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Proceedings Series 2001/23

Série des compte rendus 2001/23

PROCEEDINGS OF THE WORKSHOP ON

"THE NORTHWEST ATLANTIC ECOSYSTEM - A BASIN SCALE APPROACH"

World Trade and Convention Centre
Argyll Street, Halifax, Nova Scotia, Canada

21-23 June 2001

Convened by:

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ABSTRACT

The NW Atlantic is an area of high secondary production that supports major fisheries in the fringing shelf seas. One species dominates the zooplankton biomass throughout the NW Atlantic in spring and early summer: the copepod *Calanus finmarchicus*. Thus, *C. finmarchicus* has a critical role in the transfer of primary production to higher trophic levels and the flux of faecal material to the sediments. A broad international consensus is building for a number of modelling and field studies in the next few years focussed on the NW Atlantic ecosystem and the role of *C. finmarchicus*, with groups from the UK, US, Germany and Canada involved. This large international effort provides a unique opportunity for tackling ecosystem research questions at a basin scale including the linkage between primary and secondary production, advective coupling between N. Atlantic basins, and variation in *C. finmarchicus* abundance in relation to interannual and longer-term fluctuations in basin-scale climate indices. Members of the Canadian research community, with support internationally, concluded that a workshop was needed to co-ordinate the research efforts and programmes directed towards *C. finmarchicus* in the North Atlantic Ocean. The aims of the workshop were to allow Canadian researchers to take advantage of knowledge acquired during recent international programmes, to form working relationships with colleagues from overseas having similar interests and to put together a co-ordinated programme and a research plan.

The workshop was held in Halifax in June 2001. Scientists involved in North Atlantic *C. finmarchicus* research as well as other national and international experts were extended invitations. The workshop included a number of talks discussing the challenge of a North Atlantic basin-scale study of *C. finmarchicus*, the current state of knowledge of its distribution and ecology in the NW Atlantic, the physical oceanography of the region and potential modelling approaches (hydrodynamic and biological). In addition, there were descriptions of upcoming (*e.g*. UK-GLOBEC) or ongoing (*e.g*. AZMP) field programmes. Three working groups then identified questions and major knowledge gaps with regard to the problem of describing and modelling the basin-scale population dynamics of *C. finmarchicus* across the North Atlantic. The results of these working groups were reviewed in plenary session, and three different groups were formed to discuss elements of an overall research plan that would address the important questions. These proceedings summarise both the presentations made at the workshop as well as the results of the working groups' discussions and the final research plan.

RÉSUMÉ

L'Atlantique Nord-Ouest est une région de forte production secondaire, qui alimente d'importantes pêches au sein des mers périphériques du plateau continental. Au printemps et au début de l'été, la biomasse de zooplancton de l'Atlantique Nord-Ouest est dominée par le copépode *Calanus finmarchicus*. C'est dire que *C. finmarchicus* joue un rôle déterminant dans le transfert de production primaire aux plus hauts niveaux de la chaîne trophique et dans le flux de matières fécales vers les sédiments. Un large consensus international est en train de se former, qui vise la tenue de diverses études de modélisation et recherches in situ sur l'écosystème de l'Atlantique Nord-Ouest et le rôle de *C. finmarchicus* au cours des prochaines années; il rallie des groupes de scientifiques du Royaume-Uni, des États-Unis et du Canada. Ce grand projet international représente une occasion unique de s'attaquer à la question de la recherche sur l'écosystème à l'échelle des bassins et notamment d'étudier le lien entre la production primaire et la production secondaire, le couplage d'advection entre les bassins de l'Atlantique Nord et la variation dans l'abondance de *C. finmarchicus* par rapport aux fluctuations, interannuelles et à plus long terme, des indices climatiques à l'échelle des bassins. Des chercheurs canadiens ayant reçu des appuis internationaux ont conclu qu'un atelier était nécessaire pour coordonner les programmes et activités de recherche axés sur *C. finmarchicus* dans l'Atlantique Nord. Cet atelier avait pour but de permettre aux chercheurs canadiens de tirer parti des connaissances acquises dans les programmes internationaux récents, de créer des liens de travail avec des homologues étrangers ayant les mêmes intérêts et de mettre sur pied un programme et un plan de recherche coordonnés.

L'atelier en question a eu lieu à Halifax en juin 2001. Y ont été invités les scientifiques qui effectuent des recherches sur *C. finmarchicus* dans l'Atlantique Nord, ainsi que d'autres experts internationaux. On y a discuté des défis que pose une étude de *C. finmarchicus* à l'échelle des bassins de l'Atlantique Nord-Ouest, de l'état actuel des connaissances sur la distribution et l'écologie de ce copépode dans l'Atlantique Nord-Ouest, de l'océanographie physique de la région et des approches possibles de modélisation (hydrodynamique et biologique). On y a également décrit les programmes de recherche in situ en cours (p. ex. AZMP) ou à venir (p. ex. GLOBEC - R.-U.). Trois groupes de travail ont ensuite mis en évidence diverses questions ainsi que les principales lacunes des connaissances en matière de description et de modélisation de la dynamique de la population de *C. finmarchicus* à l'échelle des bassins de l'Atlantique Nord. Les résultats des délibérations des trois groupes de travail ont été examinés en séance plénière et trois autres groupes de travail ont alors été constitués pour discuter des éléments d'un plan de recherche général qui traiterait des questions importantes. Le présent compte rendu résume les présentations faites à l'atelier ainsi que les résultats des discussions des groupes de travail et le plan de recherche final.

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EXECUTIVE SUMMARY

The NW Atlantic is an area of high secondary production that supports major fisheries in the fringing shelf seas. Throughout the entire NW Atlantic ecosystem, one species of zooplankton, the copepod *Calanus finmarchicus*, accounts for up to 80% of the zooplankton biomass and has a dominant role in the transfer of energy from the primary producers (*i.e.* phytoplankton) to higher trophic levels. This organism is fundamentally an oceanic species which is transported onto the continental shelf in spring and summer but must return to the depths of the deep ocean, or some local deepwater haven, to overwinter in a resting stage known as diapause.

In late 2000, the NW Atlantic had become the focus of modelling and field studies for several groups including: UK-GLOBEC programme in the Irminger Sea (2001-2004); US-GLOBEC Phase IV synthesis studies (2001-2004); a German hydrographic observational programme; DFO's continuing occupation of the WOCE transect across the Labrador Sea; Canadian SOLAS sampling programme (2001-2006). A workshop was held in June 2001 to allow Canadian researchers to take advantage of knowledge acquired during recent international programmes, to form working relationships with colleagues from overseas and to put together a co-ordinated Research Plan that would meet the needs of DFO while enhancing Canadian participation in international activities.

The goals of the workshop were:

- To review existing knowledge and to identify major knowledge gaps
- To engage physical oceanographers and modellers in the development and planning of *C. finmarchicus* related studies
- To aid co-ordination between current and planned research programmes (inter-regionally and internationally)
- To develop a research plan focussing on the North West Atlantic

After reviewing the state of knowledge and with a summary of ongoing research activities, working groups identified major gaps and our understanding of the dynamics of *Calanus finmarchius* and outlined a Research Plan which includes:

- The formation of a Synthesis Working Group;
- Short term objectives for Canadian activities;
- Short and long term objectives for international collaboration.

The objectives of the Synthesis Working Group (SWG) would be:

- To identify key issues that need to be addressed and approaches that could be taken
- To co-ordinate development of meetings (workshops) where analyses could be presented and results implemented in demographic and circulation models

The SWG would involve scientists from all the major participants in North Atlantic GLOBEC studies and other related activities. Canada would be an active participant in the formation and development of the SWG. The approach to be taken by the SWG could follow the retrospective meetings held by the ICES WG on Cod and Climate Change, which have been so successful and produced so many insights into the factors affecting population dynamics of cod and other species. ICES and GLOBEC-International will be approached and invited to act as sponsors of this Synthesis Working Group.

Short term research initiatives in three major topic areas include:

Modelling

- Undertake the development a basin-scale coupled circulation/NPZ model for the NW Atlantic. D. Wright and A. Vezina are already involved in a DFO funded research initiative dealing with this need. B.deYoung (MUN) also has similar activities underway (or planned).

Extension of Field observations in the NW Atlantic sub-Polar and Slope Sea gyres

The workshop identified the need for more extensive sampling beyond the continental shelves. Most of the observations of *C. finmarchicus* distribution and ecology in the NW Atlantic have been made near the coast or on continental shelves, while the open ocean gyres have been generally poorly sampled. Workshop participants identified the following Canadian activities that could serve to enhance DFO's ability to forecast population dynamics as well as enhance international research initiatives:

- The fall Newfoundland region AZMP mission in Nov. 2001 should include Multi-net sampling to determine vertical distribution of *C. finmarchicus* to depths of 2000 m, in Newfoundland slope waters. (To be financed out of existing funds, E. Head)
- The annual DFO mission to sample the AR7 WOCE line in the Labrador Sea should be extended in May/June 2002, to include a NS line south from Cape Farewell and a NE/SW line to Cape Bonavista. (Proposal to be prepared, E. Head)
- The fall Newfoundland region AZMP mission in Nov. 2002 should include sampling along the AR7 WOCE line in the Labrador Sea. (Proposal to be prepared, P. Pepin, E. Head)
- Deployment of observational multidisciplinary mooring in the Labrador Sea. (Proposal to be prepared, P. Pepin, B. de Young).
- Spring and fall AZMP missions to the Scotian Shelf in 2003 to be extended to allow time to extend existing lines to the north wall of the Gulf Stream. An additional mission to the Scotian Shelf and Slope Sea to be carried out in January 2004. (Proposal to be prepared E. Head)

Investigations of physiological status of C. finmarchicus

Workshop participants also identified a number of areas dealing with the physiological activities that required further research. They include development of physiological indices of condition to measure food web dynamics; knowledge of the reproductive state of populations of *Calanus finmarchicus*; and further studies on the onset of diapause. Canadian activities in this area include:

- US scientists will participate in fall AZMP mission to the Scotian Shelf in 2001. They will take samples of individual *C. finmarchicus* for lipid/RNA/DNA analysis from selected net tows. (No funds required)
- Reproductive index will be determined by US colleagues in female *C. finmarchicus* in preserved samples from AZMP and other time series stations throughout the NW Atlantic. (Funds to be sought from NSF by US scientists)
- Levels of biochemical markers of diapause (once they have been identified) will be determined in individual *C. finmarchicus* from AZMP and other time series stations. (Funds to be sought from NSF by US scientists)

Workshop participants noted the limited amount of Canadian expertise in this area of knowledge.

In the short-term term, Canadian activities are to be co-ordinated with the following international research activities:

- Modelling studies in the UK-GLOBEC programme (basin-scale circulation, production and *Calanus finmarchicus* population dynamics)
- A proposed US project on "Climate-related basin-scale variability and its impact on *Calanus finmarchicus* populations in the Scotian Shelf, Gulf of Maine, and Georges Bank region", which includes the participation of 5 DFO scientists.
- The UK-GLOBEC sampling programme, which will involve 4 cruises (Nov. 2001, May, Aug. Nov. 2002) with sampling along 4 transects in the Irminger Sea. (Funded)
- A US mission in 2003, to the examine the vertical distribution of *C. finmarchicus* in the SE and SW Grand Bank slope waters, to study the connection between the Labrador Sea and Slope Sea populations. (Proposal to be prepared for funding by NSF, E. Durbin)
- Sampling in the western Slope Sea in 2003. (Proposal may be prepared for funding by NSF, P. Wiebe)

The workshop concluded that with a relatively modest addition to ongoing Canadian research initiatives (outlined above), coupled with strong and well supported ties with ongoing and planned international research programmes, knowledge and understanding of the dynamics of *Calanus finmarchus* in Canadian and adjacent waters would be greatly enhanced, as would the standing of Canada in the international scientific community.

Long-term goals were also addressed. Workshop participants decided that a Science Plan for a trans-Atlantic study entitled "Basin-Scale Dynamics of Zooplankton in the North Atlantic: *Calanus*" should be drafted. This plan will be written by workshop participants, with input from European colleagues and it will be published under the auspices of GLOBEC-International in late fall 2001.

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INTRODUCTION

The NW Atlantic is an area of high secondary production that supports major fisheries in the fringing shelf seas. It comprises a variety of distinctive environments: continental shelves and their associated banks and deepwater basins, open ocean regions and the Gulf of St. Lawrence. One species of zooplankton occupies a dominant role in the transfer of energy from the primary producers (*i.e.* phytoplankton) to higher trophic levels throughout the entire region: namely the copepod, *Calanus finmarchicus*. This organism often accounts for 70% of the zooplankton biomass of the shelf regions in spring and early summer, but it is actually an oceanic species, having a North Atlantic basin-wide distribution from off the New England coast in the southwest to the Norwegian and Barents Seas in the northeast. Shelf populations of *C. finmarchicus* throughout the North Atlantic must return to the depths of the deep ocean, or some local deepwater haven, to spend part of the year in a resting stage known as diapause. Thus, their presence in high abundance over large areas of the continental shelves, where they are of considerable ecological importance as food for a variety of higher predators (*e.g*. herring, mackeral, larval groundfish etc.), is dependent on replenishment from the deep ocean. *C. finmarchicus* populations in the deep ocean, where they can account for up to 80% of the zooplankton biomass, also play a significant role as food for oceanic higher predators (*e.g*. redfish, salmon etc.).

A considerable amount of information on the distribution and ecology of *Calanus finmarchicus* has been gathered over the last decade in the a series of European programmes in the Northeast Atlantic (*e.g*. Mare Cognitum, ICOS, TASC etc.), in the mid-North Atlantic in Icelandic coastal waters (MRI) and in the Northwestern Atlantic on and around Georges Bank (US-GLOBEC), the Scotian Shelf and Gulf of St. Lawrence (GLOBEC-Canada). Within the Dept. of Fisheries and Oceans, members of the Biological Oceanography Section (Oceans Sciences Division, Bedford Institute of Oceanography) have been collecting hydrographic data and biological samples on a regular basis in the Labrador Sea and on the Scotian Shelf since 1995. The work in the Labrador Sea has generally been carried out in concert with the Ocean Circulation Section sampling along the AR7 WOCE (World Ocean Circulation Experiment) Line. Sampling on the Scotian Shelf was part of the GLOBEC (Global Ocean Ecosystem Dynamics) Canada Programme between April 1996 and 2001, but has been carried out in concert with sampling for the AZMP (Atlantic Zone Monitoring Programme) since 1998. In the Gulf of St. Lawrence and Lower St. Lawrence Estuary there have also been regular biological and hydrographic sampling programmes since 1982 and 1991, respectively, with the AZMP starting in 1998. In Newfoundland, ichthyoplankton surveys were carried out on the Newfoundland and southern Labrador shelves between 1991-1999 and in late 1998 the AZMP was established. Thus, Canada has been and is still collecting large amount of data which have provided, and will continue to provide, considerable insights into regional variations in the ecology of *C. finmarchicus* in the Northwestern Atlantic and its role in local ecosystems.

The proposal to hold a Workshop focussing on studies in the Northwest Atlantic was put forward in November 2000 in response to a number of events. First members of the Canadian research community were invited to collaborate in an upcoming UK programme which will include a field programme in the Irminger Sea with 4 cruises between Nov-Dec. 2001 and Nov.-Dec. 2002. This programme is focussed on determining the population dynamics of the copepod *Calanus finmarchicus* in the Northwest Atlantic sub-Polar gyre (including the Labrador Sea). Secondly, during the EurOCEAN 2000 meeting in Hamburg, Germany, in August 2000 a special GLOBEC session was held to discuss the possibility for Trans-Atlantic GLOBEC-like studies. There was unanimous agreement that such studies are needed but that before they can be undertaken co-operation and co-ordination between national funding agencies is required. Representatives of the EU commission and the National Science Foundation (NSF) commented that they want to promote such efforts and see an important role for Canada in such studies. Concentrations of *C. finmarchicus* in the NW Atlantic (Labrador Sea, Labrador Basin, Irminger Sea) are amongst the highest found in the entire North Atlantic (Planque *et al*. 1997) and the area is vast, but in general these deep ocean populations have been relatively poorly sampled. In addition, the relation between these and the better studied populations of the US and Canadian shelves is unknown, although recent measurements have shown that advection from the north via the slope waters is significant (Drinkwater *et al*. 2000) and that the slope waters are an important source of *C. finmarchicus* to the Scotian Shelf in spring (Head *et al*. 1999). With the prospect of UK sampling in the Irminger Sea, it was decided that a proposal for a Canadian component in a Northwest Atlantic basin-scale programme starting in 2002 would be appropriate and timely. Furthermore, it was concluded that a workshop to co-ordinate research efforts and programmes directed towards *C. finmarchicus* was needed, in order: to allow Canadian researchers to take advantage of the knowledge recently acquired elsewhere; to form working relationships with U.S. and overseas colleagueswith similar interests; and to put together a co-ordinated research plan and programme.

In the proposal put forward in November 2000 the following Workshop Objectives were identified.

- To review existing knowledge and to identify major knowledge gaps
- To engage physical oceanographers and modellers in the development and planning or *C. finmarchicus* related studies
- To aid co-ordination between current and planned research programmes (inter-regionally and internationally)
- To foster collaborations (partnerships, networks etc.) leading to the alignment of existing programmes and the development of new research proposals for future projects
- To develop a research plan focussing on the North West Atlantic

Both national and international experts as well as local participants were invited. The list of participants is given in Appendix I.

After opening remarks by E. Head, the first day of the Workshop was devoted to presentations (Appendix II). The first was “A Grand Challenge” argued by P. Wiebe (Woods Hole Oceanographic Institution) for a truly basin-wide study of zooplankton throughout the N. Atlantic for which synthesis, observations and modelling components were identified. Thereafter came a series of review papers on existing knowledge (*e.g*. *Calanus* spp. distribution in the N or NW Atlantic, physical oceanography of the NW Atlantic sub-polar gyre, modelling approaches, *C. finmarchicus* population growth and transport in the Gulf of St. Lawrence/Scotian Shelf system etc.). Following these were presentations by representatives from existing or upcoming programmes in the NW Atlantic (Canadian SOLAS, AZMP, University of Kiel programme etc.). On the second day the upcoming UK-GLOBEC Irminger Sea programme and results from an ongoing Icelandic programme were described. In addition to invited presentations a series of impromptu short talks were given: at the end of the first day; during the latter part of the second morning; and at the start of the third day. On the second afternoon the group broke into three breakout working groups to identify what each considered to be the major knowledge gaps, based on what they had heard and on their individual knowledge. The breakout groups met in the afternoon to compare the results of their deliberations and the new breakout groups were formed to discuss how these knowledge gaps could be addressed and to identify research ideas for a Canadian programme. At the end of the second day the three group leaders (J. Runge, E. Head,

P. Pepin) met to compare results and put together a summary to present in Plenary Session on the third day. During these breakout discussions suggestions for collaborative projects between regions (*e.g*. Maritimes/Newfoundland) and between countries (*e.g*. Canadian/US, Canadian/UK) arose, some of which appear in the Research Plan (See Appendix III) and some of which will be included in SSF proposals to DFO this fall seeking funding in 2002. On the third day the summary of the breakout groups' results was presented in Plenary Session (See Appendix III). During the ensuing discussion, it was agreed that the group would like to consider a broader scope than had been envisaged to this point. Specifically, it was decided that a Science Plan should be prepared, to be published under the auspices of GLOBEC-International, that would build on many of the discussions that had taken place at this Workshop, but that would encompass the entire North Atlantic, as had been suggested in the Grand Challenge put forward by Peter Wiebe on the first day. The members of the group charged with preparing this document are B. de Young, E. Head, J. Runge, P. Wiebe, K. Brander, P. Pepin and J. Roff, although it is anticipated that there will be additional input from European colleagues not present at this meeting. Thereafter most of the group split for more informal discussions on future collaborations etc., while the subset discussed the form and content of the Science Plan and assigned writing tasks. The "Basin-Scale Dynamics of Zooplankton in the North Atlantic: *Calanus*" Science Plan will be finished sometime in late fall. Extended Abstracts of the presentations are provided in Appendix IV.

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OVERVIEW OF PRESENTATIONS AND ENSUING DISCUSSIONS

A Grand Challenge – Synthesis of North Atlantic GLOBEC data sets through basin-wide studies of zooplankton involving observations and modeling (P. Wiebe, WHOI, USA)

Dr. Wiebe pointed out that several programmes have been underway in the North Atlantic for the past 5 years whose primary goal has been to understand the dynamics of key zooplankton species. He suggested that now, to reach a new level of understanding of plankton dynamics, including impacts of environmental perturbations and linkages to fish stocks, we need to:

- compile information on key species' biology, behaviour and physiology
- develop indices of stock structure
- develop basin-scale conceptual and analytical models to understand/predict spatial/temporal population distributions
- apply new technologies to document spatial/temporal distributions.

