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**Shrimp and its environment in the  
Northwest Atlantic – implications for  
forecasting abundance and population  
dynamics**

**Battery Hotel, St. John's, NL  
May 25-27, 2005**

**Meeting Chairperson:  
B. Bergström**

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Du 25 au 27 mai 2005**

**Président de réunion  
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Science Branch  
80 East White Hills Road  
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**September 2006**

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## SUMMARY

The fishery for northern shrimp (*Pandalus borealis*) is one of the largest and most important off Canada's Atlantic coast. Shrimp abundance and biomass are at high levels at a time when the environment is changing. In order to manage stocks in a sustainable manner it is necessary to understand how shrimp are affected by their environment. Therefore, the Northern Shrimp Foundation (NSRF) in partnership with the Department of Fisheries and Oceans (Newfoundland and Labrador (NL) Region) co-sponsored a workshop entitled:

“Shrimp and its environment in the Northwest Atlantic – implications for forecasting abundance and population dynamics”

The workshop was convened to initiate focused research and improve our understanding of shrimp biology and how population dynamics are affected by the environment. Accordingly the workshop was divided into three main theme sessions describing:

- An overview of shrimp biology and sources of environmental information;
- Recruitment and growth; and
- Mortality.

The workshop included participants from Greenland, Iceland, Nova Scotia, Québec, Newfoundland and Labrador, British Columbia, as well as, representatives from the Newfoundland and Labrador Department of Fisheries and Aquaculture and the shrimp fishing industry.

This document presents extended abstracts from the presentations and reports upon discussions held during each session.

All of the presentations indicated that shrimp are part of a very complex ecosystem. Various sources of information were described that provide a wealth of data that could be used to develop conceptual or mathematical relationships. Multi-species surveys were presented as sources of biological (i.e. shrimp length frequency, maturity, biomass/abundance, predator abundance etc.) and environmental data (i.e. bottom temperatures), while Atlantic Zonal Monitoring Program (AZMP) and Continuous Plankton Recorder (CPR) programs provide environmental information (water temperature, measurements of chlorophyll a, zooplankton abundances etc.). Various laboratory and field studies provided information used to describe relationships between shrimp and their environment. For instance, the “match mis-match” hypothesis suggesting that recruitment was directly related to timing of the spring bloom was a recurrent theme throughout the workshop. Studies that made use of satellite imaging were able to link size at sex change with indices describing the spring bloom. However, the workshop also noted that there were no simple stock-recruit relationships. Auto-regressive models used to forecast catch rates while other models demonstrated the relationship between

recruitment and spring sea surface temperature. Of equal importance, some of these studies demonstrated that anomalous environmental conditions caused some of these relationships to erode over time. There were no simple relationships between predator biomass and shrimp biomass. The eventual failure of relationships or the lack of apparent relationships relate back to complexities within the environment. This does not mean that we should stop looking for relationships, but rather that there are no simple answers.

Single and multi-species models were presented to evaluate the performance of harvest policies.

The workshop ended with a synthesis of conclusions and a set of research recommendations. A conceptual framework was developed to focus future research and a recommendation was made to hold a follow-up meeting during which researchers should develop a proposal(s) to study linkages between shrimp and their environment.

## SOMMAIRE

La pêche à la crevette nordique (*Pandalus borealis*) est l'une des pêches les plus abondantes et importantes pratiquées au large de la côte canadienne de l'Atlantique. La crevette affiche une abondance et une biomasse élevées en cette période de changement environnemental. Pour gérer les stocks d'une façon durable, nous devons comprendre comment la crevette est affectée par son environnement. C'est pourquoi la Northern Shrimp Foundation (NSRF) et le ministère des Pêches et des Océans (région de Terre-Neuve et du Labrador (T.-N.-L.) ont parrainé conjointement l'atelier intitulé :

« Crevette et son environnement dans l'Atlantique Nord-Ouest – répercussions sur les prévisions relatives à l'abondance et à la dynamique de la population ».

L'atelier avait pour but d'entreprendre des recherches ciblées et de mieux comprendre la biologie de la crevette ainsi que l'incidence de l'environnement sur la dynamique des populations. Pour ce faire, l'atelier a été divisé en trois séances thématiques principales :

- vue d'ensemble de la biologie de la crevette et des sources de données environnementales;
- recrutement et croissance;
- mortalité.

Des personnes provenant du Groenland, de l'Islande, de la Nouvelle-Écosse, du Québec, de Terre-Neuve et du Labrador, de la Colombie-Britannique de même que

des représentants du ministère des Pêches et de l'Aquaculture de Terre-Neuve et du Labrador et de l'industrie de la pêche à la crevette ont participé à l'atelier.

Le présent document des veut un résumé exhaustif des présentations et des rapports sur les discussions tenues lors de chaque séance.

Toutes les présentations indiquent que la crevette fait partie d'un écosystème très complexe. Diverses sources riches en renseignements pouvant servir à élaborer des rapports conceptuels ou mathématiques sont décrites. Les relevés multi-espèces sont également présentés en tant que sources de données biologiques (fréquence de longueur, maturité, rapport biomasse/abondance, abondance des prédateurs, etc.) et environnementales (températures au fond de l'océan, etc.). En outre, le Programme de monitoring de la zone Atlantique (PMZA) et le Système d'enregistrement continu des données sur le plancton fournissent des données environnementales (température de l'eau, mesures de la chlorophylle-a, abondance du zooplancton etc.). Diverses études menées en laboratoire et sur le terrain ont fourni des données qui ont servi à décrire des rapports entre la crevette et son environnement. Par exemple, l'hypothèse de l'appariement et du mésappariement selon laquelle le recrutement serait directement lié à la période de l'éclosion printanière a été un thème récurrent durant tout l'atelier. Les chercheurs qui se sont servis de l'imagerie par satellite ont pu établir des liens entre la taille au changement de sexe et des indices relatifs à l'éclosion printanière. Cependant, les participants notent également qu'il n'y avait aucune relation stock-recrutement simple. On a utilisé des modèles auto-régressifs pour prévoir les taux de prise de même que d'autres modèles pour établir le rapport entre le recrutement et la température à la surface de la mer au printemps. Il est également important de noter que certaines de ces études ont démontré que les conditions environnementales anormales ont provoqué l'érosion de certains de ces rapports avec le temps. Il n'existait aucun rapport simple entre la biomasse des prédateurs et la biomasse des crevettes. L'échec potentiel des rapports ou le manque de rapports apparents renvoie à des éléments environnementaux complexes. Cela ne signifie pas que l'on doit cesser de chercher des rapports; cela signifie plutôt qu'il n'y a pas de réponse simple.

On présente aussi des modèles pour une espèce et multi-espèce afin d'évaluer le rendement des politiques en matière de récolte.

L'atelier se termine par une synthèse des conclusions et par la formulation d'un ensemble de recommandations relative à la recherche. On élabore un cadre conceptuel pour orienter la recherche future; par ailleurs, on recommande la tenue d'une réunion de suivi au cours de laquelle des chercheurs pourraient élaborer une ou des propositions d'étude sur les liens entre la crevette et son environnement.





## INTRODUCTION

The northern shrimp (*Pandalus borealis*) fishery is one of the largest and most important fisheries off Canada's Atlantic coast, with the fishery off Newfoundland and Labrador being worth approximately \$260,000,000 during 2004 (F. Corbett, Policy and Economics Branch, DFO, NL-Region, pers. comm.). Shrimp abundance and biomass are at high levels at a time when the marine environment appears to be changing. In order to manage the stocks in a sustainable manner it is necessary to understand how shrimp are affected by their surroundings. Therefore, the Northern Shrimp Research Foundation (NSRF) in partnership with the Department of Fisheries and Oceans (Newfoundland and Labrador Region) sponsored a workshop, entitled "Shrimp and its environment in the Northwest Atlantic – implications for forecasting abundance and population dynamics". The workshop was a means of initiating focused research to improve our understanding of shrimp biology and population dynamics in relation to the physical and biological environment (e.g. ocean climate, predation, density dependence) and develop strategies for forecasting. Throughout the workshop's evolution, the following relevant and achievable objectives had been developed to meet this goal.

### Objectives:

- a) Environment - describe interactions between shrimp and
  - i) Ocean climate,
  - ii) Key predators, and
  - iii) Themselves (i.e. density dependence);
- b) Forecasting – integrate relationships between shrimp and the environment into forecasting tools for assessments; and
- c) Synthesis – determine key outstanding questions/issues that remain, in the context of the above, and focused research activities that would provide the most cost effective and timely opportunity to resolve them.

The workshop took place at the Battery Hotel from May 25–27, 2005 and included participants from Greenland, Iceland, Nova Scotia, Quebec, Newfoundland and Labrador, British Columbia, as well as, representatives from the Newfoundland and Labrador Department of Fisheries and Aquaculture and the shrimp fishing industry. This document includes extended abstracts from each of the presentations followed by a discussion, a synthesis of ideas and a set of research recommendations.

The workshop was convened by Dave Orr (DFO–NL Region) and chaired by Bo Bergström (Greenland Institute of Natural Resources). Don Parsons and Derek Osborne (DFO–NL Region) and Louise Savard (DFO-Quebec Region) were instrumental in the organization of the workshop.

Appendix I is the agenda for the meeting, appendix II is the list of participants, while Appendix III summarizes the recommendations from the workshop.

### **Opening Remarks**

Julian Goodyear (Regional Director – Science, NL Region) welcomed everyone, noted the importance of the shrimp fishery and hoped that the workshop would be successful.

Bo Bergström (Workshop Chair) provided a brief introduction to the workshop noting that northern shrimp is a very important resource within the North Atlantic with catches totaling over 300,000 tons in 2004. He noted that the workshop was timely because it focused upon relationships between shrimp and their environment at a time when northern shrimp (*Pandalus borealis*) biomass is at a historically high level and the environment appears to be changing. Bergström hoped that we would be successful in developing focused research strategies that would result in an increased understanding of shrimp population dynamics and allow us to predict future stock status.

Bruce Chapman (Director–Canadian Association of Prawn Producers) reiterated the importance of the Northern shrimp stock and the need to ensure sustainability of the shrimp fishery. If the shrimp industry is to remain viable then industry must be able to predict the status of future stocks. Even though Science does not have the tools necessary to make accurate predictions he hoped that recommendations from the workshop would result in focused research that could be used in making forecasts.

## Session 1 – Overview

### Mythology of *Pandalus borealis*

Bo Bergström

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An overview of the present status of knowledge about the biology of the northern shrimp (*P. borealis*) was given based upon a literature review within “The Biology of *Pandalus*” (Bergström 2000). Nineteen species of this genus are reported from the Pacific (17 species) and Atlantic Oceans (2 species). Information sources on taxonomy, external morphology as well as species descriptions, keys to adult stages and systems for classification and species determination of larvae were briefly described.

Present knowledge on the geographic distribution, depth distribution and salinity, temperature, and habitat preferences of *P. borealis* on the continental shelves and slopes were accounted for and compared with that of congeneric species.

Various aspects of the life history of the species were described. A section on reproductive biology included a discussion on the evolutionary maintenance of protandric hermaphroditism, the dominant mode of reproduction in the genus *Pandalus*, as well as an account of the present knowledge of the mechanism of sex change in these shrimp. Methods used to describe reproductive cycles as well as results were described and exemplified. Temperature effects on the duration of different phases of the reproductive cycles represented in the genus were discussed.

Adult behaviour in connection with mating, ovoposition and hatching were briefly accounted for. A section on *Pandalus* larvae included an overview of the present state of published knowledge on behaviour, nutrition, growth and survival. Adult behaviour was treated both on individual and population levels, reports on schooling, migrations and food and feeding were reviewed and discussed. Predators, diseases and parasites on *Pandalus* were mentioned and some information was given about competitors.

Methods for estimating growth and age, as well as, factors affecting growth were described and evaluated.

Population dynamics, including population discrimination, abundance and standing stock estimation, stock-recruitment relationships and factors affecting mortality were discussed.

In conclusion, it was noted that only the fishery for penaeid shrimp surpasses the fishery for *Pandalus*, in economical value. *P. borealis* stocks in the North Atlantic constitute a resource of utmost importance for many nations. Despite high amounts of effort exerted in this fishery, there are no indications that *Pandalus* stocks are being overexploited off the western coast of Greenland or along the eastern coast of Canada. However, the need for a more integrated understanding of the regional biology and population dynamics of this species was stressed. Such understanding is fundamental to a sustainable and predictable development of the fishery in the future.

**Reference:**

Bergström, B. I. 2000. The Biology of *Pandalus*. *In* Advances in Marine Biology (Vol.38). Edited by A. J. Southward, P.A. Tyler, C.M. Young and L. Fuiman. Academic Press. London. pp.55-244.

**The Physical Oceanography of the Northeast Newfoundland and Labrador shelf**

E. Colbourne, J. Craig, C. Fitzpatrick, D. Senciall, P. Stead and W. Bailey

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Oceanographic conditions were reviewed for 2004 and the past several decades. 2004 was noted to be an exceptionally warm year with near record temperatures in almost all areas and depths of the ocean. The North Atlantic Oscillation (NAO), which has historically accounted for up to 40 percent of the ocean variability, was low again in 2004. The reduced arctic wind along the Labrador coast caused higher than normal air temperatures, reduced winter ice cover and warm water conditions.

The annual water-column averaged temperature at Station 27 for 2004 remained above the long-term mean and reached the highest value on record (Fig. 1). The annual surface temperature at Station 27 was 1°C above normal, also the highest on record, while the annual bottom temperature was the highest since 1966. Water-column averaged (0-50 m) annual salinities at Station 27 remained above normal for the third consecutive year.

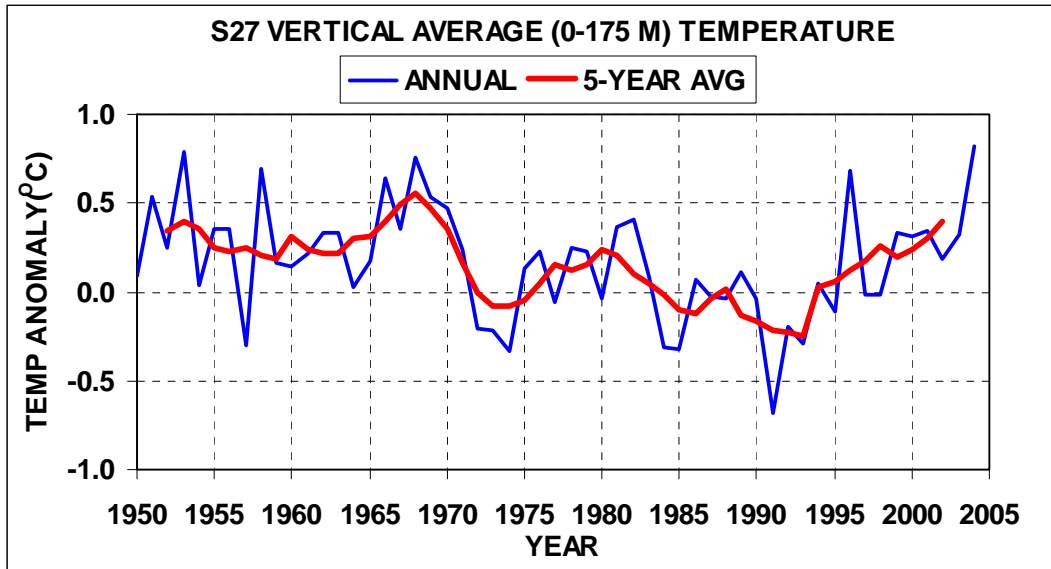


Figure 1. Time series of the annual vertically averaged temperature anomalies at Station 27 near St. John's, NL.

The summer cross-sectional area of the water mass with temperatures  $<0^{\circ}\text{C}$  (cold intermediate layer, CIL) on the Newfoundland and Labrador Shelf decreased since 2003. The CIL areas were below normal from the Flemish Cap section on the Grand Bank, to the Seal Island section off southern Labrador. Off Bonavista for example, the CIL area was below normal for the tenth consecutive year (Fig. 2). Seasonally, the CIL water mass extended to the surface during the spring, decreased to the smallest level, since 1965, in the summer and was completely eroded by late autumn of 2004. The areas of the CIL in recent years are in sharp contrast to the near record high values measured during the extremely cold years of the early 1990's on the Newfoundland and Labrador Shelf.

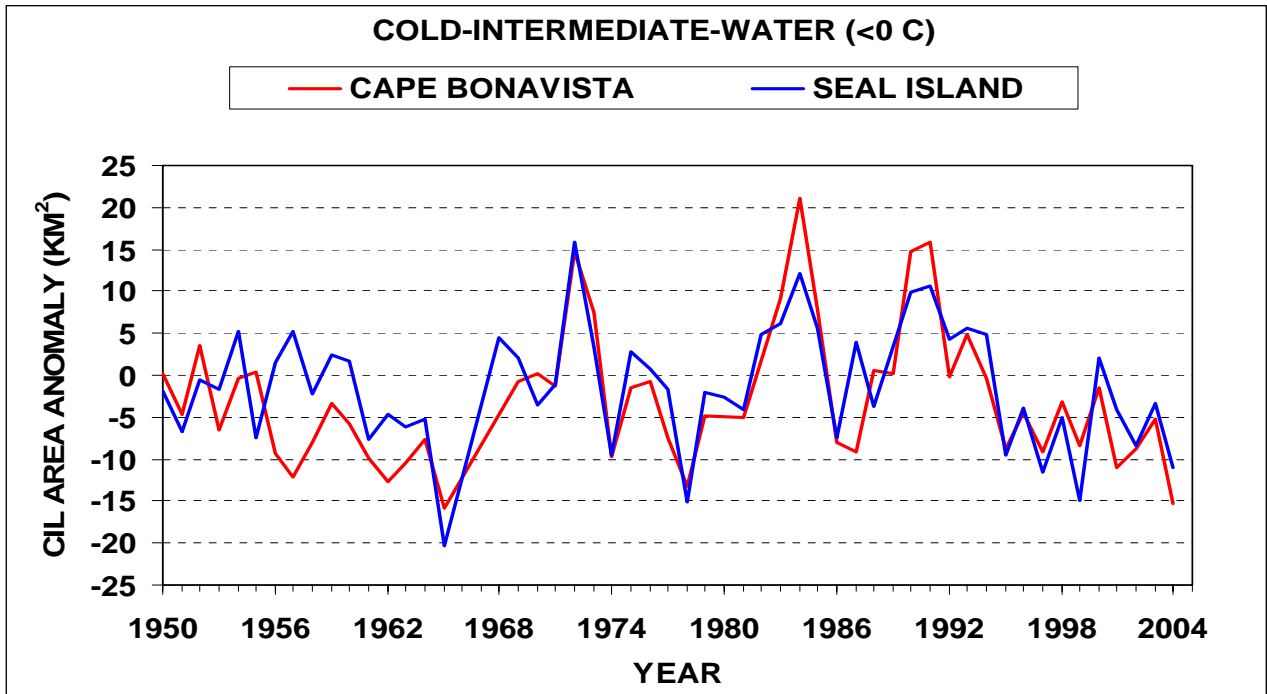


Figure 2. Time series of the Bonavista Section and Seal Island summer estimates of the Cold Intermediate-Layer (CIL) cross sectional area.

Temperatures along the standard sections, except for some isolated cold surface anomalies, were generally above normal by 1°C to 2°C in most areas during spring and summer and in all areas during the fall. Except for slightly negative salinity anomalies at mid depth over the inner shelf during the spring, most areas of the shelf during 2004 experienced generally saltier-than-normal conditions, particularly during the fall.

In 2004, the 3LNO spring bottom temperatures were above normal in all areas of the Grand Banks by 1°C to 1.5°C. As a result the spring of 2004 had the lowest area of <0°C water in Div. 3L since the surveys began in the early 1970s. Bottom temperatures during the fall of 2004 were predominately above normal in all areas by 0.5°C to 2°C and were the highest on record in Div. 2J.

In summary, the NAO index for 2004 was below normal for the fourth consecutive year resulting in reduced Arctic outflow to the region which kept annual air temperatures over much of the Northwest Atlantic above normal for the tenth consecutive year in some areas. Winter sea ice extent on the Newfoundland and Labrador Shelf was also below normal for the tenth consecutive year. As a consequence water temperatures on the Newfoundland and Labrador Shelf remained above normal, reaching record highs in some areas, continuing the warm trend experienced during the past several years. Shelf water salinities which increased to the highest observed in over a decade during 2002 also remained above normal in the upper water column during 2004.

Data were sparse for the shrimp fishing areas off the Labrador coast with no oceanographic transects traversing the deep channels where the high catch rates occurred. The ocean floor topography is complex, and there appears to be an intrusion of warm saline slope water into the deep channels where shrimp seem to be more abundant. This feature is persistent from year to year (Fig. 3).

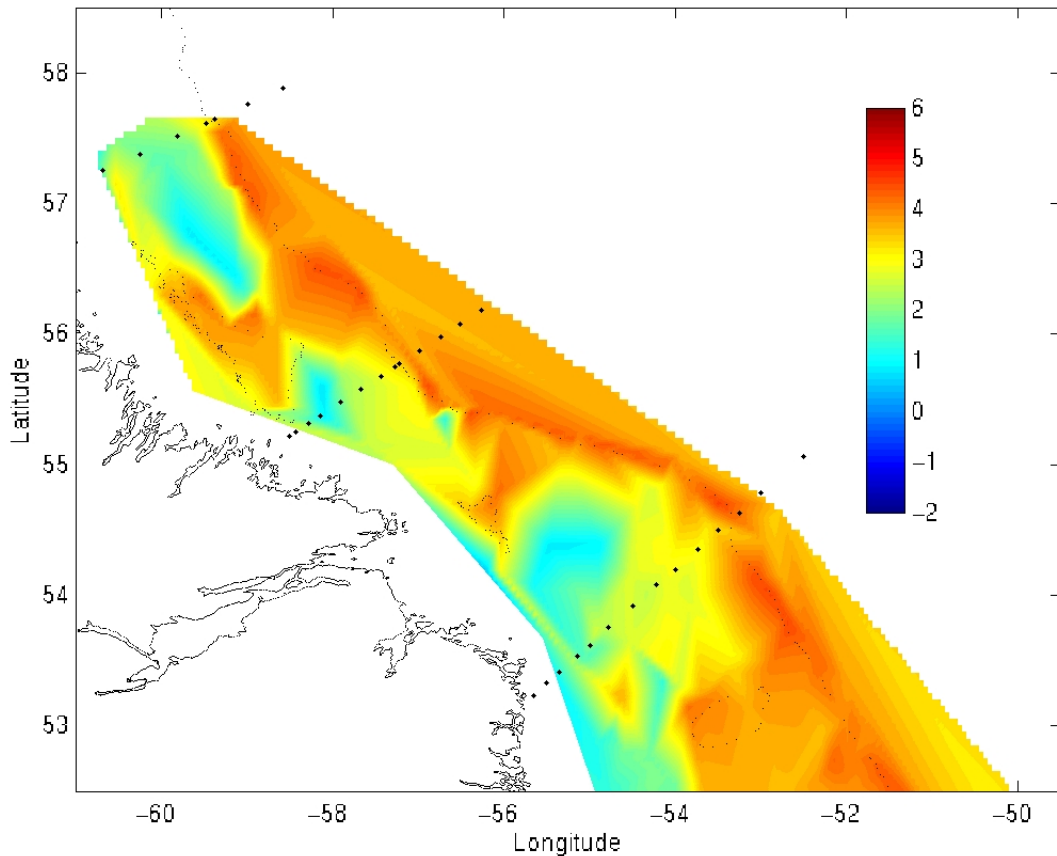


Figure 3. Shrimp Fishing Area 5 for 2004 showing cross-shelf intrusion of warm slope water into the deep Hopedale and Cartwright channels. The temperatures are in degrees Celsius.

