords and in the Beaufort Sea;

- In close collaboration with ArcticNet's CERC on the remote sensing of the new Canadian Arctic frontier, we are progressing with the acquisition of an HUGIN 1000 Autonomous Underwater Vehicle (AUV) which would enable us to describe the under-ice ecosystem with unmatched resolution.

## Objectives

- Describe annual and decadal variations (2002-2016) in the absolute and relative abundance of the main arctic copepods and their predators (Arctic cod, chaetognaths, and the hyperiid amphipod *Themisto libellulla*) in the Beaufort Sea;
- Track with high vertical resolution the seasonal migration 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) variation of prey 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;
- 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;
- In the longer term, 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 fulfillment. As the sea-ice cover of Arctic seas shrinks 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 (e.g. access to oil and other mineral resources, new shipping lanes, fish stocks of commercial interest, and ecotourism).

The objective of ArcticNet 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 of 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 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 are 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 and sand lance have replaced Arctic cod as the main prey brought back to nests by thick-billed murres to feed their young (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 likely 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” and “Moorings” 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, surface temperature, and zooplankton prey abundance, and to monitor changes in the ichthyoplankton assemblage to which it belongs. 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. In 2012, we collaborated with the Department of Fisheries and Oceans to acquire acoustic data validated by trawling to confirm our hypothesis that the fish aggregations detected at depth on the slope are Arctic cod.

## Activities

Time frame and study area: Sampling activities in 2012 were significantly impacted by the unavailability of the *CCGS Amundsen*. This situation was palliated first by testing the LOKI from the *CCGS Radisson* during experimental trials in Hudson Bay. These trials were highly successful and enabled us to iron out several minor technical issues and to obtain a unique data set on the fine-scale distribution of zooplankton. We are progressing presently on the computer-assisted identification of the main taxonomic groups imaged by the LOKI. A second initiative to compensate for the absence of the *Amundsen* was to deploy our acoustic instruments in the Beaufort Sea from the trawler F/V Frosti chartered by DFO as part of BREA. This strategy proved highly profitable, as we were able to validate by trawling that fish aggregations on the slope of the continental shelf were actually Arctic cod. This validation will enable us to interpret with accrued confidence the extent of acoustic records collected in the area since 2002.

***Research activities in 2012-2013:***

- Acoustic surveys of fish and sampling of zooplankton from the M/V Frosti in the offshore Beaufort Sea in collaboration with DFO at the Freshwater Institute (Jim Reist). Thirty-three days (August 6 – September 2) of continuous multifrequency (38, 120, 200 kHz) echo sounder data during the ice-free season. Validation of echoes with ichthyoplankton nets, mesopelagic and benthic trawls.
- Successful sea trials of the Lightframe On-sight Keyspecies Investigation System (LOKI), an *in situ* profiling mesozooplankton imager, in Hudson Bay. Development of a computer-assisted identification protocol.
- Most precise ever description of the vertical migration of arctic copepods over a quasi-annual cycle (CFL, October 2007 to July 2008).
- A new criteria based on the size of the nucleus of the lapillus was developed to discriminate the morphologically identical larval and juvenile stages of the Arctic cod (*Boreogadus saida*) and the Ice cod (*Arctogadus glacialis*).

- Using this new discrimination tool, Ice cod were isolated from our collections of gadids and its hatching season determined for both 2004 and 2008.
- Sets of microsatellite loci were developed for the study of the population genetics of Arctic cod (19 loci) and Ice cod (16 loci).
- We initiated a comparison of the diet of the larval and juvenile stages of Arctic cod and Pacific sand lance in the offshore Beaufort Sea in summer.
- We initiated a study comparing the diet of the chaetognaths *Parasagitta elegans* between Svalbard and the Beaufort Sea.
- Work is ongoing on the preparation of contributions focusing on fish stocks and fisheries potential for the IRIS-1 and IRIS-2.
- As part of the Canadian IPY synthesis sponsored by AANDC, our team led the chapter synthesizing the results of Canadian studies of the pelagic ecosystems and ecosystem services (Darnis G, Robert D, Pomerleau C, Link H, Archambault P, Nelson RJ, Geoffroy M, Tremblay J-É, Lovejoy C, Ferguson SH, Hunt BPV, Fortier L. 2012. Current state and trends in Canadian Arctic marine ecosystems: II. Heterotrophic food web, pelagic-benthic coupling, and biodiversity. Climatic Change 115: 179–205. doi:10.1007/s10584-012-0483-8)
- We pursued our efforts to secure funding for the acquisition of a HUGIN 1000 Autonomous Underwater Vehicle that would create a whole new research capacity for the *Amundsen* and enable us to develop new expertise in arctic marine geophysics and the study of the under-ice ecosystem.