Dr. Wiebe then put forward his Grand Challenge, which is "to create a collaborative programme involving physicists, biologists, and modellers from across the North Atlantic and to build and test coupled physical/biological models that can effectively caricature the space and time variation of broadly-distributed and dominant members of the zooplankton community". He identified *Calanus finmarchicus* as a suitable target species, recognising that techniques developed in its study could subsequently be applied to other species. He suggested there are three *C. finmarchicus* populations centres, associated with the three N Atlantic gyres: the Norwegian Sea gyre, the NW Atlantic sub-Polar gyre (including the Labrador Sea) and the Slope Sea (northern recirculation) gyre (See Fig. in Extended Abstract, Appendix IV). Basin-scale questions that need to be addressed include how much exchange there is among these populations and how the different populations respond to climatic variations.

Apart from the scientific challenge of a basin-scale study, Dr. Wiebe also described the organisational problems. National funding bodies fund only their own nationals. The EU funds only European nations and funding cycles are often out of synchrony. In order to put together the interdisciplinary international research teams envisaged in the Grand Challenge, it is clear that a breakthrough in international planning is needed.

Discussion

Following the presentation by Peter Wiebe the group discussed approaches to stating the importance of *C. finmarchius* to fisheries related issues. The group agreed that the circumstantial evidence is strongly suggestive of a linkage between marine exploited resources and fluctuations in *C. finmarchius*. However, one of the problems noted is that there is no clear understanding of the dynamic linkages between the various time series of information that are closely related to fluctuations in fisheries and *C. finmarchicus*.

Calanus abundance in the North Atlantic as determined from the Continuous Plankton Recorder (CPR) survey. (D. Johns, SAHFOS)

Dr. Johns presented results of CPR survey data collected since 1960. He pointed out that there have been notable changes in distribution of the 4 species of *Calanus* that occur in the N Atlantic. In particular, he pointed to the changes in abundance of *Calanus finmarchicus* and *C.*

helgolandicus in the North Sea. Recent increases (decreases) in the abundance of the latter (former) have been accompanied by increases in sea surface temperature and generally high NAO. Dr. Johns discussed some theories that have been put forward to account for these changes. In the NW Atlantic he noted that high NAO conditions through the '90s have been associated with cooler conditions and increased levels of the Arctic species *C. glacialis* and *C. hyperboreus*.

Discussion

Following the presentation by David John discussion centered around the continued need for monthly sampling across the entire North Atlantic over a broader range of region. It was noted that one of the major gaps in knowledge is located in the Labrador Sea, where a substantial portion of the *C. finmarchius* population over-winters. Furthermore, concomitant information on environmental conditions (*e.g.* temperature) would be beneficial in interpreting the patterns observed by the collections. There was also discussion about whether the current frequency of collections was sufficient to allow an interpretation of possible shifts in the timing of the seasonal production cycle of *C. finmarchius*.

Physical Oceanography of the Labrador Sea and Newfoundland Basin. (A. Clarke, DFO)

Dr Clarke gave an overview of the meridional overturning circulation of the North Atlantic. He followed it with a more detailed description of the circulation in the near-surface layers of the NW Atlantic, including the sub polar gyre (which includes the Irminger and Labrador Seas) and in the sub-surface layers of the sub polar gyre. He summarised the physical oceanographic characteristics of the sub polar gyre as follows:

- It is driven by a cyclonic wind stress that varies seasonally and interannually
- It is also driven cyclonically at its shelf breaks by low density (and salinity) Arctic Outflows
- Its bottom layers are driven by the western boundary under currents carrying North Atlantic Deep Water from the overflows southward to the Southern Ocean.
- Ekman fluxes are divergent over its interior.
- Deep convection results in convergences in the upper layers.
- The meridional overturning circulation requires a significant through flow or exchange from the sub tropical to sub polar gyre and from the sub polar gyre to the Nordic seas.
- The currents within the gyre are increasingly barotropic as the surface waters become denser and the stratification decreases.

Dr. Clarke's talk included a description of recirculation features in the Irminger and Labrador Seas at 700 m that were elucidated in recent drifter studies. He also discussed exchange of water between the sub polar gyre and the slope waters of the Scotian Shelf and talked in some detail about changes in hydrographic properties that have occurred in upper layers (0-500 m) of the Newfoundland Basin and Labrador Sea over the last few decades. He suggested that these are likely of importance to marine ecologists and fisheries scientists, since these are the waters that impinge upon the continental slope and flood the shelf basins and Laurentian Channel.

Modelling the Physical Oceanography of the NW Atlantic (Dan Wright, BIO/DFO)

Dr Wright gave a brief overview of the different circulation models being used by the international community in the North Atlantic. This was followed by a discussion of some of the modelling work being done at BIO and Dalhousie.

The separation of the Gulf Stream from the coast near Cape Hatteras and its subsequent path is important locally because of its relation to the recirculation gyre between the northern edge of the Gulf Stream and the shelf break from Georges Bank to the Tail of the Grand Bank. This northern gyre is a significant feature for the interpretation of *C. finmarchicus* observations in the slope water.

High-resolution (1/10th degree) models have demonstrated the ability to reproduce the Gulf Stream separation and the northern recirculation gyre. However, the required computing resources are not available locally. North Atlantic models with grid resolutions of 1/3-1/6th degree can be run routinely, however at these resolutions the modelled temperature and salinity fields drift away from reality and the northern recirculation gyre collapses in 1 or 2 years.

Keith Thompson and Dan Wright are pursuing a novel approach to the problem of nudging the model climatology towards the observed climatology without interfering with higher frequency variability. The standard approach to nudging uses the difference between the model's instantaneous temperature (and salinity) and the observed climatology as the basis for nudging. This strongly damps the higher frequency variability. The new approach uses Kalman filter technology to estimate the model's climatology while the model is running and uses the difference between the modelled and observed climatology as the basis for nudging. Preliminary results are encouraging.

<u>Discussion (Clarke and Wright papers)</u>

The three-dimensional nature of the circulation was outlined in the presentations by Allyn Clarke and Dan Wright. Evidence of subsurface recirculation in the subarctic gyre, at depths in which *C. finmarchius* might over-winter highlighted the need from robust circulation models at the basin scale. There is evidence that surface drifters lend some support to the scale of the recirculation features in the region. The various approaches to determining the circulation field in the Northwest Atlantic were outlined by Dan Wright. The group then raised questions about the ability of existing models to represent the small scale features and events that may be critical in determining the life cycle of *C. finmarchius* throughout the North Atlantic basin. It was noted that such events might be difficult to model and forecast. Furthermore, processes that transport the organisms onto the continental shelf, where many species rely on *C. finmarchius* as a major food source, are poorly understood and there were no current modelling efforts directed specifically at addressing the forcing and variability of transport across isobaths.

Distribution and ecology of *Calanus* spp. in the Northwest Atlantic. (E. Head, DFO)

Dr. Head described the spring/early summer (1995-2000) distribution of abundance of *Calanus finmarchicus*, *C. glacialis* and *C. hyperboreus* at stations in the NW Atlantic region (with sampling concentrated on the Scotian Shelf and along a transect across the Labrador Sea). Dr. Head reported: *C. finmarchicus* occurred in all sampling areas, with high concentrations over shelves and deep water; *C. hyperboreus* occurred over shelves and deep waters, with high concentrations in colder areas (eastern Scotian Shelf, Labrador and Greenland shelves); *C. glacialis* occurred only over shelves.

Dr. Head reported that along the Labrador Sea transect there were high numbers of egg-laying females in May, June and July, whereas young stages occurred occasionally only on or near either shelf. Dr. Head suggested that the new year's generation in the central Labrador Sea must be recruited after July suggesting low egg survival in May-June. Dr. Head went on to discuss how regional and interannual differences in environmental conditions (hydrodynamics, temperature) on the Scotian Shelf affect the timing of reproduction and rate of development of *C. finmarchicus* there.

Finally, Dr. Head described the vertical distribution of *C. finmarchicus* and *C. hyperboreus* at stations at and beyond the shelf-break of the Scotian Shelf in fall 1998 and 2000. She suggested that *C. finmarchicus* at depth off the western Scotian Shelf are a mixture of individuals that grew up on the shelf and in the Slope Sea and that *C. finmarchcius* at depth off the eastern Scotian Shelf are a mixture of Slope Sea animals and animals derived from farther northeast (*e.g*. Labrador Sea). In 1998 there were higher numbers of the Arctic species *C. hyperboreus* at depth in the fall than in 2000. Dr. Head suggested that this was due to a greater infusion of Labrador Slope Water into the Slope Sea during the spring of 1998.

<u>Discussion</u>

The final presentation of the morning dealt with current knowledge concerning the broadscale distribution and ecology of *C. finmarchius* in the Northwest Atlantic. Some of the most striking information to arise was simply the lack of observations over much of the region. There was a clear need to get a better base of information from which to develop coupled biophysical models. There are also many questions related to the lack of understanding of processes. Dr. Head presented evidence of a high and continued egg production rate, even in the apparent absence of food. Questions arose about the possible role of predatory/cannibalistic feeding by *C. finmarchius* on its own young. Investigation of variations in survival of early developmental stages clearly represents an area for further research.

Preliminary results of North Atlantic basin-scale modeling with the Parallel Ocean Program (POP) (Y. Chao, JPL, Caltech.)

Dr. Chao discussed the need for a basin-scale hydrodynamics model to interpret variations of patterns of *C. finmarchicus* abundance in the Gulf of Maine and elsewhere that occur with changes in NAO index and in ocean circulation. He also presented an animation of a preliminary model that appeared to give a realistic simulation of the major features of the N. Atlantic circulation.

<u>Discussion</u>

Q. Do you include ice in your models?
A. No. We are using the simplest possible model so we do not have ice included. We can make adjustments by forcing the temperatures to remain close to reality.

Numerical simulations of the Labrador Sea and Baffin Bay (Nicolai Kliem, DFO)

Dr. Kliem discussed the hydrodynamics modelling component of a Danish programme designed to examine the effects of changes in hydrography and biological processes on the recruitment of shrimp and fish off the western coast of Greenland. He related that his initial approach had been to model circulation over the shelf alone, but his results were not realistic and suggested that he should extend his domain to cover the Labrador Sea and Baffin Bay. In future his hydrodynamical model will be linked to a biological model for shrimp larvae.

Discussion

Q. Will it be possible to look at interannual variability with the model you are developing? In the paper by Pedersen and Smidt they discussed data collected over approximately 40 years.
A. The purpose in developing the model was not to examine interannual variability but rather to reproduce the observations obtained in 2000, in particular the drift buoy data.

Transport of *Calanus finmarchicus* on the Scotian Shelf: the roles of the Gulf of St. Lawrence, slope waters and the Labrador current (J. Runge, DFO)

Dr. Runge described the results of a physical-biological model study for the Gulf of St. Lawrence (GSL) and Scotian Shelf (SS) which links a life-history model of *Calanus finmarchicus* to a three dimensional ocean circulation model that predicts 3D temperature, salinity and flow fields. The initial standard run was initialised in October, with a population of stage 5s in diapause that are homogeneously distributed in waters <1000 m in depth. Stage dependent vertical migration and observed spawning times are included in the model which gives results which compare reasonably well with observations in the lower St. Lawrence Estuary, GSL and on the SS. Calculations of horizontal fluxes between regions indicate that advection plays an important role. Dr. Runge gave the main points of the study as follows:

- the Gulf of St. Lawrence appears to be auto-sustainable, *i.e*. no external source is needed to ensure persistence of *C. finmarchicus* there
- the annual exchange between the GSL and the SS nearly balances, due to the input of young stages from the eastern SS in the spring and the output of older copepodite stages to the SS in the late summer and fall.
- much of the SS *C. finmarchicus* production is exported to the offshore and the Gulf of Maine

Dr. Runge pointed out that in the model the slope waters (Slope Sea) receive individuals from shallower regions and that this region (the so-called Slope Sea gyre) appears to be a productive area for *C. finmarchicus*. This finding has yet to be confirmed by any systematic detailed study, but opportunistic observations are not inconsistent with it. Dr. Runge suggested that the Slope Sea merits further observational studies, since the model indicates it may be an important source of *Calanus* to the SS and the Gulf of Maine. In addition, Dr. Runge noted that in the model the role of advection from the Newfoundland Shelf/Slope and Labrador Slope/Sea to the Slope Sea needs further elucidation, including field observations.

Discussion

Q. Calanus finmarchicus in your model are not distributed very deep in slope waters off the Scotian Shelf. Have you considered distributing them deeper in the water column?

A. We placed the diapause stage at a depth of about 200 m because this is where our observations of vertical distribution (collected in shelf areas) showed them to be overwintering. If we had vertical distributions of the *C. finmarchicus* in the deep offshore waters we would include them.
C. We have vertical distribution data from off the Scotian Shelf. We also have found large numbers of *C. finmarchicus* in the surface layers off the Shelf, particularly the spring of 2001.
C. We have vertical distribution data offshore down to 1000 m but generally have found few *C. finmarchicus* below 800 m. We also found large numbers near the shelf edge in deep water but the distributions were very patchy. Sampling carried out in connection with ring studies also showed patchy concentrations in the slope water region. We found that the water properties associated with warm core rings do not always extend very deep vertically and indeed found *C. finmarchicus* below ring water in Slope Water. It is very difficult to obtain good estimates of *C. finmarchicus* abundance in these regions because of the dynamic nature of the flow.
C. My recollection from the (Gulf Stream) ring studies was that euphausiids were limited to 1000 m but it was deeper for *C. finmarchicus*.
C. Off the Scotian Shelf *C. finmarchicus* were found down to 1500 m and for *C. hyperboreus* to 2000 m.
C. In the Irminger Sea, *Calanus finmarchicus* are found to 2000 m and deeper but it is not clear that all of these would manage to make it to the surface.
C. What effect does the vertical distribution have on the modelling results?
C. Overwintering *Calanus finmarchicus* can only last so long at depth. How long can they overwinter in the Labrador Sea and still survive? Does this make a difference?
C. Calanus finmarchicus may not survive at 12ºC.

Interannual variaibility of *Calanus finmarchicus* on Georges Bank and in the Gulf of Maine: Results from the GLOBEC study (E. Durbin, URI)

Dr. Durbin presented results from the US-GLOBEC study on Georges Bank (1995-1999). He reported that *C. finmarchicus* start to reproduce in Dec/Jan in the Gulf of Maine and that the new generation are advected on to Georges Bank. Maturation of this generation occurs in March and one or more generations follow it. Dr. Durbin reported that interannual differences in temperature gave differences in maturation times, but lower rates (1996 *vs.* 1995) were associated with higher peak abundances. He also pointed out that size analysis suggested that there are interannual differences in the contribution of spring (large) *vs.* summer/fall (small) spawned C5s to the G0 female stock. Dr. Durbin also presented evidence that suggested that food limitation of nauplii in February in some years in the Gulf of Maine may delay recruitment of that year's generation.

<u>Discussion</u>

Q. You showed a plot of the mean abundance of *C. finmarchicus* by stage for 1999 and 2000 and suggested that the difference between the two curves (primarily reduced copepodite stages in 2000) was due to increased mortality in 2000. How can you make this interpretation?
A. My interpretation is predicated on the assumption of no advection, which we have not proven. I agree that such interpretations are difficult.
Q. The CPR data from the Scotian Shelf have shown that *C. finmarchicus* declined significantly while the colour index increased, especially during the winter-spring period. A high colour index suggests high abundance of phytoplankton. On the Scotian Shelf, we also noted changes in community structure. Is the colour index indicative of what is happening throughout the whole size range of the phytoplankton?
A. The colour index is not fully representative but more dependent upon the larger diatoms.

C. We do not expect that there should be a linear relationship between *C. finmarchicus* and phytoplankton production. *C. finmarchicus* is not a major grazer of the phytoplankton. One might expect poor growth with low phytoplankton and no relationship with high phytoplankton.
C. Dianne Gifford would say that phytoplankton is not important to *C. finmarchicus* at all.
C. Every relationship with egg production seems to show the same result.
C. There are temperature effects on egg production.
C. The Georges Bank GLOBEC data shows a hyperbolic relationship between total chl. a (integrated to 50 m) and egg production rate. It is likely that chlorophyll is just a proxy for phytoplankton and microzooplankton prey availability. Information on the relationship of egg production with temperature and chlorophyll would be useful across the North Atlantic.
Q. Does *Calanus finmarchicus* have an effect on phytoplankton abundance in the models?
A. My recollection is that they don't.
C. Maybe they have an important effect during the time of the phytoplankton blooms.
C. Any effect will depend on nutrient dynamics. If there is an injection of nutrients then it would be unlikely that the *C. finmarchicus* grazing could keep up to the primary production to observe any effect.
C. Perhaps grazing by *Calanus hyperboreus* would have an effect on phytoplankton abundance.

SOLAS in the NW Atlantic. (W.Miller, Dalhousie Univ.)

Dr. Miller reported on the overall tenets and field programme planned in the newly funded Canadian SOLAS programme. SOLAS stands for Surface-Ocean Lower-Atmosphere Study and the central tenet is that "Marine production and emissions of climatically-active trace gases in surface oceans have a significant effect on the chemistry and physics of the overlying atmosphere and on climate". Dr. Miller indicated that the programme on the east coast would involve three sampling cruises in 2003, ideally in April, July and September, to characterise the patterns of emission of DMS and other climatically active gases in different seasons. The trip in April would also include a 12 day experiment following a tagged water mass and the course of a "spring bloom" in the Slope Sea.

Discussion

Q. Where in the Northwest Atlantic will the field studies within Canadian SOLAS programme take place?
A. They will take place in the slope water region off the Scotian Shelf.
Q. You mentioned some problems with regard to funding. Could you elaborate?
A. We have been requested by NSERC to firm up the Foundation's (CFI) funding. The difficulty has been that CFI has no cash this year but is willing to fund the research in the coming year. Having been the first nation to receive SOLAS funding has meant that the Canadian component of the programme will be used as leverage to obtain funds for other national SOLAS programmes. Canada has been approached by the UK and Spain who wish to contribute to the project including offering ships. More collaborations are expected.

German programmes in the Northwest Atlantic. (S. Harms, Univ. of Kiel)

Dr. Harms described a European mooring observation programme that is starting in the North Atlantic in the near future. The German group will deploy 3 moorings that will provide observations of hydrographic parameters, carbon dioxide and nutrient levels, particle flux, zooplankton and currents. Some data recovery will be by satellite telemetry, and the moorings are located on commercial routes to allow regular servicing. It is anticipated that in future additional sensors could be deployed on the moorings, perhaps in collaborations with other research groups.

Discussion

Q. How much circulation modelling is included in the German programme?
A. Biogeochemical and circulation modelling are included but I am not familiar with the details.

The Atlantic Zone Monitoring Programme. (P. Pepin, DFO)

Dr. Pepin outlined main aims of the Atlantic Zone Monitoring Programme (AZMP) "(1) to increase DFO's capacity to understand, describe and forecast the state of the marine ecosystem and (2) to quantify changes in the ocean physical, chemical and biological properties". He went on to describe the elements of the ongoing operational programmes at a network of sampling locations (fixed point time series stations, cross shelf sections and groundfish surveys) and noted the further input of information from Continuous Plankton Recorder sampling (mesozooplankton) and satellite imagery (temperature, colour/phytoplankton). Dr. Pepin illustrated his talk with examples of data collected at time series stations and on shelf-wide surveys and results of satellite imagery.

Discussion

C. It should be stated that the AZMP is also a framework upon which we will build other programmes.
A. That is correct and we also have collaborations associated with the AZMP.
Q. How is the AZMP related to GOOS?
A. The AZMP may be part of Canada's contribution to GOOS but this decision hasn't been made yet.
C. Perhaps you could also indicate that there is a formal structure for reporting and analyzing the data.
A. The results from the AZMP programme are reported annual to DFO's Fisheries Oceanography Committee (FOC). Papers are written up and published as DFO Research Documents and posted on the web. As well, the data are posted on the web in an effort to make the data as widely available as possible.
Q. You showed chlorophyll sections across the Flemish Cap for 1999 and 2000. The 1999 distribution shows very high chlorophyll in the spring throughout the water column but it is based on the first sampling of the year. Is this pattern correct?
A. Yes we did observed high chlorophyll in the spring of 1999. We are not sure what caused these high values.
C. Looking at satellite data from the Flemish Cap section we saw relatively consistent levels of colour from the SEAWIFFS satellite from year to year. There were some interesting physical dynamics, however and differences in the timing of the spring bloom.
C. My recollection was the satellite data suggested large phytoplankton blooms that appeared earlier in 1999.
C. This was true for the Scotian Shelf but not for the Grand Banks.
C. The variability in the spring bloom on the Grand Banks can vary by upwards of 2 months.

Basin-scale *Calanus* models. (W. Gurney, Univ. of Strathclyde)

Dr Gurney was the first of the non-scheduled speakers, and he described the approach being taken to modelling the demography and spatial distribution of *C. finmarchicus* in the UK GLOBEC study. Firstly, he indicated the importance of diffusion in maintaining persistence of a population in a given area. Then, he discussed the relative merits of Lagrangian *vs.* Eulerian methods in modelling spatial distributions of stage-structured populations. Overall the latter method is favoured because reductions in resolution do not compromise the results, and reduced resolution means much higher run-speed.