There was much spatial variability in bottom temperatures for the shelf and this was confounded by strong seasonal changes in the shallow shelf waters. This limited the meaningfulness of temperature averages derived from spatially and temporally gridded data because of a high signal to noise ratio. To understand and quantify the relationships between shrimp dynamics and distribution with their physical environment, it is proposed to identify and exclude areas of high seasonal variability and instead focus on trends in the deeper waters which show little seasonal variation.

## **Overview of Environmental Monitoring in the Northwest Atlantic: Summary of Data Products Available**

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Despite logistic and operational difficulties, environmental monitoring has greatly expanded in recent years in the Northwest Atlantic in order to provide spatial and temporal information for a large variety of physical and biological variables of relevance to marine populations. Two large-scale environmental monitoring programs in the Northwest Atlantic are described. One is a relatively new program referred to as the Atlantic Zonal Monitoring Program (AZMP) which has been in operation since the late 1990's. The key element of the AZMP sampling strategy is the oceanographic sampling at fixed sites distributed at strategic locations throughout the Maritimes including the Bay of Fundy, Scotian Shelf, Gulf of St. Lawrence, as well as the Newfoundland and Labrador region. In addition to the fixed sites, a series of primary sections are occupied across these areas (Fig. 1).

The fixed stations are occupied about every two weeks from ice-out conditions, and the sections are sampled from one to three times during the year, typically during the spring, summer, and autumn periods. The observations and measurements collected as part of the AZMP fall into 5 major categories consisting of hydrographic, plankton, climate, meteorological, and remote sensing data. The ability of the AZMP to resolve seasonal and interannual variability is greatest for physical variables and least for biological measures (Table 1).

This is due in part to the limited time series of biological measures during the 1990's; however, more regular measurements have been collected in recent years. These programs resulted in several studies describing the physical variables throughout the Atlantic zone, as well as very basic atlases for nutrients. The latter are primarily confined to the Gulf of St. Lawrence and Scotian Shelf. However, the largest gaps in our knowledge remain for phytoplankton and zooplankton populations in many parts of the zonal network due to inadequate sampling.



## Core observation sites and temporal coverage

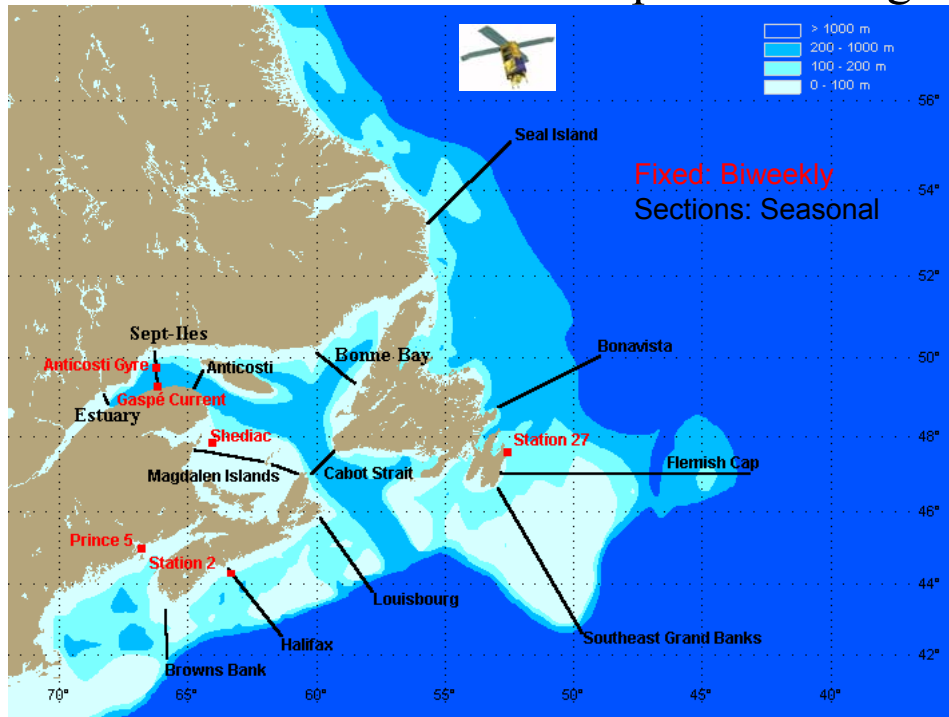


Figure 1. Atlantic Zonal Monitoring Program (AZMP) fixed stations and primary sections in the Northwest Atlantic.

The Continuous Plankton Recorder (CPR) program has been in existence since the late 1950's. This is rather unique among biological time series in the marine realm which seldom last longer than a few years. The CPR survey provides an assessment of long-term changes in abundance and geographic distribution of planktonic organisms ranging from small phytoplankton cells to large macrozooplankton. The CPR is towed by ships of opportunity along a number of standard routes throughout the North Atlantic (Fig. 2).

The CPR device collects plankton, at a nominal depth of 7 m, through an aperture and organisms are retained on a moving band of silk material after which they are preserved. Sections of silk representing an 18.5 km tow distance and 3 m<sup>3</sup> of water are filtered and analyzed microscopically. The CPR taxon categories vary from species to subspecies, while others are identified at coarser levels such as genus or family.

## AZMP Variables and Temporal Scales

<b>Variables</b>	<b>Seasonal</b>	<b>Interannual</b>	<b>Decadal</b>
<b>Biological</b> - Chlorophyll - Plankton - Optical Properties	Surface chl every-where, chl and plankton at fixed sites, along CPR and AZMP sections	Southern Gulf of St. Lawrence (SGSL), Scotian Shelf Gulf of Maine (SSGoM), Georges Bank	Everywhere
<b>Chemical</b> - Nutrients - Oxygen	Fixed stations and representative areas,	SGSL, SSGoM, Georges Bank	Everywhere
<b>Physical</b> - Temperature - Salinity	Sea surface temperature everywhere, fixed stations and their representative areas, ESS, other limited areas, year-round Long-term Temperature Monitoring Program stations	Everywhere	Everywhere

Table 1. Atlantic Zonal Monitoring Program (AZMP) variables and temporal resolution.

There is considerable short term variability in all elements of the lower food chain (nutrients, phytoplankton and zooplankton). Current collections from AZMP and CPR programs will provide insight into the possible mechanisms that control and influence the production of resource populations such as shrimp; however, the time series are currently limited. With respect to the Newfoundland and Labrador Shelf, we have only limited information about the long term trends (from CPR which excludes the higher trophic levels). The latter do hint at a change in lower food web dynamics over the past decade but, suggest relatively stable timing of plankton cycles, unlike that observed in the Northeast Atlantic. This may be linked to changes in the physical environment but further analyses are required before a link can be established on the Newfoundland and Labrador Shelf. Expansion of the trawl-mounted Conductivity Temperature Depth (CTD) sensors, vessel profilers, moored systems together with remote sensing will improve our ability to make inferences regarding the potential influence of environmental variability on resource populations.

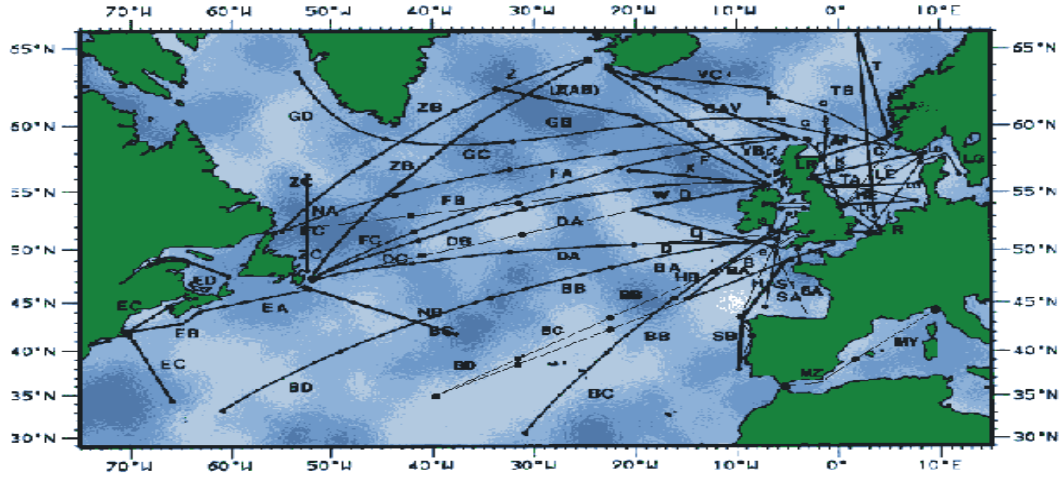


Figure 2. Continuous Plankton Recorder (CPR) standard routes in the North Atlantic since the late 1940's.

**Distribution and Abundance of Northern Shrimp (*Pandalus borealis*) in Relation to Bottom Temperatures in NAFO Divisions 3LNO based on Multi-Species Surveys from 1995-2004**

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Since the fall of 1995, the Canadian research vessel surveys in the Newfoundland and Labrador Region used a Campelen 1800 shrimp trawl to provide abundance and distribution data on northern shrimp (*Pandalus borealis*). Trawl-mounted conductivity-temperature-depth (Seabird model SBE-19 CTD systems) recorders were used as the primary instrument to collect oceanographic data corresponding to each trawl set location. This system records temperature and salinity data during trawl deployment and recovery and for the duration of the fishing tow. In this presentation we examined the mean catch rates and the cumulative distributions of available temperature in relation to catch numbers for the complete range of temperatures encountered in the region. We then presented spatial distribution maps of northern shrimp in relation to the near-bottom temperature fields for both the spring and fall surveys.

Data on shrimp abundance and distribution in NAFO Div. 3LNO were available for the years 1995-2003 for the fall and from 1998-2004 for the spring surveys. Fishing sets of 15 minute duration at a towing speed of 3 knots were randomly allocated to strata covering the Grand Banks and slope waters to a depth of 1500 m. The mean number and weight of northern shrimp were computed within 1°C-temperature bins for each survey. Cumulative percent distributions of catch numbers for each temperature bin were compared to the available temperature distribution within the 3LNO region for all surveys. Near-bottom temperature grids for NAFO Divisions 3LNO were then produced from all available spring data for the years 1998-2004 and for the fall surveys for the years 1995 to 2003. All near-bottom temperature values for the time period of each survey were interpolated onto a regular grid and contoured using a geostatistical (2-dimensional Kriging) procedure. The number and total weight of northern shrimp per fishing set were displayed over the temperature contours as expanding solid circles proportional to the magnitude of the catch.

The analyses show that the highest numbers of shrimp are generally found in the 2°C-4°C temperature range during the spring with lower numbers in water <2°C and >4°C. During the fall, most shrimp are found in a colder temperature range of 1°C-3°C (Fig. 1).

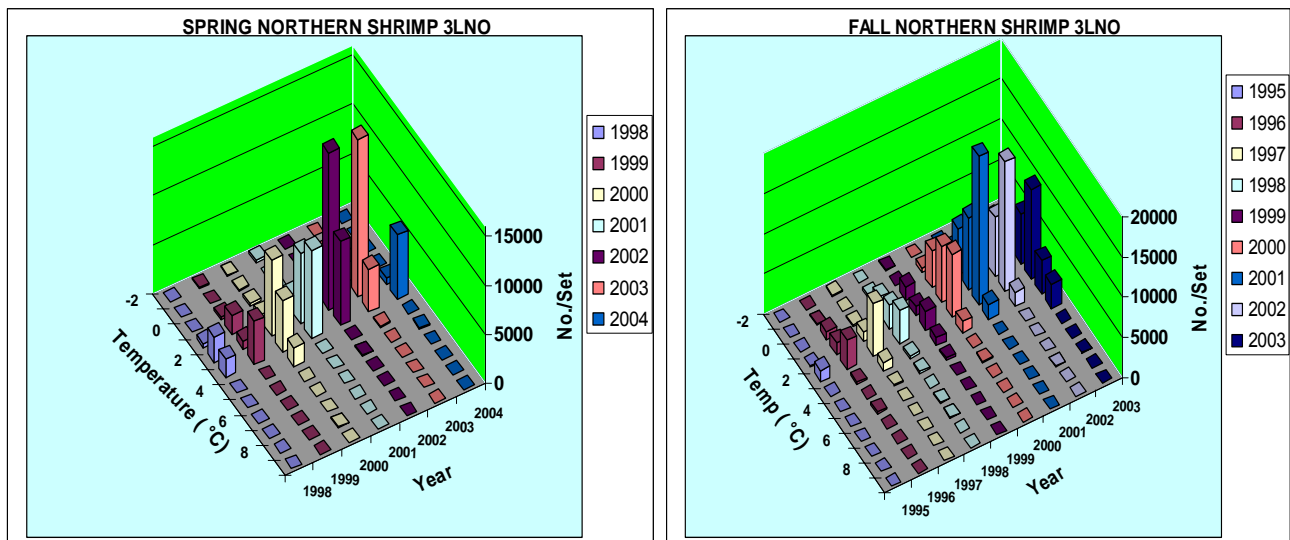


Figure 1. The average number of northern shrimp per fishing set in 1°C temperature bins during the spring for the years 1998 to 2004 and during the fall for the years 1995-2003 in NAFO Div. 3LNO.

Cumulative percent distributions of the number of shrimp caught and temperature indicated that <5% of the catches were associated with temperatures <1°C in the spring and up to 30% were associated with temperatures <1°C in the fall. About 80-90% of the shrimp were caught in the 2°C-4°C temperature range during the spring, while only about half that number appeared in this temperature range during the fall. In terms of available thermal habitat, about 30% of the surveyed

region was covered with water in the 2°C-4°C-temperature range during the spring, while about 40% was covered by water in this temperature range in the fall. An apparent shift in the shrimp distribution toward colder temperatures further upon the Grand Banks and toward inshore regions occurred during the fall compared to spring and as a result, a greater proportion (30%) of the catch shifted into the 0°C-1°C temperature range. Few shrimp were found in temperatures <0°C and >4°C during either spring or fall. Shrimp catches were mostly zero in all surveys in the shallow waters (<100 m) of the southeast Grand Banks, where temperatures generally range from 2°C-7°C. In general, during the spring most of the large catches were found in the warmer water along the slopes of Div. 3LN, while in the fall, larger catches were found in most areas of Div. 3L including the inshore areas of the bays along the east coast of Newfoundland (Fig. 2). During the spring of 2004 most of the shrimp were found in the 3°- 4°C temperature range with a significant decrease in the overall catches over the previous two years. It is not known if the changes in abundance during the spring were related to the warming environment on the Grand Banks during the spring of 2004. Furthermore, it is not clear if the observed changes in the distribution from spring to fall are environmentally driven, or due to other factors, such as changes in trawl catchability due to vertical migration, feeding behaviour or other unknown environmental variables.

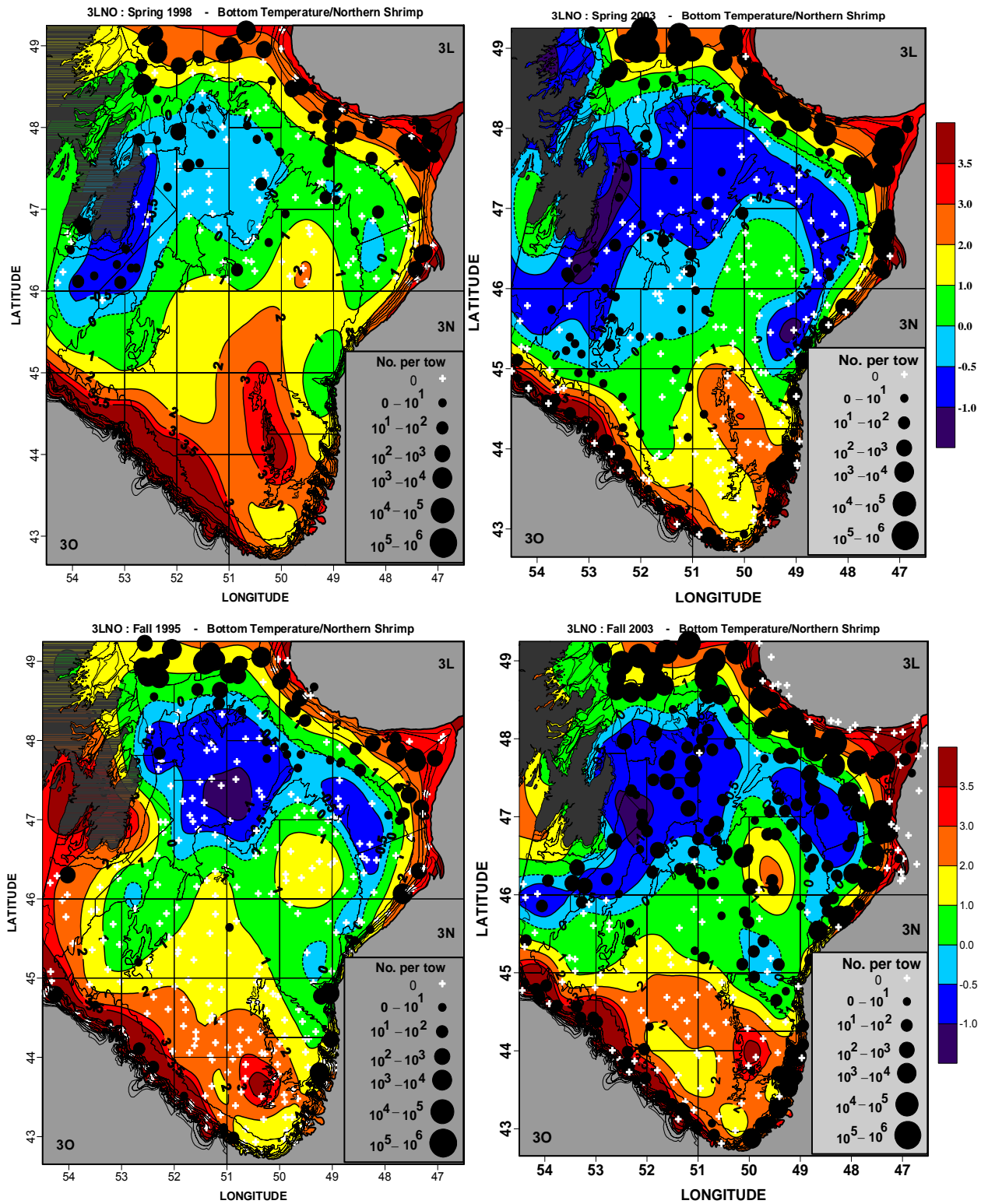


Figure 2. Bottom temperature contour maps (in °C) for the spring of 1998 and 2003 and the fall of 1995 and 2003 from the annual 3LNO survey and the numbers of shrimp in each fishing set shown as solid circles. The white crosses represent zero catches.

## How the Northern Shrimp industry can contribute to and benefit from operational ocean forecasting of the Labrador Current

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Currently there is a capacity building endeavor within Fisheries and Oceans Canada (Operational Oceanography), Environment Canada and the Department of National Defense. In the Newfoundland and Labrador Region, DFO is forging ahead with the research and development phase of the Newfoundland Operational Ocean Forecasting System (NOOFS) (Fig. 1). Compared with traditional ocean forecasting models, an operational ocean model is designed to deliver timely forecasts and oceanographic analysis in near real time to scientists and to other end users such as the fishing industry and the oil industry.

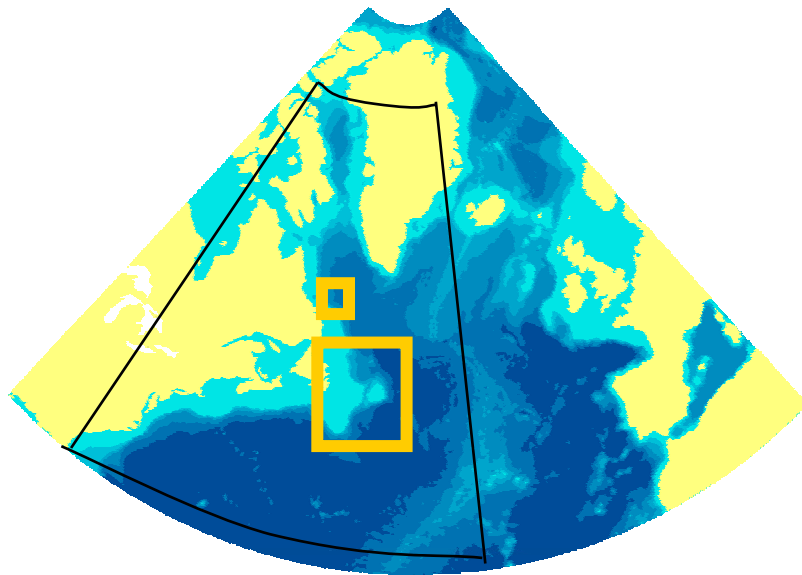


Figure 1. The operational area covered by the Newfoundland Operational Ocean Forecasting System. The model domain is shown here. An outer layer (black line) covers the North West Atlantic. Boundary forcing (inflow/outflow) conditions are specified by the French Operational Ocean Forecasting system MERCATOR which

forecasts the entire North Atlantic in real time. The thick yellow lines represent higher resolutions nests which permit model resolution to increase from 20 km for the North West Atlantic to 4 km resolution for specific regions such as the Grand Banks and Hamilton Bank (or other locations of choice).

The forecasting system will be developed over three years, with a system ready for operation by 2008. Forecasting comprises of an observations component, a modeling component and a forecast dissemination mechanism (i.e. web page).

Observations for the model forecasts are required in near real time for constraining the model towards reality and model validation. Necessary observations include satellite based remote sensing data and complementary in-situ based observations of the water column. While there are numerous satellite products available in near real time over the northwest Atlantic, there are little *in-situ* near real time information available. Traditionally *in-situ* temperature and salinity profiles are obtained from scientific ship based surveys as well as ships of opportunity.

However additional temperature and salinity observations could be collected by fishing fleets for use in ocean forecasting. This would ensure that the model forecasts of ocean state would be more accurate, particularly in the locations where these new observations would be collected. It is suggested here that the use of shrimp vessels as ships of opportunity be explored. Other new *in-situ* data collection methods we are exploring include the use of temperature and salinity observations from seals and the use of ocean gliders to name a few (fig. 2).

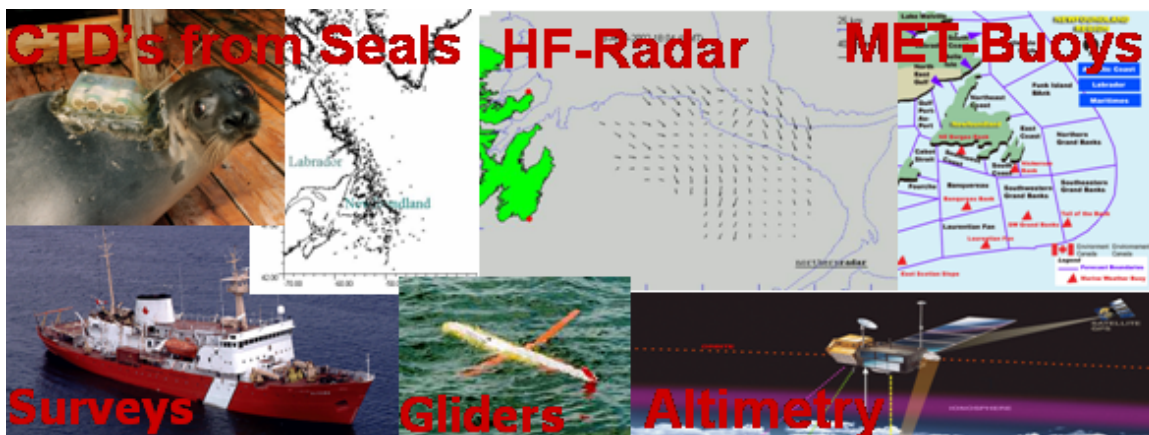


Figure 2. Examples of *in situ* data collection methods being explored by the Oceanography Section in DFO-NL Region.