## 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 physical processes 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.

### *The Lightframe Onsight Key-species Investigation System (LOKI) was successfully deployed during the BaySys cruise in Hudson Bay*

The Lightframe Onsight Key-species Investigation System (LOKI) developed at the Alfred-Wegener Institute was deployed for the first time in early September 2012 at four stations in Hudson Bay. The LOKI was mounted together on the same frame with a reference net identical to those used since 2002 by our team (Fig. 1). This approach will allow for a direct comparison between the images and the standard mesozooplankton collections archived by our team. It also saves precious wire time, as a single deployment is now all that is needed. Different settings were used on each cast to optimize image and data quality in preparation for upcoming systematic sampling in 2013.

Preliminary results are very promising. A subset of the thousands of images of single organisms or particles taken by the system during the first haul (Station 780) were analyzed by a taxonomist and manually classified into a preliminary classification tree covering the range of particles imaged. Then a machine-learning algorithm (TreeNet) was used to automatically apply the classification tree to all images, to obtain a completely classified first haul consisting of around

Figure 1. The Lightframe Onsight Key-species Investigation System (LOKI, left on the picture) deployed simultaneously with a standard 1-$m^2$ opening square conical mesozooplankton net.

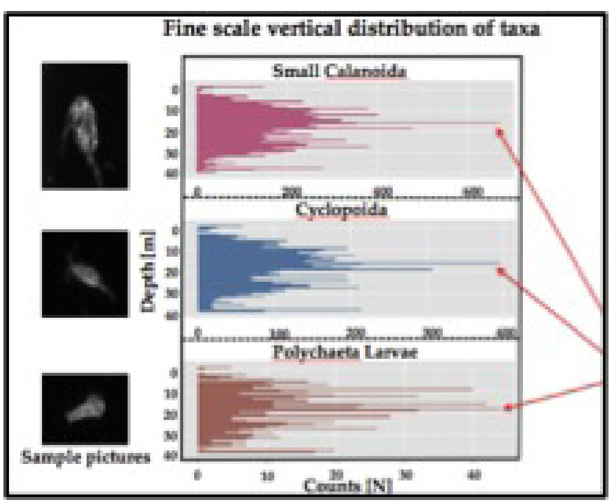


Figure 2. The vertical distribution of three mesozooplankton taxa in southwest Hudson Bay in September 2012 as measured by the LOKI, showing the micro-layering of abundance.

20,000 images. Using these first images of somewhat inferior quality, the overall classification success pooled over all 15 taxa. Classification success will be substantially increased when images of better quality can be obtained with the optimal camera settings identified during the cruise. Preliminary results revealed the fine scale vertical distribution of some taxa with clear thin vertical layering (Fig. 2).

### *The annual vertical migrations of key arctic copepods in southeastern Beaufort Sea*

We investigated the diel and seasonal vertical migration of 7 dominant species of arctic copepods based on 78 abundance and biomass profiles sampled from October 2007 to July 2008 in southeastern Beaufort Sea (Arctic Ocean). Zooplankton biomass was dominated by copepods and was highest (4.2-17.9 g C $m^{-2}$) in the deep central Amundsen Gulf (250-630 m). In all species, diel vertical migrations (DVM) were negligible throughout the year. The seasonal vertical migration (SVM) was most pronounced in the large pelagic herbivore copepod *Calanus hyperboreus* which remained in the deep Atlantic layer from December to mid April, rapidly invaded the surface layer at the onset of the phytoplankton bloom in early May, and started its descent to overwintering depth in July. Following a similar SVM pattern, *C. glacialis* overwintered at shallower depths than *C. hyperboreus*, moved in the surface layer in early April as ice algae bloomed, and remained in the surface layer until late July. Small cyclopoids followed a typical, if weak, SVM pattern: *Oithona similis* was found at mid depth in January, ascended slowly to the surface layer from February to April, and initiated its gradual return to mid-depth in July; *Triconia borealis* remained well below mid depth from November to April, ascended slowly above mid depth from April to May and returned at depth in July. The medium-sized neritic *Pseudocalanus sp.* presented no clear SVM, remaining in the surface layer throughout the year. As well, the omnivores *Metridia longa* and *Microcalanus sp.* exhibited little SVM, hovering around mid depth in all seasons.