<u>Discussion</u>

Q. In one of the figures you showed, application of the Eulerian method seemed to result in the disappearance of one of the *Calanus* patches compared to the Lagrangian method. Is this true and is it a concern?
A. It is true that with the lower model resolution of the Eulerian method (but improved computer efficiency) means that we lose some of the fine-scale details. That particular patch of *Calanus* was lost but in terms of abundance it was only a few percent of the total.
C. It seems that we should use crude models when there are little data available and then improve the models as the data improve. The Eulerian modelling fits well in the incremental approach to modelling.
Q. Is what you are doing similar to flux corrections?
A. No. We are dealing with long-time increments. The key is to remove numerical dispersion. Our approach is to decide on the hydrodynamics and assume it is adequate and then worry about biology. The Eulerian method is useful for optimization.

Regime shifts and long-term climate impacts on the marine ecosystem. (B. Topliss, DFO)

Dr Topliss (the second impromtu speaker) described her work in developing a new index technique to examine non-linear climate-ecosystem links. The method incorporates the idea that the oceans have "memory" of previous climatic events, whereas the atmosphere does not, but that the latter is nevertheless affected by the ocean's memory. Dr. Topliss described how regime shifts in regional index and fish catch match and occur on variable time scales (20-70 years) and she questions whether the changeovers result in environmental "stress". Over longer time scales in the NE Atlantic she reported that the 1700s and 1900s were periods of high environmental variability, whereas the 1800s were more stable.

UK plans for GLOBEC work in the NW Atlantic. (M. Heath, FRS Marine Laboratory)

Dr Heath presented an overview of the proposal which had been put forward to the UK National Environmental Research Council as part of the Marine Productivity Thematic Programme, a programme involving investigation of how climate fluctuations affect secondary production in the ocean. The rationale for studies in the Irminger/Labrador Sea sub polar gyre is:

- it is a locus of high secondary production, fringed by productive fisheries
- the zooplankton community is "simple", *i.e*. dominated by few species
- the physical oceanography has varied since the '60s (with changes in NAO index)

- a major plankton-oceanography study was carried out in 1963 (providing a database for comparative analysis with data to be collected in 2001-2002)

The rationale for choosing *Calanus finmarchicus* (+ *Thysanoessa longicaudata* and *Metridia norvegica*) as a target species is:

- they are characteristic of the sub-arctic N Atlantic (and represent a large proportion of the biomass)
- they have a historical relationship with the NAO index
- they play a key role in the food web and are important prey for many predators (*e.g*. baleen whales, redfish, herring, squid, salmon etc.)

The main hypothesis of the study is that "climate fluctuations lead to disruption in the space-time dimension of the life cycle of *C. finmarchicus* (+ other species), which manifests as changes in abundance and demography". Disruptions might be caused directly by variations in hydrography, but trophic factors (bottom-up or top-down controls) might also be involved. Thus, the overall aim of the UK programme is to discover how the population structures of *C. finmarchicus* (*T*. and *M. norvegica*) are maintained, how they respond to physical forcing and the consequences for the structure of the pelagic food web.

Dr. Heath went on to briefly describe the field campaign in the Irminger Sea, which will consist of 4 cruises (winter 2001, spring, summer, winter 2002), during which there will be hydrographic and biological sampling (phytoplankton, mesozooplankton, micronekton, cetaceans) and process studies. Dr. Heath pointed out that hydrographic and ice conditions during the 1963 NORWESTLANT survey period were very different from those in the late '90s. He suggested that these changes have likely lead to differences in the spatial structure of the food web and the timing of life history events (and hence spatial distribution and demography) of target zooplankton species, which should be explicable in terms of circulation, water mass distribution and sea-ice cover.

Finally, Dr. Heath noted that the Irminger Sea and Labrador Sea are part of the same sub polar gyre, within which *C. finmarchicus* may be transported between regions (in the surface-layers in spring/summer and at depth in winter). Dr. Heath encouraged Canadian participation in a collaborative field campaign to enable UK and Canadian scientists to attain a better understanding of the population dynamics of this key organsim throughout the Irminger Sea/Labrador Sea sub polar gyre ecosystem.

<u>Points Arising From Discussion</u>

Evidence from previous information indicates that *C. finmarchius* females exit diapause before the onset of the spring bloom. The subsequent cohort development depends heavily on the survivorship experienced during the early stages of development. It highlights the need to resolve the dynamics of the lower food webs in the region. It was pointed out that in order to contrast the results obtained from the various ongoing and planned research initiatives, there was a need to establish the catchability characteristics of the various sampling methods used in the diverse programmes.

A more important question in studying *C. finmarchius* on a basin scale is to determine the potential phase lag one might expect in the response of the Irminger and Labrador Sea *C. finmarchius* if the processes that determine the demographic changes are driven primarily by trophic versus transport processes. Once again, the issue of differences in the spatio-temporal patterns in egg production and juvenile survivorship are key elements that require further knowledge. It was pointed out that food web dynamics probably depend more on local forcing than oceanic forcing which typically affects large-scale circulation features.

One of the major gaps in the British activities in the Irminger Sea is a complete lack of collections in the Labrador Sea. If the population dynamics in the subarctic gyre are regionally linked, then it is difficult to gain an understanding of the teleconnections without widespread data collection. It was pointed out that there may be berths available on the Irminger Sea cruises for Canadian and American researchers that would be willing to address some of the issues currently not being addressed by the programme.

Ecology of *Calanus* in Icelandic waters and the Irminger Sea (A. Gislason, FRI)

Dr. Gislason pointed out that Iceland occupies a unique position at the junction of two great submarine ridges and that these ridges affect the circulation and distribution of water masses around Iceland. He reported that areas to the northeast of Iceland show highest zooplankton biomass because of immigration of Arctic species (*Calanus hyperboreus*, *Metridia longa*), whereas to the southwest high zooplankton biomass reflects high local production of *Calanus finmarchicus*. In the latter region, where temperatures are warmest, there are two peaks in *C. finmarchicus* abundance in the spring/summer suggesting the occurrence of two generations per year, whereas elsewhere around the island there is only one.

Dr. Gislason went on to describe the vertical distribution of *C. finmarchicus* in the Irminger Sea in fall, winter, April and June. *C. finmarchicus* were more-or-less evenly dispersed between 400 and 1600 m in fall and winter, but occurred at depths of <600 m in April and <200 m in June. Dr. Gislason presented evidence that *C. finmarchicus* are advected from the Labrador Sea to the Irminger Sea at depth during their overwintering period.

Finally, Dr. Gislason described the relationships between *C. finmarchicus* reproduction and the spring bloom and between reproduction and location. Reproduction generally started earlier on the shelf than farther offshore, and highest rates were found in frontal regions and the central Irminger Sea.

Observations of exchange between the North Atlantic Sub-polar gyre and the Slope Sea gyre around the tail of the Grand Bank (R. Hendry, DFO)

Dr. Hendry (the third impromptu speaker) presented results of the 1988-90 Intergyre Exchange Experiment, which included current meter measurements of flow around the tail of the Grand Bank. He pointed out that changes in transport were generally correlated with changes in sea level and suggested that altimetric data could provide a useful proxy measure of the variability of Labrador Slope Water inflows into the Slope Water system.

The fish-*Calanus* connection. (K. Brander, ICES)

Dr. Brander presented three propositions to the group which relate to the “assumed” important connection between fish and *Calanus finmarchicus* and the anticipated basin-scale view for future research. These were:

- Cod, whose larvae are supposed to feed largely on *C. finmarchicus* eggs and nauplii, thrive on other species in some areas of the N. Atlantic where *C. finmarchicus* is not abundant (*e.g*. the Baltic)
- Food production for cod larvae seems to depend on local forcing (*e.g*. hydrography, bloom dynamics) rather than oceanic forcing
- Correlations between copepod abundance and fish recruitment are often negative (*e.g*. *C. finmarchicus vs.* cod on the eastern Scotian Shelf).

<u>Discussion</u>

It was recognised by the group that making direct connections between *Calanus finmarchicus* and fisheries questions is a difficult task, and that establishment of such links is not the immediate aim of the group. Rather the group accepted that links do exist, and put their study as one of the long-term goals. In addition, it was noted that linkage may not only be through recruitment, as the growth and distribution of many important planktivores (*e.g*. capelin and herring) is dependent on the distribution and abundance of *C. finmarchicus.*

Climate connections in the Gulf of Maine. (A. Pershing, Cornell Univ.)

Dr. Pershing discussed how changes in the "mode" of the Slope Water system may be related to the phase of the NAO and how both may influence the Gulf of Maine ecosystem and the abundance of *C. finmarchicus* in the region.

General Discussion

The general discussion centred on identifying approaches that will allow the ongoing and planned activities centred around the study of *C. finmarchius* to develop the synergy necessary to provide a more effective approach for the development of a basin scale synthesis of the underlying processes that affect the demographic of this key species. Although the meeting was initially developed on the principal of outlining a Canadian contribution for the North Atlantic study of *C. finmarchius*, it was clear that the only effective approach was to develop a framework that formalized the need for international collaboration and project development. As such, this formalization must include a multi-national framework to provide the necessary funding for the various programme activities. There are two underlying reasons for the need for a co-operative and coordinated international effort. First, the dominant physical forcing is at the large scale, which is considerably larger than the regional studies. Second, a common framework can allow a more effective approach to undertaking comparative studies of how the different information levels and models allow researchers to understand and predict the dynamics of *C. finmarchius*.

The participants decided to work in three groups to identify the underlying key issues that should be addressed by a joint programme.

WORKING GROUP DISCUSSIONS

In the first series of discussions the three working groups were asked to identify major questions and major information gaps that are hindering progress in out understanding of the population dynamics of *Calanus finmarchicus* in the NW Atlantic.

GROUP 1 – Leader - P. Pepin

This group took as its starting point the ideas set out in Dr. Wiebe's talk: *i.e*. the existence of three population centres for *Calanus finmarchicus* in the N. Atlantic associated with three gryes (the Norwegian Sea gyre, the sub polar Irminger Sea/Labrador Sea gyre and the Slope Sea gyre). The results of this working group were presented as a series of questions and some approaches that could be taken to address them.

1) To what extent are the *Calanus* gyres self-sustaining and/or inter-linked? What are the roles of transport and *in situ* processes?
2) What are (and how variable are) the processes that affect the movement of *Calanus* on to the continental shelves?
3) Are the areas most studied (*i.e*. continental shelves) important to the dynamics of the three gyres (*i.e*. open oceans)?

To address these questions, the working group suggested the following directions for study:

<u>Hydrodynamics modelling</u>
a) Assess the robustness of our knowledge and identify a suite of basin-scale circulation models
b) Identify methods to compare model predictions/output and decide how to base the comparisons to determine sources of discrepancies among them

<u>Biological modelling</u>
a) Assess the robustness of knowledge and identify a suite of demographic models (whether they are driven by NPZ predictions of by *in situ* observations of lower trophic levels).
b) As (b) above

<u>Data synthesis</u>
Synthesize available data (*e.g*. distribution, rates, "environmental responses") that can be used to initialise or validate hydrodynamics and biological models

The working group also identified some major observational gaps:

1) Most observations of *Calanus* abundance, life-history etc. are on continental shelves. The lack of observations in the deep waters of the sub polar and Slope Sea gyres represents a major knowledge gap.
2) Diapause – there is little understanding of the processes that lead to the initiation and termination of diapause. Possible candidates for external factors for initiation might include daylength, light intensity, temperature, food concentration. Termination might involve external (light, daylength) or internal (biological clock) factors.
3) Mortality – *in situ* mortality rates, their causes and regulators, are largely unknown.

GROUP 2 – Leader – E. Head

The discussions of this group started with a challenge from one of the members (C. Hannah), which was as follows:

"Our goal should be to develop a universal model for *Calanus finmarchicus* demography which is driven by appropriate external factors and which is appropriate throughout its geographic range".

This challenge was met by considerable resistance amongst the biologists and lead to the discussion of some major knowledge gaps, for example:

<u>Knowledge gap</u> 1) Diapause.
We know that *C. finmarchicus* populations descend to overwintering depths and return to the surface layers at different times in different areas, but we do not know the factors that regulate this behaviour.

<u>Knowledge gap</u> 2) Diapause *versus* multiple generations
In some areas of its distribution *C. finmarchicus* produces one generation per year, in other areas a portion of the first generation remains in the surface layers to produce a second generation, and in some cases a third generation may occur. We do not know how individuals "decide" which behaviour to adopt.

There was discussion about how these information gaps could be tackled. It was pointed out that the experimental approach is problematic. No-one has been able to induce *C. finmarchicus* to go into diapause in the laboratory, and when diapausing individuals are brought to the surface and into the laboratory they soon "wake up" regardless of experimental treatment. It was suggested that a data synthesis approach might be more feasible: *i.e*. collect as much field data on diapausing populations as possible throughout the geographic range (*e.g*. timing of entry and arousal, food, temperature, surface and underwater light, daylength etc.) and look for commonality. Other impediments to the development of a universal model were also identified. For example:

<u>Knowledge gap</u> 3) The timing of the onset of reproduction
In some areas reproduction starts as the spring bloom starts, whereas in others it precedes the spring bloom. Thus, it remains unclear as to how the timing of reproduction is regulated (and therefore how to model it).

<u>Knowledge gap</u> 4) Mortality
It appears that when reproduction precedes the spring bloom most of the eggs and nauplii do not survive. Whether this is due to predation (cannibalism and/or consumption by other species) or food limitation is unknown. It was acknowledged that mortality rates of later copepodite stages are also largely unknown.

It was concluded that although a "universal model" is not feasible in the short-term, further studies may lead to development of such a model in the distant future.

Further knowledge gaps were also identified:

<u>Knowledge gap</u> 5) Distribution of *C. finmarchicus* in the Slope Sea
It was recognised that there had been several talks describing/assuming the existence of a recirculation gyre between the shelf-break and the north wall of the Gulf Stream bounded by the

NE US coast in the west and the tail of the Grand Bank in the east. The retentive properties of this gyre make it a possible overwintering area for *C. finmarchicus*, and according to J. Runge's talk, it may also be a very productive area, and a source to the central and western Scotian Shelf. This working group noted that biological observations in the Slope Sea are very limited, and that there are no wintertime observations.

Knowledge gap 6) Distribution of *C. finmarchicus* in the Labrador Sea in fall/winter
It was noted that there have been very few observations of *C. finmarchicus* at depths >100 m along the L3 section and no studies of its vertical distribution. Such observations are critical in fall and winter, in order to calculate transport fluxes of diapausing *C. finmarchicus* to the Slope Sea, and within the sub polar gyre, to the Irminger Sea.

GROUP 3 – Leader – J. Runge

Gaps and issues for collaborative effort

1) We should pull all the existing data together (*e.g*. UK to digitalize Huntley data in Labrador Sea and Nortwestlant data).

2) There is a need to obtain winter vertical distribution of *C. finmarchicus* and association with water masses, including spatial variation across the N. Atlantic.

3) Genetic/phenotypic differences in subpopulations. There is evidence, for example, that NW Atlantic and NE Atlantic *Calanus finmarchicus* are genetically different and that their reproductive response to the spring bloom is different (reproduction occurs before bloom in deep regions of NE and NW Atlantic, suggesting contribution of internal stores to egg production; onset of reproduction often occurs during the spring bloom in shelf regions, so lipid stores may be used primarily for metabolism).

4) There is a need to obtain data on the abundance and distribution of *Calanus finmarchicus* life stages in the Iceland and Greenland Seas (needs participation of countries with icebreakers).

5) Vital rates/ process studies

- *Diapause*. Factors and cues controlling timing; how to formulate in models; subpopulation differences between diapausing Stage CIV and Stage CV; spatial variation in timing and depth distribution; buoyancy control questions; development of biochemical indices to identify diapausing vs active individuals.
- *Development times*: Primarily a function of temperature? Or, is there food limitation of molting rates seasonally and spatially?
- *Egg production*: Spatial variation and relation to primary production; phenotypic variation among N. Atlantic populations; empirical relationships to food indices (*e.g*. chlorophyll a); Reproductive Index could be determined in females in existing preserved samples - calibration and application to existing series of samples to obtain data on spatial/temporal distribution of spawning.
- *Mortality*: measurement of mortality at all stages using: vertical life table approach for spatial/temporal series; horizontal life table approach during dedicated process cruise when there is intensive, daily sequential sampling for all life stages; spatial and temporal variation in mortality; comparison of field measurements with estimates backed out from models.

6) NPZ linkage: estimated of food environments

- Appropriate indices of food (*e.g*. empirical relationship of chl. a with egg production rates and growth)
- What to use for microzooplankton: is Chl.a a proxy?
- Hesitation to get involved in budget approach (where growth and reproduction are predicted from ingestion rates)

PLENARY DISCUSSION

As the results of the three working groups were presented in Plenary Session it became obvious that there was a considerable degree of overlap in views amongst the groups. A general discussion ensued during which it was decided that three working groups should reformed, with the same leaders, but different participants, to distil the ideas presented previously and to discuss specifics for a Research Plan to address the issues raised during the first set of deliberations. The following summaries were presented by each of the working groups at the end of the day.

GROUP 1 – Leader – P. Pepin

This group took a general view, i.e. distilled the important questions and aims that a research plan should address

<u>Questions</u>

- To what extent are the *Calanus* gyres self-sustaining and/or inter-linked? What are the roles of transport and in situ processes?
- What are (and how variable are) the process that affect the movement of *Calanus* on to the continental shelves

<u>General tasks</u>

- Undertake the development of basin scale applicable demographic model
- Assess the robustness of models (independently). Identify how to compare outputs.
- Implement coupled models with observations/data that represent local characteristics

<u>General gaps</u>

- Diapause function
- Mortality
- Vertical structure (distribution, stage, physiological state)
- Physiological dependencies (temperature, food, history)
- Spatial distribution
- Genetic/phenotypic variation across regions

GROUP 2 – Leader – E. Head

This group took a more pragmatic/practical view of the question by considering possible projects/programmes, over short and long-term time scales. They conceived of a time line that they thought should form the basis for planning over the next 10 years.

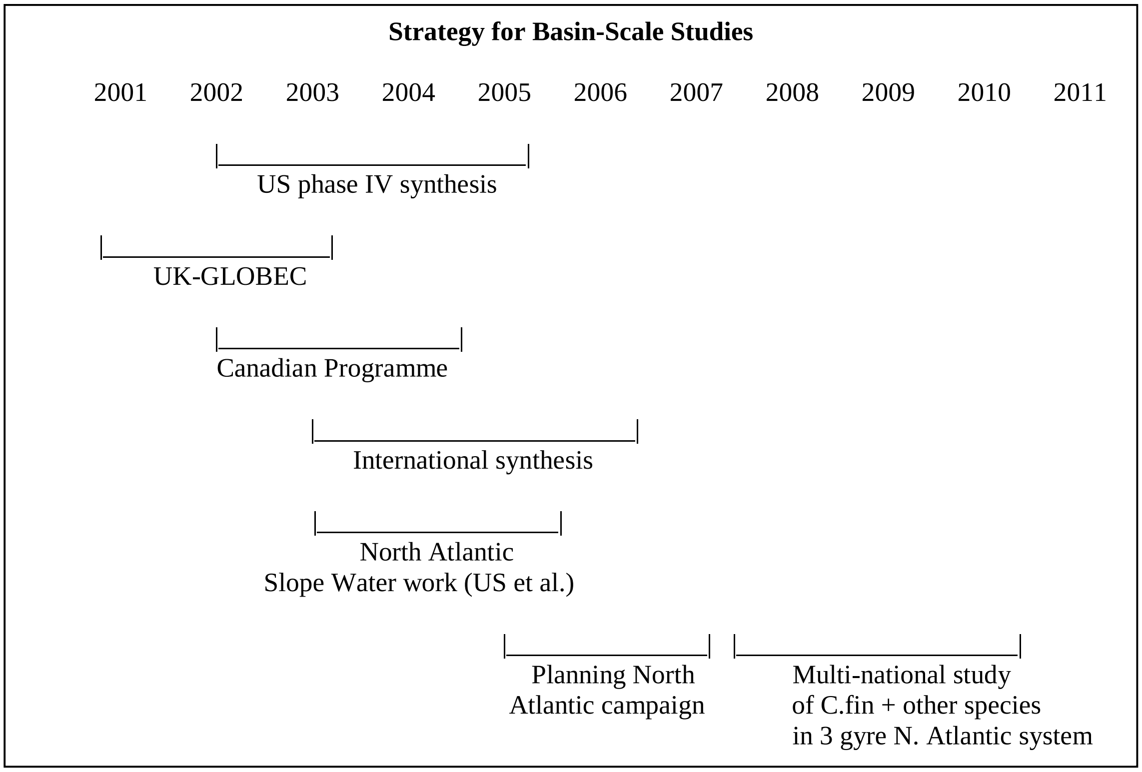

Table 1. Possible time line for international collaborative programme for *Calanus finmarchicus* research in the North Atlantic.

In the near future (2002) it was felt that the emphasis should be on the North West Atlantic sub polar gyre (Irminger Sea/Labrador Sea). The UK programme in the Irminger Sea is already funded (to a total of ca. $14 million Cdn.) for field studies in 2001-2002 and it is evident that the scientific knowledge gained would be greatly increased with Canadian participation in the west (*i.e*. Labrador Sea/Newfoundland Basin). It was therefore considered desirable that E. Head and P. Pepin seek funding/ship time to extend sampling coverage on the regular spring/summer Labrador Sea mission and the fall Newfoundland AZMP mission in 2002 to include sampling in the Labrador Sea. Collaboration with the UK programme would allow Canadians to take part in UK missions and *vice versa* and data and expertise would be shared amongst all parties.