## Session 1: Biological Overview

### Synthesis and discussion:

Bo Bergström provided an overview of the Pandalid biology. He noted that Pandalids are second in economic value to Penaeid shrimp on a worldwide basis. Northern shrimp (*Pandalus borealis*) are found within temperature and salinity ranges of  $-1.6^{\circ}\text{C}$ – $12^{\circ}\text{C}$  and 23.4 psu–35.7 psu respectively. While northern shrimp range in depth from 9m–1450m exploitable densities are generally found between 50m–500m. He noted that there is a high positive correlation between high organic sediment content and high northern shrimp abundance.

Pandalids are generally protandric hermaphrodites; however, some individuals begin life as primary females and some are early maturing females while the majority are males and change into females at 3–5 years of age. There are no clear mechanisms initiating the change from males to females; the change could be triggered by exogenous environmental cues such as sex ratio or could be endogenously triggered by genetics.

He noted a strong negative relationship between the duration of the ovigerous period and temperature. Research indicates that females may release larval shrimp within 5 months of spawning at temperatures as high as  $10^{\circ}\text{C}$  or remain ovigerous over a 10 month period at  $0^{\circ}\text{C}$ . Early stage larvae exhibit positive phototaxis, drift in the water column and are chance encounter feeders. Larvae feed upon diatoms, meroplankton and early stages of holoplankton ranging in size from  $50\mu\text{m}$ – $1000\mu\text{m}$ . Over the next few months they become increasingly demersal as their abilities to swim and forage become stronger.

Laboratory studies indicate that the optimum salinity and temperature for growth and survival are 32 psu–33 psu and  $9^{\circ}\text{C}$ . At salinities below 25 psu osmotic stress results in low survival while increased temperatures generally resulted in increased respiratory demands. However, gradually increased temperatures in combination with increased food may result in increased survival and growth.

Factors affecting growth included seasonal variations within the ecosystem: in particular temperature and primary productivity. Physiology also influences growth, for instance, young animals may grow at a relatively fast rate with growth slowing as animals age. There is also a trade off between somatic growth and gonadal development. The production of sperm is less expensive than the production of eggs allowing mature males to grow at a faster rate than females. As well, females do not moult while carrying eggs, and therefore do not grow during the ovigerous period. The various growth models that Bergström introduced tried to account for changes in the environment and physiology of the animals.

Bergström ended his presentation by noting that we have a great deal to learn about shrimp and their environment. We do not understand how temperature affects survival and growth of shrimp, why shrimp undergo horizontal migrations, how to properly define stocks and populations etc.

### **Oceanographic Overview**

The biological overview led into the first three papers dealing with oceanography off the east coasts of Newfoundland and Labrador and the types of data products that can be used to address some of the questions posed by Bergström.

The multi-species surveys, AZMP and the CPR surveys are the main sources of environmental data for the Northwest Atlantic. The AZMP program provides remote sensing, hydrographic, plankton, climate indices and meteorological data. The following is a brief outline of the data captured by the AZMP program:

#### **1) Hydrographic data:**

- Multi-species survey

An annual fall multi-species survey has been conducted in NAFO Div. 2J3KLNO with alternating years extending as far north as the top of Div. 2H since 1995. An annual spring multi-species survey is conducted in NAFO Div. 3LNOPns. Both surveys are depth stratified and make use of random set allocation. Both surveys make use of a Campelen 1800 shrimp trawl with a 12.7 mm codend liner. The trawl which is towed at 3.0 Nmi for 15 minutes along the bottom, at depths ranging from 50m–1500 m. The trawl provides samples from which biological data are collected for several fin and shellfish species while a trawl mounted conductivity-temperature-depth recorder (Seabird model SBE-19 CTD system) provides oceanographic data at each tow location.

- Climatic datasets:

- a) Standard oceanographic transect survey

The following standard oceanographic transect surveys (Fig. 1) are conducted by NL-Region each year:

1. SE Grand Bank (Spring and Fall)
2. Flemish Cap (Spring, Summer and Fall)
3. Bonavista (Spring, Summer and Fall)
4. White Bay (Summer)
5. Seal Island (Summer)
6. Makkovik Bank (Summer)

## 7. Nain Bank (Summer)

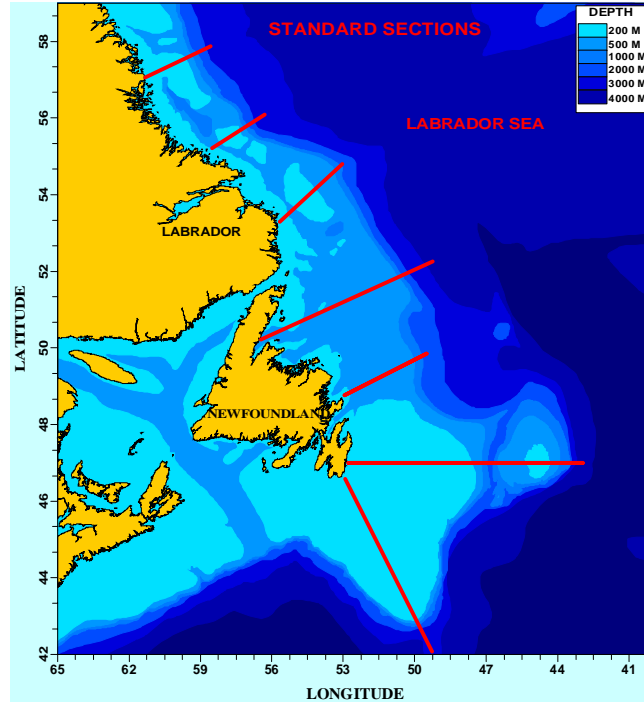


Figure 1. Standard oceanographic transected surveyed each year by DFO - NL Region.

A vertical CTD with a rosette of Niskin bottles is cast every 10 Nmi along each transect from which high resolution vertical profiles of standard variables (temperature, salinity, dissolved oxygen and fluorescence) are collected at each station. Water samples, collected by Niskin bottles at fixed depths, are analysed for *in situ* measures of nutrients and chlorophyll a.

Oceanographic data from the multi-species and transect surveys capture information used to monitor changes in the Cold Intermediate Layer (CIL) as well as temperature and salinity anomalies.

It should be noted that standard oceanographic sampling is also conducted by Scotia-Fundy, Gulf and Quebec Regions within the Department of Fisheries and Oceans.

### b) Remote Sensing

The Bedford Institute of Oceanography (BIO) and the Institut Maurice Lamontagne (IML) provide high resolution spatial and temporal imaging of Sea Surface Temperature (SST). BIO also provides analyses of ocean color that can be used as a proxy for chlorophyll a concentration

and phytoplankton biomass. BIO analyses have provided a means of monitoring the timing, magnitude, and duration of the production cycle across the Northwest Atlantic.

Dr. Guoqi Han of the NL Region Biological and Physical Oceanography Section within DFO–NL Region makes use satellite altimetry to model the speed and path of water currents such as the Labrador Current.

Iceberg counts and areal extent of sea ice are also monitored by AZMP.

## 2) Atmospheric data

Environment Canada collects sea level pressure, dew point, temperature, dry bulb temperature, wind speed, wind direction, total cloud cover, rainfall and solar radiation data, on an hourly basis, at a number of fixed meteorological stations along the east coast of Canada from southern Nova Scotia to Ellsmere Island in the north.

By studying atmospheric pressure anomalies meteorologists can monitor the NAO, which is one of the dominant environmental forces in the north Atlantic. The NAO is the difference in atmospheric pressure between Iceland, in the north, and the Azores, in the south. Typically a positive NAO results in high NW winds, cold sea temperatures and heavy sea ice conditions.

## 3) CPR data

Continuous plankton recorders are instruments that have been carried by “ships of opportunity” since the 1940’s. The recorders are set at a depth of 7 m as the ships travel from port to port. Data from these surveys are used to monitor long-term changes in abundance and geographic distribution of planktonic organisms ranging from small phytoplankton cells to larger macrozooplankton. Unfortunately there is a data gap between 1976 and 1991 when samples were not processed.

The NAO had been increasing over a 30 year period between the 1960’s and the early 1990’s when it reached the highest level in 100 years. Since then the NAO has been trending downward with 2001-2004 estimates below the long term norm. Concurrent with the decreased NAO was a decrease in the areal extent of winter sea ice. For the past 10 consecutive years, the area covered by sea ice has been below normal; the 2004 estimate was the lowest since 1969. Similarly, the area weighted fall bottom temperatures, in NAFO Div. 2J3K, have been trending upward. Fall bottom temperatures were near normal in 3LNO over the period 2000–03 but then increased during 2004. The area occupied by the eastern Newfoundland Shelf portion of the CIL (<0°C) was below normal for the tenth consecutive year and, in 2004, was the lowest since 1965.

The fourth presentation indicated that increased temperatures may have implications for shrimp distribution patterns. During the spring 3LNO research survey most of the large catches were found in the warmer water along the slopes of Div. 3LN, while in the fall, larger catches were found in most areas of Div. 3L including the inshore areas. Thus there was an apparent shift in shrimp distribution toward colder temperatures during the fall. Less than 5% of the spring 3LNO research survey catches were taken in bottom temperatures less than 1°C while approximately 30% of the fall research catches were associated with temperatures less than 1°C. Approximately 80-90% of the shrimp caught during the spring 3LNO research survey were taken in 2°C – 4°C water while most of the fall survey catches were taken in 1°C – 3°C temperature range.

AZMP analyses indicate that there is considerable short term variability in all elements of the lower food chain (nutrients, phytoplankton and zooplankton). However, there appeared to be a direct relationship between total CPR decapod counts and snow crab catches eight years later. A weaker relationship was found between decapod counts and shrimp catches three years later.

Dr. Fraser Davidson's presentation focused upon the NOOFS. By making use of real-time "*in situ*" measurements of ocean currents, it may be possible to create predictive models that would narrow the areas covered by search and rescue teams, thereby saving valuable time and hence lives. Davidson made use of Environment Canada wind monitoring data, satellite remote sensing altimeter data, as well as, CTD data from research vessels and tagged marine mammals, international data sets and experimental sea gliders in his present models to forecast drift. He noted that his models would be greatly improved by having more real-time data over a broader area. Therefore he requested real-time temperature data from the fishing industry.

#### **Recommendation:**

1) Davidson would like to include real-time temperature, from the fishing fleets, in his drift forecasting models. Many of the vessels obtain this data from trawl mounted temperature sensors. Therefore, it was recommended that the vessel owners bring their sensors to the Biological and Physical Oceanography Section within DFO–NL Region so that they may be calibrated and he could determine whether fishing vessel sensors could provide a reliable source of temperature data. If the sensors can be calibrated and reliable data obtained then the next step would be to request real-time data and develop acquisition protocols.

## Session 2 - Recruitment and Growth

**Question:** *What are the perspectives on production in shrimp populations throughout the North Atlantic in relation to density dependent and density independent factors?*

### **Growth and Recruitment of Northern Shrimp – a research program at Maurice Lamontagne Institute, Department of Fisheries and Oceans, Mont-Joli, Québec**

L. Savard, P. Ouellet and Y. Lambert,

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Variations in the physical and biological environment in the Northwest Atlantic have important effects on the dynamics of northern shrimp (*Pandalus borealis*) populations. Conversely, spatial and temporal variations in the life history characteristics of shrimp populations inevitably influence harvesting strategies. Shrimp stocks are formally assessed every year and scientific information is taken into account when setting TACs and establishing fishery management plans. Monitoring programs (fishery statistics, commercial sampling, and research surveys) allow a fair assessment of past and current status of the stocks but recruitment processes and mechanisms responsible for variations in growth and biomass are still poorly understood. Therefore, it is still difficult to forecast the production of a year-class and to identify reference points for conservation and management purposes.

Future research strategies were identified at an international workshop held in 1997 in Nuuk, Greenland (Hvingel 1997). During that workshop, it was stated that progress towards understanding and forecasting fluctuations of fishable biomass would come from a better knowledge of the factors that control recruitment to the populations. Research initiatives on the recruitment of a year-class to the fishery were then seen as priorities. The research program “Growth and Recruitment of Northern Shrimp” is in line with this priority and investigates growth dynamics, sex change, reproduction and contribution to the spawning stock of distinct year-classes.

The program is based on the hypothesis that growth and condition of the larval and juvenile shrimp are driving the growth trajectory, survival probability and cohort strength in subsequent years. The growth and strength of a cohort would be determined during the first year and, under stable predation mortality, preserved up to recruitment to the fishery and subsequent sex change. The growth trajectory in the first year of life will also have a major role in determining the age and size at maturity, the age and size at sex change and the reproductive contribution of the females.

The research program “Growth and Recruitment of Northern Shrimp” aims at studying the production of shrimp under a variety of conditions. The research program is based on a dual approach using field surveys and controlled experimental studies. Life history characteristics of shrimp are examined in wild populations as well as in tank experiments conducted on individuals of the same year-classes. This dual approach provides a better understanding of field results by testing different hypotheses on condition, growth and survival in controlled conditions.

The research program benefits from the collaboration of the Gulf shrimp fishermen associations who financially support some aspects of the research through a co-management agreement.

**Reference:**

Hvingel, C. 1997. Northern shrimp research in the North Atlantic—state of the art and future research strategy. Report of the Northern Shrimp Working Group, 18-20 March 1997, Nuuk, Greenland. TemaNord 1997: 592. Nordic Council of Ministers, Copenhagen, Denmark. 65 p.

**Recruitment processes in the Western Gulf: Importance of the spring conditions in the determination of the strength of cohorts**

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In the northern Gulf of St. Lawrence, shrimp larvae begin hatching in late April. The larvae are planktonic and, although there is little information on the complete sequence of larval development at sea, pelagic development is estimated to pass through four or five moults and last up to three to four months before the first juveniles descend to the bottom. During laboratory feeding experiments, stage II larvae were more efficient in capturing small prey (e.g. invertebrate eggs and nauplii stages) and feeding rate increased with increasing temperature, while still feeding on early developmental stages of mesozooplankton species, stage IV larvae also fed on larger prey, i.e. stages CIII–CV of *Calanus finmarchicus* (Harvey and Morrier 2003). In addition, under laboratory conditions, the best growth performances were observed for temperatures at or higher than 5°C (Ouellet and Chabot 2005).

In spring 2002 (May 20-26) and early summer 2003 (June 26-July 3), two cruises were conducted in the northwestern Gulf of St. Lawrence (NWGSL) and the Lower St. Lawrence Estuary (LSLE) to investigate the vertical distribution of *P. borealis* larval stages. The objectives during these cruises were to describe the vertical distribution and identify the thermal habitat of the different shrimp larval

stages. The field sampling was complemented by a laboratory experiment to investigate the response of all developmental stages in thermally stratified water columns. The pattern that we infer from our results is that the first two larval stages are in the upper layer and, beginning with stage III, later-stage larvae have an increasing range of vertical distributions (and probably in the intensity of the vertical migrations) until a shift to the deep-water preferred habitat after the fifth moult, at stage VI. Settlement after the fifth moult also means that the time of the migration to the bottom habitat is at about three months of age in the northern Gulf of St. Lawrence (Ouellet and Allard 2005).

It is therefore expected that spring conditions (the rate of vernal warming, onset of the biological production cycle, formation of the seasonal thermocline, etc) would be important ecological factors for larval shrimp cohort success. Time series of seasonal (April–July) daily mean SST in the NWGSL were compiled from available CTD, thermographs, and satellite data available for the period 1994 to 2004. For each year, a time series of standardized daily SST anomalies was estimated from deviation of daily SST from the long-term (1994-2004) daily mean. Shrimp recruitment indices for the NWGLS were obtained from research vessel surveys. Two indices were estimated for the period 1990 to 2003: 1) cohort strength or the abundance of recruits (R), and 2) the recruitment rate (R/SS), where SS is the abundance of females that produce the eggs at the origin of each cohort in the spring catches. The analysis of both time series revealed four years of high recruitment since 1994 (1994, 1997, 1999 and 2002) and six years of low recruitment (1995, 1996, 1998, 2000, 2001 and 2003). Spearman rank correlation analyses revealed a negative relationship between shrimp recruitment indices (R and R/SS) and SST at May 1<sup>st</sup> in the NWGSL with two noticeable outliers: 1999 (highest R) and 2003 (lowest R and R/SS). Cold SST and anomalous cold springs appear favorable for high shrimp recruitment.

Low SST in early May in the NWGLS reflects a weak stratification of the surface layer and probably the conditions for the initiation of the annual cycle of biological production in that system. We therefore propose the hypothesis of a strong coupling between the timing of the spring production and the growth and survival of the early shrimp larval stages in the NWGLS.

### **References:**

- Harvey, M., and G. Morrier. 2003. Laboratory feeding experiments on zoea of northern shrimp *Pandalus borealis* fed with natural zooplankton. Mar. Ecol. Prog. Ser. 265: 165-174.
- Ouellet, P., and Allard, J.P. 2005. Vertical distribution and behaviour of shrimp *Pandalus borealis* larval stages in thermally stratified water columns: Laboratory experiment and field observations. Fish. Oceanogr. (accepted)



Ouellet, P., and Chabot, D. 2005. Rearing *Pandalus borealis* larvae in the laboratory: I – development and growth at three temperatures. Mar. Biol. (In press).

**Recruitment variations in the Gulf of St. Lawrence: Variations in recruitment to the fishery and fishable biomass in the Gulf; variations in cohort strength from recruitment surveys in the Western Gulf**

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Landings of northern shrimp in Sept-Iles fishing area (northern Gulf of St. Lawrence) have increased gradually since the fishery began in the 1960s and reached about 16,000 tons in 2004. Different management measures including total allowable catch (TAC) were implemented in the 1980s and 1990s to limit fishing. The stock is assessed each year and the status is determined by examining a number of indicators from the commercial fishery and research surveys.

Most of the indicators were negative during the first half of the 1990s but thereafter, the productivity increased with the result that most of the indicators were positive during the second half of the 1990s. Indeed, commercial catch rate and survey fishable biomass data (1990-2003) are coherent and show an increase in the size of the stock during the second half of the 1990s and the 2000s ( $R^2=0.88$ ). Several year-classes with higher than average abundance were recruited during the second half of the 1990s causing the commercial catch rate and the fishable biomass to increase. The relationship between survey fishable biomass of a given year and fishery catch rate, in the succeeding year, is positive ( $R^2=0.75$ ) indicating that there is a possibility of forecasting the success of the fishery from the survey results. Therefore, exploratory work was conducted to develop year-class abundance indices that could be used to forecast some years in advance, the recruitment to the female component and the fishable biomass.

Length frequency distributions from survey and fishery catches are coherent and indicate that cohorts can be identified at a modal size of 15 mm carapace length (CL). Thereafter, abundant cohorts can be followed up to the recruitment to the female component (22 mm, CL) while weak cohorts are difficult to identify when they approach 20 mm (CL). The abundance at 19 mm (CL) in the survey and the catch rate (in number) at 18 mm (CL) in the fishery were used as indices of recruit abundance. These indices are coherent ( $R^2=0.79$ ) however our ability to predict fishery success from them less certain. The relationship between the abundance of recruits in the survey or in the commercial catch of a given year and the fishery catch

rate two years later is weak ( $0.17 < R^2 < 0.36$ ). Fishery catch rates depend on the abundance of large shrimp over the fishing grounds; this group of shrimp is composed of several year classes so it is difficult to forecast its abundance from an index that relies on only one year class.

An independent survey aimed at estimating the relative abundance of year classes that could be used as an index of recruitment was conducted in the Estuary in October from 1999 to 2004. A rigid frame trawl with a small mesh size was designed and built to efficiently catch all sizes of shrimp. The trawl proved to be very efficient at catching all components of a shrimp stock, including age groups of six months ( $\approx 5$  mm, CL), one year and a half ( $\approx 11$  mm, CL), and two years and a half ( $\approx 15$  mm, CL) that would otherwise not be caught or retained by commercial or existing research fishing gears. Preliminary results indicate wide inter annual variation in year class strength. For each survey, the abundance of the first three age groups (6 months, 18 months and 30 months) was estimated. With the exception of the 2002 year-class estimated at 18 months in the 2003 survey, good correlations are observed between the indices estimated for the same year-class at different ages ( $0.36 < r < 0.91$  with the 2002-18 month data point;  $0.91 < r < 0.99$  without the 2002-18 month data point).

Given the size distributions of shrimp caught in the recruitment survey, it was possible to determine that the year-class abundance index obtained at 19 mm (CL) from the biomass survey corresponds to three-year-old shrimp. Since the biomass survey was conducted from 1990 to 2003, the first and the last year classes that could be estimated at three years old were the 1987 and the 2000 year-classes. Likewise, the first and the last year classes for which an abundance index could be estimated from the recruitment survey were the 1997 year-class (at the age of 30 months in 1999) and the 2003 year-class (at the age of 18 months in 2004 (Figure 1).

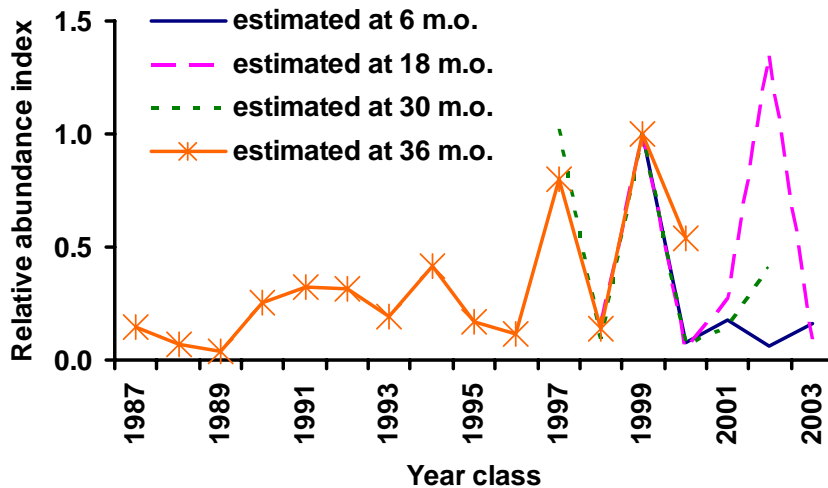


Figure 1. Relative abundance indices estimated from the biomass survey (at 36 months old) and from the recruitment survey (estimated at 6, 18 and 30 months old). Each series is scaled to the 1999 year-class value.

The 1994, 1997 and 1999 year-classes are the most abundant in the series while the 1998, 2000, 2001 and 2003 year-classes are among the weakest. The 1997 and 1999 year-classes were responsible for the increase in biomass in the 2000s and for the recent success of the fishery. The relative abundance of the 2002 year-class is uncertain given the wide range of estimates.

In an attempt to extend the series for studying recruitment processes, an extended recruitment series including indices from the 1987 year-class to the 2003 year-class was put together. The relationship between the spawning stock and the recruitment was examined. Spring female catch rates were used to provide indications of the spawning stock abundance while the mean of the relative abundance indices for each year-class was used as an estimate of recruitment. Data did not show any apparent stock recruitment relationship. The 1998, 2001 and 2003 year-classes were produced by a spawning stock for which the abundance was among the highest of the series. The 1997 and 1999 year classes were produced when the stock abundance was average.

Surveys designed to catch young shrimp can provide essential information on juvenile relative abundance and growth. From the GSL recruitment survey, it seems that the strength of a year class can be estimated as early as six months of age. Therefore, the period before settlement (larval phase) seems to be the determinant for recruitment success. Thereafter, the year-class strength appears to be preserved up to the recruitment to the fishery and to the female component. However, it is difficult to forecast the fishing success from an index that relies on only one year class. Indeed, commercial fishing targets mainly large shrimp made of several year classes and fishing success is likely to be explained by the successive recruitment to the fishery of several year classes.