### *Arctic copepods and recent upwelling-favourable conditions in southeastern Beaufort Sea*

We tested the hypothesis that wind-driven upwelling along the increasingly ice-free edge of Arctic shelves increases the standing stock of copepods. Zooplankton were sampled in early fall of each year from 2002 to 2007 on and off the Mackenzie Shelf (Beaufort Sea). For each year, an index of cumulative along-shelf upwelling was calculated for the ice-free period preceding zooplankton sampling. The index of summer upwelling remained relatively constant from 2002 to 2005 and increased sharply in 2006 and 2007. Average salinity in the 0-50 m layer in early fall, another index of upwelling, increased regularly from 29 in 2002 to 31 in 2007 (Fig. 3). A majority of copepod taxa, mostly rare species and mesopelagic species, remained inert to interannual variations in upwelling. Thirteen species of epipelagic herbivores and omnivores varied significantly in abundance over the 6 years. Consistent with the hypothesis, the distribution of the Spearman correlation coefficient between abundance and upwelling or salinity was systematically skewed towards positive values for these epipelagic species. The abundance of the CI-CV copepodites stages of the large *Calanus glacialis*, a key forage species for vertebrates, was positively correlated to salinity. Hence, we could not reject the hypothesis that increased upwelling at the edge of the continental shelf increases secondary production on the shelf. However, longer time series of observations are needed to assess the actual impact of accrued upwelling on the structure of the pelagic ecosystem of the Beaufort Sea.

### *Microsatellite loci for genetic analysis of the arctic gadids Boreogadus saida and Arctogadus glacialis*

We report sets of 19 and 16 microsatellite loci for the examination of the population genetics of *Boreogadus saida* and *Arctogadus glacialis*, respectively. Six of these loci were developed from a collection of 9,497 expressed sequences from *B. saida* while the remaining loci were found in the literature and optimized for use in *B. saida* and *A. glacialis*. The numbers of alleles observed for each locus ranged from 3 to 33 in *B. saida* and 1–22 in *A. glacialis*. Observed heterozygosities ranged from 0.02 to 0.93 in B. saida and 0.17–1.0 in A. glacialis. Species-specific differences were observed for the loci providing new tools for the identification of these two arctic gadids which are morphologically similar during the juvenile stage. The loci presented here can be used to distinguish between the two species and fill fundamental biological knowledge gaps, thus promoting conservation of these important fishes.

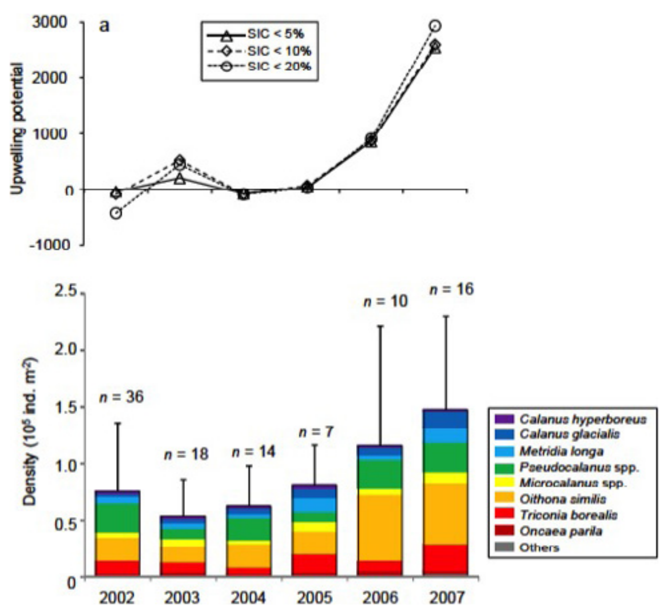


*Figure 3. Interannual variations in summer upwelling index (top panel) and total copepod density (mean with standard deviation, bottom panel) in the southeastern Beaufort Sea in autumn from 2002 to 2007. The ten dominant taxa making up the total are represented by different colors. N is the number of samples available in each year.*