It has become apparent in the US-GLOBEC programme that understanding the dynamics of *C. finmarchicus* on Georges Bank and in the Gulf of Maine requires information about the source populations, namely, the Scotian Shelf and Slope Sea. Before and during the course of this workshop several Canadian researchers were invited to participate in a basin-scale modelling project proposed in the US-Phase IV synthesis programme, which will address such questions as “What are the pathways for exchange among populations of *C. finmarchicus* in the Slope Sea, Labrador Sea, Gulf of Maine and on the Scotian Shelf and how are they influenced by climate variability?” (See Appendix III). This will be a theoretical study, however, since there is very little data to validate the model, especially in the Slope Sea. Thus, the possibility of a Slope Sea study was discussed. P. Wiebe (and in discussions elsewhere, E. Durbin) are considering putting forward proposals to NSF for field work in the Slope Sea and around the tail of the Grand Bank to start in 2003. Canadian participation, via extension of the AZMP spring and fall missions into the Slope Sea, would require relatively modest inputs of time and money. The need for winter data, however, was also discussed, and this would require an extra mission (Dec. 2003), if it were to be included in a Canadian programme.

The need for winter data in other Slope Water regions was also discussed. The possibility of extending the Newfoundland AZMP mission in Nov. to sample in deep water using a Multi-net (to give vertical distribution of *C. finmarchicus*) was discussed. E. Head will try to undertake this operation in Nov. 2001, assuming she can find the modest financial support needed. Programmes on the West Greenland Shelf and in the Norwegian Sea/North Sea may also be starting in 2003.

The group then went on to discuss the knowledge gaps in other areas: firstly, diapause and mortality. The group heard that there are US projects underway to identify biomarkers for diapause. In addition, both UK and US researchers are, or will be, studying mortality in ongoing or upcoming projects. W. Saumweber also discussed the possibility of using lipid composition as indicators or feeding history (and source). E. Head offered him and his associates berths on the fall AZMP cruise so that he can compare biomarkers in diapausing individuals from the Gulf of Maine with those in diapausing animals in Emerald Basin and slope waters.

Further discussions identified the need to compile a common database, which would include: data on spatial and vertical distribution; data on physiological rates; old data (*e.g*. Station Bravo in the 50s) etc. It was realised that setting up such a database would require time (long-term commitment), funds and international participation.

The final areas of discussion were: genotypic/phenotypic variations and questions relating to sex determination. Genotypic variations using mitochondrial and nuclear nucleic acid sequencing are being used to examine gene flow between the 3 gyres, and the UK group are planning to use microsatellite DNA techniques for the same purpose. Species identification of nauplii (*e.g. C. finmarchicus vs. C. glaicialis*) requires the use of genetic identification. On the question of sex ratio the group heard that the sex of young (stage 3-4) *C. finmarchicus* can change but is fixed at stage 5. The factors controlling the proportion of females/males are not clearly understood, but may include food concentration. It is also unclear whether all females are always inseminated.

GROUP 3 – Leader – J. Runge

This group considered some areas where there could be collaboration between US and Canadian groups.

<u>Diapause.</u>

One question the group posed, but did not answer, was whether there is in existence sufficient data to compile a database to try to identify the factors that lead to diapause. They also suggested taking a field-based experimental approach, which would involve sampling at Time Series stations, such as the AZMP Station off Halifax, St. John's etc. and Portsmouth (New Hampshire). The object would be to identify biomarkers to determine when diapause is starting and when emergence occurs. M Wagner also indicated that she would be undertaking laboratory experiments.

<u>Mortality</u>

Three approaches were suggested:

1) Process cruises in the field. A patch is followed and samples of all life history stages are collected at frequent intervals. It was noted that each environmental situation is probably different, however, so that a number of such cruises are needed to examine a variety of

environmental conditions. (One such study has been carried out by US-Canadian group on Georges Bank already)
2) Monitoring (time series) stations. Vertical life tables can be applied. This could be applied to all AZMP and US time series stations and is planned for in UK-GLOBEC study for coastal and Norwegian Sea (weather ship) stations. (Note: all US and Canadian time series stations are coastal)
3) Inverse modelling, with adjoint data assimilation (Underway in US)

Other topics that were discussed that would involve participation of other nations included:

<u>Vertical structure</u>
Determination of vertical structure (needed for coupled physical-biological modelling) would involve:
1) Data synthesis
2) Measurements (BIONESS, Multi-net, OPC, Acoustics)

<u>Physiological dependencies</u>
We need to:
1) Assemble data on egg production rates versus environmental parameters (e.g. chl. a concentration)
2) Ascertain "Reproductive index" on females in existing preserved samples (where it would give good spatial coverage)

<u>Spatial distribution</u>
We need to:
1) Synthesise existing data
2) Determine distribution and abundance in slope waters (*e.g*. Slope Sea)
3) Examine the relationship between the life history of *C. finmarchicus* and circulation in the NW Atlantic sub polar gyre

<u>Phenotypic/genetic variation</u>
We need a "Trans-Atlantic" study, where researchers carry out the same experiments on animals from different regions of the N. Atlantic, to see whether responses are uniform. The idea would be to transport animals to a number of different laboratories throughout the N Atlantic. Groups of researchers would combine in these laboratories to carry out the experiments to insure experimental treatments are uniform etc.

<u>Long-term goals</u>
Ultimately we would want to determine:
1) the influence of climate on primary production, *Calanus finmarchicus*, redfish, cod, capelin etc.
2) Basin-shelf connections
3) Redfish, herring, capelin –*C. fin*. connections
4) The role of euphausiids

The entire group met briefly in plenary session during which the three group leaders presented the results of their discussions. The group leaders then withdrew to put together a summary of the results that would comprise the project elements of a Research Plan for a NW Atlantic study.

On Saturday morning, following a presentation by A. Pershing (included in the Overview of Presentations and Ensuing Discussions Section), the summary of the working groups' findings was presented in plenary session. The summary is given in Appendix III. It is anticipated that one or more Canadian proposal(s) will go forward to DFO (SSF) and/or NSERC in the near future, based on the ideas presented in this summary. Others may be anticipated in the more distant future to address some of the long-term goals also outlined in the summary. During the ensuing discussion the group moved beyond the immediate area of interest (the NW Atlantic) to consider the broader issue – the three gyre hypothesis encompassing the entire N. Atlantic system and the “Grand Challenge”. For many of the same reasons that were used to justify this meeting, it seemed that this is/was an appropriate time to be considering a Trans-Atlantic study and a basin-scale approach to zooplankton dynamics. Specifically, it was decided that a sub-set of the workshop participants should write a Science Plan for such a study. The members of the group charged with preparing this document are B. de Young, M. Heath, E. Head, J. Runge, P. Wiebe, K. Brander, P. Pepin and J. Roff (as editor), although it is anticipated that there will be additional input from European colleagues not present at this meeting.

Dr. Head then thanked the rest of the group for their presentations and their participation in the working groups and thereafter most of the workshop participants left to carry on informal discussions on future collaborations *etc*. elsewhere. The subset identified above discussed the form and content of their intended Science Plan and assigned writing tasks. The “Basin-Scale Dynamics of Zooplankton in the North Atlantic: *Calanus*” Science Plan will be finished sometime in late fall. The group broke up at *ca*. 15.00.

It should be noted that since this workshop, Roger Harris (Chair of the GLOBEC-International) has endorsed the idea of the Science Plan and has agreed to publish it under the auspices of GLOBEC-International. In addition, Dr. Wiebe has made overtures to NSF to investigate how previous suggestions to organise a joint US-EURO funding account are going. The idea is that participating nations would put funds into this account and international teams would be funded, according to the recommendations of a Scientific Steering Committee. Dr. Wiebe cited the holding of and findings of this workshop as being further evidence of the need for an international funding arrangement.

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APPENDIX II – WORKSHOP AGENDA

THURSDAY, 21 JUNE 2001

08:30 - 09:00 - Introduction - Overview of the Workshop's aims and schedule

09:00 - 09:30 - Peter Wiebe (Woods Hole Oceanographic Institute, US) – A Grand Challenge: Synthesis of North Atlantic GLOBEC data sets through basin-wide studies of zooplankton involving observations and modelling

09:30 - 10:00 - David Johns (Sir Alistair Hardy Foundation for Ocean Science, UK) – Variations in *Calanus* abundance in the North Atlantic over the last few decades, as determined from CPR data

10:00 - 10:30 - BREAK

10:30 - 11:00 - Allyn Clarke (DFO, BIO) - Physical Oceanography of the Labrador Sea and Newfoundland Basin

11:00 - 11:30 - Dan Wright (DFO, BIO) - Modelling the physical oceanography of the Northwest Atlantic

11:30 - 12:00 - Erica Head (DFO, BIO) – Distribution and ecology of *Calanus* spp. in the Northwest Atlantic.

12:00 - 13:30 - LUNCH

13:30 - 13:45 - Yi Chao (Jet Propulsion Laboratory, Caltech., US) – Preliminary results of North Atlantic basin-scale modeling with the Parallel Ocean Program (POP)

13:45 - 14:00 - Nicolai Kliem (DFO, BIO) – Hydrodynamics modelling on the West Greenland Shelf

14:00 - 14:30 - Jeff Runge (DFO, IML) - Transport of *Calanus finmarchicus* on the Scotian Shelf: the roles of the Gulf of St. Lawrence, slope waters and the Labrador current

14:30 - 15:00 - Ted Durbin (University of Rhode Island, US) – Interannual variaibility of Calanus finmarchicus on Georges Bank and in the Gulf of Maine: Results from the GLOBEC study

15:00 - 15:30 - BREAK

15:30 - 15:50 - Bill Miller (Dalhousie Univ.) - SOLAS in the NW Atlantic

15:50 - 16:10 - Sabine Harms (Univ. of Kiel, Germany) - German programmes in the Northwest Atlantic

16:10 - 16:30 - Pierre Pepin (DFO, NWAFC) – The Atlantic Zone Monitoring Programme

16:30 - 16:50 - Bill Gurney (Univ. of Strathclyde, UK) –Basin-scale *Calanus* models

16:50 - 17:10 - Phil Williamson (Univ. of East Anglia, UK) – UK-GLOBEC – Organisational considerations for the upcoming programme

17:10 - 17:20 - Brenda Topliss (DFO, BIO) – Regime shifts and long-term climate impacts on the marine ecosystem

FRIDAY, 22 JUNE 2001

08:30 - 09:00 - Mike Heath (FRS Marine Laboratory, Aberdeen, UK) - UK plans for GLOBEC work in the NW Atlantic

09:00 - 09:30 - Astthor Gislason (Fisheries Research Institute, Reykjavik, Iceland) - Ecology of *Calanus* in Icelandic waters and the Irminger Sea

09:30 - 09:50 - Ross Hendry (DFO, BIO) – Observations of exchange between the North Atlantic Sub-polar gyre and the Slope Sea gyre around the tail of the Grand Bank

09:50 - 10:10 - Keith Brander (ICES, Denmark) – Three challenging questions concerning the *Calanus*/groundfish connection

10:10 - 10:30 - General Discussion

10:30 - 11:00 - BREAK

11:00 - 12:00 - Breakout groups meet to identify most important areas for discussion

12:00 - 13:30 - LUNCH

13:30 - 14:00 - Breakout groups meet in Plenary Session to compare notes and select areas for further discussion

14:00 - 15:00 - Breakout groups reform and continue discussions on selected topics

15:00 - 15:30 - BREAK

15:30 - 16:30 - Breakout groups report back to Plenary Session. Group leaders meet to prepare a synthesis of project elements that could go into proposals (See Appendix III).

SATURDAY, 23 JUNE 2001

09:15 - 09:30 - Andrew Pershing (Cornell Univ., US) Climate connections in the Gulf of Maine

09:30 - 10:00 - Presentation of Workshop's recommendations for project elements for a Canadian research programme directed at research on *Calanus finmarchicus* in the NW Atlantic and general discussion thereof.

10:00 - 10:30 - BREAK

10:30 - 12:00 - Discussion of the "Grand Challenge" of P. Wiebe, *i.e*. discussion of how to move forward from a NW Atlantic Study of *Calanus* to a Trans-Atlantic Study of *Calanus*.

12:00 - 12.30 - LUNCH

13:30 - 15:00 - Subset of participants discuss the form and content of a Science Plan to be written to address the Grand Challenge entitled "Basin-scale dynamics of zooplankton in the North Atlantic: *Calanus*".

APPENDIX III – SUMMARY OF A RESEARCH PLAN FOR THE STUDY OF *CALANUS* SPP. IN THE NORTHWEST ATLANTIC

1) Formation of a Synthesis Working Group

Its objectives would be:

- To identify key issues that need to be addressed and approaches that could be adopted to gain a common perspective.
- To co-ordinate development of meetings where analyses would be presented and results implemented in demographic and circulation models. Such meetings could take as a model the series of retrospective meetings held by *the* ICES Working Group on Cod and Climate Change.

Examples of key issues that arose in discussions at this Workshop are:

- Patterns of vertical distribution in relation to (a) season, (b) life history stage, (c) hydrography and (d) other environmental variables.
- Synthesis of data on physiological dependencies (*e.g*. reproduction rate *versus* food/temperature, growth/development rate *versus* food/temperature, etc.)
- Synthesis of existing spatial and vertical distribution data
- Synthesis of existing knowledge of the timing and diapause in populations in different areas

2) Existing projects or projects identified for study in the near future (3-5 year time scale)

Modelling

- Development of a basin-scale coupled circulation/NPZ model. This project is already underway at BIO (2001-2004, Alain Vezina, Dan Wright)
- Climate-related basin-Scale variability and its impact on *Calanus finmarchicus* populations in the Scotian Shelf, Gulf of Maine, and Georges Bank regions. Funding is being sought in US-GLOBEC Phase IV (US colleagues + Guoqi Han, Charles Hannah, Erica Head, Ross Hendry, Peter Smith)
- Population dynamics study of *Calanus finmarchicus* in the Gulf of Maine and Georges Bank. Funding is being sought in US-GLOBEC Phase IV (US colleagues)
- Validation of basin- scale circulation fields using hydrographic databases. (Included in proposal above (Charles Hannah))

Extension of field observations in the NW Atlantic sub-Polar gyre and Slope Sea

- UK sampling programme in the Irminger Sea to include 4 cruises (Nov. 2001, May, Aug. Nov. 2002). Funded under UK-GLOBEC programme (Mike Heath *et al*.)
- Spring Labrador Sea cruise in 2002 to be extended to include a line NS from Cape Farewell and a line NE/SW to Cape Bonavista. Funding to be sought from DFO via an SSF (Erica Head)
- AZMP lines to be extended into the deep ocean and use multiple net samplers to investigate the depth distribution of *C. finmarchicus.* Already underway in the Maritimes region, will take place in Newfoundland region in fall 2001, if funding can be found. (Pierre Pepin, Erica Head)
- Fall AZMP cruise in Newfoundland region in 2002 to be extended to include sampling along the WOCE section across the Labrador Sea. Funding to be sought from DFO via an SSF (Pierre Pepin, Erica Head)

- Deployment of observational multidisciplinary mooring in the Labrador Sea. Planning to be undertaken by Brad de Young and Pierre Pepin
- Spring and fall AZMP cruises in 2003 to be extended to explore the distribution of *C. finmarchicus* in the Slope Sea (+ additional areal and seasonal coverage by US collaborators). Funding to be sought from DFO via an SSF and from NSF. (Erica Head + US Collaborators *e.g.* Peter Wiebe, Ted Durbin)
- Winter cruise in Jan. 2004 to cover selected Scotian Shelf AZMP and Slope Sea stations (Erica Head)

Investigations of physiological status of C. finmarchicus

- Collection of stage 5 *C. finmarchicus* samples for lipid/DNA/RNA etc. analysis on Scotian Shelf AZMP cruise(s). Planned for fall of 2001, no funding required (Erica Head + US colleagues, Ted Durbin, Whitley Saumweber)
- Examination of reproductive state of female *C. finmarchicus* in existing preserved sample collections. Funding source unidentified (Jeffrey Runge)
- Identification of genetic and biochemical markers for diapause status using samples collected at time series stations on NW Atlantic shelves (*e.g*. AZMP, GOM, Gulf of St. Lawrence) + experimental studies of diapause state. Funding to be sought from NSF (Jeffrey Runge, Melissa Wagner , Ann Bucklin, Bruno Zakardjian)

Mortality

- Intensive field sampling study on Georges Bank to include modelling and observations of predator-prey conditions. This project is underway, with the field component completed (US colleagues: Ohman, Runge, Durbin and others)
- Application of vertical life table approach to estimate mortality at time series stations (*e.g*. AZMP etc.) (US colleagues: funding source unidentified). Inverse modelling and adjoint data assimilation. (US colleagues: GLOBEC Phase IV submitted)

3) Aims over the longer-term (2004-2010)

- Development of a long-term strategy to co-ordinate field and modelling activities among national (international) programmes, with the ultimate goal of a combined multinational Trans-Atlantic programme (*ca*. 2008-2010)
- Development of circulation models that can address basin-shelf exchange questions
- Studies focussed on the relationship between variations in *C. finmarchcius* abundance/life history etc. and the success of predators (*e.g*. timing of reproduction *versus* groundfish recruitment success, abundance *versus* herring/mackerel condition)
- Development of multi-sensor (CTD, HF hydroacoustics) ARGO floats for long-term deployment
- Development of proposals for sampling in undersampled areas (*e.g*. Newfoundland Basin, N Labrador Sea) if models suggest the need.

APPENDIX IV – ABSTRACTS

A Grand Challenge - Synthesis of North Atlantic GLOBEC data sets through basin-wide studies of zooplankton involving observations and modeling

Peter H. Wiebe
Woods Hole Oceanographic Institution

A number of Global Ocean Ecosystem Dynamics Programs (GLOBEC) have been underway in the North Atlantic for the past five years with a primary goal to understand the dynamics of key zooplankton species in terms of their coupling to the physical and biological environment and their response to climate change. These include the U.S. GLOBEC Georges Bank Study, the Trans-Atlantic Study of Calanus (TASC), Mare Cognitum, and Canadian GLOBEC. These programs have completed major field work, data have been collected at the various study sites, and comprehensive databases are being assembled. These programs are now entering synthesis phases and the issue is how to proceed. A four-step program is proposed to work towards a new level of understanding of the dynamics of plankton, the impacts of environmental perturbations, and their linkages to fish stocks. The steps are: 1) compile information on features of the key species' biology, behavior, and physiology across their range; 2) develop indices of their stock structure to convey their status; 3) develop basin-scale conceptual and analytical models to understand and predict spatial/temporal structuring of populations (Figure 1); and 4) apply new technologies to document the spatial and temporal patterns of the key species throughout their entire range.

The Grand Challenge is to create a collaborative program involving physicists, biologists, and modelers from across the North Atlantic and to build and test coupled physical/biological models that can effectively caricature the space and time variation of broadly-distributed and dominant members of the North Atlantic zooplankton community. To understand the changes that are likely to take place under different climate scenarios will require ocean basin models that include the shelf sea and fiord models and basin-scale forcing, and have high enough resolution to include the major physical and biological features that govern the dynamics of the population. The initial focus would be on *Calanus finmarchicus*, which would pave the way for the development of models for other species and for the ecosystem as a whole. An ocean-basin scale analysis through synthesis of observations and modeling should lead to fundamentally new understanding of ecosystem dynamics, and thus allow prediction of responses to climatic variation.

The GLOBEC programs have been nationally (USA, Canada, Norway) or regionally (European Union) funded. Funding has usually been limited to citizens from that country or region. Although there is a strong motivation on the part of individual scientists of different nationalities to work together during this synthesis phase of GLOBEC, the lack of a coherent funding structure is a serious impediment to achieving the goals embodied by The Grand Challenge. Funding cycles and priorities in the different countries are generally out of synch, making it difficult or impossible to develop integrated research plans and proposals. In order to eliminate the structural impediments to basin-scale synthesis of GLOBEC data sets and development of model(s) described above, two actions are needed: 1) the holding of collaborative international workshops to facilitate exchanges of ideas and to build working partnerships among the scientists involved in or interested in conducting the synthesis research; and 2) the development of mechanisms to enable the funding of collaborative studies involving international multi-disciplinary teams of researchers.