**Egg development under variable conditions: Egg survival, embryonic development, and larval characteristics of northern shrimp females subject to different temperature and feeding conditions.**

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(from: Brillon, S., Lambert, Y., and Dodson, J. 2005. Egg development under variable conditions: Egg survival, embryonic development, and larval characteristics of northern shrimp (*Pandalus borealis*) females subject to different temperature and feeding conditions. Mar. Biol. DOI 10.1007/s00227-005-1633-6 )

Laboratory experiments on ovigerous females of northern shrimp (*Pandalus borealis*) were used to assess the effects of temperature and food ration on female condition during incubation and examine how combined effects of temperature and female condition influenced egg survival, embryonic development, and larval characteristics. Ovigerous females were maintained at 2°C, 5°C, and 8°C and fed on a low (three times/week; 2-2.7% W/W) or high ration (five times/week at satiation). Experimental results on female condition, egg and larval production and characteristics were also compared with observations from the wild.

Temperature treatments of 2°C, 5°C, and 8°C and a low or high food ration were randomly assigned to different tanks. The three levels of temperature and two levels of food ration resulted in six experimental treatments each one having two replicates. Thirty shrimp were placed in each experimental unit (division) with half of them being individually identified with a Visual Implant Tag. Tagged specimens were used to monitor the variations in the energy content of the eggs during embryogenesis and untagged specimens, which were not manipulated during the experiment, were used to evaluate egg and larval production and characteristics at hatching.

Female condition was significantly influenced by temperature. A significant increase in female somatic energy was observed during the incubation period but at the time of hatching, ovigerous females held at 8°C had lower energetic condition than females held at 2°C and 5°C. Lower hepatosomatic index and lower specific energy content in the hepatopancreas also indicated that ovigerous females at 8°C accumulated less lipid reserves than ovigerous females at lower temperatures. Lower lipid reserves could indicate that higher metabolic costs are associated with respiration and parental care among ovigerous females held at high temperature. These observations are consistent with Apollonio et al.'s (1986) hypothesis that later in its life cycle (i.e. female size); northern shrimp are less tolerant of warmer temperature.

The incubation temperature of ovigerous females of northern shrimp had marked effects on egg survival, embryonic development and larval characteristics at hatching. Significant differences in hatching dates were observed between the temperatures. Mean hatching date varied from March 10 at 8°C to June 9 at 2°C. Mean incubation time calculated from the beginning of the experiment (November 7<sup>th</sup>) was 123±10, 162±10, and 214±14 days at 8°C, 5°C, and 2°C, respectively. For 50% of the females, the hatching date was within a 12-14 days interval around the median date of hatching. No significant effect of food ration on incubation time was detected.

The increase in temperature accelerated developmental time but egg survival at the highest temperature (8°C) was significantly reduced. Grouped data for each temperature (high and low rations) indicated that mean egg loss was higher at 5°C and 8°C (respectively 64% and 63%) than at 2°C (50%).

The higher temperature reduced the duration of yolk reserves and the conversion efficiency of yolk into tissue growth. As a result, significantly lower larval size, mass and protein content were observed at 8°C than at 2°C and 5°C. A negative gradient in the morphological characteristics (CL, total length (TL), dry, and wet mass) of the larvae was observed in relation to temperature. Mean CL of hatching larvae at 2°C was significantly greater than at 5°C and 8°C. TL of the larvae was similar at 2°C and 5°C but significantly greater than at 8°C. Mean wet mass of larvae hatching at 2°C was significantly higher than at 8°C. Mean protein content of larvae was significantly lower in larvae hatching at 8°C than at 2°C and 5°C. However, no significant effect of temperature was observed on the dry mass of larvae at hatching.

Food rations, used in the experiment did not result in any difference in the mean condition of the females. However, within each food ration a large range in the physiological condition of the females was observed. The significant relationships between hepatosomatic index (i.e. lipid reserves) of the females and larval size, dry mass and energy content could indicate a possible effect of the physiological condition of ovigerous females on the characteristics of the embryos. However, physiological condition should not directly influence larval characteristics as the embryos rely on energy reserves accumulated during vitellogenesis for their development. On the other hand, parental care provided through the oxygenation of the egg mass by the beating of the pleopods may potentially be reduced in ovigerous females with lower physiological condition. It has been demonstrated that parental care is important for the development of embryos, especially for embryos arranged in large and compact masses. Oxygen limitation caused by the position of the embryos in the mass can lead to longer development times or smaller size at hatching. However, this hypothesis is speculative as higher cost associated with parental care does not necessarily indicate a decrease in parental care. Other studies, with more appropriate experimental design are needed to test these possible relationships.

The results of this study suggest that the recruitment success of northern shrimp will be influenced by temperature. Populations of northern shrimp which are largely distributed in the Northwest Atlantic from Davis Strait to the Gulf of Maine are subjected to a large range of temperature according to their geographic position. For example, Scotian Shelf may represent a transition area in oceanographic conditions for northern shrimp (Koeller 2000). While western Scotian Shelf and Gulf of Maine populations evolve in similar conditions of temperature near the upper physiological and/or ecological limit, the eastern Scotian Shelf population is found in conditions similar to those on the southern Newfoundland Shelf which are believed to represent the preferred temperature range for northern shrimp. However, the optimum temperature for the physiological condition of the females during maturation and embryogenesis and consequently for larval characteristics at hatching is not necessarily the same for the other developmental stages of the life cycle. While lower temperatures appear optimal for maturation and reproduction (Stickney and Perkins 1977, Nunes 1984, Bergström 1991, this study) larval survival and growth as well as juvenile growth seem to be favored at higher temperatures or in environments

with continuously increasing temperature (Nunes and Nishiyama 1984, Shumway et al. 1985, Rasmussen 1992, Tande et al. 1994, Rasmussen and Tande 1995). Further research on the ontogenetic changes in the response of shrimp to temperature is needed to understand how abiotic and biotic factors will affect shrimp population dynamics.

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**Changes in growth pattern of different developmental stages under variable conditions: Molting frequency, size and mass increments of larvae, juveniles, males, transitional females and females of northern shrimp under laboratory conditions**

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Laboratory experiments were used to estimate growth in length and mass, molting frequency and size increment between molts for the different developmental stages of shrimp. The experiments were conducted at three temperatures. Larvae were raised at 3°C, 5°C, and 8°C while all other experiments on juvenile and adult stages were conducted at 2°C, 5°C, and 8°C. Larvae and juveniles in their first and second year of life were obtained from ovigerous females raised in the laboratory. Experiments with males and females were conducted with individuals caught at sea and brought to the laboratory. An acclimation period of at least one month was allowed before the beginning of the experiments.

Larval growth was much slower and the larvae were significantly smaller at each stage at 3°C relative to 5°C and 8°C (Ouellet and Chabot 2005). In addition, growth appeared not to be constant but to slow down after the second molt (stage III) at each experimental temperature. Molt increment was maximal at the first molt and then declined to reach a minimum at the third molt (passage from stage III to stage IV). The first interpretation of these results was to conclude that a change in shrimp larval growth rate was observed. It was hypothesized that the observed change in growth rate might coincide with the transition from “pure” pelagic zoea-type larvae to late larval stages able to migrate in deeper waters.

Juvenile growth during the first year of life was measured from the stage corresponding to the transition from pelagic to benthic life (age of 2-3 months) to one year of age. Larvae raised in the laboratory between April and July were used for the experiments. Juveniles were either raised in groups in 80 l circular tanks or individually in small cubicles. Bimonthly samples of the circular tanks and daily monitoring of the cubicles were used to measure growth in length and mass, molting frequency, and length increment between molts. A positive relationship between juvenile growth rate and temperature was observed. Growth rates obtained at 2°C were much slower than at 5°C and 8°C. After 10 months, the increase in size at 8°C

was 63 % higher than at 2°C. The difference in mass increment was much higher; juveniles reared at 8°C being 380% heavier than at 2°C. Differences in growth were largely associated with higher molting frequency at high temperature. Juveniles molted on average every 46 days at 2°C while they molted every 33 days at 5°C and every 26 days at 8°C. The size increments at each molt were on average between 9.7% and 11%; higher size increments between molts were observed at 2°C.

Juvenile growth during the second year of life (age one to age two) was also measured by rearing the juveniles individually and in groups. The increase in length and mass was measured at two temperatures (2°C and 5°C). Groups of juveniles raised in the laboratory at three different temperatures during their first year of life were used for the experiment. Thus, the increase in length and mass of juveniles previously raised at 2°C, 5°C and 8°C was measured at 2°C and 5°C. Juveniles were sampled on four occasions during this period to measure changes in mean carapace length and mass in each experimental condition. Juveniles raised at 2°C and 5°C during their first year of life showed higher increase in length and mass at 5°C than at 2°C in their second year of life. However, no difference in length and mass increments during the second year was observed between 2°C and 5°C for juveniles raised at 8°C during the first year of life. These results suggest that ontogenic changes in the effect of temperature could be observed in shrimp. Temperatures between 2°C and 5°C would generate differences in the growth of juveniles with sizes and masses below ~10.5 mm in CL and ~800 mg respectively. The growth of juveniles above these sizes and masses was not influenced by temperature for the range between 2°C and 5°C. Juveniles showing slow growth during the first year could compensate during the second year if temperatures are higher (i.e. 5°C vs 2°C). On the other hand, juveniles having fast growth during the first year of life would be less dependent on temperature during the second year of life. Molting frequency also decreased during the second year of life. A molting frequency of 46 days was observed at 5°C during the second year of life compared to 33 days during the first year of life at the same temperature.

Molting frequency and growth of individually reared males were also examined at 2°C, 5°C, and 8°C. The males were monitored for a period of 10 months. Mean carapace length and mass of males at the beginning of the experiment were: 18.0±1.0 mm and 3.55±0.58 g. For each male, CL and mass were measured after each molt. A mean value in days for molting intervals was calculated and growth was estimated as the difference between initial and final values of CL and mass. A positive relationship was observed between temperature and molting frequency with significant differences between each temperature. The molting frequency was twice as fast at 8°C than at 2°C. The number of days between molts at 2°C, 5°C, and 8°C was 129, 80, and 63 days, respectively. Despite the difference in molting frequency, similar increases in CL and mass were observed over the duration of the experiment. A mean increase in CL of 0.9 mm and a mean increase in mass of 0.48 g were observed. These results indicate that the increase in temperature will increase the molting frequency but on the other hand, it will decrease the gain in CL and mass at



each molt with, as a net result, similar increases in growth between temperatures over longer periods.

Molting frequency and growth of female shrimp was also determined by monitoring individually raised females. Molting frequency was the same at 2°C (124 days) and 5°C (120 days) and higher at 8°C (85 days). Growth in CL and mass was very low and even negative in many females. No differences between temperatures were observed.

Experiments completed during 2002 and 2003 were used to follow the sex change of shrimp of the 1999 year class. Live males of ~18-20 mm (CL) in 2002 and ~20-22 mm (CL) in 2003 were brought from the St. Lawrence estuary in October of both years. Shrimp were kept at 2°C and 5°C in the first year and at 5°C only in the second year. They were sampled on three occasions during the winter and spring to follow the morphological changes and growth during sex inversion. The results indicated that transitional females had a significantly higher growth in CL and mass than males that did not become transitional. No significant growth was observed for males that did not begin the sex transition. Moreover, no difference in growth for males and transitional females was observed between 2°C and 5°C. In the first experiment, 24% of the males became transitional while in the second one, 32% of them entered the process of sex transition during the experimental period.

Important differences in the molting frequency and in increases in CL and mass were observed between the different developmental stages. All these growth characteristics were decreasing with the increase in size. However, significant differences in the growth of shrimp of similar sizes were observed in association with the process of sex transition. Transitional females had a significantly faster growth than males. Increased temperature in the range of 2°C to 8°C had a strong positive effect on the growth of larval and juvenile stages. The effect of temperature on the growth of adult male and female stages was reduced or even absent. This ontogenic response to temperature will be important in determining the consequences of changes in the environmental conditions on shrimp population dynamics.

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## Egg Bearing Periods of Northern Shrimp (*Pandalus borealis*) in Icelandic Waters

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Female *Pandalus borealis* carry fertilized eggs on their pleopods while they are getting ripe for hatching during the spring or summer. The ovigerous period for northern shrimp has been shown to depend upon ambient temperature. Populations of shrimp in various locations around Iceland are exposed to various temperature regimes. The warm Irminger Current flows along the coast from south to west clockwise around the country. The warm current meets the cold East Greenland current in the southern Denmark Strait. At the junction a branch of the Irminger current turns westward and mixes in part with waters of the East Greenland Current. This appears to be near the area where the main shrimp concentrations are fished by Icelanders. The North Icelandic Irminger Current, flows eastwards into the shelf waters north of Iceland and ultimately dissipates into the Norwegian Sea. To the north of Iceland, the North Icelandic Irminger Current becomes mixed with a branch of the East Greenland Current. The East Greenland Current is characterized by arctic water of about 0°C (Malmberg and Blindheim 1994).

In this paper there is a revision of the length of egg bearing periods of northern shrimp in five areas in Icelandic waters. Two of those are shallow water areas with temperatures well above 0°C while two areas of three areas feature annual bottom temperatures ranging 0.1°C–0.8 °C. Temperature data, from the offshore, were calculated by the hydrographer Valdemarsson (MRI Reykjavik, pers. comm.).

The methods for studying spawning were as described in Skúladóttir et al. 2004 for Flemish Cap. The eggbearing period was averaged over the years 1985-2004. Bottom temperatures extended over the period 1985-2004 for all areas except Isafjardardjup where temperature was calculated for the years 1970-1993. The length of the ovigerous period was assessed from the time when half of the females that were going to spawn in a particular year had spawned to the time when half of the shrimp had hatched. In relation to temperature, lengths of the ovigerous periods seemed to fall within the range of other *Pandalus borealis* populations as previously described by Shumway et al. (1985). The relationship in which Bergström (2000) fits the length of the ovigerous periods to the average bottom temperature of each area for 33 populations of all species of *Pandalus*, is even easier to compare with these results and are in good agreement with the findings here. The egg bearing periods of Isafjardardjup have previously been found to be about eight months on average, but are here estimated to be seven months. The method of assessing spawning and hatching was now a tiny bit different and more accurate but data were also lacking in

May for Isafjardardjup which could result in the egg bearing period being underestimated. The Snaefellsnes area is now considered to be a week longer on average for all years while the egg bearing period in the Nordurkantur area is considered to be a week shorter than previously assessed (Skúladóttir et al. 1991) (Table 1).

Area	Temp. °C	Depth corresp. to temp. m	No. of Months	Eggbearing %
Snaefellsnes	6.64	100-200	5 & ¾	95.7
Isafjardardjup	4.50	80	7	92.5
Nordurkantur	0.10	300-500	9 & ¾	60.2
Spordagrunn-Grimsey	0.76	300-500	9	70.3
Denmark Strait			10 & ¾	73.0

Table 1. Egg bearing period in relation to area fished, water temperature and water depth.

The average bottom temperature in the northern areas Nordurkantur and Spordagrunn-Grimsey had not warmed up over the past 5-10 years as had been expected. However the temperature of the Snaefellsnes area had warmed up from 6.72°C in the period 1995-99 to 7.02°C in the period 2000-04. The data in the spawning period were, however, too scanty to detect a shortening of the ovigerous period due to a warming up. Also water temperatures warmed up very little in the Snaefellsnes area. The same applies to Isafjardardjup where the hatching period was not well documented.

Analysis of percentage of ovigerous animals indicates that most animals spawn each year at Snaefellsnes and Isafjardardjup while a higher proportion spawn every second year in the three remaining colder areas (see Table 1).

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### **Changes in stock biomass, recruitment and size of Northern shrimp (*Pandalus borealis*) in West Greenland waters—environmental or fishery effects?**

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Stock size of northern shrimp (*Pandalus borealis*) in West Greenland waters had been fairly stable from the late 1980s to the mid 1990s. Thereafter, survey estimates of biomass as well as commercial Catch per Unit Effort (CPUE) increased considerably (Fig. 1). This increase was preceded by an increase in water temperature and several years during which recruitment was substantially above average. In the most recent years, however, recruitment decreased and has been below what could have been expected from record high levels of spawning stock biomass. The increase in recruitment and, with a lag of two years, in stock biomass was most pronounced in the northern part of its distributional range. Changes in length at age (Fig. 2) were positively correlated with bottom temperature in general, but a trend towards slower growth was observed in areas with the highest stock densities in the most recent years. Length at sex transition and maximum length decreased significantly since the mid 1990s (Fig. 3). Positive correlations between length at sex transition and bottom temperature were highly significant for three out of the five regions and for all regions combined. On the other hand, length at sex transition was negatively correlated with stock density in general. Ratios of length at sex transition and maximum length lagged by several years were highly variable without any consistent relationship between the two variables. Mean female size decreased similarly in both, samples from the survey and the commercial fishery. Exploitation rate declined in both, the offshore and the inshore area since the mid 1990s, and the observed changes in the size of northern shrimp were apparently independent from the fishery (Fig. 4).

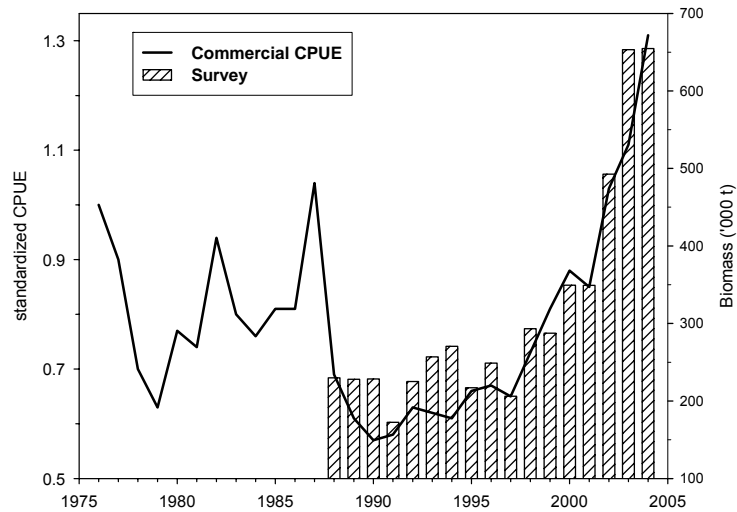


Figure 1. Time series of commercial CPUE and survey indices of northern shrimp biomass at West Greenland. Data from Hvingel (2004) and Wieland et al. (2004).

It is concluded that the moderate increase in temperature above a lower threshold of the optimal range in the northern regions has extended the distributional area that is favourable for northern shrimp. This, together with a decreasing exploitation rate and continuous low predation pressure, resulted in an increase in the stock to a level at which density-dependent effects have become prominent in parts of the area (Wieland 2005). The timing of sex transition appeared to be environmentally driven (Wieland 2004) and no support was found for a reduction in length at sex transition during periods of low female abundance as suggested by sex allocation theory.

The observed changes in recruitment, stock density and mean size can be explained by environmental effects leading to a series of hypotheses on the underlying processes (Table 1). A substantial impact of the fishery, i.e. through an effective selection of larger individuals, was not evident (Wieland and Hvingel, in prep.).

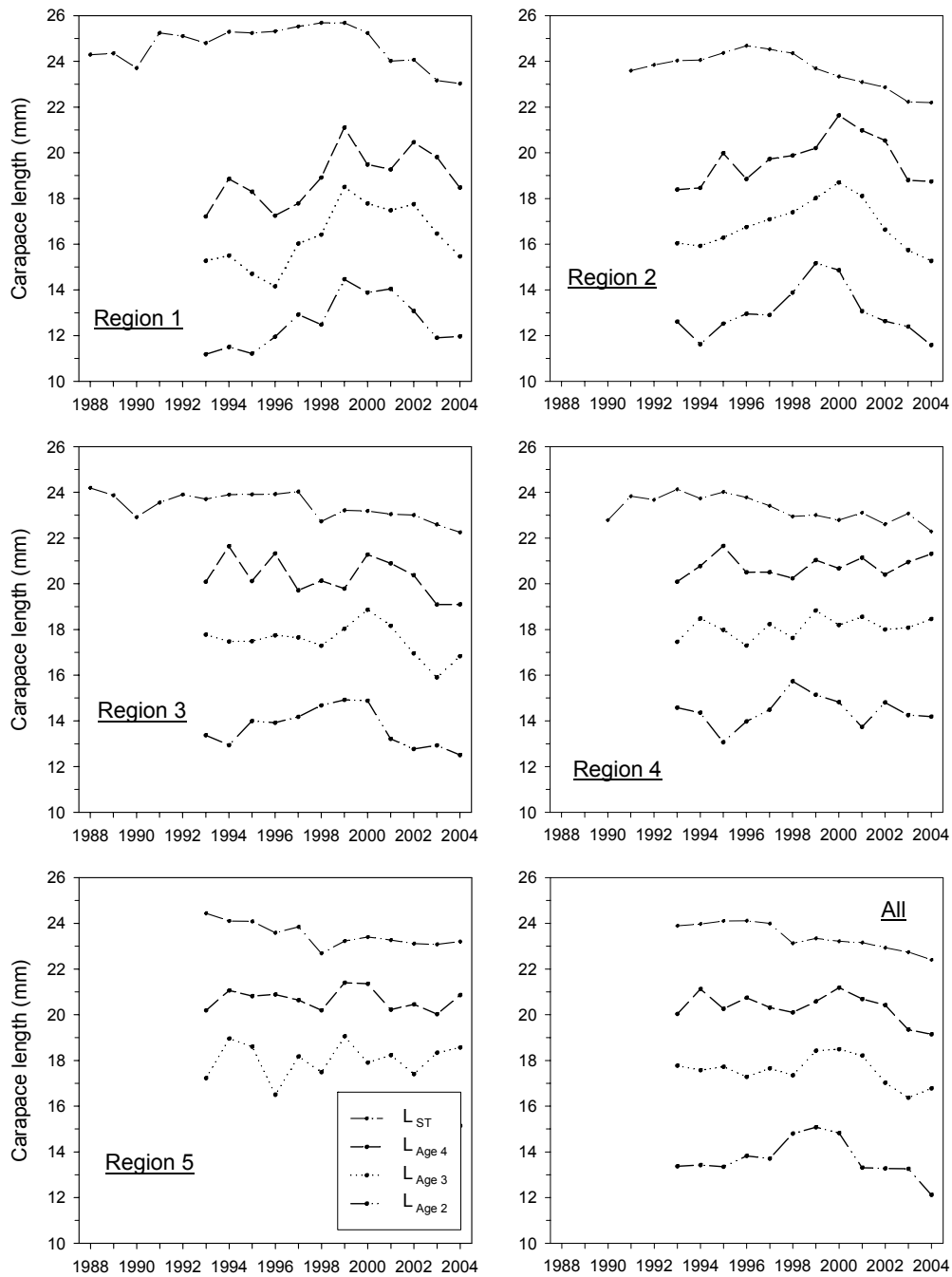


Figure 2. Length at sex transition ( $L_{ST}$ ) in comparison with mean lengths at age two, three and four (no reliable estimates of mean length at age five available for region five due to rather low abundance in the respective size range; see Wieland (2004, 2005) for survey area and its division into regions).