### *The otolith nucleus as a tool to discriminate the early life stages of Boreogadus saida and Arctogadus glacialis*

The young stages of the polar cod (*Boreogadus saida*) and the ice cod (*Arctogadus glacialis*) are morphologically indistinguishable. The nucleus of the lapillar otolith of genetically identified *B. saida* (n = 436; age 0-235 d) and *A. glacialis* (n = 85; age 11-174 d) were analysed. At a given age, the product of the shortest by the longest diameters of the nucleus was 58% smaller in *B. saida* than in *A. glacialis*. A discriminant function based on these simple conservative measures of the nucleus classified 91% of all specimens into the correct species.

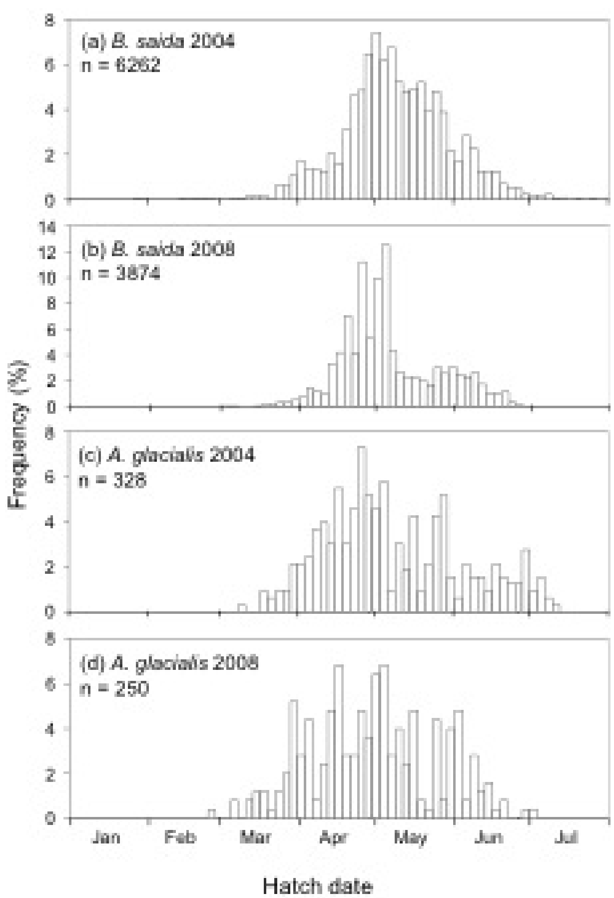


*Figure 4. The hatch date frequency distribution of juvenile Arctic cod (Boreogadus saida) and Ice cod (Arctogadus glacialis) sampled in the Beaufort Sea in 2003-2004 (CASES program) and 2007-2008 (CFL program).*

The above criterion was used to discriminate Arctic cod and Ice cod among gadids that have been aged by otolith analysis, enabling us to contrast the hatching season of the two species. In the Beaufort Sea, the hatching season of Ice cod coincided precisely with that of Arctic cod from mid-March to late June in both 2004 and 2008 (Fig. 4), suggesting (1) that the two species share what could be the only temporal window of potential larval survival, and (2) that competition could occur between the two very similar species. This potential for competition will be further explored by comparing the diet at age of the two fish.

### *Larval polar cod (Boreogadus saida) and sandlance (Ammodytes sp.) trophodynamics in the warming Beaufort Sea*

Starting in 2010, significant numbers of Pacific sand lance (*Ammodytes hexapterus*) juveniles were detected for the first time in the offshore distribution area of Arctic cod juveniles in the Beaufort Sea. Since the presence of juveniles necessarily implies successful reproduction in the area, this progression suggests that sand lance is invading the distribution of Arctic cod as the sea-ice regime becomes less severe and the summer surface layer warms up in the Beaufort Sea.