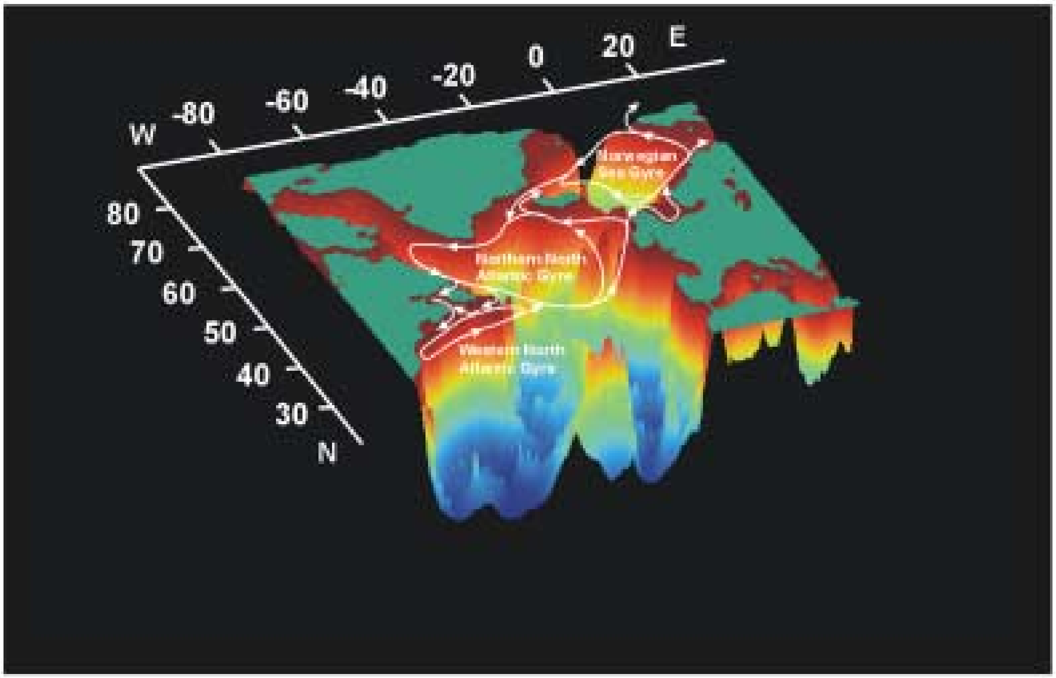

Figure 1. A conceptual model for the distribution and dynamics *of Calanus finmarchicus* in the North Atlantic that can be used as a means of thinking about the requirements of sampling *C. finmarchicus* across the ocean basin.

The North Atlantic *C. finmarchicus* population can be thought of as inhabiting three gyres. Most southerly (1) is a small gyre in the Northwestern Atlantic consisting of the western portion of the Grand Banks, Gulf of Saint Lawrence, Scotian Shelf, Gulf of Maine, Georges Bank, and the Slope Water. The largest gyre (2) consists of the northern North Atlantic Ocean basin bounded on the west by Labrador; on the north by Greenland, Iceland, the Faeroes, and the submarine ridges in between; on the east by the UK; and on the south by the Gulf Stream extension and the North Atlantic current (including the Labrador Sea and the Irminger Sea). Most northerly (3) is the Norwegian Sea, including the North Sea shelf, Norwegian shelf and fjords, and Barents Sea. Exchange between these gyres is restricted relative to the exchange within each gyre; the amount of exchange of *C. finmarchicus* between each of the gyres needs to be determined.

References related to this talk.

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Wiebe, P.H. 2001. Basin-wide studies of zooplankton through observation and modeling: Synthesis of North Atlantic GLOBEC data sets. EurOcean2000, The European Conference on Marine Science and Ocean Technology, 29 August – 2 September. To be published in conference proceedings volume.

Calanus abundance in the North Atlantic as determined from the Continuous Plankton Recorder surveys

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The CPR survey has been collecting plankton samples in the North Atlantic for 70 years. The survey utilises merchant ships of opportunity on monthly routes, using a methodology that has remained unchanged since 1931, thus providing a constant comparable time series of plankton abundance data. One of the most important genera, *Calanus*, is represented primarily in the survey by *Calanus finmarchicus*, but also *Calanus helgolandicus*, *C. glacialis* and *C. hyperboreus*. Over the last decade the biogeographical ranges of these four species have changed, notably for *C. finmarchicus* and *C. helgolandicus* in the North Sea area. Figures 1 to 4 show maps of distribution for each of the species, highlighting decadal change.

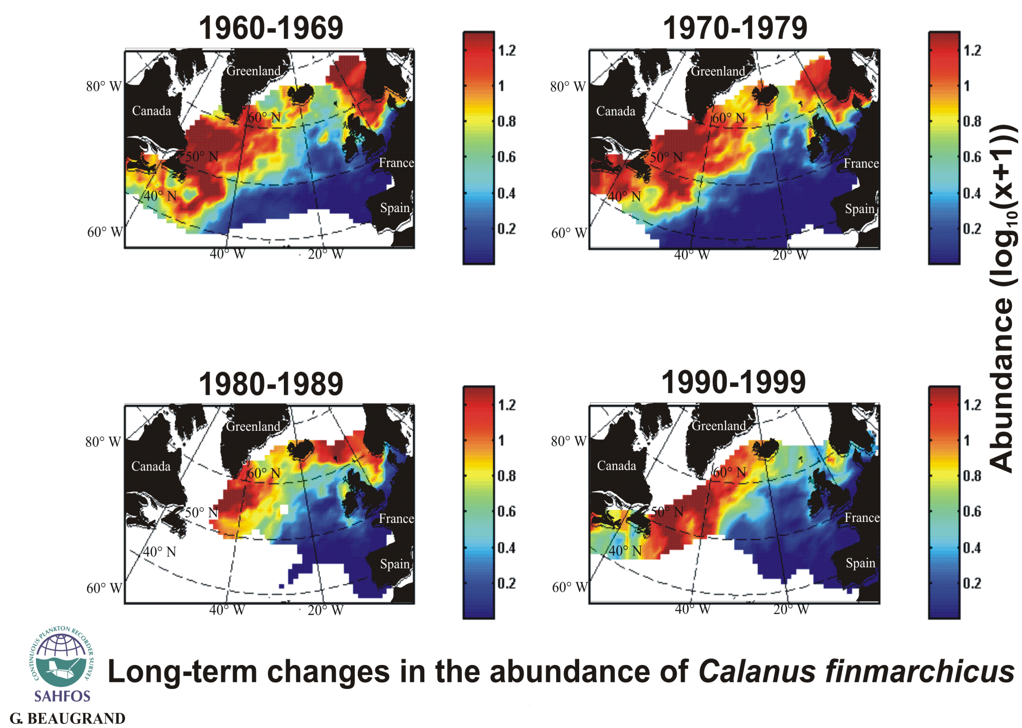

Figure 1. *Calanus finmarchicus* abundance in CPR surveys.

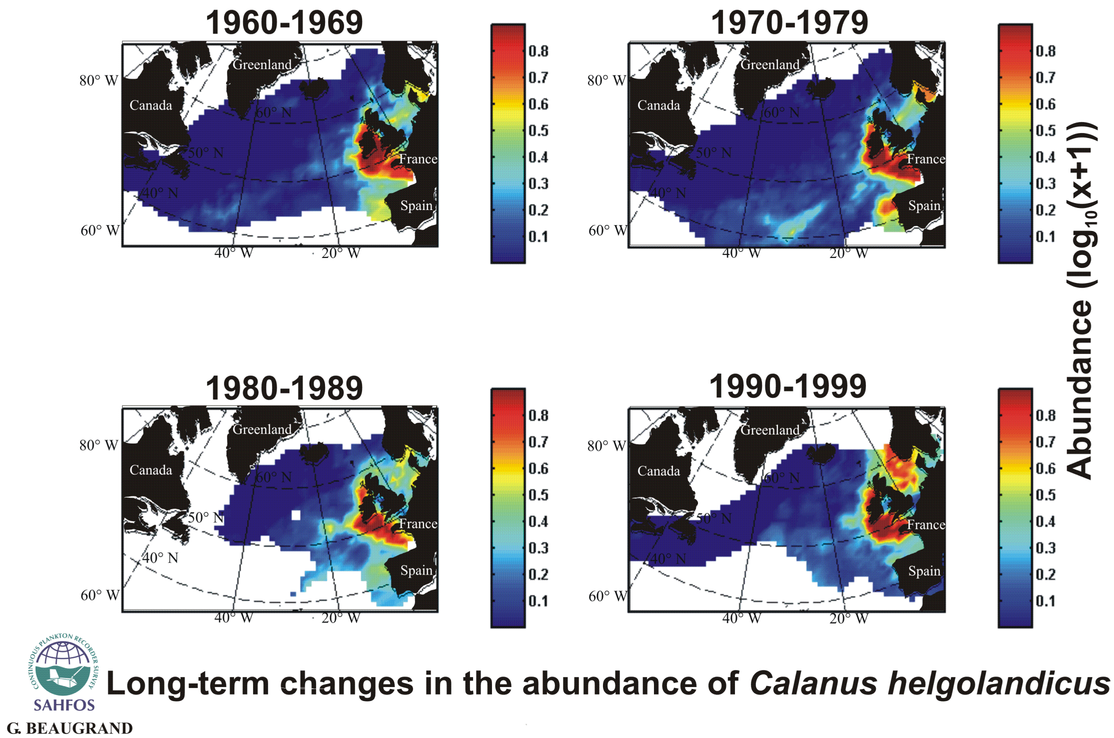

Figure 2. *Calanus hegolandicus* abundance in CPR surveys.

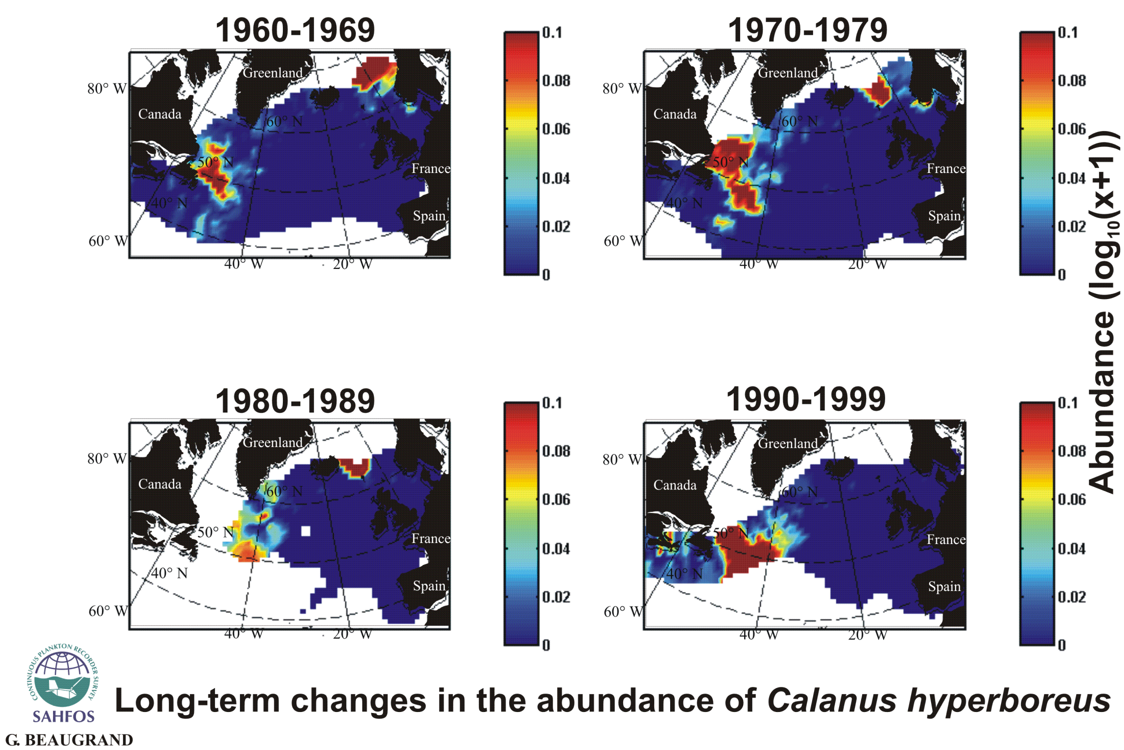

Figure 3. *Calanus hyperboreus* abundance in CPR surveys.

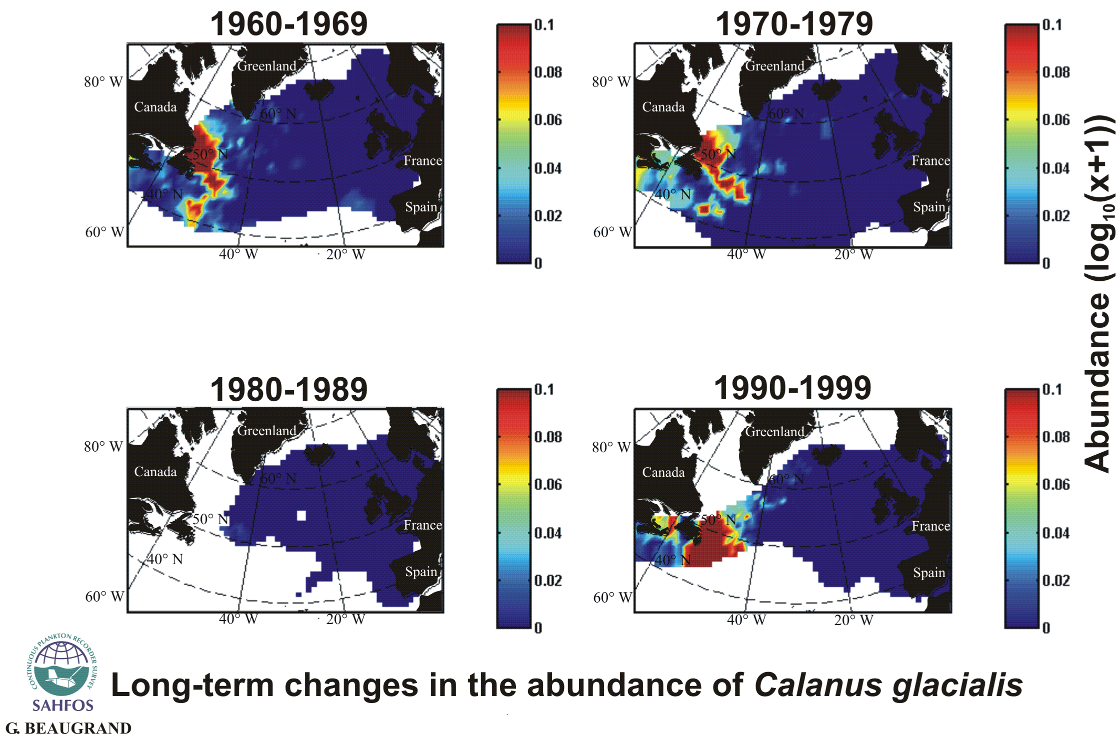

Figure 4. *Calanus glacialis* abundance in CPR surveys

Changes in the *Calanus* population on the eastern side of the Atlantic have been most notable in the North Sea. Here, over recent years the SST of the area has increased, giving rise to a variation in the distribution of *C. finmarchicus* and *C. helgolandicus*. In the late 1990s *C. finmarchicus* has declined sharply in the area, and *C. helgolandicus* has increased. The exact reason for the change is not known, but various hypotheses have been suggested. *C. finmarchicus* is at the southerly extent of its distribution in the North Sea, and thus a warming of conditions would not prove favourable. The species is known to have a negative correlation with the NAO (Figure 5), possibly because of an increase in the westerly wind component, causing warmer conditions and preventing stratification, therefore affecting the spring bloom, but this relationship broke down in 1996. This may be because the species numbers reached a critical low, and are no longer seen to respond to the NAO index. *Calanus helgolandicus* has responded to the same conditions in the opposite way, as the species favours warm-temperate conditions.

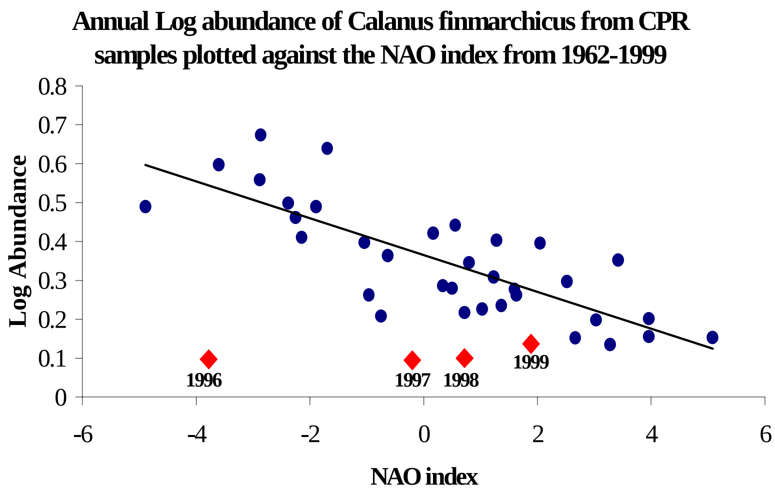

Figure 5. Graph showing negative correlation between NAO and *Calanus finmarchicus* abundance in the North Sea. Note the breakdown in the relationship after 1996, when the NAO exhibited an extreme shift to a negative phase.

In the north western Atlantic the opposite conditions have occurred. The predominately positive NAO of the last decade displays a bipolar manifestation, causing colder conditions in the north west, as opposed to a raised SST in the east. This is evident in the production of Labrador Sea Water, and the extent to which Labrador Slope Water has traveled. In 1998 LSW was detected south of the Georges Bank, and correspondingly the arctic boreal copepod *Calanus hyperboreus* was also recorded there for the first time in the CPR survey (see Figure 6). Numbers of this species, as well as *Calanus glacialis* have also increased through the late 1990s. The intrusion of cold water has had an effect noted not only on the plankton community, but also upwards through the trophic levels.

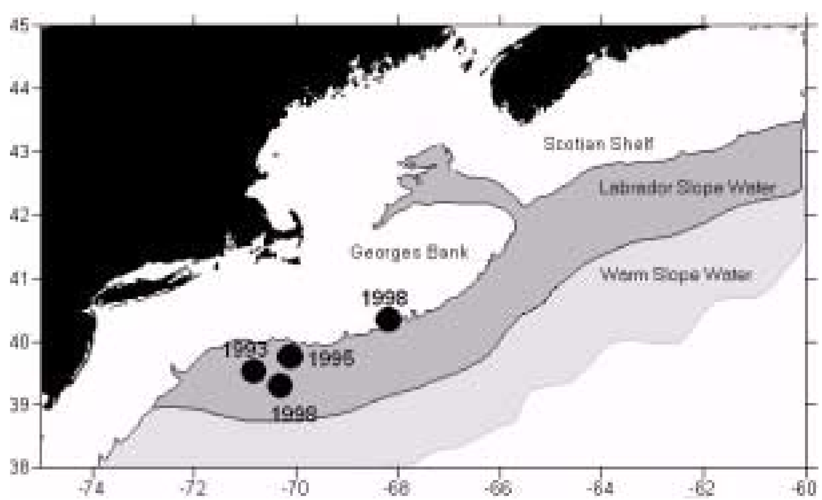

Figure 6. The most southerly extent of *Calanus hyperboreus* in the CPR survey in the late 1990s (after Drinkwater *et al*. 2001).

Reference

Drinkwater, K.F., Mountain, D.B., Herman, A. (2001) Variability in the slope water properties off eastern North America and their effects on the adjacent shelves. J. Geophys. Res. (Accepted).

Physical Oceanography of the Northwest Atlantic

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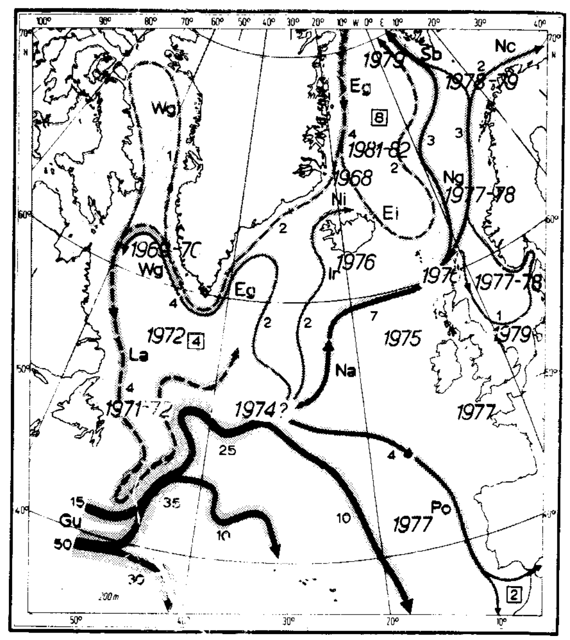
The circulation of the Labrador Sea and Northwest Atlantic is part of the overall circulation of the North Atlantic. This consists of a combination of the sub tropical and sub polar wind driven gyres as well as the Atlantic branch of the meridional overturning circulation (MOC). These work together in the upper 1000 metres to transport warm and salty water from the tropics and sub tropics northward and eastward across the northern North Atlantic and into the Norwegian and Barents seas and Arctic Ocean. Within the sub-polar North Atlantic, the cyclonic gyre circulation brings part of this warm salty inflow into and around the Irminger Sea to the Labrador Sea.

The upper waters cool and freshen as they move along these paths and eventually form the intermediate and deep waters of the North Atlantic through winter deep convection. The deep waters flow southward along the western boundary of the Atlantic as a deep western boundary undercurrent, eventually reaching the Southern Ocean and hence the rest of the global ocean.

In addition to this oceanic influence, cold and fresh surface waters and sea ice leave the Arctic Ocean through Fram Strait and the various passages of the Canadian Archipelago and flow southward along the continental shelves of west Greenland, Baffin Island and Labrador. The low salinity surface layer of the Arctic Ocean attains its properties from an inflow of Pacific surface water through Bering Strait, the considerable river runoff entering the basin from Asia and western North America and through the formation and subsequent melting of several metres of sea ice in the Arctic Ocean.