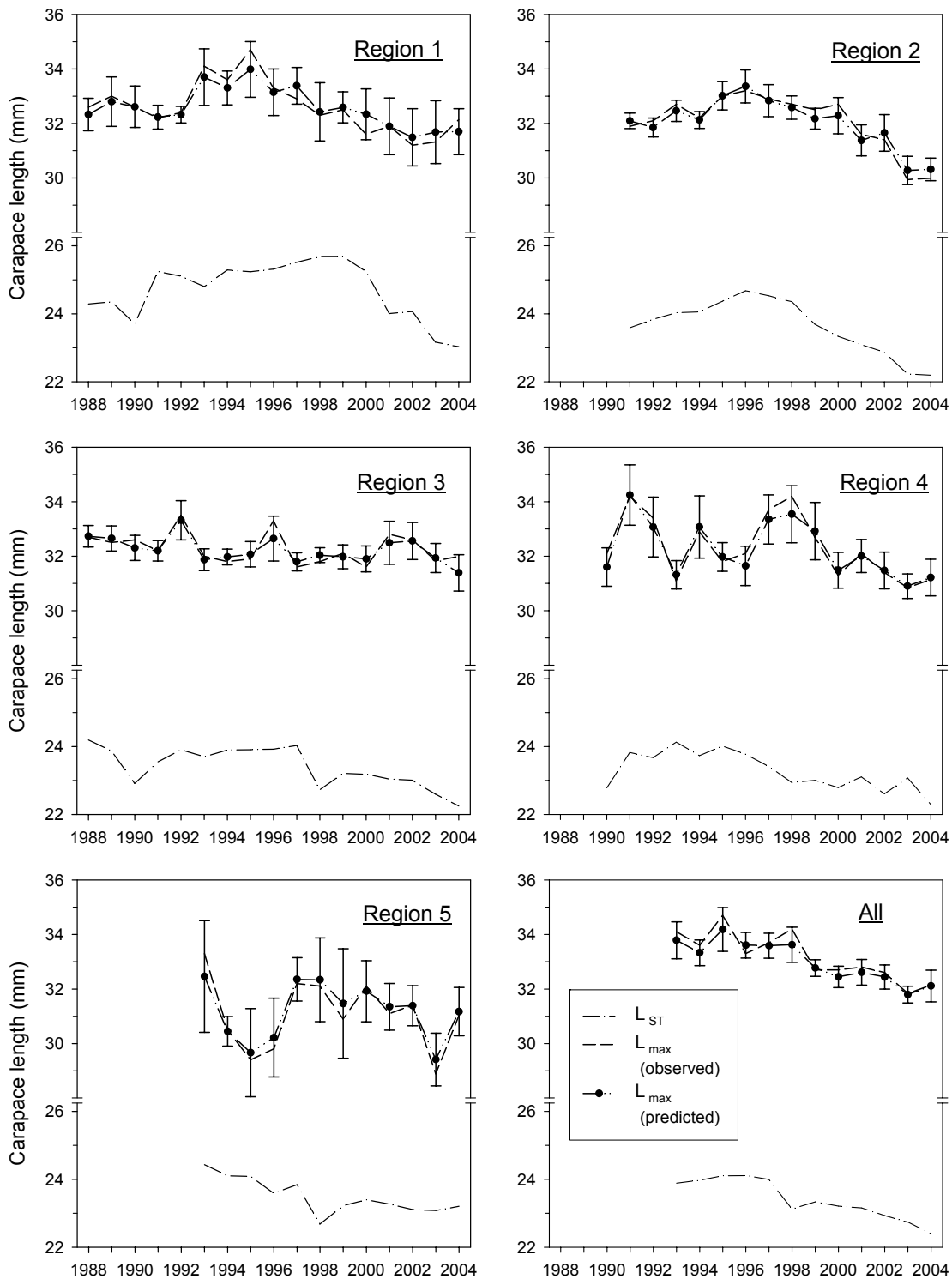


Figure 3. Observed and predicted maximum length ( $L_{max}$ , error bars correspond to 95 % confidence limits) in comparison with length at sex transition ( $L_{ST}$ ); predicted maximum length was calculated according to Formacion et al. (1991); see Wieland (2004, 2005) for survey area and its division into regions).

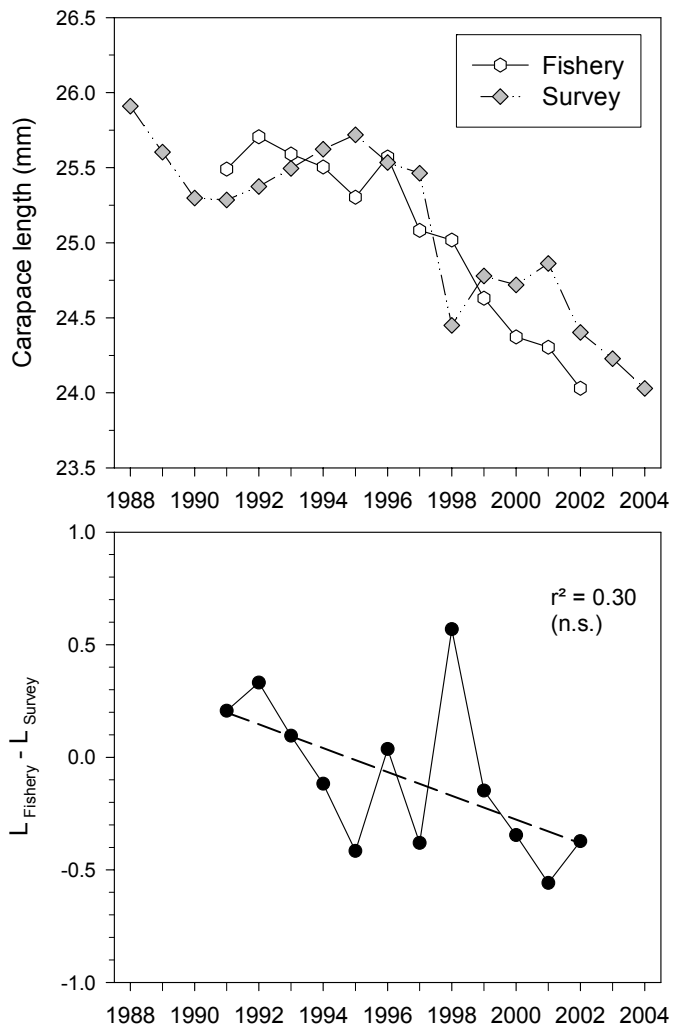


Figure 4. Comparison between mean female length from the survey and the commercial fishery (offshore areas only due to missing information from the inshore fishery in the Disko Bay/Vaigat area).



Table 1. Conceptual summary of density-independent (temperature) and density-dependent (available food) effects on recruitment, stock density and length of northern shrimp at West Greenland (broken arrows indicate delayed response with different time lags according to differences in age).

<u>Scenario</u>	<u>Effects</u>	<u>Mechanisms</u>
Stock density low	high recruitment	Temperature increase cause:
Predation low	increase in larval size	- an extension of the geographical distribution
Temperature increase	increase in juvenile size	- enhanced food conditions (higher carrying capacity)
	decrease in $L_{ST}$	- a shorter egg bearing period (earlier hatch)
	decrease in mean female size	- higher growth rates (and survival) of larvae
	decrease in $L_{max}$	- earlier maturation
Stock density high	decrease in recruitment	Food limitation cause:
Predation increase	decrease in larval size	- a decline of growth rates
Temperature stable	decrease in juvenile size	- slower maturation
	increase in $L_{ST}$	- decrease of larval and juvenile survival (competition in particular within cohorts)
	increase in mean female size	
	increase in $L_{max}$	

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Wieland, K. and C. Hvingel. (in prep.) Size changes of Northern shrimp (*Pandalus borealis*) in West Greenland waters—environmental or fishery effects?

### **Decreasing shrimp (*Pandalus borealis*) sizes off Newfoundland and Labrador—environment or fishing?**

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(Adapted from: Koeller, P., Fuentes-Yaco, C., Platt, T. (in press). Decreasing shrimp (*Pandalus borealis*) sizes off Newfoundland and Labrador—environment or fishing? Fish. Oceanogr.

During the 1990s, CL statistics including minimum size caught ( $L_{min}$ ), mean male and female lengths, size at sex transition ( $L_{50}$ ), and maximum size ( $L_{max}$ ), of northern shrimp (*Pandalus borealis*) decreased in commercial and survey catches off Newfoundland and Labrador. Decreased growth rates caused by decreases in per-capita food availability due to large population increases, exacerbated by increased metabolic demands from higher water temperatures in the mid 1990s, appear to be the main causes of the size decrease. Fishing could have had an accelerating effect on environmentally-driven decreases in shrimp growth and size by “cropping” the largest shrimp from the population. The greatest decreases in shrimp size occurred in Hudson Strait and the adjacent northern shelf, the area which also has the highest densities and largest shrimp. We hypothesize that the greater size decrease here during the 1990s resulted from decreased primary production from decreased nutrient flux into the euphotic zone, caused by increased atmospheric warming, freshwater runoff and stratification during the warming trend of the 1990s.

## **Inferring shrimp (*Pandalus borealis*) growth characteristics from life history stage structure** (ms in preparation)

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Temporal or spatial differences in the lengths of northern shrimp (*Pandalus borealis*) life history stages have been used to infer changes in growth rate, however, it is usually not possible to discriminate between changes in growth rate versus longevity (number of male year classes) without laborious and often inaccurate modal analysis to estimate actual growth rates. Summary statistics such as mean female length are generally used by themselves to make inferences about growth. In this paper we examine the possibility that the mean CL of all stages, when considered together (termed the population's "stage structure"), contains more information on population growth characteristics than individual stage CL statistics alone. We compared the stage structure of populations with known longevities and growth rates and used an age-based population growth model to determine stage structure characteristics under different growth regimes. We found that stage structure is largely determined by longevity and growth rate and that different combinations of longevities and growth rates result in characteristic stage structures. Thus, the population stage structure can be used to infer spatial and temporal differences in longevities and growth rates in situations where these cannot be determined accurately or easily through modal analysis. For example, stage structure analysis suggested that the longevities of shrimp on the northern and southern Newfoundland shelf have the same longevity, but that the former have faster growth rates.

## **Spring phytoplankton bloom and shrimp growth in Newfoundland-Labrador shelf**

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Adapted from: Fuentes-Yaco, C., Koeller, P.A., Sathyendranath, S., Platt, T. (In press) Shrimp (*Pandalus borealis*) growth and timing of the spring phytoplankton bloom on the Newfoundland-Labrador Shelf. Fish. Oceanogr.

Latitudinal and temporal changes in the availability of food for young shrimp (*Pandalus borealis*) on the Newfoundland-Labrador Shelf were examined using a

suite of quantitative characteristics of the spring phytoplankton bloom determined from satellite ocean-colour data, including bloom initiation time, maximum chlorophyll concentration, timing of the maximum, and bloom duration. Significant correlations between bloom intensity, timing and the size of young shrimp were found during particular years. The results are discussed in relation to the observation that, since the early 1990s, CL of shrimps have been decreasing in many Northwest Atlantic stocks.

### **Factors influencing carapace length at sex change of *Pandalus borealis***

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Numerous studies indicate that pandalid shrimp have neither a fixed size nor a fixed age at sex change and that age or size at sex change alters in response to yearly changes in their environment. These changes may include age and size distribution of breeding adults, in which case, size at sex change may be positively correlated with size of mature shrimp (Charnov and Anderson 1989; Skúlladóttir and Pétursson 1999; Charnov and Skúlladóttir 2000). Localized decreases in size at sex change could be related to temporary decreases in female biomass, or a very large year class of males, as a means of compensating for a reduction in reproductive potential (Charnov 1982). Faster growth and earlier maturation are positively related to higher temperatures (Skúlladóttir and Pétursson 1999; Wieland, in prep; Wieland 2004), within the optima of 1-6°C (Shumway et al. 1985). Koeller et al. (2000) and Wieland (2004) found that size at sex change could decrease at times of high density when there is competition for resources. It is important to understand the mechanism(s) causing changes in growth rates and size at sex reversal, because faster growth and early maturation are normally associated with lower fecundity, higher natural mortality and shorter life span.

A logistic model with a logit link function and a binomial error was fit to commercial observed length frequency data to estimate the size at 50% maturity by shrimp fishing area (SFA), month and year. Size at sex change differed spatially and temporally. Mean size at sex change was directly related to latitude but decreased in all SFAs between 1990 and 2000 after which size at sex change stabilized at a low level (Fig. 1). In most SFAs, size at sex change was dependent upon season with the lowest size during the early spring just after the animals molted in preparation for mating (Fig. 2). In order to simplify the study, analyses were therefore limited to data

collected from SFA 6 during the autumn. This allowed direct comparisons between analyses using observer data, which are collected throughout the year, and research survey data, which are collected during the autumn.

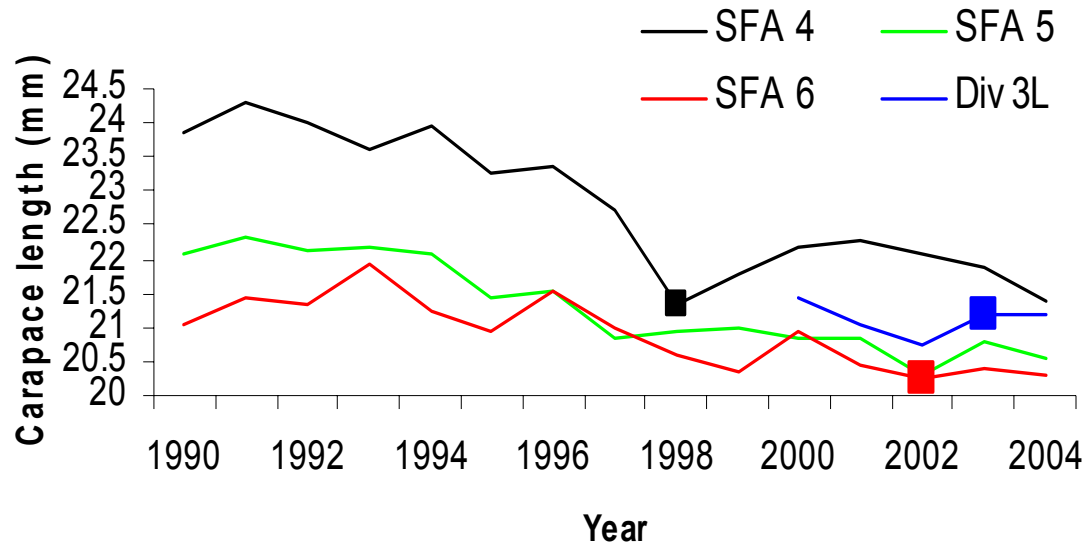


Figure 1. Changes in size at sex change of northern shrimp by area over time. Blocks indicate years that are statistically similar to the 2004 value.

Statistically significant relationships could be made between size at sex change and biomass/abundance of shrimp, bottom water temperature and sex ratio. Sex ratio was based upon age three 3+ male abundance/total female abundance. Age 3+ males were used in the ratio because they would be mature males. Size at sex change was negatively related to biomass, water temperature and ratio of male abundance to female abundance (Fig. 3). It quickly became evident that it would be difficult to determine which factors are driving the change in size at sex change due to the fact that the time series were short (early 1990's – 2004), had no dynamic ranges and several biotic and abiotic parameters were monotonic over time. The sex ratio was near one throughout much of the history, therefore this analysis was inconclusive in testing the sex allocation theory.

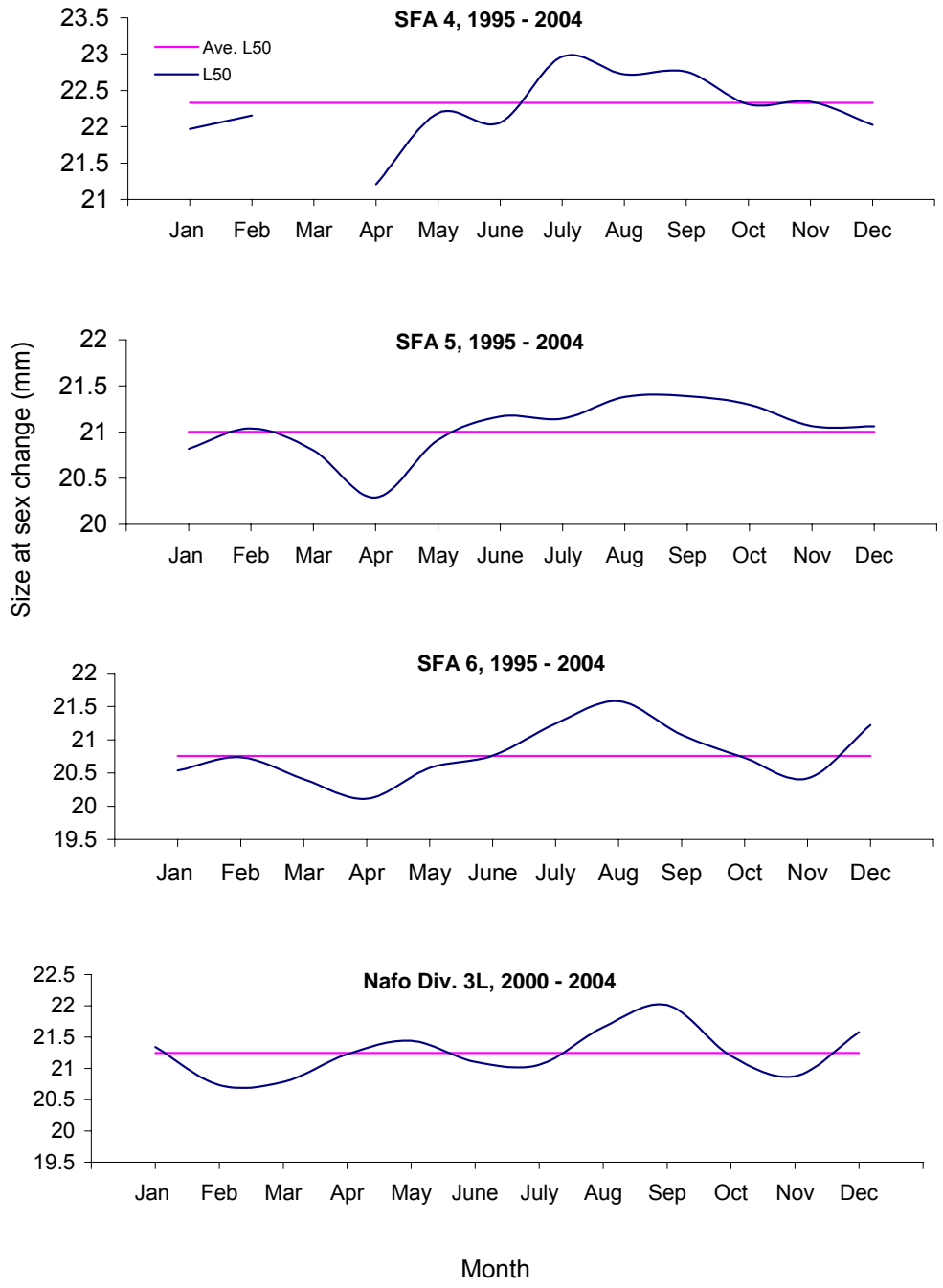


Figure 2. Average size at sex change of northern shrimp by shrimp fishing area and month using observer data.

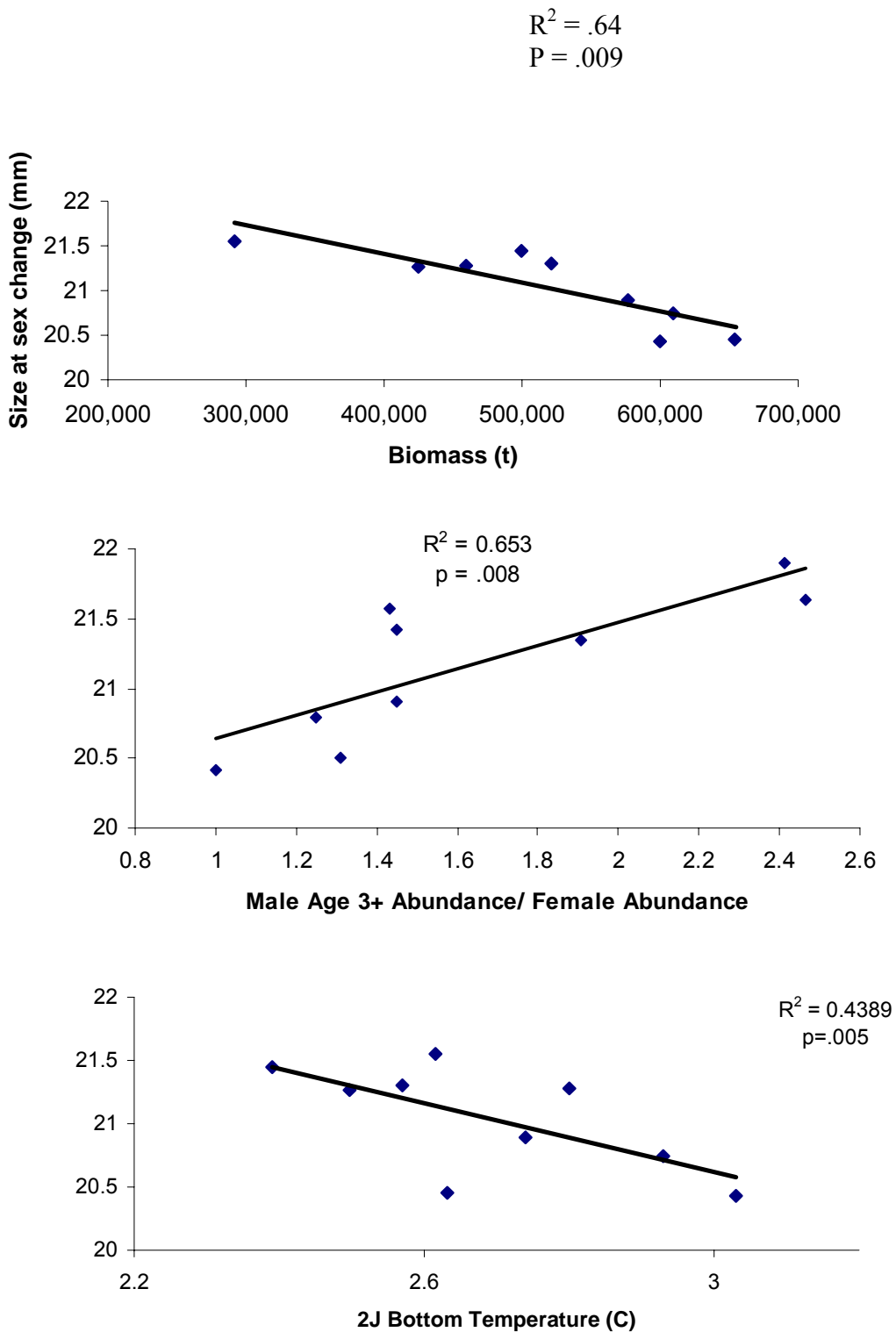


Figure 3. Relationships between size at sex change of northern shrimp and various environmental parameters. All data were from that portion of the Canadian autumn multi-species bottom trawl survey within SFA 6.

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## Life cycle and recruitment of northern shrimp (*Pandalus borealis*) in West Greenland waters

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Presented by: Kai Wieland

The project entitled “*Hydrographic and biological processes of importance for variability in recruitment of fish and shellfish stocks in West Greenland waters*” started in 1999 with financial support from the Danish Research Council’s Committee on North Atlantic Research. It is of major importance for the shrimp stock assessments to get information on the relative strength of recruiting year classes, as early as possible. This is of particular importance for Greenland where today’s economy is mainly based on a large shrimp fishery.

In 1999 and 2000 four research cruises were carried out over the West Greenland shelf area with the main purpose of investigating the distributions of shrimp and fish larvae in relation to key hydrographic processes, potential prey and predators. Distributions and abundance indices of different stages and sizes of shrimp larvae were obtained from zooplankton hauls during transect studies across the fishing banks. To evaluate the factors affecting the survival and recruitment of larval shrimp, larval distributions and abundance indices were related to hydrographic patterns, fluorescence, plankton species compositions, abundance indices and sizes (potential food and predators) along transects, at different survey time periods and locations.

Information on larval distributions, their possible drift and fate are important to understand the life cycle of shrimp populations and their stock-recruitment relationships. The latter information is important in assessing and forecasting shrimp stocks and fishery yields. Shrimp have pelagic larvae and the time and location of larval settling are critical components for successful recruitment to the population. Shrimp larvae occur in the surface layers after hatching and have been found in progressively deeper water layers until settling as juveniles.