Fish larvae were captured in September and October 2011 with a double-square net (1-$m^2$ mouth aperture, 500µm and 750µm mesh oblique tows) along with their prey (50µm and 200µm mesh vertical tows) over 24 stations located on the MacKenzie Shelf and in Amundsen Gulf. At each station, the potential prey field was described and quantified to the lowest taxonomic level possible. The gut content of a larval subsample of larvae (42 polar cod and 42 sand lance) was dissected and prey were measured, counted and identified to the species to evaluate prey selectivity, feeding success and diet overlap. Diet overlap was sufficient for the possibility of interspecific competition to exist (Fig. 5). However, for such competition to exist, it must be demonstrated that food is limiting at least at some of the stations sampled. The next step in the analysis will be to verify that gut content volume and carbon intake by the larvae

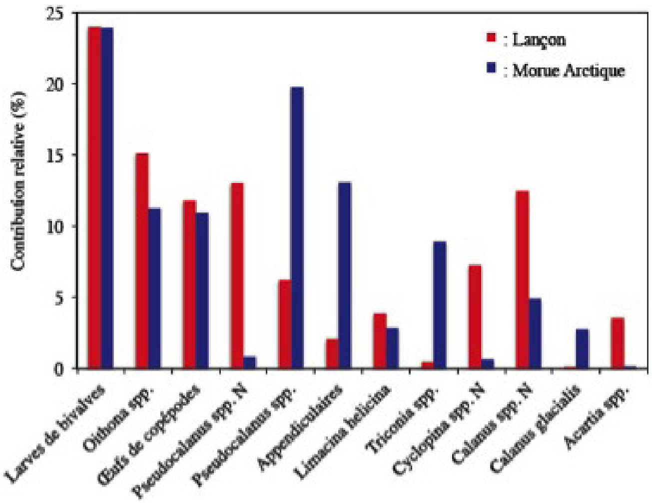


*Figure 5. Compared diet of Arctic cod (Boreogadus saida) (correspond to Morue Arctique in the Figure) and sand lance (Ammodytes sp.) larvae (Lancon in the Figure) and juveniles sampled together in the offshore Beaufort Sea in summer.*

increase with the density of their prey or preferred prey in the environment.

## *The summer distribution of Arctic cod in the offshore Beaufort Sea*

The deployment of a trawler by DFO as part of the BREA program in 2012 resulted in an important breakthrough for our team as the acoustic echoes detected for several years on the slope of the Mackenzie continental shelf could be validated by trawling. These echoes turned out to be quasi-monospecific aggregations of Arctic cod as we assumed. The sampling of Arctic cod also enabled us to calculate with unprecedented accuracy the relationship between Target Strength (TS, i.e. the strength of the echo) and the size of the target fish. Armed with this new information we were able to show how small young-of-the-year (0+ year) Arctic cod are distributed in the 0 to 100 m layer over much of the shelf and continental slope in summer (Fig. 6). Meanwhile, the 1+ fish congregated near the bottom over the slope in depths ranging from 200 to 1000 m, a distribution similar to that of the adults in winter. Such segregation by size of the adults and their offspring is often reported in gadids.