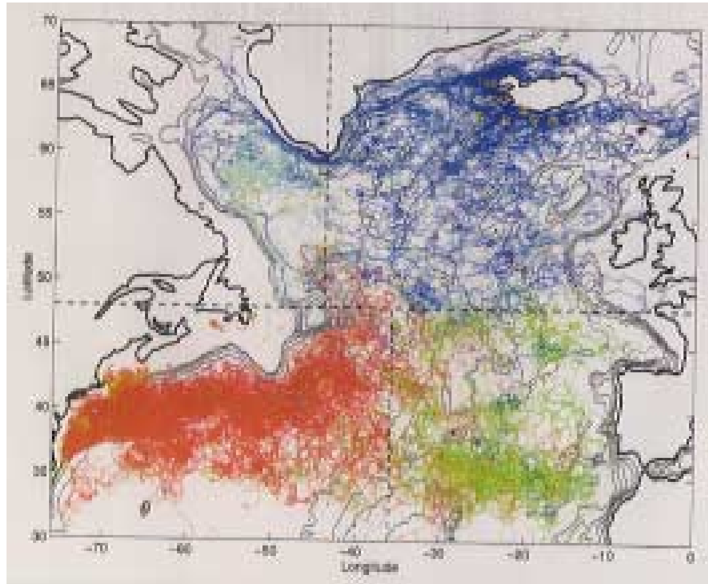
The circulation is clearly more complex than this simple schematic of the MOC. Dietrich (1969) created a more complex surface circulation schematic from the ICES Polar Front surveys of 1958. This particular version is from Dickson *et al.* (1988), the numbers assigned to each branch are the transport estimates for the upper 2000 metres. These schematic illustrates two important aspects of the North Atlantic circulation.



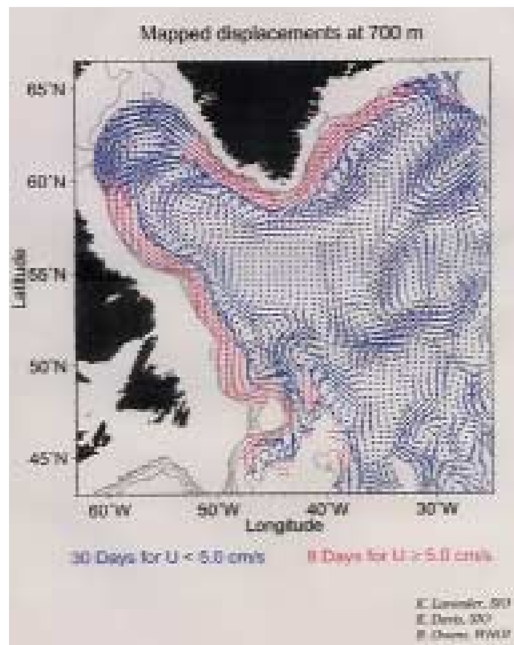
First is the multiple branching of the North Atlantic Current. A particle in the North Atlantic Current in the Newfoundland Basin can be transported to any latitude as it proceeds eastward. This current branching should not be considered to be steady state currents, but rather the result of instabilities and eddies within the circulation pattern.

The second is the tight recirculation of the sub-polar gyre to the immediate east of the Grand Banks of Newfoundland. This recirculation has been of considerable interest since it brings the cold and fresh waters from the Labrador Sea in close proximity to the warm salty waters of the North Atlantic Current creating the most extreme horizontal gradients of the Atlantic if not of the world ocean.

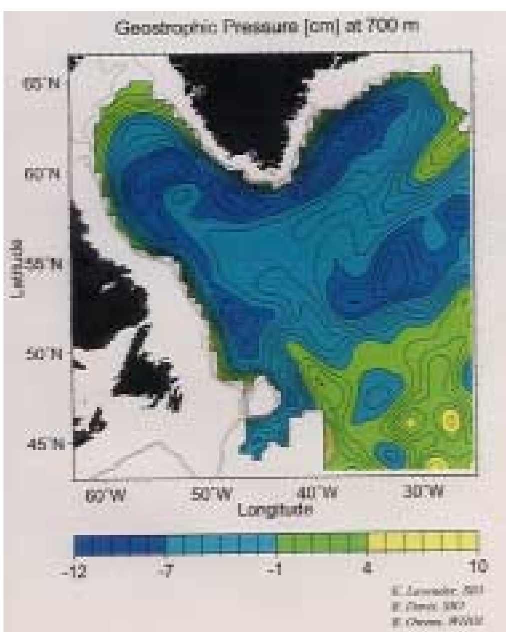
The chaotic nature of the surface circulation can be illustrated from the trajectories of satellite tracked surface drifters. Many drifters, drogued at 15 metres, were deployed during the World Ocean Circulation Experiment (WOCE). The figure shows the tracks observed during 1996-2000. On the average, tracks represent 200 days of travel. All tracks are coloured by the quadrant they started in; their starting position is marked by a yellow circle. In looking at this figure, one sees that drifters generally move in the pattern given by the Dietrich schematic but there are exceptions with green trajectories entering the southeastern part of the red quadrant, dark blue drifters entering the green quadrant and light blue drifters entering the dark blue quadrant. Throughout the interior, drifters spend much of their lifetime trapped in eddy features .



Lagrangian drifters were also used in the late 1990s to map the sub-surface velocity field. The Autonomous Lagrangian Explorer (ALACE) float is programmed to remain at a set pressure level for periods of 10 or more days and then to come to the surface to report its position via satellite before returning to its drift depth to begin another cycle. A large number of these instruments were deployed in the Labrador and Irminger seas in 1996 and over their 3-4 year lifetime have provided a remarkable new picture of the flow field at 700 metres (Lavender *et al*, 2000).

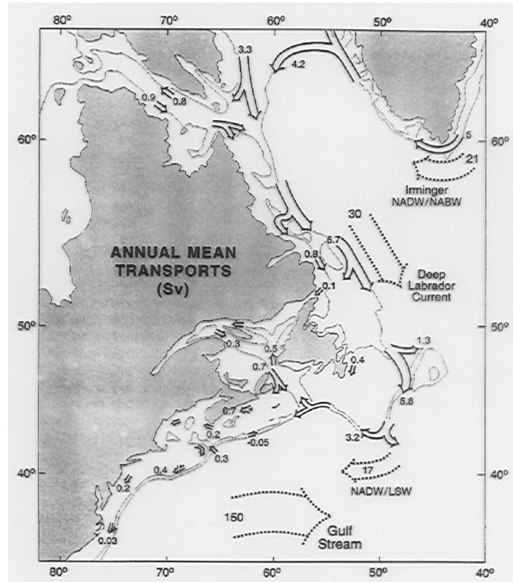


This flow field shows the classical strong cyclonic flow around the boundaries of the Labrador and Irminger seas. This flow follows the bathymetry, accelerates where the bathymetry is steep (southwest Greenland slope) and deccelerates where it is more gentle (Davis Strait). What is new and remarkable in this field is the strong anticyclonic circulation just offshore of the boundary flow in both the Irminger and the Labrador seas. This circulation appears to be a series of connected recirculation gyres along the path of the boundary current. Clarke and Gascard (1983) had argued that such a recirculation gyre developed in the western Labrador Sea as part of the pre-conditioning process for deep convection, but these recirculation gyres appear more extensive and more sustained than they had postulated.

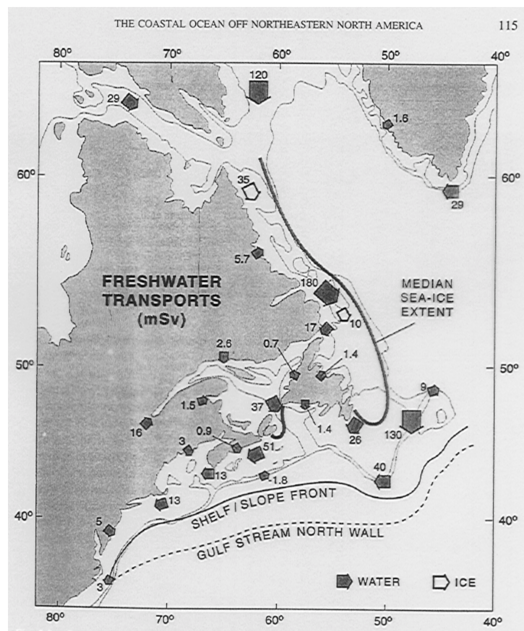


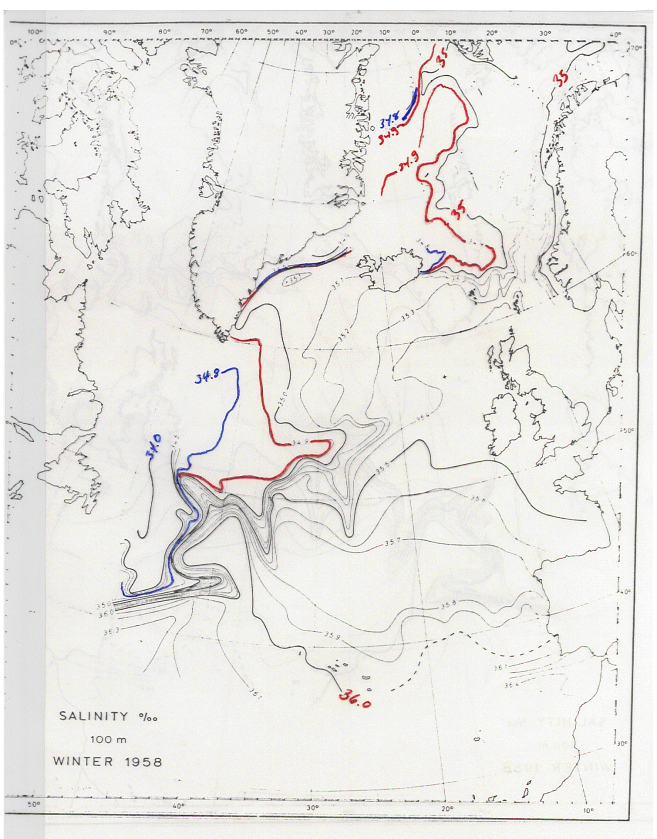
These gyres are more pronounced if these trajectories are used to produce an estimate of the geostrophic pressure field at 700 metres. This analysis also captures the penetration of the North Atlantic Current northward into the southern Labrador Sea north of Flemish Cap and its eastward extension between 50 and 52 N. Because the floats used in this analysis were originally placed in the sub-polar waters, the North Atlantic Current south of 50 N is not well sampled. Floats set in the sub-tropical waters in the Newfoundland Basin to the east of the Grand Banks of Newfoundland would have mapped out a stronger northward circulation to the east of Flemish Cap. In spite of this, the picture is remarkably like the Dietrich schematic.

Particularly noteworthy is the penetration of floats south past Flemish Cap and their subsequent recirculation northward along the inshore edge of the North Atlantic Current. None of these floats penetrated south and west of the Tail of the Banks. This is a common result from subsurface float deployment in this region. The water properties show that the sub polar waters such as the upper and classical Labrador Sea waters do pass around the Tail of the Banks in some quantity.



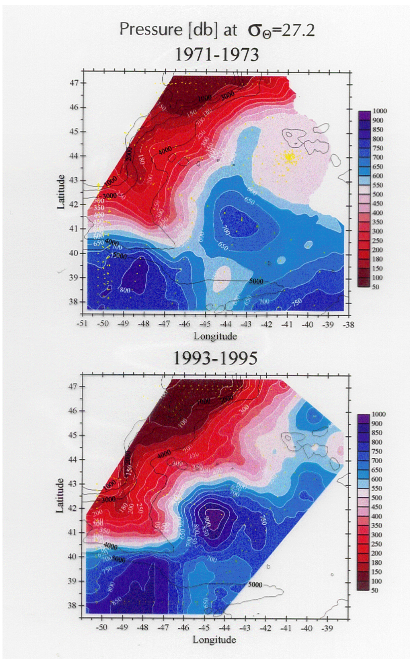
Loder *et al* (1998) summarized what is known about the transports of the major current systems of the NW Atlantic. The boundary current of the sub polar gyre carries 21 to 30 sv of flow cyclonically around the Irminger and Labrador seas over the deep continental slope. The shelf break currents (West Greenland Current, Baffin Current and Labrador Current) carry 3 to 7 sv of water cyclonically around the Labrador Sea over the upper continental slope. This is the cold, fresh water of Pacific and Arctic origin. There is considerable exchange of these waters with the offshore between Hamilton Bank and Flemish Cap and between Flemish Cap and the Tail of the Banks. The Tail of the Banks represents a significant bifurcation of this current with about half of the water proceeding westward toward the Laurentian Channel and the Scotian Shelf.



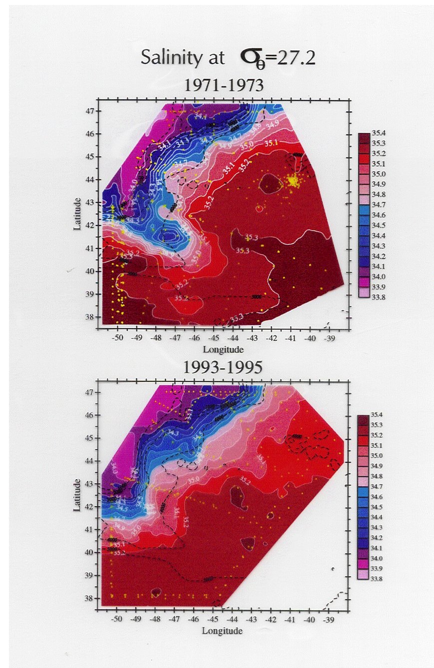


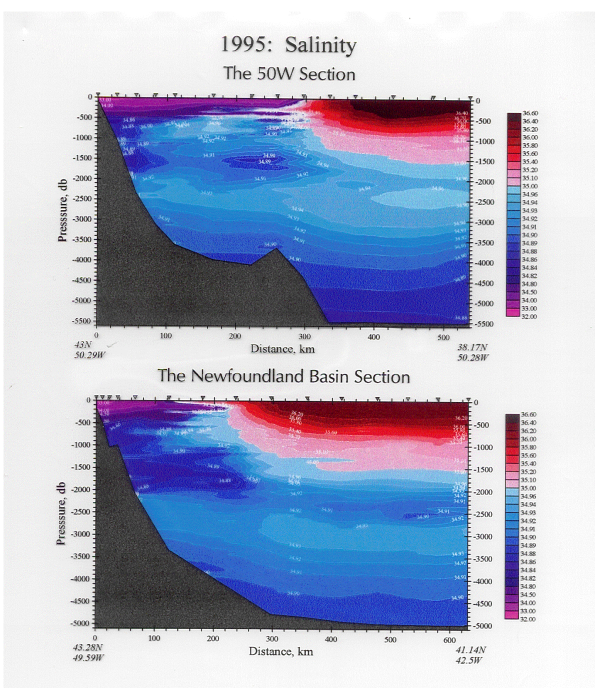
These mass transports are interesting; however, more interesting are the fresh water transports since it is this that determines the density and the stratification of the water columns, particularly during the winter cooling season. Loder *et al* (1998) also estimated the freshwater transports carried in the shelf and shelf break currents. This shows the large freshwater transport from Baffin Bay and Hudson Bay flowing southward along the Labrador shelves on to the Grand Banks. The fresh water transport westward along the Grand Banks and Scotian Shelf is much reduced in spite of the influx of fresh water from the Gulf of Saint Lawrence. This is due to continued exchange of fresh water with the offshore in the NW Atlantic. The effect of this exchange can be seen in the distribution of salinity at 100 metres measured during the winter 1958 Polar Front survey. Here we see the low salinity waters entering the North Atlantic from the Labrador Sea and to a lesser extent from the Grand Banks.

The Newfoundland Basin region is of particular interest. Here the warm salty sub tropical waters are in close proximity to the cold fresh polar waters brought southward by the Labrador Current and the sub-polar gyre circulation. The horizontal temperature / salinity gradients in this region are among the strongest in the world ocean.



The σ_θ = 27.2 surface in the sub-tropical North Atlantic is coincident with the 10° isotherm in the main thermocline and also lies at the centre of the oxygen minimum layer. The isoline where this surface is at a depth of 500 metres is a traditional measure of the position of the north wall of the Gulf Stream and North Atlantic Current. Considerable work was carried out around the Tail of the Banks in both the early 70s and the mid 90s. In the 90s, the sub polar waters were denser, thus this surface is found at shallower depths within the cyclonic extension of the sub-polar gyre between Flemish Cap and the Tail of the Banks. At the same time, this surface is deeper offshore of the Gulf Stream and North Atlantic Current indicating that these currents were stronger in the later period. The salinity gradient on this surface is as much as 0.8/100 km.



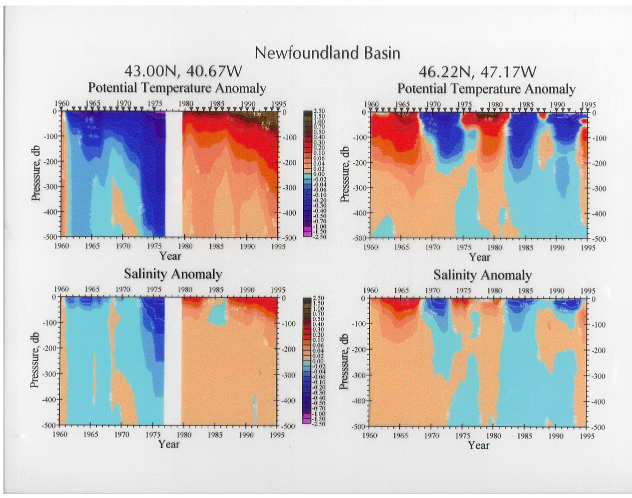


On salinity sections across the continental slope in the Newfoundland Basin, the strong salinity contrast between the sub polar and sub tropical waters extends from the surface to 1500 metres. In 1995, the Gulf Stream was crossing 50 W at close to its southerly extreme within its normal envelope of positions at this longitude. Below the very low salinity surface waters, there are a number of sub surface salinity minima located both on the continental slope and also just inshore of the Gulf Stream front. The shallower of these minima are the upper Labrador Sea waters (500-1000m). The deeper are the classical Labrador Sea Water (1200-2000m). The minima adjacent to the continental slope are flowing southward and westward as a continuation of the sub-polar gyre past Flemish

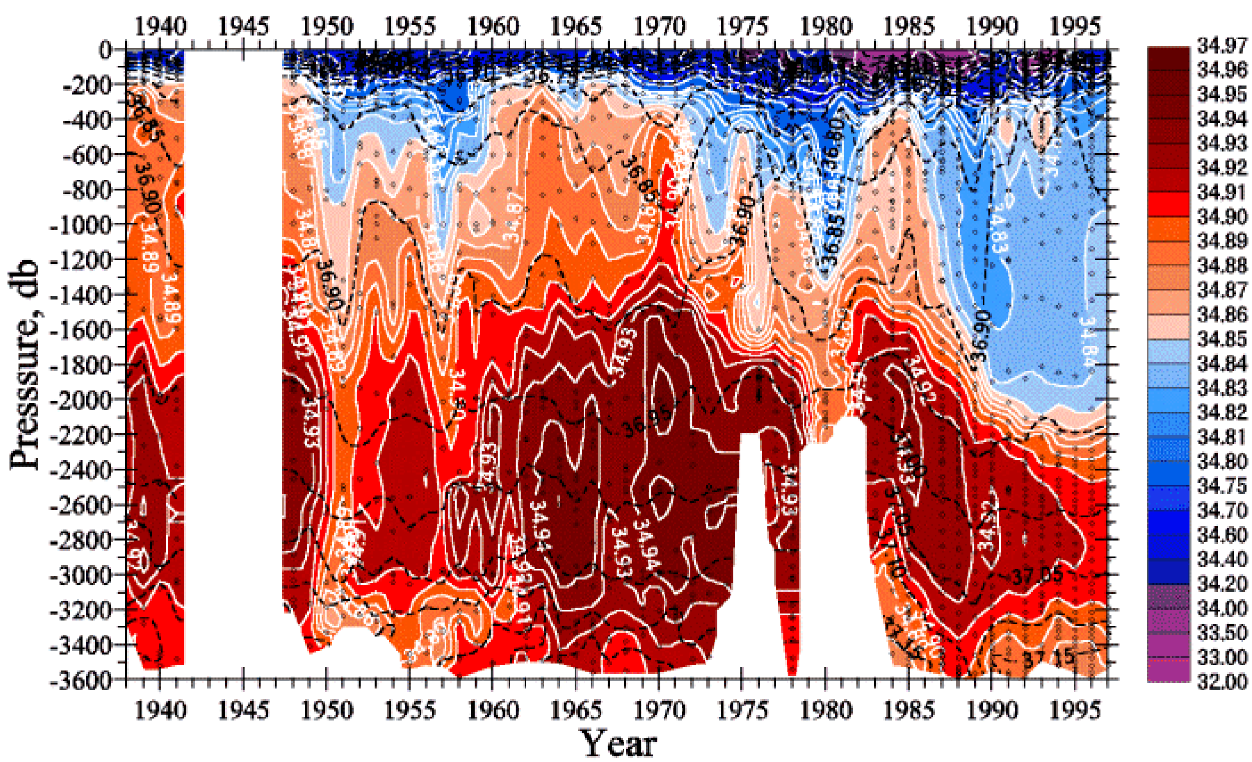
Cap and the Tail of the Banks into the Slope Water region of the Northwest Atlantic. The minima adjacent to the Gulf Stream and North Atlantic Current are the easterly and northerly return flow of this extension of the gyre.