A coupled physical-biological model was used to simulate the potential distances that shrimp larvae move from hatching sites in spring to settling locations. The physical modeling was based on a 3D hydrodynamic finite element model forced by wind, pressure and temperature field data calculated from the operational atmospheric model for Greenland and tides at the open boundary. Calculated current fields were fed into a particle-tracking model to simulate the transport of ocean

drifters and the potential distances of shrimp larvae transport from larval release to settling at the bottom.

Particles released (hatched shrimp larvae) south of 62°N had a probability of about 2% of being lost to the Canadian Shelf, whereas almost no particles released north of 64°N drifted off the West Greenland Shelf. The particles tended to have long retention times at the shelf banks because of residual anticyclonic eddies. The retention times increased slightly for particles tracked at depths from 80 to 30 m with minor implications for potential transport distances of larval shrimp and plankton.

An individual based shrimp life-cycle model coupled to a hydrodynamic ocean model will be useful in predicting changes in shrimp distributions and productivity of northern shrimp under different scenarios of anticipated climate change.

Future Danish/Greenland field research will cover the West Greenland shelf banks and a fjord system as well as their interaction with the open waters. The field work will focus on resolving vertical larval shrimp distributions (transports), thermal habitat and prey field of the larval stages, as well as, egg spawning and hatching dates, fecundity and quality of spawners.

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**Forecasting Fishery Performance for Northern Shrimp (*Pandalus borealis*)  
on the Labrador Shelf (NAFO Divisions 2HJ)**

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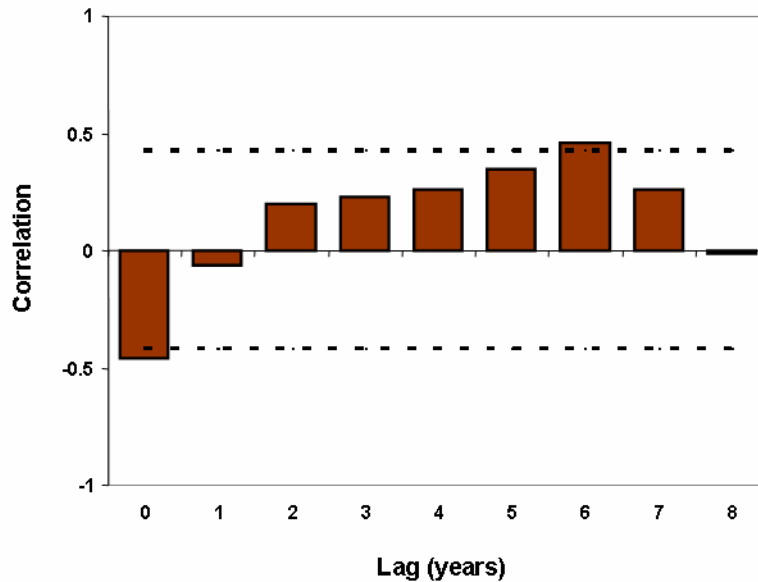
**(J. Northw. Atl. Fish. Sci., Vol. 27, 2000)**

**Updated**

Presented by  
E.B.Colbourne

The importance of the physical ocean environment to the dynamics of pandalid shrimp populations is widely recognized and the relevant literature is extensive. Commercial CPUE for shrimp off Newfoundland and Labrador appeared to be related to variations in several environmental variables (e.g. temperature, ice cover, CIL, NAO) at lags approximating the mean age in the catch (five to seven years). The implications for environmental affects on early life history of shrimp and forecasting were investigated.

CPUE in the northern shrimp fishery had increased up to 1998 and questions had been raised with respect to the possibility of further increases. Time-series analysis, incorporating winter ice cover with a shift of six years, determined by correlation (Fig. 1),



**Fig.1. Crosscorrelation of Northern Shrimp CPUE and Ice cover after correction for autocorrelation (prewhitening)**

produced a transfer function model for shrimp CPUE off Labrador in NAFO Divisions 2HJ (updated from Parsons and Colbourne 2000). The model (Fig. 2) fit the data well and provided a six year forecast (1999-2004), indicating that CPUE would increase in 1999, followed by a decline or, at best, stability at a high level. Actual CPUE within the forecast period (1999–2004) increased in 1999 and conformed to the best-case scenario thereafter. The forecast performed reasonably well but, given the broad confidence intervals, it was a pretty safe call. The significant correlation between CPUE and ice cover six years previous supported the hypothesis that survival of shrimp during early life history is related to physical processes in the ocean that are linked to primary and secondary production during spring within the euphotic zone.

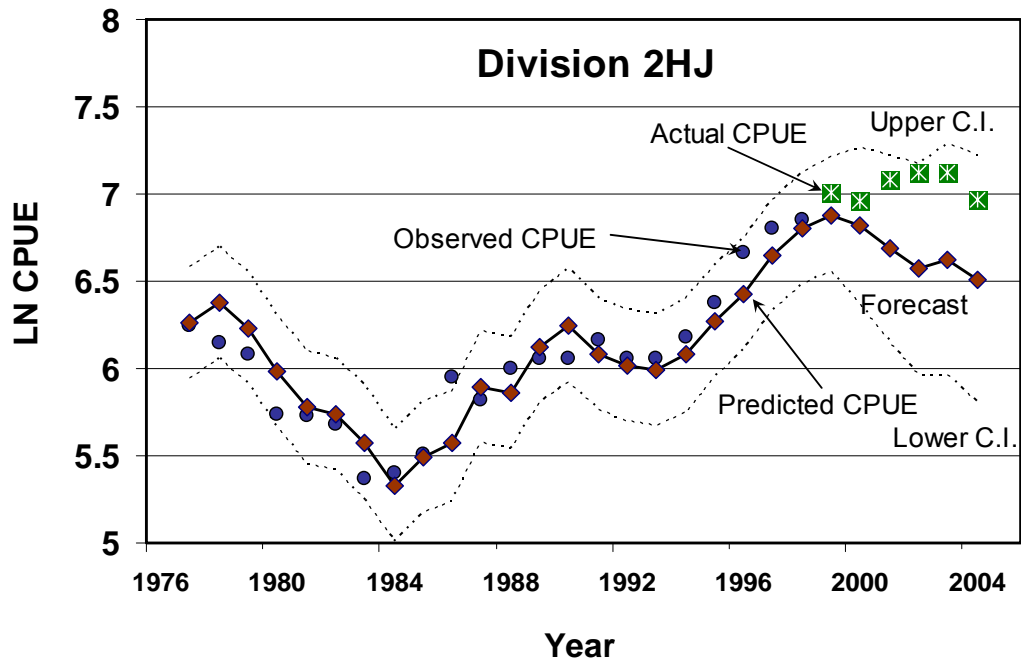


Figure 2. 1977 - 2004 shrimp CPUE model.

An updated model included the period of the previous CPUE forecast from 1999 to 2004 in the time series, used the same modeling method to standardize the annual CPUE estimates and, again, incorporated ice cover as the input series. A new six year forecast was produced indicating a decline in CPUE during 2005–10 (Fig 3).

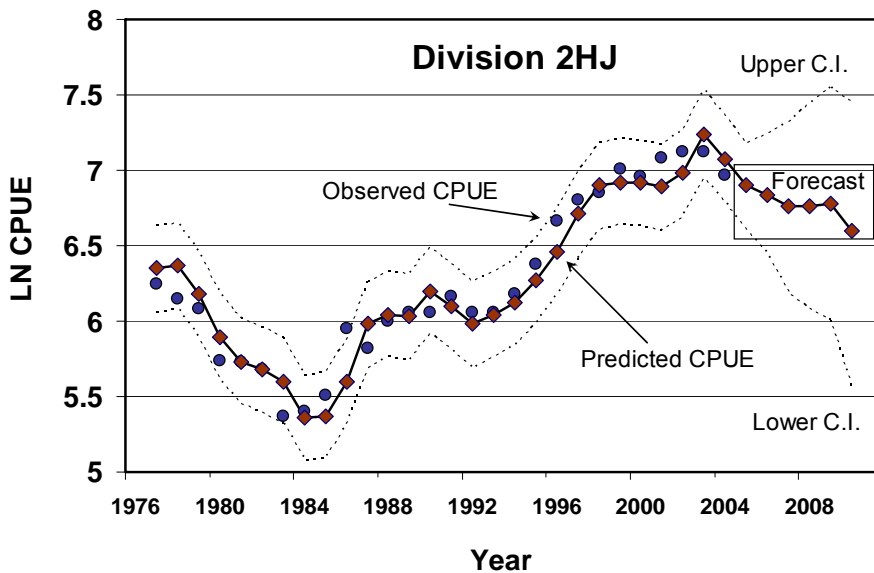


Figure 3. 1977 - 2004 shrimp CPUE model

However, the positive relationship between CPUE and ice cover six years previous eroded after 2000 and correlations that included data for 2002–04 were not significant (Fig. 4). Ice cover (lagged) declined while CPUE remained at a high level. Consequently, the revised forecast was not conclusive, being compromised by diverging confidence intervals.

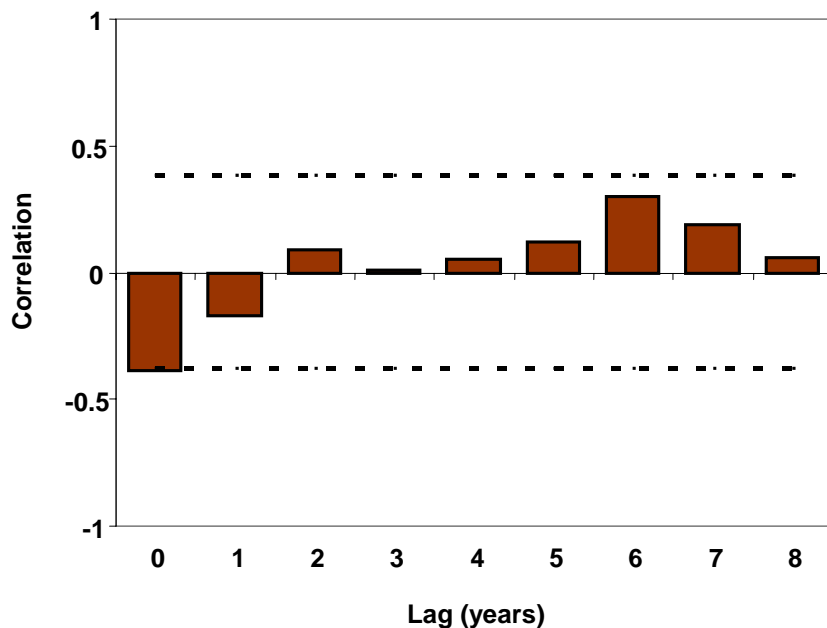


Figure 4. Updated cross-correlation of Northern Shrimp CPUE and ice cover after correction for autocorrelation.

Environmental conditions appear to be important during early life history of shrimp off Newfoundland and Labrador but inferential relationships (several years later) are tenuous. Forecasts are unreliable when correlations between indices of stock size and environmental conditions break down.

Recent factors controlling shrimp population dynamics are likely different from those present during earlier periods (e.g. predation pressure) and relationships between climate indices have changed in recent years. “It is commonplace that time series correlations come and go. Of course, there are many possible ways to explain these results without excluding a link between NAO and fisheries. Instead, the point is that the link is more complicated than that suggested by analyses of short time series.” (Solow 2002).

## **Reference:**

- Parsons, D.G. and Colbourne, E.B. 2000. Forecasting fishery performance for Northern Shrimp (*Pandalus borealis*) on the Labrador Shelf (NAFO Divisions 2HJ). J. Northw. Atl. Fish. Sci., Vol 27:11-20.
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## **Session 2: Recruitment and Growth Synthesis and discussion:**

Louise Savard began this session by pointing out that shrimp assessments in eastern Canada are descriptive with no standard set of reference points and harvest control rules. Monitoring programs are mainly based upon analyses of fishery statistics, research and observer data sets. In most cases, we are not able to produce meaningful forecasts because the ecosystem is very complex and we do not have a good understanding of relationships that allow shrimp populations to thrive or decline. We are however busy conducting research that will increase our predictive abilities.

The research within this session had two main themes:

1. the match/mismatch hypothesis, and
2. relationships between shrimp and their environment do not always hold.

Strong year classes will recruit to the fishery under certain conditions. The spawning stock biomass has to be large enough to produce large numbers of larvae. The fact that there is no spawning stock – recruitment relationship does not mean that there is no relationship, but that it is very complex. The duration of the ovigerous period is inversely related to temperatures and the percent of spawning females decreases with decreasing temperatures. If larval hatching and the spring bloom of phytoplankton do not overlap then there may not be enough food for survival and growth. Fortunately, hatching usually overlaps the spring bloom.

Fuentes-Yaco et al. (in press a) examined latitudinal and temporal changes in the availability of food for young shrimp (*Pandalus borealis*) on the Newfoundland-Labrador Shelf, using a suite of quantitative characteristics of the spring phytoplankton bloom determined from satellite ocean-colour data, including bloom initiation time, maximum chlorophyll concentration, timing of the maximum, and bloom duration. The results showed significant correlations between bloom intensity, timing and the size of young shrimp in particular years. The findings were discussed in relation to the observation that, since the early 1990s, CL of shrimps have been decreasing in many Northwest Atlantic stocks.

Briefly, satellite-remote sensing has been used as an important tool to produce objective indices of ecosystem performance to characterise the phytoplankton spring bloom. In this study, the authors used all available data from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on OrbView-2 satellite for the area 39°N to 62.5°N and 42°W to 71°W. The data were received and processed at the Bedford Institute of Oceanography to compute weekly composite images of concentration of Chlorophyll-*a* (an index of phytoplankton biomass).

The indices of ecosystem performance are: the maximum chlorophyll-*a* (an index of phytoplankton biomass) referred to as the intensity, the week when the biomass first exceeded 20% of the maximum (bloom initiation), the week when the maximum intensity occurred (bloom timing), and the period during the biomass remained above the 20% threshold (bloom duration). The period of analysis was from February to September and was repeated each year to compute the climatology for the six years of available satellite data (1998 until 2003). The annual values were compared with temporal and latitudinal data on shrimp size in the same years.

The authors demonstrated a link between remotely-sensed ocean colour data and shrimp growth. It allowed them to frame two plausible hypotheses about latitudinal differences and temporal changes in shrimp carapace lengths and growth which include, arguably, the most important factor contributing to growth—the availability of food. While not providing definitive conclusions due to data limitations, the study demonstrated that large-scale and long-term changes in the food sources of important commercial marine species can be measured and, given suitably long time series, hypotheses involving changes in these measurements and the resource itself can be tested.

The investigation focused on growth, but linkages to recruitment success have not yet been investigated. The results have also not considered the effects of larval advection to the south on shrimp growth and length frequency patterns. Still, these results and those presented in Koeller et al. (2005) are of relevance to current issues facing the shrimp industry. Clearly, environmental changes have significantly influenced the decrease in shrimp size at sex change over the 1990s—it seems unlikely that lowering exploitation rates would have mitigated this decrease. Remotely sensed data, even if requiring an additional effort, could be of immediate interest as ancillary information in stock assessments as such issues arises. In longer-term fisheries research, remotely-sensed chlorophyll data could be useful in identifying “hot spots” (e.g. Hudson Strait) for future study of shrimp population dynamics and in the design of field programs.

Wieland asked whether the remote imaging had been checked against “*in situ*” values. Fuentes-Yaco noted that they made comparisons of field measurements of chlorophyll-*a* from the Northwest Atlantic with concurrent pigment concentrations derived from SeaWiFS data using NASA/SeaDAS algorithms (Fuentes-Yaco et al., in press *b*). Their results showed broad agreement but tended to show lower satellite



derived measurements than *in situ* values at concentrations greater than 1 mg chl-*a* m<sup>-3</sup>. However, the algorithms used in this study (Fuentes-Yaco et al., in press a) should not have affected the conclusions because the analysis is not compromised by systematic errors in the chlorophyll-retrieval algorithms i.e. the use of only relative values renders the indices independent of absolute chlorophyll concentration estimates. In addition, Trevor Platt's research team developed a regionally-, and seasonally-, adapted empirical correction in an attempt to reduce the bias (Devred et al., in press) and improve the accuracy of the remotely sensed data.

Lambert's experiments indicate that egg mortality increases and embryos hatched earlier, but they were smaller and exhibited a higher proportion of abnormalities if they were incubated at 8°C rather than 2°C or 5°C. Animals hatched at 8°C had lower energy contents suggesting higher maintenance costs and lower conversion efficiencies are associated with high temperatures. This is in agreement with Bo Bergström's introductory presentation which noted that higher maintenance costs were associated with increased temperatures. Increased embryonic developmental rates, at higher temperatures, may therefore result in decreased foraging ability or increased susceptibility to predation. Koeller noted that this may explain the shoreward migration of ovigerous females. Possibly females are seeking cooler water to aid in the development of their young.

Conversely, Ouellet and Savard found that larval shrimp performed better at 8°C than at 2 or 5°C, in the laboratory. Larval shrimp were more efficient at capturing the larvae of other animals and fed more frequently at 8°C. While still feeding upon mesozooplankton, stage IV larvae also fed upon larger prey such as stage C III and IV *Calanus finmarchius*. These experiments indicated that spring zooplankton production was important for the development and survival of young shrimp. This helped confirm the importance in the timing of the spring bloom. As they develop, young shrimp first feed upon diatoms in the water and then upon larvae of other invertebrates. These larval food sources are present because of the availability of phytoplankton food sources. When phytoplankton die, they sink to the bottom of the ocean and become food for shrimp, or food for organisms that shrimp feed upon. Thus large supplies of phytoplankton are necessary to support large abundances of shrimp.

Ouellet and Savard found that under laboratory conditions, at 2°C, 5°C and 8°C water temperatures, highest larval growth was achieved in 5°C water. However, they also noted, that larval shrimp grow quickly in the field even though they occupy cooler habitats. Through field observations, they were able to show that larval shrimp are pelagic for five moults and become demersal at stage VI. They also showed that recruitment strength was negatively related to SST anomalies occurring early in May, when the larvae hatch.

Kai Wieland presented a research project to study shrimp survival and transport off the West coast of Greenland (Pedersen et al., this workshop). Drogues were used to estimate current flows along the west coast of Greenland and transect

surveys have been run in June 1999, May 2000 and July 2000 to determine the abundance of larval shrimp. These two sources of data were coupled into hydrographic models that predicted the potential distances that shrimp larvae move from hatching sites in spring to settling locations. Model predictions were verified through comparisons between predicted and actual abundances of age one shrimp from the annual research shrimp survey. However, considerable work must still be completed to account for wind forcing, possible stage/age dependent vertical migrations and temperature dependent growth.

Wieland, Hvingle and Lambert found that juvenile shrimp growth increased with increased temperature. However, off West Greenland, shrimp growth increased as temperatures increased to 3°C after which size at age remained constant. Wieland and Hvingle indicated that temperature may be important in promoting growth, but growth may be impaired if food is limiting. This related back to the importance of food created during the spring bloom, but also introduced the idea of density dependent effects upon growth. Analyses of data from West Greenland indicate that decreases in size at sex change were related to shrimp density rather than number of mature females relative to number of mature males as suggested by the sex allocation theory. Likewise reductions in size at sex change could not be related to size selectivity by the fishery.

Analyses of NL-Region observer and research survey data indicated that several factors must be accounted for when studying changes in size at sex transition. The decrease in size at sex transition is location and season dependent. The greatest decreases occurred in SFA 4, in the north, while smaller decreases were observed in SFA's 5 to 7 (Koeller et al. (this workshop) and Orr et al. (this workshop)). Analyses by Orr et al. indicate that size at sex change stabilized at a lower level in all areas since 2000. In general, smaller sizes at sex change occurred during April than during other months. Orr *et al.* went on the note that size at sex change was complicated by the fact that we are dealing with short time series with no dynamic range while several biotic and abiotic parameters are monotonic over time therefore it was difficult to determine which factors are driving the change in size at sex change. Nevertheless, they were able to demonstrate that decreased size at sex change could be related to increased temperatures, or increased densities.

Koeller proposed the use of stage structure analysis as an additional tool that could be used to detect changes in growth rate in time and between stocks. He compared the CL statistics ( $L_{\min}$ ,  $L_m$ ,  $L_{50}$ ,  $L_{f1}$ ,  $L_{f2}$ , and  $L_{\max}$ ) between shrimp from the Gulf of Maine, Southeastern Nova Scotia and off the coasts of Labrador and northeastern Newfoundland.

The session ended with an attempt to forecast shrimp CPUE in SFA 5, from past performance in relation to changes in the amount of area covered by winter sea ice. The model was developed around auto-regressive transfer function techniques described in (Parsons and Colbourne 2000) as an update to the model presented in that paper. The forecast developed during 1999 was a safe call because there were

broad confidence limits around the model projections. However, since then the relationship between the environment and CPUE six years later has eroded. The model developed, with six more years of data, is now inconclusive. Ouellet and Savard also indicated a recent break down of environmental/recruitment relationships. The fact that relationships “come and go” was an important second theme within this session.

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Devred, E., Fuentes-Yaco, C., Sathyendranath, S., Caverhill, C., Maass, H., Stuart, V., Platt, T., and White, G. “A semi-analytic, seasonal algorithm to retrieve chlorophyll-a concentration in the Northwest Atlantic from SeaWiFS data”, *Indian J. Mar. Sci.* (in press).

Fuentes-Yaco, C., Koeller, P.A., Sathyendranath, S., and Platt, T. “Shrimp (*Pandalus borealis*) growth and timing of the spring phytoplankton bloom on the Newfoundland-Labrador Shelf”. *Fish. Oceanogr.* (In press a).

Fuentes-Yaco, C., Devred, E., Sathyendranath, S., Platt, T., Payzant, L., Caverhill, C., Porter, C., Maass, H., and White III, J.G. “Comparison of *in situ* and remotely-sensed (SeaWiFS) chlorophyll-a in the Northwest Atlantic”. *Indian J. Mar. Sci.* (in press b).

Koeller, P., Fuentes-Yaco, C., and Platt, T. “Decreasing shrimp sizes off Newfoundland and Labrador – environment or fishing?” *Fish.Oceanogr.* (In press).

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### **Recommendations:**

- 1) We continue to research relationships between shrimp and their environment.
- 2) The use of remote-sensing be explored as a tool to learn more about the timing, initiation, duration and intensity of the spring blooms in the various SFAs. These indices should be used in future stock assessments and once there is a long time series (20–30 years) they may be used in model creation.
- 3) Lead researchers within Quebec–Region, NL–Region, West Greenland should write a synoptic report describing and comparing various shrimp

indices in relation to the environment. This report would become a part of the Ecosystem of the Sub-Arctic (ESSA) project.

### Session 3 - Mortality

Question: *What are the perspectives given the current conditions, and expected changes in the physical and biological environment and their affects on predator abundance? Are fishery affects detectable?*

#### **Predators of Northern Shrimp, *Pandalus borealis*, in the North Atlantic and Interactions within the Eastern Newfoundland and Labrador Marine Ecosystem (NAFO Divisions 2HJ3KL) <sup>1</sup>**

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Presented by  
E.G. Dawe

Although the importance of predation as a component of natural mortality for northern shrimp (*Pandalus borealis*) populations is routinely emphasized when issues related to resource assessment, management and species' ecology arise, supporting information is often anecdotal. A recent review of northern shrimp predators, compiled from decades of research, described trophic interactions among relevant marine species throughout the North Atlantic. The importance of shrimp as prey and the impacts of predation on shrimp populations were established, where possible, from the literature. The review (not exhaustive) identified twenty-six species that prey on shrimp within North Atlantic ecosystems (Table 1). Results confirmed that shrimp provide an abundant source of food for marine fish, mammals and invertebrates throughout the study area. Notable predators included Atlantic cod (*Gadus morhua*), thorny skate (*Amblyraja radiata*), redfish (*Sebastes* spp.), harp seals (*Phoca groenlandica*) and snow crab (*Chionoecetes opilio*). The evidence supported the likelihood of predation mortality as one of the key factors regulating shrimp population dynamics. However, there were no objective criteria to evaluate the importance of shrimp as prey within and between species, compare consumption estimates and separate predation as a component of natural mortality.