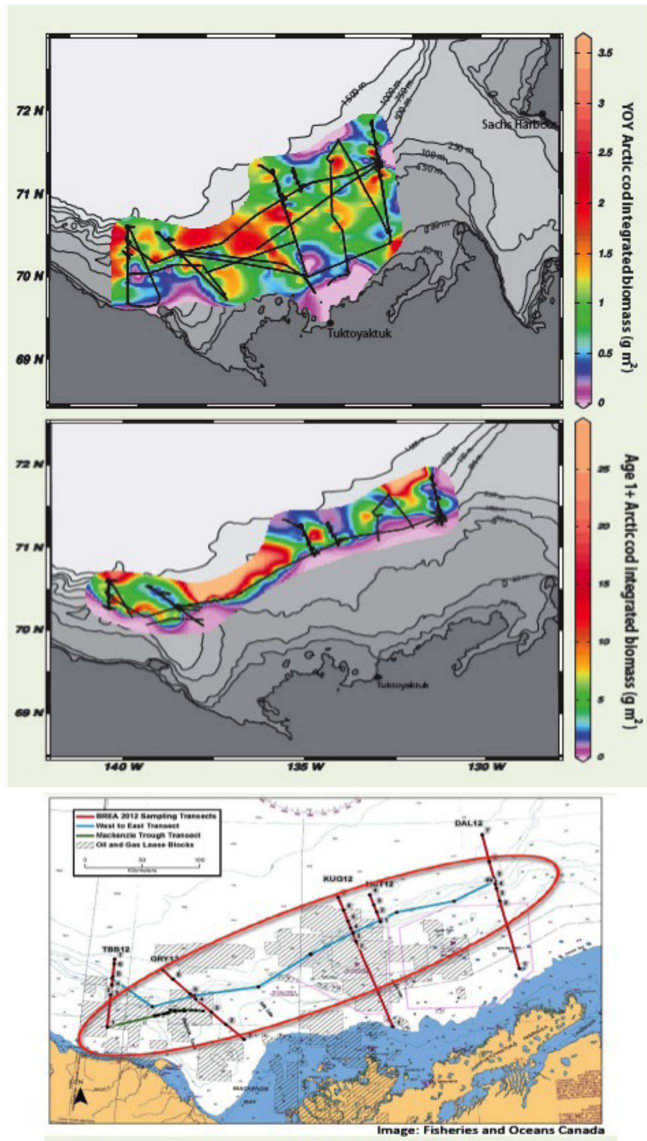


*Figure 6. Distribution of Arctic cod fry (0+year) in the 0-100 m surface layer of the shelf and slope of the Beaufort Sea (top panel); distribution of late juvenile and adult Arctic cod (1+ year) on the slope (middle panel); and location of oil exploration claims in the Beaufort Sea (bottom panel).*

These maps are particularly relevant for the BREA assessment as they document the potential vulnerability of the different developmental stages of Arctic cod in case of an oil spill. The 0+ would be particularly vulnerable to a surface spill while the 1+ would be threatened by any isopycnal intrusion of oil over the slope.

Our analysis increasingly supports the notion that Arctic cod is the main (if not sole) organism responsible for the acoustic signals recorded in the offshore pelagic Beaufort Sea since 2002 during the annual fall missions of ArcticNet on the *Amundsen* and during the overwintering expeditions of 2003-2004 and 2007-2008. Further contrasting the TS recorded in the surface layer (0-100 m) and the size of juvenile fish collected in areas outside of the Beaufort Sea should enable us to test that the same dominance of Arctic cod holds for much of the Canadian Archipelago and eastern Arctic seaboard.

## Discussion

Although much remains to be elucidated, our continuing studies of Arctic cod and its ecosystem in the Beaufort Sea is yielding an increasingly clear picture of the life cycle of this key species, and of its potential response to the on-going reduction of the sea-ice cover and warming of the surface layer of Arctic seas. Starting with the ice formation in October, Arctic cod 1 year and older aggregate on the continental slope within the lower part of the Pacific Halocline and the Atlantic Water (Geoffroy et al. 2011). Spawning probably takes place at this time in early winter. The aggregations tend to move to deeper regions over the winter, perhaps to avoid predation by the ringed seal and other diving predators. Entrainment by the circulation of the deep Pacific Halocline may result in the concentration of the fish into extremely dense schools at depth under the ice of coastal embayments (Benoit et al. 2010). During the winter months, the younger Arctic cod migrate on a diel basis into the cold intermediate arctic layer (100-140 m) most likely to feed on copepods, while the larger adults sporting large liver reserves remain at depth to limit predation by seals (Benoit 2012). With the ice break-up, the winter aggregations of Arctic cod were observed to disperse, most likely into the surface layer to follow the upward migration of their copepod prey as the spring bloom unfolds (Benoit et al. 2010; Geoffroy et al. 2011). The larvae hatch from January to early July with the bulk of hatching taking place from April to June (Bouchard and Fortier 2011). Early hatching in winter under poor survival conditions guarantees a large size at the end of summer, which increases chances of surviving the first winter. Late hatching in early summer ensures optimal temperature and feeding conditions for the larvae which however may not attain a sufficient pre-winter size (Bouchard et al. 2011). By late summer, the 0+ juveniles are distributed in the surface 0-100 m layer while the 1+ start to aggregate on the slope (this report).