As will be shown later, these 1995 observations were made following a period of sustained production of cold and fresh sub-polar waters in the Labrador and Irminger seas. Consequently, the extension of the sub-polar gyre into the slope water region may be at its maximum. Other occupations of this same section during the early 1970s and even in 1993 show a much reduced volume of sub polar waters and weaker salinity minima.

The sub polar and sub tropical waters are within 10s of km of each other in the Newfoundland Basin but they exhibit very different properties both in their average values and in the nature of their variability. The waters of the sub tropical gyre offshore of the North Atlantic Current exhibit an increasing temperature and salinity from the 60s through the 90s similar to what has been reported at Bermuda (Joyce and Robbins, 1996). There is a pentadal to decadal component to the variability but the eye is drawn to the long term change over the three and a half decades. In contrast, the sub polar waters as seen just south of Flemish Pass exhibit decadal variability between warm/salty and cool/fresh conditions with little indication of longer term change.

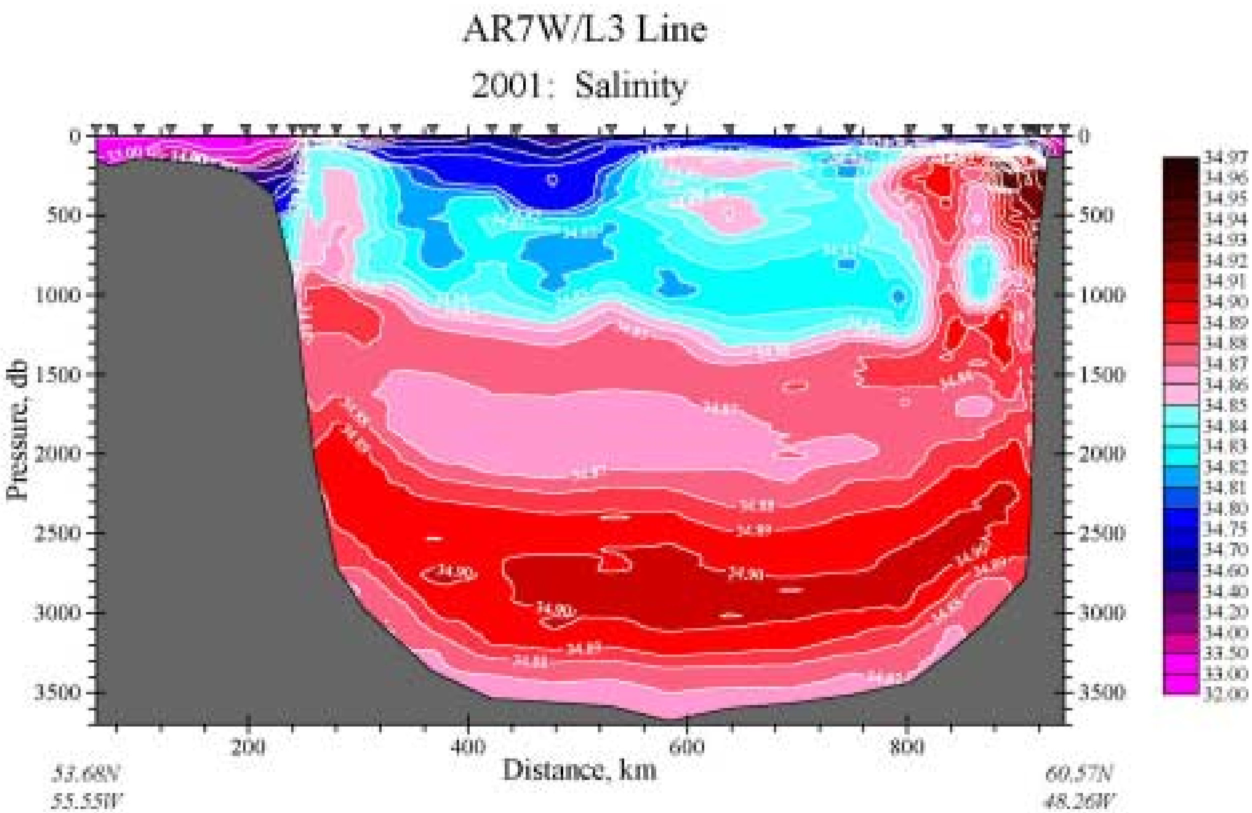


It should be emphasized that these changes are occurring in the upper 500 metres in those parts of the two gyres where the upper waters are their lightest.



The densest surface waters of the sub polar gyre are found in the western interior of the Labrador Sea, near the old site of OWS Bravo. The Labrador Sea Water (LSW), the densest water mass formed in the North Atlantic basin south of the Shetland – Færœ – Iceland – Greenland ridge system appears at this site as a pycnostad between 400 and 2200 metres depth. Its salinity and thickness has fluctuated on pentadal and decadal scales since the late 40s. The present low salinity period is unique in the record in the thickness of the layer and its low salinity, cold temperature and high density. The Labrador Sea has been restratifying since 1994; the period of this strong burst of LSW is not significantly longer than period of strong stratification of the 60s. While LSW is of great interest to climate scientists, it is the light upper Labrador Sea Water formed in the western boundary regions that is likely of greater interest to the marine ecologists and fisheries scientists. This is the water that is found along the upper continental slope and enters the Laurentian Channel and the deep basins of the Scotian shelf.

Warm saline waters Irminger Sea waters enter the Labrador Sea within the boundary current and appear as strong temperature salinity maxima in the upper 600 metres. Along AR7W, these appear as a series of maxima across the eastern end of the section. It is not certain whether this pattern is a result of the recirculation gyres associated with the boundary current or an eddy field. Satellite and hydrographic



observations suggest that the boundary current spawns eddies as it encounters the spreading topography of Davis Strait. These eddies carry within them the warm/saline Irminger Sea water and also appear to be particularly productive in the ocean colour imagery. These eddies spread westward and could be carried southward by the recirculation gyres. Weak temperature/salinity maxima are also seen on the western end of the section. These are believed to be Irminger Sea water carried around the Labrador Sea by the boundary current. They are considered an important source of salt (and density) for the winter convection processes taking place in the western Labrador Sea.

Important Physical Oceanographic Characteristics of the Sub-polar gyre of the North Atlantic

- It is driven by a cyclonic wind stress that varies seasonally and interannually
- Is also driven cyclonically at its shelf breaks by low density (and salinity) Arctic Outflows

- Its bottom layers are driven by the western boundary under currents carrying North Atlantic Deep Water from the overflows southward to the Southern Ocean.
- Ekman fluxes are divergent over its interior.
- Deep convection results in convergences in the upper layers.
- The meridional overturning circulation requires a significant through flow or exchange from the sub tropical to sub polar gyre and from the sub polar gyre to the Nordic seas.
- The currents within the gyre are increasingly barotropic as the surface waters become denser and the stratification decreases.

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Modelling the Physical Oceanography of the NW Atlantic

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Ocean Sciences Division
Bedford Institute of Oceanography

In this talk, a brief discussion of modelling activities relevant to the North-west Atlantic will be presented. The discussion will touch on some international activities, but will concentrate on local work. A very useful review of recent developments in ocean modelling is given by Griffies et al. (2000) and comprehensive discussions of two recent international modelling activities can be found in the following reports.

<u>The DYNAMO report</u>
Institut fur Meereskunde an der Universitat Kiel
Abt. Theoretische Ozeanographie
Dusternbrooker Weg 20
D-24105 Kiel

3 NA basin models (1/3rd degree/20S – 70N)

- MOM (z-coordinates)
- SCRUM (terrain-following coordinates)
- MICOM (isopycnic coordinates)

<u>The DAMEE Report</u>
Chassignet and Malanotte-Rizzoli (2000)

5 NA basin models (6N – 50N)

- MOM (z-coordinates)
- DieCAST (z-coordinates)
- POM (terrain-following coordinates)
- ROMS (terrain-following coordinates)
- MICOM (Isopycnic coordinates)

The primary differences between the models discussed in the above reports are in the choices made for the vertical and the horizontal discretisations. A very brief discussion of the different choices of vertical discretisation and their pros and cons will be given.

There are also significant differences in the horizontal grids and the corresponding discretisations of the governing equations. These are discussed in the references cited above, but will not be discussed in the talk.

BENEFITS OF THE DIFFERENT VERTICAL DISCRETISATIONS

- z-coordinates are easiest to use and analyse. There is a lot of experience to fall back on.
- sigma-coordinates give a “nice” representation of depth and are well suited for dealing with surface and bottom boundary layers
- isopycnic coordinates avoid (or control) diapycnal mixing

SPECIAL PROBLEMS AND CORRECTIVE ACTIONS

- Discretised bottom is a problem for z-coordinates
  - ⇨ partial or shaved cells can correct this problem
- Pressure gradient errors are a problem for sigma-coordinates
  - ⇨ remove rho(z)/smooth topography/use more sophisticated discretisation schemes
- isopycnic coordinates use a single potential density per layer to maintain adiabaticity
  - ⇨ reference to 2000db/introduce a “virtual density”.

The main point here is that there are several different types of models in use and they all have limitations. However, problems encountered with any of the model formulations can generally be solved through new developments.

Local Efforts

There are many problems to address in the area of deep ocean modelling, but the available resources are limited and some pragmatic choices have to be made. Before continuing with a discussion of our present focus, we should at least mention some aspects of deep-ocean modelling that warrant further attention. These include air-sea exchange, mixed layer modelling (including convective mixing), eddy mixing, smaller scale mixing processes, sea-ice growth, decay and transport, shelf-slope exchange and plume dynamics. There is significant work being done on each of these topics both locally and internationally, but I will not discuss these efforts here.

From a regional perspective, an important feature of the North Atlantic circulation that has received, and will continue to receive, considerable attention from the modelling community is the separation of the Gulf Stream from the coast near Cape Hatteras and its subsequent path. Related to this problem is the dynamics of the recirculation gyres north and south of the Stream: the Northern gyre appears to be a particularly significant feature for the interpretation of Cal. Fin. observations. Understanding the connnection between the sub-polar gyre, the Northern Recirculation and the Gulf Stream path is a fundamental problem for ocean modellers.

Recent high-resolution (1/10th degree) models have demonstrated an ability to realistically reproduce the Northern Recirculation (Smith et al., 2000). However, the resolution required by these models is presently beyond the reach of the computing resources available to us. We must seek alternatives. One possibility is to use diagnostic models to represent the large-scale circulation. In these models, the temperature and salinity fields are strongly constrained to follow observational estimates and experience shows that they give a credible representation of the circulation climatology. Useful results can be obtained relatively easily from diagnostic calculations but they do not provide any opportunity for prediction of anomalies and they do not resolve eddy effects. Perhaps even more restrictive in the present context is the fact that artificial sources and sinks are required to prevent the temperature and salinity fields from straying and this raises questions about the reliability of results for any other tracers (e.g., nutrients) that the model might be used to study.

An obvious step to take is to allow the temperature and salinity to evolve according to the dynamical equations (i.e., progress to prognostic integrations). A problem with this approach is that the temperature and salinity properties are well known to drift away from reality when models are run with the horizontal resolution that we are presently able to deal with. The recirculations north and south of the Gulf Stream in the diagnostic calculation are substantially reduced during the first year of prognostic integration and they are all but eliminated by the fourth year. As the Northern Recirculation collapses, a strong anticyclonic gyre develops north-east of Cape Hatteras and the Gulf Stream extension weakens and shifts towards the slope along the Scotian Shelf and the Grand Bank. These results are typical of those obtained for marginally eddy-resolving models. Annual means for the second and third years of the integration show that the largest changes occur during the first two years, showing that the drift occurs quite rapidly.

Until substantially improved parameterisation schemes are developed and verified in numerical models, there is a need to assimilate data into models of the resolution considered here. Two distinct approaches have been developed locally.

The first approach is discussed by Sheng et al. (2001). They show that strongly nudging the baroclinic pressure gradient towards observational estimates provides a methodology by which the drift in tracers can be greatly reduced without directly modifying the tracer equations. That is, if the baroclinic velocity field is nudged towards climatology, the feedback between the tracer fields and the velocity field that results in the rapid degradation of the prognostic results is suppressed and tracers evolve realistically. The fact that temperature and salinity evolve realistically with this approach suggests that the same might be true for other tracers. This is an interesting approach for problems in which the main interest is the evolution of passive tracers under present-day conditions. Examples of tracer evolution for the NW Atlantic will be presented.

The second approach has been developed by Keith Thompson and myself and is still being refined. The essence of the method is that we wish to nudge the model climatology towards the observed climatology without interfering with higher frequency variability.

In the conventional approach to nudging, a simple restoring term is added to the tracer equations

$$T_t = \ldots + \gamma(T_{obs} - T) \ ,$$

where T represents the model estimate of either temperature or salinty and T_{obs} represents the corresponding climatological estimate. A major drawback of this approach is that all space and time scales are pushed towards the (generally over-smoothed) observational estimates. Thus <u>all</u> deviations from the observational estimate tend to be eliminated. What we really want to do is to push the model climatology towards the observed climatology without suppressing variability about this climatology any more than is necessary. We achieve this goal by replacing the standard equation given above with the modified equation

$$T_t = \ldots + \gamma(\tilde{T}_{obs} - \tilde{T}) \ .$$

where the tilde indicates an estimate of the *climatology* at the current time step. We have the freedom to decide what we will include in our definition of climatology. For example $\tilde{T}$ could be given by the mean and annual cycle based on the period from the initiation of the run to the present. Taking γ to be large will then nudge the model climatology strongly toward the mean and annual cycle in the observed climatology while leaving the eddy contribution relatively unchanged. The advantage of this approach will be illustrated with examples.

The catch in the above approach is that you need a meaningful estimate of the difference between the model and the observed climatology that is valid at the current time step. To proceed we express $\tilde{x} = \tilde{T}_{obs} - \tilde{T}$ in terms of a simple model with a small number of parameters and estimate these model parameters from the misfits between the results of the complex dynamical model and observations. The climatology is then provided by the simple model.

For simplicity we have assumed the model for the climatology to be

$$\tilde{x}_t = \mathbf{q}_t'\boldsymbol{\alpha} \tag{8}$$

where

$$\mathbf{q}_t' = [1 \quad \cos\omega t \quad \sin\omega t] \tag{9}$$

$$\boldsymbol{\alpha}' = [\alpha_0 \quad \alpha_1 \quad \alpha_2] \tag{10}$$

where ω is the annual frequency. Thus $\tilde{x}_t$ is made up of a mean and annual cycle. The three parameters to be estimated are the mean (α_0) and the amplitudes of the cosine and sine components of the annual cycle (α_1 and α_2 respectively). By using a Kalman filtering approach, estimates of the uncertainty in the model parameters and the expected variability of instantaneous estimates of temperature and salinity about their climatological values are readily accounted for and the best estimate of the climatology is determined both efficiently and as accurately as possible. Examples of the results of this approach will be given.

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Distribution and Ecology of *Calanus* spp. in the Northwest Atlantic

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Three species of *Calanus* are commonly found in the NW Atlantic and all share a life history which involves diapause, a resting period spent at depth during times when conditions at the surface are unsuitable. The distributions of the three species in spring and early summer are determined by: proximity to and advection from deep overwintering areas; the timing of emergence from diapause and subsequent reproduction; the dynamics of survival and development. Since 1995, we have determined *Calanus* spp. abundance in samples collected during spring and early summer on the Scotian Shelf and in the Labrador Sea. The number of stations has varied between years, but *Calanus finmarchicus* occurred at virtually every station so that a plot of its abundance shows nearly every station sampled on each cruise (Fig. 1).

C. finmarchicus concentrations were highest (>100K m^{-2}) in July (1995, 1999) near the eastern margin of the Labrador Sea and east of the Newfoundland Shelf and Grand Bank and in June (1997) in the northern Labrador Sea. Concentrations were generally intermediate (20-60K m^{-2}) in central and western regions of the Scotian Shelf and low (<10K m^{-2}) over the eastern Scotian Shelf in April and in the western central Labrador Sea in May, June and July. These patterns of abundance will be discussed in detail later. *C. glacialis* was restricted to shelf regions and was most abundant (*ca*. 40K m^{-2}) on the Labrador and Newfoundland Shelves in July (1995). Concentrations on the Scotian Shelf in April varied from year to year. The overwintering source populations for these regions are thought to be Hudson Bay (or the Baffin Island Current) and the Gulf of St. Lawrence, respectively. *C. hyperboreus* concentrations were often high (>20K m^{-2}) over the eastern Scotian Shelf in April and intermediate over the Labrador and Greenland shelves (especially early in the year). The Scotian Shelf population probably derives from one that overwinters in the Gulf of St. Lawrence, while the others are probably derived from Arctic waters. Low concentrations observed in the central Labrador Sea probably derive from animals that overwintered there.

Along the transect that crosses the Labrador Sea (that was sampled each year) stations with high concentrations of *C. finmarchicus* had large numbers young copepodites (stages 1-4) of the new years' generations, while stations with low numbers were mostly, or totally, comprised of the previous years' pre-adults and adults (Fig. 1). It is of note that in the central and western central Labrador Sea only a few young stages were ever collected (July 1995). Young stages were found mostly on the shelves or in slope regions, but in some years the Labrador Shelf ('97,'00) and in some, the Greenland Shelf ('98,'00), was not sampled because of ice. In some areas of its distribution *C. finmarchicus* reproduction starts as the spring bloom occurs (*e.g.* Plourde and Runge, 1993). In May in the central Labrador Sea basin, chlorophyll concentrations were always low and only 15% of the nitrate in the 0-50 m depth range had been consumed, implying the bloom had not started. Nevertheless, in May, female *C. finmarchicus* were laying eggs at

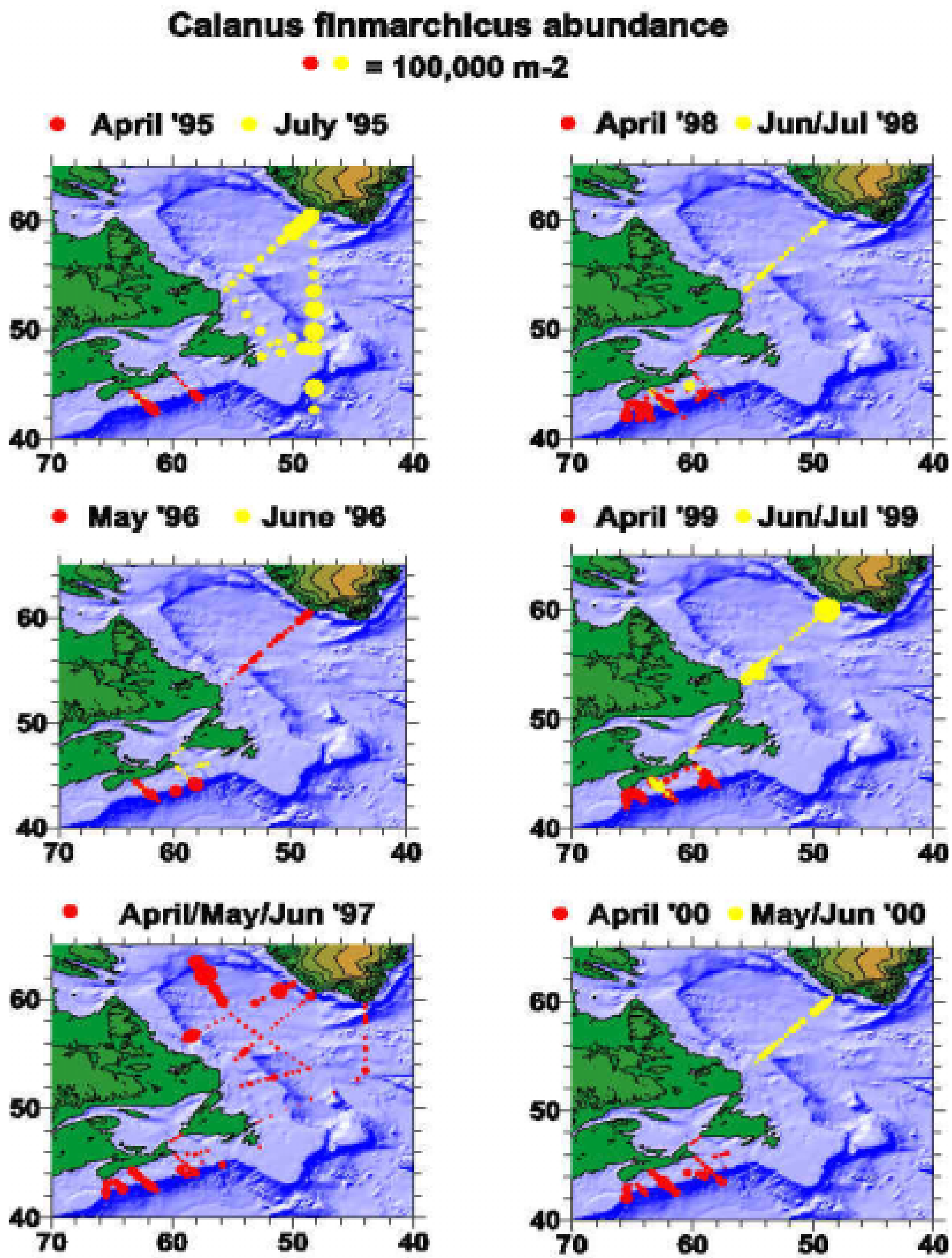

Figure 1. Distribution of *Calanus finmarchicus* abundance in the near surface layers in spring and early summer 1995-2000.

maximal rates (Campbell & Head, 2000), so that the onset of reproduction preceded the bloom (see also Head *et al*., 2000). In June/July chlorophyll concentrations were also generally low, but >50% of the nitrate in the 0-50 m depth range had been consumed and females were still producing eggs at maximal rates. Near-surface temperatures were 2-4°C in May and 5-6°C in June/July, so that eggs laid in May should have developed into early stage copepodites by June/July (Corkett *et al*. 1986): they had not however, implying that survival of eggs laid in May is negligible. Thus, the new year's generation probably appears after July in the central Labrador Sea basin.