Table 1. Documented predators of northern shrimp (*Pandalus borealis*) in the North Atlantic. One reference is provided for each predator/area combination.

Predator	References	Area
<i>Gadus morhua</i> Linnaeus, 1758	Horsted and Smidt 1956 Howard 1980 Klemetsen 1982 Bowering et al. 1984 Gilbert and Gascon 1987 Mehl 1989 Lilly 1991 Magnusson and Palsson 1991 Parsons et al. 1998	West Greenland North Sea Northern Norway Labrador Gulf of St. Lawrence Barents Sea Northeast Newfoundland Shelf Iceland Flemish Cap
<i>Melanogrammus aeglefinus</i> (Linnaeus 1758)	Jiang and Jørgensen 1996	Barents Sea
<i>Pollachias virens</i> (Linnaeus 1758)	Langton and Bowman 1980	Cape Hatteras to Nova Scotia
<i>Merluccius bilinearis</i> (Mitchill 1814)	Langton and Bowman 1980	Cape Hatteras to Nova Scotia
<i>Urophycis tenuis</i> (Mitchill 1814)	Langton and Bowman 1980	Cape Hatteras to Nova Scotia
<i>Phycis chesteri</i> Goode and Bean, 1879	Rodriguez-Marin, et al. 1994	Flemish Cap
<i>Brosme brosme</i> (Ascanius 1772)	Langton and Bowman 1980	Cape Hatteras to Nova Scotia
<i>Reinhardtius hippoglossoides</i> (Walbaum 1792)	Smidt 1969 Chumakov and Podrazhanskaya 1986 Skuladottir and Jonsson 1991 Bowering and Lilly 1992 Rodriguez-Marin, et al. 1994 Orr and Bowering 1997	West Greenland Davis Strait to Grand Bank Iceland Newfoundland-Labrador Flemish Cap Davis Strait
<i>Hippoglossoides platessoides</i> (Fabricius 1780)	Pitt 1973 Langton and Bowman 1981 Pedersen 1994 Rodriguez-Marin, et al. 1994	Grand Bank of Newfoundland Cape Hatteras to Nova Scotia West Greenland Flemish Cap
<i>Sebastes marinus</i> (Linnaeus 1758)	Lambert 1960 Rodriguez-Marin, et al. 1994	Newfoundland area Flemish Cap
<i>Sebastes mentella</i> (Travin 1951)	Rodriguez-Marin, et al. 1994	Flemish Cap
<i>Sebastes fasciatus</i> Storer, 1856	Rodriguez-Marin, et al. 1994	Flemish Cap
<i>Sebastes</i> (unspecified)	Pedersen and Riget 1992	West Greenland
<i>Anarhichas lupus</i> Linnaeus, 1758	Albikovskaya 1983 Rodriguez-Marin, et al. 1994	Newfoundland-Labrador Flemish Cap
<i>Anarhichas denticulatus</i> Krøyer, 1845	Albikovskaya 1983	Newfoundland-Labrador
<i>Amblyraja radiata</i> (Donovan 1808)	McEachran et al. 1976 Antipova and Nikiforova 1983 Pedersen 1994 Rodriguez-Marin et al. 1994	Northeastern U.S. and Canada Barents Sea West Greenland Flemish Cap
<i>Leucoraja erinacea</i> (Mitchill 1825)	McEachran et al. 1976	Northeastern U.S. and Canada
<i>Malacoraja senta</i> (Garman 1885)	McEachran et al. 1976	Northeastern U.S. and Canada

<i>Macrourus berglax</i> Lacepède, 1801	Geistdoerfer 1979 Rodriguez-Marin, et al. 1994	North Atlantic Flemish Cap
<i>Lycodes seminudus</i> Reinhardt, 1837	Horsted and Smidt, 1956	West Greenland
<i>Lycodes vahlii</i> Reinhardt, 1831	Horsted and Smidt, 1956	West Greenland
<i>Lycodes reticulatus</i> Reinhardt, 1835	Rodriguez-Marin, et al. 1994	Flemish Cap
<i>Myxine glutinosa</i> Linnaeus, 1758	Shelton 1978	North Sea
<i>Phoca groenlandica</i> Erxleben, 1777	Sergeant 1991 Lawson, et al. 1994 Nilssen et al. 1995 Kapel and Angantyr 1989	North Atlantic (east and west) Newfoundland-Labrador Barents Sea West Greenland
<i>Chionoecetes opilio</i> (Fabricius 1788)	Squires and Dawe 2003	Northeast Newfoundland Shelf

The widely-held notion that the increase in shrimp abundance during the 1990's off Newfoundland and Labrador resulted from a decrease in predation (especially due to the collapse of Atlantic cod in NAFO Div. 2J3KL) had not been thoroughly investigated. Another recent study compared population trends for northern shrimp and its key predators off eastern Newfoundland and Labrador, providing a basis for investigating predator-prey relationships within an ecosystem that experienced major changes in species composition during the 1980's and 1990's (Fig. 1). Populations of several demersal fish species, known to feed on northern shrimp (e.g. Atlantic cod, redfish, skate), declined to historically low levels by the early 1990's and remained depressed, thereafter. Some declines were precipitous from the late 1980's to early 1990's, coincident with an increase in shrimp. The implied reduction in predation provided a convincing explanation for the prolonged increase in shrimp biomass. Populations of other predator species (e.g. Greenland halibut - *Reinhardtius hippoglossoides*, harp seals, snow crab), by contrast, increased throughout the 1990's along with shrimp. The implied increased predation could not be linked, functionally, to the increase in shrimp biomass. Lacking representative estimates of shrimp consumption, the net effect on predation mortality was unquantifiable and it was not possible to establish with certainty that the major increase in shrimp biomass that occurred throughout the 1990's resulted from a concomitant reduction in predation mortality. The notion that the release in predation was greater than any increase is plausible, but remains speculative. Factors relevant to the dynamics of shrimp populations include the effects of ocean climate, predation, competition, as well as commercial harvesting. Their main effects and interactions are difficult to demonstrate. Within the uncertainty, there is ample room to question the impact of commercial fishing relative to environmental influences on shrimp stocks off Newfoundland and Labrador.

<sup>1</sup> Adapted from: Parsons, D.G. 2005. "Predators of northern shrimp, *Pandalus borealis* (Pandalidae), throughout the North Atlantic" and "Interactions between northern shrimp, *Pandalus borealis* (Pandalidae), and its key predators within the eastern Newfoundland and Labrador marine ecosystem" *Mar. Biol. Res.*, [www.tandf.no/marinebiology](http://www.tandf.no/marinebiology), 1: 48 – 58 and 59 – 67, (by permission of Taylor & Francis AS.)

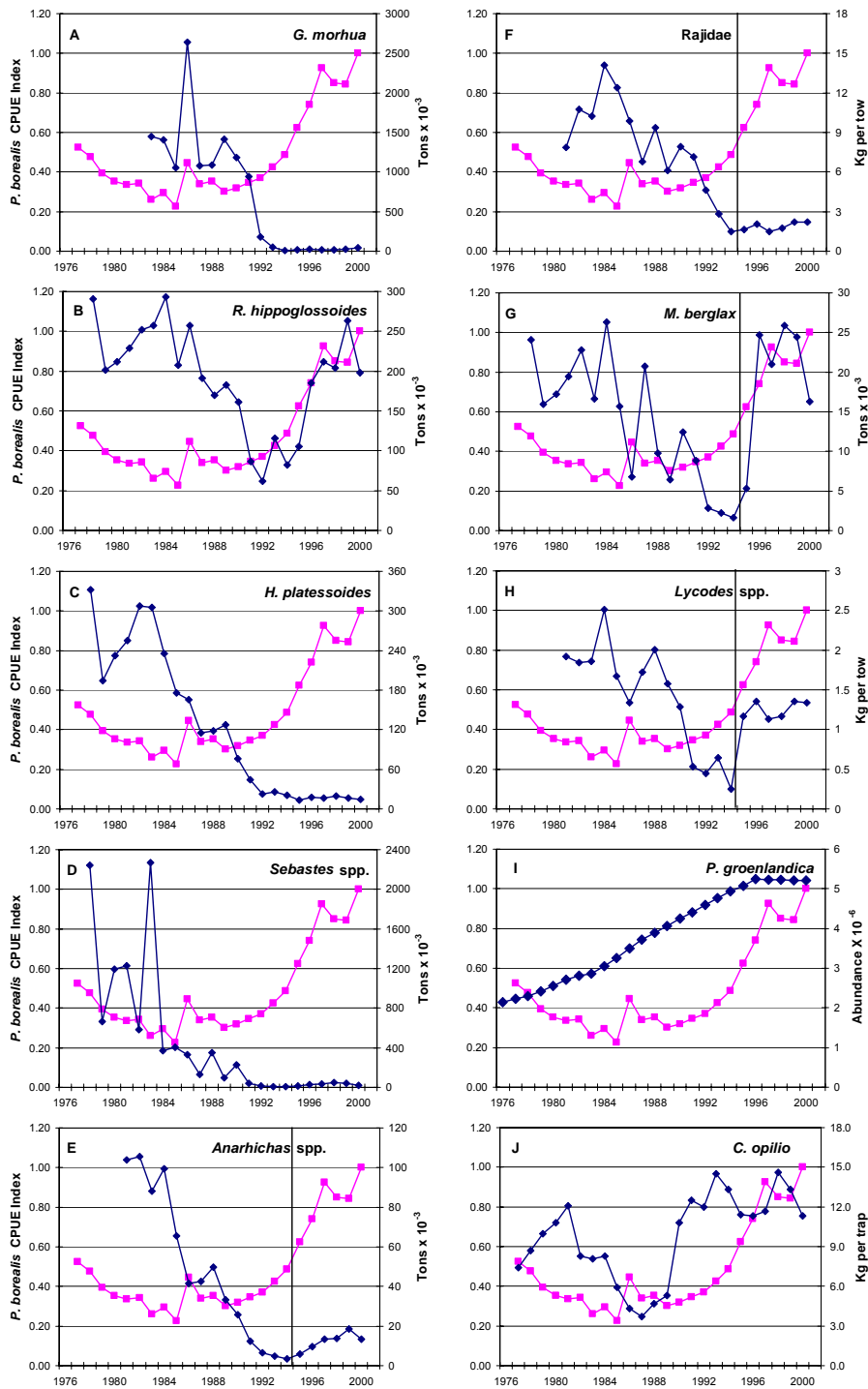


Figure 1. Population trends for northern shrimp (*Pandalus borealis*) and key predators off eastern Newfoundland and Labrador. The biomass series for shrimp (■, left Y-axis) is represented by the CPUE index for Div. 2HJ3K. The biomass series for fish predators (◆, right Y-axis), obtained from published documents in most cases, are given as tons x 10<sup>-3</sup> or kilograms per tow from annual research trawl surveys.



**Predation on northern shrimp (*Pandalus borealis*) by Atlantic cod (*Gadus morhua*) off southern Labrador and eastern Newfoundland: the release in predation pressure is expected to continue**

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This short paper has the following objectives: (i) to summarize earlier observations regarding the predation by Atlantic cod (*Gadus morhua*) on northern shrimp (*Pandalus borealis*) off southern Labrador and eastern Newfoundland; (ii) to restate conclusions regarding the role that the collapse of the northern (2J+3KL) cod stock may have had in the surge of shrimp off Labrador and eastern Newfoundland; and (iii) to discuss prospects for recovery of the northern cod stock and implications for the shrimp resource and the shrimp fishery.

Predation by cod on shrimp

Predation by cod on shrimp has been documented from observations in the Hopedale and Cartwright Channels off Labrador (Bowering et al. 1982, 1984) and more broadly in the deeper waters of the Labrador and Northeast Newfoundland shelves (Lilly 1991). Shrimp has historically been a minor prey of cod (Lilly 1991, 1995). For example, in 1987 shrimp represented about 6% of the food consumed by cod sampled during the autumn research survey in the offshore of Shrimp Fishing Area 6 (Lilly et al. 2000). Shrimp would have been even less important for the northern (2J3KL) cod stock as a whole on an annual basis because shrimp was less important to cod in Div. 3L than in Div. 2J3K and cod preyed intensively on capelin in inshore waters during summer (Lilly 1987; Bundy et al. 2000).

Shrimp are consumed by a broad size range of cod (Lilly 1991, 1995). The maximum size of shrimp consumed by cod increases with cod length. A cod would have to be at least 45 cm-50 cm in length to prey on a shrimp of 29 mm CL, which is the largest shrimp found in cod stomachs in this area (Lilly 1995). With increasing cod length, there is a gradual change from feeding entirely on small shrimp to feeding mainly on medium and large shrimp. The finding of prominent modes at 3 mm-5 mm and 8 mm-11 mm CL amongst the shrimp in stomachs of cod sampled during autumn has aided the interpretation of shrimp length at age (Parsons et al. 1986, 1989).

Although shrimp is a relatively minor prey of cod, it did occur in a sufficiently large number of cod stomachs during the 1980s to enable cod to be used as a sampling device to study the distribution of shrimp (Lilly 1984, 1995; Lilly et al. 1998).

The smallest shrimp, assumed to be age zero, were found primarily in deep water on the shelf off northeastern Newfoundland. Older juveniles were found primarily in shallower water. With increasing size, the shrimp moved deeper and onto the commercial fishing grounds.

### Collapse of cod and the surge of shrimp

As noted by Lilly and Carscadden (2002), there is considerable support for the hypothesis that the increase in northern shrimp off northeastern Canada was, at least in part, a consequence of a reduction in predation pressure from Atlantic cod and other groundfish. Lilly et al. (2000) demonstrated that the consumption of shrimp by cod declined to a very low level as the cod stock collapsed during the late 1980s and early 1990s. Estimates of the quantity of shrimp consumed by the cod on an annual basis are considered to be very uncertain; indeed, Lilly et al. (2000) strongly emphasized the challenges associated with obtaining reliable estimates. It is nevertheless clear that there was a very large decline in the quantity of shrimp removed by cod, and the authors concluded that the large increase in shrimp biomass in the 1990s was related at least in part to the collapse of the cod. Bundy (2001) conducted trophodynamic simulations that indicated that the increase in shrimp biomass was consistent with the hypothesis that the shrimp increased as a result of the collapsed biomass of cod and the consequent reduction in predation. Worm and Myers (2003) examined cod and shrimp biomass in several ecosystems across the North Atlantic, including the area off Labrador and eastern Newfoundland, and concluded that the size of shrimp populations is strongly inversely related to the size of co-occurring cod populations.

Despite these analyses supporting the role of predator release, there is evidence that other factors were involved. For example, Lilly et al. (2000) noted that the increase in shrimp density on the Northeast Newfoundland Shelf might have started during the early 1980s, a time during which the biomass of Atlantic cod was recovering toward a peak in the mid-1980s following its decline during the 1970s. If the increase in shrimp biomass did start in the early 1980s, then it would appear that the initial increase was not related to changes in cod.

The changes in shrimp from the late 1980s to the early 2000s included not just an increase in biomass but an expansion in the area where the shrimp could be commercially fished. The winter/early spring shrimp fishery expanded to the edge of the continental shelf in Div. 2J and 3K in the early 1990s, shortly after cod declined to very low density in that area. The new shrimp grounds overlap to a considerable degree the former winter cod fishing grounds (Lilly et al. 2000). The degree of overlap is less extensive at other seasons, but nevertheless, if cod were currently characterized by its former (1980s) biomass and distribution, then it would be difficult to fish for shrimp without passing through or near cod.

## Prospects for the recovery of northern cod and implications for shrimp and the shrimp fishery

The level of removals of shrimp by cod has not been monitored for almost ten years. (In the mid-1990s DFO discontinued the program of cod stomach examinations that it had started in the late 1970s.) It is assumed that the cod currently consume relatively few shrimp, because not only is the cod biomass very low (1-2% of the level during the 1980s), but there are very few of the mid-sized (roughly 50 cm-80 cm) cod that historically fed most intensively on shrimp (in terms of grams of shrimp per cod per day). The mortality rate imposed on the shrimp population by the current cod predation is presumably much lower than during the 1980s, not only because the quantity of shrimp consumed is much smaller but also because the removals are being taken from a much larger shrimp biomass.

If the surge in shrimp biomass and expansion of shrimp distribution is in part a consequence of greatly reduced predation by cod, then it is unlikely that the situation will be reversed in the near term. The populations of cod in the offshore of 2J3KL have shown no sign of recovery since their biomass reached a very low level in the mid-1990s (Lilly et al. 2003; DFO 2005), despite a ban on directed fishing that was imposed in 1992 and continues to this day. Numerous reasons for the lack of recovery have been proposed (Rice and Rivard 2003; Rice et al. 2003; Lilly and Murphy 2004). Clearly the very low spawner stock biomass (SSB) can produce only a relatively small number of eggs, so the prospects for a good year-class early in the recovery process is low. Nevertheless, year-classes are being produced and are recorded in catches during research bottom-trawl surveys. These year-classes disappear rapidly. Few fish survive beyond age five. At this time the cause of the very high mortality rate remains unidentified (Lilly and Murphy 2004). It could be caused by human influences, which would include by-catches (including discards) and possibly non-catch mortality from on-going small fisheries for Greenland halibut and more extensive fisheries for shrimp. The high mortality could also be due to natural factors, such as insufficient food or a high level of predation. The offshore cod populations are unlikely to recover until the mortality rate declines. The recovery, once it starts, is expected to be slow, because northern cod grow slowly and do not mature until about age five.

A recovering cod stock will have implications for the shrimp fishery and the shrimp resource on which it depends. As noted above, there is a large overlap between the former distribution of cod and the current fishing locations of the large and small vessel shrimp fisheries. As the cod stock starts to recover, it may become increasingly difficult for shrimp trawlers to avoid aggregations of cod. In addition, a growing cod stock will impose an increasing mortality on the shrimp stock. It is anticipated that the shrimp stock cannot exist at its current high level of biomass in the presence of a fully-recovered cod stock.

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### **Assessment models and their use in evaluating historical and future management performance**

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Fisheries management is about making choices among alternative policy options, and this implies three things: 1) managers must make predictions about how a resource will respond to alternative policies, 2) that there is some preferred outcome or management objective for choosing one policy over the other (Walters

and Martell 2004), and 3) that the chosen policy can be effectively implemented in the field. First, in order to make predictions, managers must resort to models (conceptual or quantitative) to evaluate potential outcomes as a consequence of choosing one policy over another. The second implication is that there is an underlying objective (e.g. maximize) and a measure of utility (e.g. yield) in which management strives to achieve (e.g. to maximize long-term sustainable yield). The third assertion deals with the process of achieving the management objectives. For example, in a population that is considered to be below its level that would maximize production, should the manager take decisive action and reduce TAC or even shut down the fishery until it recovers, or make no changes to the management plan and wait to see if the system recovers. It should be obvious that indecision here is the most rational choice; if you shut down the fishery a manager must face the howls of outrage from industry while realizing that there is no guarantee that the stock will recover, and conversely if they take no decisive action, they maintain industry support and hope for the possibility that the stock will recover due to favorable environmental conditions.

Models are a necessary requirement to evaluate and quantify outcomes of alternative management prescriptions by simulating proposed policies forward in time from the present estimated state. But which model is the appropriate model to use? The answer to this question is entirely dependent on the types of questions that need to be addressed, as well as, the type and availability of data and whether or not these data (e.g. relative abundance series) are informative about policy questions. For example, if one of the proposed policies is to change the size limits in the fishery, then the model must include composition information to address such regulatory changes. It might often be desirable to examine management policies with alternative model structures (e.g. Beverton-Holt vs. Ricker type recruitment functions), to reflect the uncertainty in our understanding of system dynamics, or even formally examine alternative hypotheses about system behavior. But which model is correct or the least biased? Optimal model complexity is usually addressed using statistical criterion (e.g. Akaike Information Criterion or Bayesian Information Criterion) that describe how likely the model and its associated parameters is with respect to the observed data, but none of these methods explain potential bias in key policy parameters. Potential bias can only be examined in situations where the true underlying dynamics are known, e.g. in management strategy evaluation experiments or situations of certainty such as extirpation of the stock. As a general rule, additional model complexity equates to including more unknown parameters, which increases uncertainty in key policy parameters (Hilborn 1979; Ludwig and Walters 1985).

There are only two key components of population change that are important in understanding population dynamics in natural populations, and these can be classified into components associated with production or renewal, and rate processes that govern losses from the population. Key vital rates associated with production are growth and fecundity, and in open populations, immigration rates. Key vital rates associated with losses are mortality rates and emigration rates. The ecological basis for harvesting natural populations requires that at least one of these rate processes vary with population density i.e. density-dependent. That is there must be

compensation in rate processes associated with production as population abundance declines (i.e. increased fecundity or recruitment rates), or decreases in loss rates as abundance declines. Therefore, it is important from a management perspective to understand how these vital rates change with changes in population density, as these relationships define the limits of sustainable harvest. Understanding how these vital rates change, or how these rates may vary with changes in biotic or abiotic factors, may improve forecasting. However, this information is only useful in decision making if it's possible to predict how environmental covariates will change in the future, or if the present state will influence future production.

### *Appropriate models for assessing shrimp abundance*

The general structure of most assessment models uses a system of equations that describes the unobserved states (e.g. the mature abundance), and equations that predict the observed states (e.g. CPUE data, size composition data, or tag recovery data) based on the unobserved states. Parameters that describe the dynamics of the unobserved states are then estimated using a statistical criterion that measures the “goodness of fit” between the predicted and observed states. Most assessment models in use today are modified variants of the simple depletion estimator where the dynamics of the population can be described as:

$$N_{t+1} = f(N_t) - C_t \quad (1)$$

where the units of  $N_t$  may reflect either population numbers, biomass, relative abundance, or a certain component of the population such as the spawning biomass. The simplest of these models are production models which contain two key population parameters that describe the rate of renewal and the scale of the population. These two key parameters are confounded in that many time series data on relative abundance can be explained by a large population with a low rate of renewal, or a small population with a very high rate of renewal. The requirement to discern among alternative parameter combinations is contrast in relative abundance series or auxiliary information that is informative about either parameter, or absolute abundance estimates or direct measures of exploitation rate.

Population models with additional complexity such as age/size structure do not necessarily require age/size composition data to be fitted, but do require additional parameters to describe survivorship, growth, and fecundity-at-age. In fact, it is possible to parameterize age-structured models with the same two key population parameters as the simple production models (see Walters and Martell 2004). From a policy perspective, these models are useful for exploring policies that pertain to changes in size restrictions, or in the case of shrimp delaying the start of the fishing season to gain yields associated with additional growth.

Catch-age information has radically improved our ability to estimate historical recruitment using either Virtual Population methods (i.e. VPA), or Statistical Catch-at-Age methods (i.e. SCA). Shrimp and many other invertebrate species are difficult

to age; therefore, assessment models have relied on length-age keys or length based assessment methods to incorporate size composition data to infer historical cohort strengths (e.g. Fournier and Sibert 1991). This composition information, assuming its representative of the true population composition, is informative about total mortality rates, i.e.

$$Z_t = \ln(P_{a+1,t+1}) - \ln(P_{a,t}) \quad (2)$$

where  $P_{a,t}$  represents the proportions-at-age in the population.

The ability to partition mortality into its components of fishing mortality (F) and natural mortality (M) requires additional information on relative fishing pressure. Direct observations on fishing mortality from tagging data or area swept methods (e.g. Winters and Wheeler 1985) allows for the estimation of changes in natural mortality rates over time (e.g. Fu and Quinn 2000).