As the ice cover regresses in the Beaufort Sea, indications are that increased light availability and the upwelling of nutrients in the surface layer, which fuel the primary production that sustains the production of the prey of Arctic cod, are increasing (e.g. Rysgaard et al. 1999; Tremblay et al. 2006; 2011; this report). Hence, conditions for Arctic cod survival, especially during the larval and juvenile stages, may improve in the coming decades as the severity of the ice regime abates. In the medium term however (mid-century?), milder temperatures and sea ice regimes may favour the replacement of the typical arctic zooplankton assemblage by more diversified assemblages, and the invasion of arctic seas by less specialized fish from the boreal and subarctic Atlantic and Pacific Oceans (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 longer time series of observations are needed, the first signs of an invasion of the Beaufort Sea by the Pacific sand lance (this report) and of Hudson Bay by the capelin (Gaston et al. 2003) may have been detected. Such a shift in dominant forage fish from the Arctic cod to sand lance or capelin would harbinger a profound transformation of the prevailing low-diversity and low productivity arctic pelagic marine ecosystem to a more productive ecosystem typical of the North Atlantic or North Pacific, and would transition the unique and exotic ecosystem services presently provided to local populations to a set of more mundane services.

The emerging picture of the distribution and migration of Arctic cod in the Beaufort Sea also suggests that the younger juveniles stages (0+) would be vulnerable first and foremost to oil spilling in the surface layer. Most of the time, the late juvenile and adult stages would be threatened by the release at depth of oil and its eventual isopycnal spreading over the slope after mixing with deep, dense seawater.

As pointed in last year's report, 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 our 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 and Eastern High Arctic;
- Our study of the summer offshore distribution of Arctic cod in southeastern Beaufort Sea is part of the Beaufort Region Environmental Assessment (BREA) of Aboriginal Affairs and Northern Development Canada (formerly Indian and Northern Affairs Canada);
- 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;
- All data sets generated by our Arctic research program are integrated into the Polar Data Catalogue developed jointly by ArcticNet and the Canadian Cryospheric Information Network;
- Our results and conclusions regarding the fate of Arctic cod in a warming Arctic Ocean have been summarized for an audience of over 10 000 policy makers by the European Commission DG Environment News Alert Service. Reference: Science for Environmental Policy, April 2012, Polar cod survival may be enhanced by climate warming, European Commission DG Environment News Alert Service. Thematic Issue 31: Arctic Science, p. 10;
- The expertise of our 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*

In 2013, the LOKI will be deployed systematically during the annual ArcticNet cruises in the High Arctic to explore the fine scale predator-prey relationships among fish larvae, zooplankton and phytoplankton.

In the longer term, our objective is to adapt the LOKI to the HUGIN-1000 AUV (see below) to map the fine-scale vertical and horizontal distribution of the plankton across the Marginal Ice Zone under the ice cover of arctic seas.

With the return in service of the *Amundsen* in 2013, we plan to complete our BREA program using the EK60 scientific echo sounder, the SX90 fisheries sonar and the Rectangular Midwater Trawl to investigate the distribution and schooling behaviour of Arctic cod at the offshore ice edge and in the near shore zone. For the inner shelf operations, we would like the scientific barge to scout the way for the *Amundsen* in the treacherous and pingo-infested near shore zone. We hope to muster the interest of other teams for the exploration of the inner Mackenzie Shelf.

Our Russian collaborators have detected elevated levels of methane in the surface layer and in the atmosphere of the Laptev and Siberian Seas. Similarly, our colleagues at the Bedford Institute of Oceanography (Stephen Punshon, Fisheries and Oceans) have detected high levels of methane off the east coast of Baffin Island. The methane plume was centered at around 200-300 m depth. At their request, we checked the EK60 records for the region, as gas bubbles are clearly detected by active acoustics. Using the EK60 data, we found signals that could correspond to potential methane seeps in 2004 and 2008 in the exact location indicated by BIO. It is estimated that methane clathrates accumulated in the sediments of shallow continental shelves contain up to the equivalent of 10 trillions tons of $CO_2$. The degasing of a minute fraction of these deposits, as a result of the warming of the deep layer overlaying the shelves, could seriously accelerate global climate warming. As part of a pilot project during the 2013 expedition of the *Amundsen* and in collaboration with Xie at UQAR, we propose to map the area with the EK60 and methane sensors (atmospheric and oceanic) to assess the distribution of the plume. The ROV of the ship would be deployed to inspect the eventual point source of the methane plume.

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 progressing on 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.

## 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), and the 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 Earth Observation Studies (U. Manitoba), the Norwegian Polar Institute (U. Tromso) 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.

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