*Example of estimating components of population change for Pandalus jordani*

Changes in natural mortality rates, juvenile survival, fishing mortality rates, and total population fecundity for pink shrimp off the west coast of Vancouver Island (WCVI) were estimated by fitting an age-structured model to time series information on relative abundance, size composition data, and relative estimates of fishing mortality (Fig. 1).

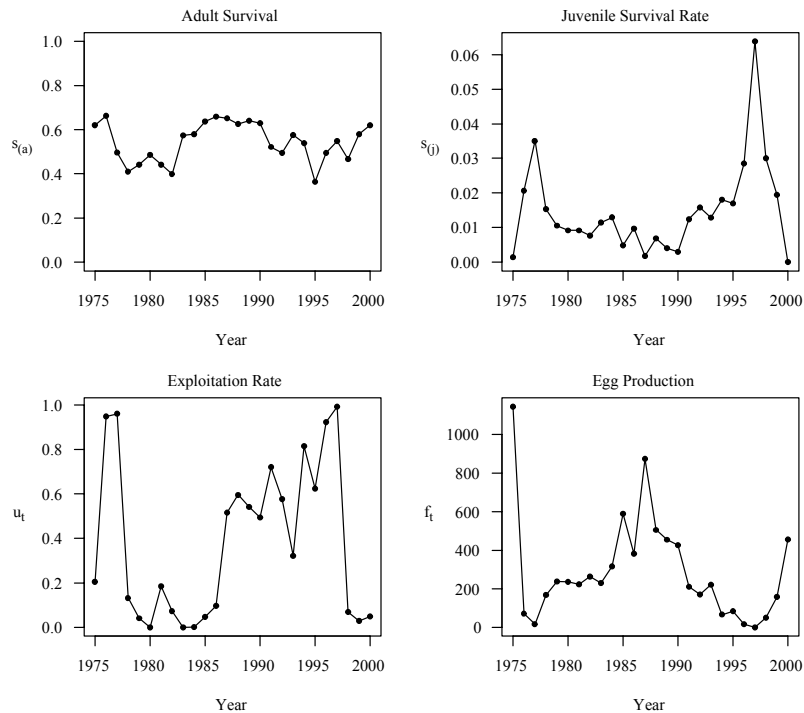


Figure 1. Components of population change for smooth pink shrimp off the WCVI. Each component was estimated by fitting an age-structured model to time series data



on relative abundance and size composition data from fisheries independent surveys, and to estimates of relative fishing mortality rates based on area swept information in commercial logbook data.

Fisheries dependent and independent data were partitioned into two separate statistical areas to explore spatial hypotheses about the advection of shrimp larvae by northward flowing coastal buoyancy currents. A state-observation model structure was used to estimate population parameters including: annual recruitment of age-1 shrimp, an overall mean natural mortality rate and associated deviations in natural mortality (Mt was modeled as a random walk), growth parameters. In addition, parameters for observation sub models included: growth parameters and size selectivity parameters in fisheries independent surveys.

Prior to 1987, the only fishery-dependent information available was total catch; therefore, fishing mortality rates in the population model are conditioned on observed catches (i.e.  $F_t = C_t/B_t$ ). In 1987, commercial log-books were a license requirement in the commercial trawl fishery. Shot-log information was used to calculate area swept information and it was assumed that fishing mortality is proportional to fishing effort:

$$F_t = \frac{a_t E_t}{A_t} \quad (3)$$

The total area swept each year is defined in the numerator of equation three, and the total area over which the stock is distributed is represented by the denominator. To estimate  $A_t$ , it was assumed that no area that contained shrimp was left untouched by the fishery. Equation three is a relative index of fishing mortality because it is uncertain what fraction of shrimp that lie in the area swept ( $a$ ) are retained by the fishing gear. This also implies that this retained fraction remains constant over time, which may be of concern in cases where changes in fishing gear or the use of by-catch reduction devices have altered gear efficiency. In the case of the WCVI shrimp trawl fishery, industry has adopted the use of by-catch reduction devices, which presumably decrease capture efficiency; therefore it is suspect that recent estimates of  $F_t$  based on area swept information are biased downward.

Since the inception of the WCVI shrimp trawl fishery, annual fisheries independent surveys have been conducted to estimate shrimp biomass. The survey was initially conducted using the GB Reed, and later using the WE Ricker. Between 50-60, 30-minute trawl surveys using a 36 foot Yankee trawl were conducted in the two statistical areas. The survey design makes use of a series of latitudinal transects designed to map out the spatial distribution of pink shrimp in each statistical area. Estimates of total abundance are based on spatial interpolation of these samples using a bicubic spline. In this assessment, survey indices were treated as an index of relative abundance, because in many years the commercial fishery landed more shrimp than was estimated by the geo-statistical estimators. In addition to abundance indices, the surveys also collect sex and size composition information. This sex information was used to calculate the proportion of the population that was

egg bearing, and the size composition data were treated as observations on population age-structure.

I used an age-structured population dynamics model where zero survival after age four was assumed. The initial age-structure and annual recruitment to age one were treated as estimated parameters and natural mortality was modeled as a random walk process, where  $M_{t+1} = M_t e(w)$  ( $w = N(0, \sigma)$ ). Size selectivity in the commercial fishery was represented using a logistic curve, where the age at 50% selectivity was set to 1.5 and age-2+ shrimp are fully vulnerable. Parameters for the selectivity function in the survey gear were simultaneously estimated by fitting the model to size composition data. Observation errors in the relative abundance indices and area swept estimates of  $F$  were assumed lognormal distributed, and errors in the size composition data were assumed to follow a multinomial distribution. An informative normal prior distribution was used to constrain the estimates of  $w$  in the random walk model for natural mortality. A modal estimate of all model parameters was obtained by minimizing the negative log-likelihood of the residual errors using a non-linear search routine, and the corresponding results are shown in Figure 1. Parameter uncertainty was characterized by marginal distributions which were obtained integrating the posterior distribution using a Metropolis-Hastings Markov Chain Monte Carlo algorithm. Further details of the assessment model can be found in Martell (2002).

Abundance of pink shrimp off the WCVI was largely determined by fishing mortality and variation in juvenile survival rate (survival rate from egg to age one recruits). Very little variation was observed in estimates of adult survival rates and total population fecundity is roughly proportional to biomass despite minor changes in age at transition to female (Martell 2002). Juvenile survival increased markedly with decreased egg production, indicating strong compensation in recruitment rates at low spawner abundance. Environmental indices available for the region did not explain much of the estimated historical variation in shrimp recruitment. Nor was there much evidence for top-down control through competition or direct predation of shrimp. In fact there is strong positive covariation in shrimp abundance and its predators, suggesting bottom-up control (Martell 2002).

The statistical catch-at-length model used here is sensitive to many of the assumptions made about observed time series data. A key piece of information that was necessary to partition total mortality rates into its components of fishing and natural mortality was the area swept information from commercial log books, and these data were then used to estimate the total area over which the stock is distributed assuming that no area that contained shrimp was left untouched. In addition, log book information for this fishery does not cover the earlier years; therefore, uncertainty in parameter estimates for the period 1973-87 are much larger than years in which log-book information is available.

I did not attempt to use the statistical catch-at-length model in a forecasting mode; however, I would recommend the use of retrospective-forecasting to evaluate

the utility of using this model as a forecasting tool. The idea is to evaluate the model's ability to forecast by using retrospective estimates of model parameters to predict the more recently observed abundance indices and composition information as well as the estimates of total abundance using all of the data. In addition, the assessment model should also be evaluated with respect to bias and precision using data generated from a reference model, where the true parameter values are known.

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## Modeling multispecies dynamics: A bioenergetic-allometric approach

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The bioenergetic-allometric approach is one among several alternative options to model multispecies dynamics. This framework describes population dynamics using a bioenergetic rationale and assumes that core model parameters can be described as power functions of individual body mass (Yodzis and Innes 1992). One advantage of this approach is that it provides guidance for model parameterization, and current advances in allometric theory (Brown et al. 2004) provide the elements for expanding its scope. As an example, I presented some results from the implementation of this approach to the Patagonia system.

The marine community of northern and central Patagonia is structured around the system conformed by anchovy (*Engraulis anchoita*), squid (*Illex argentinus*) and hake (*Merluccius hubbsi*). Squid and hake sustain major commercial fisheries. The sea lion (*Otaria flavescens*) is the most abundant marine mammal which forages over the Patagonian Shelf. Sea lions were heavily harvested in the 1920-60 period, and have been recovering since then. Currently there are questions about the potential competition between marine mammals and fisheries.

To address some of these issues, multispecies models were developed (Koen-Alonso and Yodzis 2005). These models were purely trophodynamic (i.e. no environmental effects were included) and based on the bioenergetic-allometric framework. To assess structural uncertainty, five different models were compared. The difference among them was the formulation of the functional response (i.e. the mathematical representation of the predation process), and the Akaike Information Criterion was used for model selection. Parameter uncertainty was assessed for the selected models by exploring their behavior with extreme parameter values (i.e. parameter sets with the lowest likelihoods but still within the 95<sup>th</sup> percentile range).

These simple models described the hake and sea lion dynamics fairly well, but the dynamics of squid and anchovy were poorly captured. Although the two selected models had similar fits to the data, they also produced different predictions under some exploitation scenarios (i.e. some predictions were model-dependent). Responses in the equilibrium biomasses to changes in exploitation rates were often counter-intuitive, typically nonlinear, and in most cases, non-monotonic (i.e. changes

in exploitation rate not only can affect the magnitude of the response, but also its sign).

Another element that needs to be considered is the effect of environmental variables on system dynamics. Temperature is a reasonable candidate to begin with. In the context of allometric theory and based on first principles, Gillooly et al. (2001) suggested a formulation to represent the temperature-dependence of metabolic rates. Based on these results, Vasseur and McCann (2005) recently expanded the Yodzis-Innes framework to allow for temperature-dependent vital rates. Now, we have the tools to start exploring some of the potential effects of temperature on multispecies dynamics within a mechanistic framework.

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## Session 3: Mortality

### Synthesis and discussion:

Parsons and Lilly provided evidence that the increase in northern shrimp biomass off Newfoundland and Labrador was at least in part due to release from predation pressure due to decline in Atlantic cod biomass. However, both indicated that the connection, while compelling, is still speculative. Lilly noted that shrimp made up approximately 6% of the diet of Atlantic cod during the late 1980's. At this time, the biomass of cod was high and the biomass of shrimp was low relative to present conditions. Consumption of shrimp was great enough that cod could be used as a sampling tool during the 1980's. Indeed, the analysis of cod stomach data provided information on age related distributions of shrimp and increased our knowledge about shrimp ageing. He then cited modeling exercises supporting the hypothesis that the increase in shrimp biomass was the result of reductions in cod biomass.

However, both Lilly and Parsons indicated that there are numerous challenges in quantifying the impact of reduced cod biomass. There is evidence that the increase in shrimp biomass may have preceded the decline in cod biomass. The biomass of predators such as Greenland halibut (*Reinhardtius hippoglossoides*), harp seals (*Phoca groenlandica*) and snow crab (*Chionocetes opilio*) increased concurrent with the increase in shrimp biomass. Unfortunately there are no means of comparing the consumption estimates between predators thereby allowing us to separate predation as a component of natural mortality. Thus we are left with the question of whether the release from cod predation pressure was enough to allow shrimp stocks to increase dramatically.

There was some discussion about the importance of cod as a regulator. Wieland noted that spatial distributions of shrimp and cod did not overlap to a great extent off West Greenland and therefore cod may not be important in determining the stock trajectory for shrimp in his area. Skúladóttir challenged this view noting that cod was very important in controlling shrimp stocks with the Barent Sea and off Iceland.

The final two presentations dealt with single and multiple species models that could be used in shrimp assessment. Martell provided a single species model but included predator abundance as covariates. He noted that many types of models of varying complexities could be examined as stock management tools. The main questions should include:

1. What are the management objectives;
2. Are the objectives attainable; and
3. Are sufficient data available to answer questions posed by fisheries managers?

Management policies can be evaluated using mathematical or conceptual models. The models can be of varying complexities, each with its own set of underlying assumptions, biases and levels of precision.

He then presented the WCVI pink shrimp (*Pandalus jordani*) fishery as an example of one of his modeling exercises. Martell's model included predation abundance and various environmental parameters but concluded that:

1. there was evidence of a density dependent effect; however,
2. fishing pressure was the main force driving the pink shrimp population sizes.

Koen-Alonso then presented a bioenergetic-allometric approach to multispecies dynamics modeling. He presented various models to address the questions about the potential competition between sea lions (*Otaria flavescens*) and the commercial fisheries for anchovy (*Engraulis anchoita*), squid (*Illex argentinus*) and hake (*Merluccius hubbsi*) of northern and central Patagonia. He argued that models should be multi-species in nature because a single species model can not hope to capture the complexity within the ecosystem.

**Recommendations:**

1. There was general agreement that future research had to be focused and that the following conceptual model should be used to provide this focus.

<u>Scenario</u>	<u>Effects</u>	<u>Mechanisms</u>
Stock density low Predation low Temperature increase	high recruitment increase in larval size increase in juvenile size decrease in $L_{ST}$ decrease in mean female size decrease in $L_{max}$	Temperature increase cause: - an extension of the geographical distribution - enhanced food conditions (higher carrying capacity) - a shorter egg bearing period (earlier hatch) - higher growth rates (and survival) of larvae - earlier maturation
Stock density high Predation increase Temperature stable	decrease in recruitment decrease in larval size decrease in juvenile size increase in $L_{ST}$ increase in mean female size increase in $L_{max}$	Food limitation cause: - a decline of growth rates - slower maturation - decrease of larval and juvenile survival (competition in particular within cohorts)

(Wieland, this workshop).

2. We would form a small working group to discuss various models that could be developed as forecasting tools and to evaluate the performance of various harvest policies.
3. We should make comparisons between the ecosystems over a broad geographic area covered by northern shrimp. Data from the Gulf of Maine, Nova Scotia, the Gulf of St. Lawrence, off Newfoundland and Labrador, West Greenland, Iceland and the Barent Sea should be included in this study. The study should include a comparison of indices describing shrimp population dynamics as well as the environment in which they live.
4. A follow-up meeting to discuss shrimp related science should be convened prior to the NAFO shrimp assessment meeting held in Dartmouth, Nova Scotia, October 26–November 3, 2005. Many of the participants of the



present workshop would also be participating in the NAFO assessment. Therefore the NAFO meeting would provide a cost effective opportunity for many of us to get together and develop a proposal to study linkages between shrimp and their environment. The proposal would be based upon the above conceptual model and would identify aspects of the project that each of us could work upon. The proposal would include:

- Comparisons between Northwest Atlantic ecosystems that include *Pandalus borealis*;
- Continued study of the environmental influences upon shrimp abundance, recruitment and growth; and
- A modeling exercise to produce a tool that could be used by scientists to explain changes in population dynamics as well as provide a basis for making resource decisions.

Industry suggested that they would be willing to pay for hotel and per diem costs incremental to the NAFO meeting.

### **Workshop Conclusions and Recommendations:**

The general conclusions from the workshop are that the environment in which shrimp live is very complex and that we have several sources of information from which to model relationships. The multi-species surveys were presented as sources of species information (shrimp length frequency, maturity, biomass/abundance etc.) while the AZMP and CPR programs provide environmental information (water temperature, chlorophyll a, zooplankton abundance etc.). However, we do not have all of the information necessary to understand and make meaningful predictions of population trajectories. While there are probably stock–recruit relationships, no one has demonstrated a meaningful stock-recruit relationship for northern shrimp. This does not mean that relationships can not be developed for shrimp after all a sufficient number of adults must be present if several offspring are to be released. However, as Yvan Lambert’s work demonstrated certain sets of conditions promote the development of embryonic shrimp. If the temperature is above an optimum then eggs develop too quickly resulting in early hatching, high egg mortality and abnormal small larvae that may not survive. Even if the temperature is correct, there must be ample available food to allow survival. The “match mis-match” theory formed a strong theme throughout the workshop. Fuentes-Yaco used satellite imagery to detect the initiation, and measure the peak and duration of the spring bloom. These parameters were then related to the size of shrimp at sex change of shrimp off Newfoundland and Labrador. Savard was able to develop a recruit–spawning stock relationship by following strong year classes until they recruited to the fishery and eventually became female. Parsons demonstrated that forecasts could be made using auto-regressive techniques; however, relationships between biological and environmental variables are not always stable. The original model linked CPUE to sea-ice and predicted that increased winter sea ice would favour high catch rates

several years later. However, the model predictions became inconclusive with the addition of new data. CPUE remained high even though ice cover (lagged) decreased. Similarly, Ouellet noted anomalous conditions in the Gulf of St. Lawrence in which cold spring conditions do not always favour high shrimp recruitment. Once again this relates back to the complexity of the ecosystem.

Similarly, there is no simple explanation of trends in shrimp predation and shrimp biomass. While there is compelling evidence that the decline in cod biomass off Newfoundland and Labrador allowed shrimp biomass to increase to the present high levels, there is evidence that initiation of shrimp increases may have preceded the decline of the cod stocks. Likewise, there may not be a direct link between shrimp and cod biomass off West Greenland.

Martell presented an example of models that could be used to evaluate the performance of various management policies. He offered to create the “shell” of a single species program that could be used in making resource management decisions and suggested that his students could develop the program. Koen-Alonso argued that the ecosystem was very complex and models had to include a multi-species component. His work with the ecosystem of northern and central Patagonia demonstrated that the commercial harvest of one species would have a direct or indirect impact upon other associated species. Data based approaches were also suggested as a means of studying relationships between shrimp and the environment. There was general agreement that all three approaches were good and that one approach did not necessarily exclude or compete with the other.

Chapman indicated that industry would be interested in models that could be used by industry as forecast tools. McNamara noted that industry would like to have forecasts catches four or five years in the future.

The workshop recommendations are consolidated in Appendix III.

## Appendix I

### Agenda

**Shrimp and its environment in the Northwest Atlantic—implications for forecasting abundance and population dynamics  
May 25-27, 2005  
St. John's, Newfoundland and Labrador**

#### **May 25, 2005 (Start 9AM)**

#### **Author**

Opening remarks by the Regional Director—Science

J. Goodyear

Opening remarks by the chair

B. Bergström

Presentation by industry

B. Chapman

#### **Session: 1) Overview**

Mythology of *Pandalus borealis*

B. Bergstrom

The physical oceanography of the Northeast Newfoundland and Labrador shelf

J. Craig et al.

Overview of environmental monitoring in the Northwest Atlantic: summary of data products available.

G. Maillet and P. Pepin

Distribution and Abundance of Northern Shrimp (*Pandalus borealis*) in Relation to Bottom Temperatures in NAFO Divisions 3LNO based on Multi-Species Surveys from 1995-2004

E. Colbourne and D. Orr

How the northern shrimp industry can contribute to and benefit from operational ocean forecasting of the Labrador Current

F. Davidson et al.

#### **Session: 2) Recruitment and Growth**

Question: *What are the perspectives on production in shrimp populations throughout the North Atlantic in relation to density dependent and density independent factors?*

Growth and Recruitment of Northern Shrimp—a research program at Maurice Lamontagne Institute, Department of Fisheries and Oceans, Mont-Joli, Québec

L. Savard et al.

Recruitment processes in the Western Gulf: Importance of the spring conditions in the determination of the strength of cohorts

P. Ouellet and L. Savard

Recruitment variations in the Gulf of St. Lawrence: Variations in recruitment to the fishery and fishable biomass in the Gulf; variations in cohort strength from recruitment surveys in the Western Gulf

L. Savard

Recruitment processes in the Western Gulf: Importance of the spring conditions in the determination of the strength of cohorts

P. Ouellet

Size variations in the Gulf of St. Lawrence: Size variations of males and females recruited to the fishery in the Gulf; ontogenic migrations and growth pattern in the Western Gulf

L. Savard

Egg development under variable conditions: Egg survival, embryonic development, and larval characteristics of northern shrimp females subject to different temperature and feeding conditions

Y. Lambert

Changes in growth pattern of different developmental stages under variable conditions: Molting frequency, size and mass increments of larvae, juveniles, males, transitional females and females of northern shrimp under laboratory conditions

Y. Lambert

Egg bearing periods of northern shrimp in Icelandic waters

U. Skúladóttir

Changes in stock biomass, recruitment and size of Northern shrimp (*Pandalus borealis*) in West Greenland waters—environmental or fishery effects?

K. Wieland and C. Hvingel

Trends in size at sex change off West Greenland

K. Wieland

Decreasing shrimp sizes off Newfoundland and Labrador: environment or fishing?

P. Koeller et al.

Spring phytoplankton bloom and shrimp growth on the Newfoundland-Labrador Shelf

C. Fuentes-Yaco et al

Factors affecting size at sex change off Newfoundland and Labrador

D. Orr et al.

Life cycle and recruitment of northern shrimp (*Pandalus borealis*) in West Greenland waters

S. A. Pedersen

Forecasting fishery performance off Newfoundland and Labrador

D. Parsons and E. Colbourne

Shrimp diets

(open session)

Discussion: *How do changes in the physical and biological environment affect shrimp population dynamics? Recommendations-What needs to be monitored off Newfoundland and Labrador?*

### **Session: 3) Mortality**

Question: *What are the perspectives given the current conditions, and expected changes in the physical and biological environment and their affects on predator abundance? Are fishery affects detectable?*

Predators of Northern Shrimp, *Pandalus borealis*, in the North Atlantic and Interactions within the Eastern Newfoundland and Labrador Marine Ecosystem (NAFO Div. 2HJ3KL)

D. Parsons

Predation on northern shrimp (*Pandalus borealis*) by Atlantic cod (*Gadus morhua*) off southern Labrador and eastern Newfoundland: the release in predation pressure is expected to continue

G. Lilly

Assessment models and there use in evaluating historical and future management performance

S. Martell

Modeling multi-species dynamics: a bioenergetic-allometric approach

M. Koen-Alonso

Parasites and diseases of shrimp

(open session)

Fishery affects

(open session)

Discussion: *Can we partition (quantify) mortality into fishery and natural components? Recommendation –What needs to be monitored off Newfoundland and Labrador?*

### **Session: 4) Current Forecasting Methods (open session)**

Question: *What are the perspectives concerning our ability to forecast?*

- a) recruitment
- b) fishable biomass

- c) spawning stock (female) biomass
- d) fishery performance (CPUE)
- e) shrimp sizes
- f) any others we can think of?

Question: *Are forecasts for environmental factors (e.g. predator abundance, ocean climate) useful for longer-term inferences with respect to shrimp?*

Discussion: *What methods are currently available? Are they reliable? Are there achievable alternatives?*

Closing Remarks

## **Appendix II**

### **List of participants:**

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## **Appendix III**

### **Recommendations:**

#### **Session: 1) Overview**

1) Davidson would like to include real-time temperature, from the fishing fleets, in his drift forecasting models. Many of the vessels obtain this data from trawl mounted temperature sensors. Therefore, it was recommended that the vessel owners bring their sensors to the Biological and Physical Oceanography Section within DFO–NL Region so that they may be calibrated and he could determine whether fishing vessel sensors would form a reliable source of temperature data. If the sensors can be calibrated and reliable data obtained then the next step would be to request real-time data and develop acquisition protocols.

#### **Session: 2) Recruitment and Growth**

2) We continue to research relationships between shrimp and their environment.

3) The use of remote-sensing be explored as a tool to learn more about the timing, initiation, duration and intensity of the spring blooms in the various SFAs. These indices should be used in future stock assessments and once there is a long time series (20–30 years) they may be used in model creation.

4) Lead researchers within Quebec–Region, NL–Region, West Greenland should write a synoptic report describing and comparing various shrimp indices in relation to the environment. This report would become a part of the Ecosystem of the Sub-Arctic (ESSA) project.

#### **Session: 3) Mortality**

5) There was general agreement that future research had to be focused and that the following conceptual model should be used to provide this focus.

<u>Scenario</u>	<u>Effects</u>	<u>Mechanisms</u>
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