Over much of the Scotian Shelf in April 1998-2000, abundances of overwintered pre-adults and adults were very low compared with those of the young of the year copepodites (stages 1-4) (Fig. 2). Concentrations of young of the year were very low in Cabot Strait and the northeast Scotian Shelf, and generally higher in central and western regions. On the mid- and outer eastern Scotian Shelf numbers of young stages were very low in 1998 and higher in 1999 and 2000.

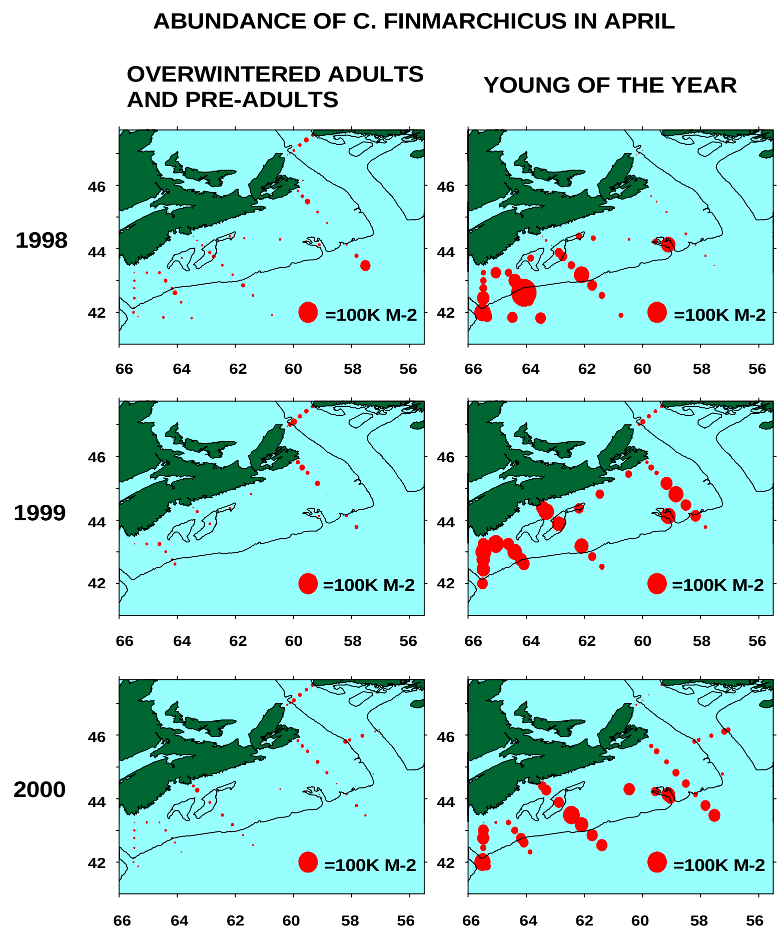

Figure 2. Distribution of abundance of *Calanus finmarchicus* adults and pre-adults versus young of the year on the Scotian Shelf in April 1998-2000

These regional and temporal differences in abundance appear to be related to differences in hydrodynamics and temperature conditions, as manifested in patterns of sea-surface temperature obtained from satellite images (Fig. 3). In 1998, the cold outflow from the Gulf of St. Lawrence (along the coast of Nova Scotia in the Nova Scotia Current) was pronounced and the slope waters adjacent to the shelf-break were cool due to an elevated influx of Labrador Slope Water (Drinkwater *et al*. 2001). In 1999 and 2000, by contrast, the Nova Scotia Current was not as prominent and the waters along the central and western regions of the shelf-break were warmer. Water from beyond the shelf-break intrudes on to the central shelf around Western Bank, and mixes with Nova Scotia Current water offshore from Halifax (Hannah *et al*. 20001). Thus, in all years, central and western regions of the shelf were warmer than eastern regions, but since both sources were cooler in 1998, the whole shelf was cooler.

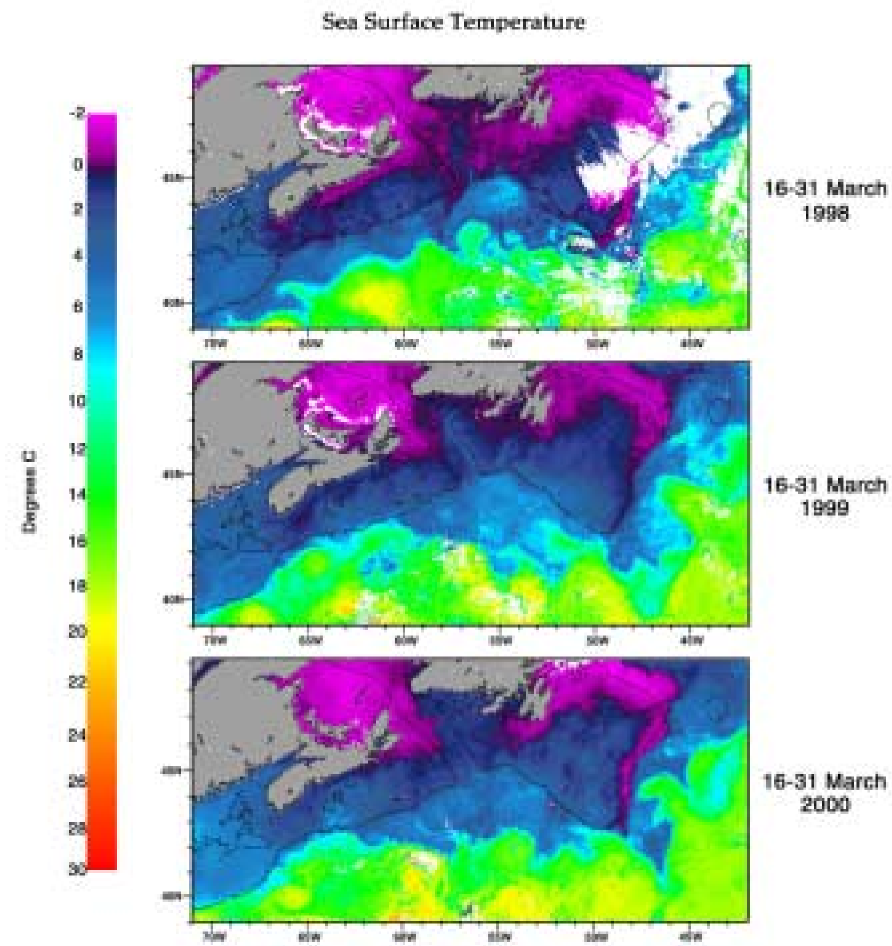

Figure 3. Bi-weekly composite images of sea surface temperature for late March 1998, 1999 and 2000, collected by the NOAA 14 satellite.

Temperature has a strong effect of development rate in *C. finmarchicus*: an egg develops to a stage 1 copepodite in *ca.* 40 days at 1°C, but only *ca.* 20 days at 6°C (Corkett *et al*. 1986). Thus, if reproduction had started at the same time everywhere every year, populations in the east should have been less developed than those in central and western regions each year and everywhere they should have been least developed in 1998. This was the observed pattern, but from the stage structures, sampling dates, temperatures and published temperature dependent development rates (Corkett *et al*. 1986), earliest birth dates were estimated to vary between January on the outer central shelf in 1999 and April on the inner eastern shelf in 1998. The onset of reproduction in central and western regions was generally earlier than in the east and often preceded the spring bloom, the timing of which was obtained from time series of SeaWiFS satellite images. In the east the two processes were more-or-less co-incident. Thus, the onset of reproduction was not always linked to the onset of the bloom. Instead it seems that temperature differences experienced by the overwintered population following emergence from diapause may contribute to the later reproduction in the east. The source to the eastern Scotian Shelf is probably the Gulf of St. Lawrence via Cabot Strait, whereas that to central and western shelf is likely the deep water at and beyond the shelf-break. Temperatures in Cabot Strait in 1998-2000 were *ca*.5^{o}C at 350 m (overwintering depth), and <2^{o}C between 100 m and the surface, whereas those along the shelf-break were *ca*. 5^{o}C at 500 m (overwintering depth), 6-12^{o}C at 100 m and 4-10^{o}C at the surface. The higher temperatures in central and western regions may have lead to higher development/maturation rates of the overwintered population and hence to earlier reproduction than in the east.

In October 1998 concentrations of *C. finmarchicus* between $\leq$100 m and the surface on and around the Scotian Shelf were low (<10K m^{-2}) except in Cabot Strait and the Nova Scotia Current, where concentrations were up to 66K m^{-2} (Fig. 4).

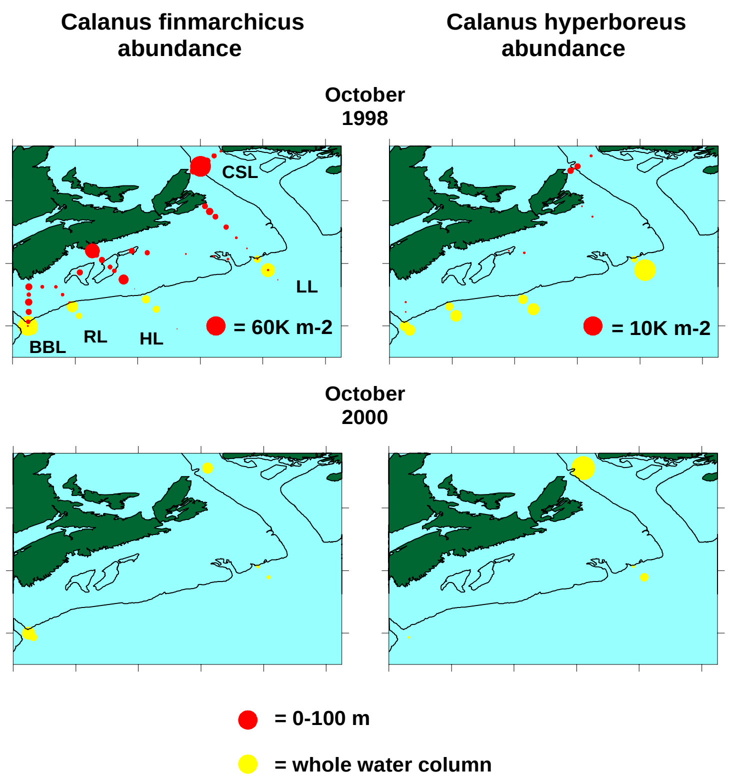

Figure 4. Distribution of *Calanus finmarchicus* abundance in the near surface layers and at depths to between 650 and 2500 m during October 1998 and 2000.

Concentrations of *C. hyperboreus* were much lower (<1K m^{-2}). These observations are consistent with those of Plourde and Runge (1993), who have suggested that *C. finmarchicus* continues to reproduce and grow in the Gulf of St. Lawrence throughout the summer and with the idea that *C. hyperboreus* has a more protracted period in the surface waters. At and beyond the shelf-break, concentrations of *C. finmarchicus* to depths of 650-2500 m reached concentrations between *ca*. 7 and 70K m^{-2} with highest levels of 62K m^{-2} at the shelf-break off Browns Bank and *ca*. 31K m^{-2} farther out off the eastern Scotian Shelf. The lowest concentration (*ca*. 7.5K m-2) occurred at the offshore station off the central Scotian Shelf. Concentrations of *C. hyperboreus* in the same waters were generally lower (1-3.7K m^{-2}), except at the offshore station off the eastern Scotian

Shelf where the abundance was *ca*. 12K m^{-2}. For October 2000 none of the near surface data are currently available and for stations at and beyond the shelf-break data from only 4 are available. These data show, however, that numbers of *C. finmarchicus* and *C. hyperboreus* were much lower than in 1998 with maximum levels for either appearing off Browns Bank (*ca*. 20K m^{-2}) or at the offshore station off the eastern Scotian Shelf (*ca*. 2K m^{-2}), respectively. For the tows to depths of >100 m, five depth stratified samples were collected per haul. For individual depth strata highest concentrations of *C. finmarchicus* (>20 m^{-3}) occurred in waters with temperatures of 4-6.2^{o}C and salinities 34.7-35, properties which identify it as Labrador Slope Water, which occupied a swath between *ca*. 300–1000 m in 1998 and between *ca*. 500-1000 m in 2000. In both years *C. finmarchicus* off Browns Bank were most concentrated at depths >500 m, while in 1998 most individuals at the offshore station in the east were found in the 100-500 m depth range. On the basis of these data the following hypotheses were formulated:

1) *C. finmarchicus* at depth off the western Scotian Shelf derived from a population that grew up either on the shelf itself, or in local slope waters
2) *C. finmarchcius* at depth offshore of the eastern Scotian Shelf derived from a population that grew up farther northeast or locally, which may have developed later than populations in the west (hence the shallower depth distribution)
3) Concentrations of *C. hyperboreus* at depth were higher in 1998 than in 2000 because in 1998 there was a greater infusion of Labrador Slope Water during the spring (Drinkwater *et al*., 2000; see Fig. 3) containing higher concentrations of this organism
4) Concentrations of *C. finmarchicus* at depth off the western Scotian Shelf were higher in 1998 than in 2000 because in 1998 most of the Scotian Shelf production was advected off the shelf to the east of Browns Bank, whereas in 2000 most was advected off the shelf into the Northeast Channel and Gulf of Maine.

It is hoped that these hypotheses will be explored during an upcoming research collaboration which was established during this workshop with colleagues from the University of Rhode Island.

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Modeling the North Atlantic Ocean Circulation and Climate Variability: Impact on Calanus *finmarchicus* populations

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The North Atlantic Oscillation (NAO), characterized by the large-scale and low-frequency variability of sea level pressure between Icelandic and Azores, is closely connected with the North Atlantic circulation. Figure 1 shows time series of the Gulf Stream position (as defined by the position of the 15^{o}C isotherm in SST) overlaid with winter NAO time series. A dominant signal in both Gulf Stream position and NAO index is the upward trend from 1970 to present. Interestingly, there is also an apparent downward trend from 1950 to 1970, suggesting that the upward trend is part of the natural climate variability on multi-decadal time scales. While the Gulf Stream was in its southern-most position during the 1960s, it attained the northern-most position during the 1950s and also during the 1980s. The Gulf Stream also exhibits pronounced interannual fluctuations with a dominant period of approximately 5-7 years. It is intriguing that the fluctuations of the Gulf Stream are highly correlated with the NAO index, although there seems to be a slight phase shift between the two.

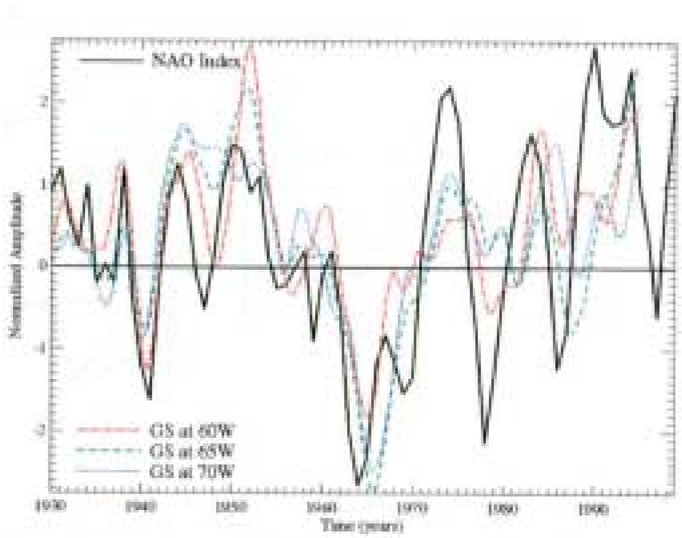

Figure 1. Multi-decadal normalized amplitude time series of Gulf Stream (15˚C isotherm position) at 60˚W, 65˚W, and 70˚W longitude and winter NAO index from Drinkwater *et al*., (2001).

During the decade of the 1960's, when the NAO Index was predominantly negative, *C. finmarchicus* abundance in the Gulf of Maine was relatively low. During the 1980's, when the NAO Index was predominantly positive, *C. finmarchicus* abundance was relatively high. During each of the maximum to minimum NAO shifts after 1980, *C. finmarchicus* abundance declined in subsequent years, and this pattern was especially evident following the 1996 NAO event.

Understanding this apparent relationship between the NAO and the associated ocean circulation changes and *C. finmarchicus* distribution has been identified as one of the grand challenges for GLOBEC Georges Bank Program and other international programs (Wiebe, 2000). A conceptual model for the distribution and dynamics of *Calanus* in the North Atlantic has been proposed based on the three-gyre hypothesis. The most southerly gyre is a small gyre in the Northwestern Atlantic consisting of the western portion of the Grand Bank, the Slope Water. The largest gyre consists of the northern North Atlantic Ocean basin bounded by Labrador on the west, Greenland and Iceland on the north, UK on the east, and the Gulf Stream extension and the North Atlantic Current on the south. The most northerly gyre is the Norwegian Sea. A number of important scientific questions have also been identified. For example, to what extent can the circulation in each of these three gyres support self-sustaining populations of *C. finmarchicus*? What is the exchange between these gyres?

To address this three-gyre hypothesis and related scientific questions requires a coupled physical-biological and fishery model to simulate the North Atlantic Ocean circulation changes and their impact on the *Calanus* distribution. Figure 2 shows the structure of the Gulf Stream and the three-gyre in the North Atlantic simulated by a 1/6 degree basin-scale ocean general circulation model (Chao et al., 1996). This represents a first step, with the physical modeling, toward addressing the grand challenge questions.

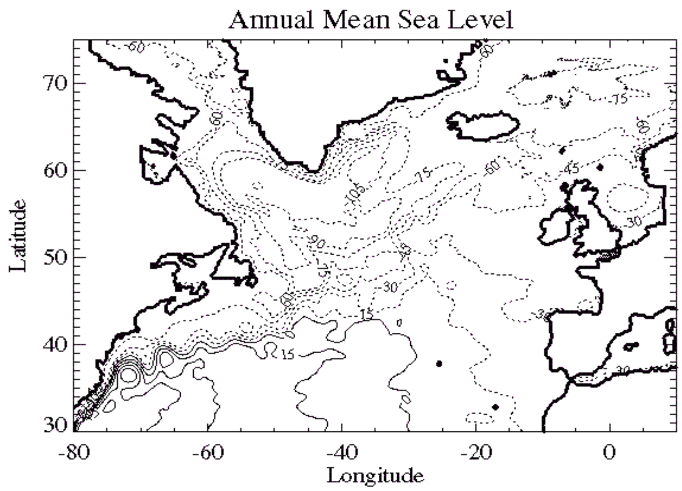

Figure 2. Mean sea surface height simulated by a 1/6 degree Atlantic Ocean general circulation model of Chao et al. (1996).

The simulated physical fields are very important for our basin-scale understanding of *C. finmarchicus* population behavior. Any basin-scale models with a claim to address the three-gyre hypothesis should at least satisfy the following criteria:

(1) Realistically simulate the three-gyre structure as shown in Fig. 2;

(2) Reproduce the multiple time-scales for the Gulf Stream path similar to that shown in Fig. 1 in response to NAO;

(3) Reproduce the water-mass variability in the Slope Sea during GLOBEC period.

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Numerical simulations of the Labrador Sea and Baffin Bay

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An ongoing Danish project "RekPro" is investigating the shelf area and the banks off West Greenland. The project is entitled "The implication of hydrographical and biological processes on variations in the recruitment of shrimp and fish at Westgreenland", and is aiming to provide a better understanding of the variations of the biological production in the marine ecological system. The goal of the project is to describe and estimate the extend of shrimp and fish larvae and their potential for survival in relation to differences in their environment, i.e. differences in temperature, salinity, fronts, and availability food on the Greenland fishing banks.

As a part of RekPro a numerical modelling study is performed aiming to estimate the drift of shrimp larvae in the area. The main goal is to indicate possible pathways and spawn areas by means of the numerical models.

Initially a limited area just covering the local area was applied. Though, the results were found to be very sensitive to the boundary conditions, and in poor agreement with reality. Therefore, the model domain was extended to a basin scale covering the Labrador Sea and Baffin Bay (Fig. 1).

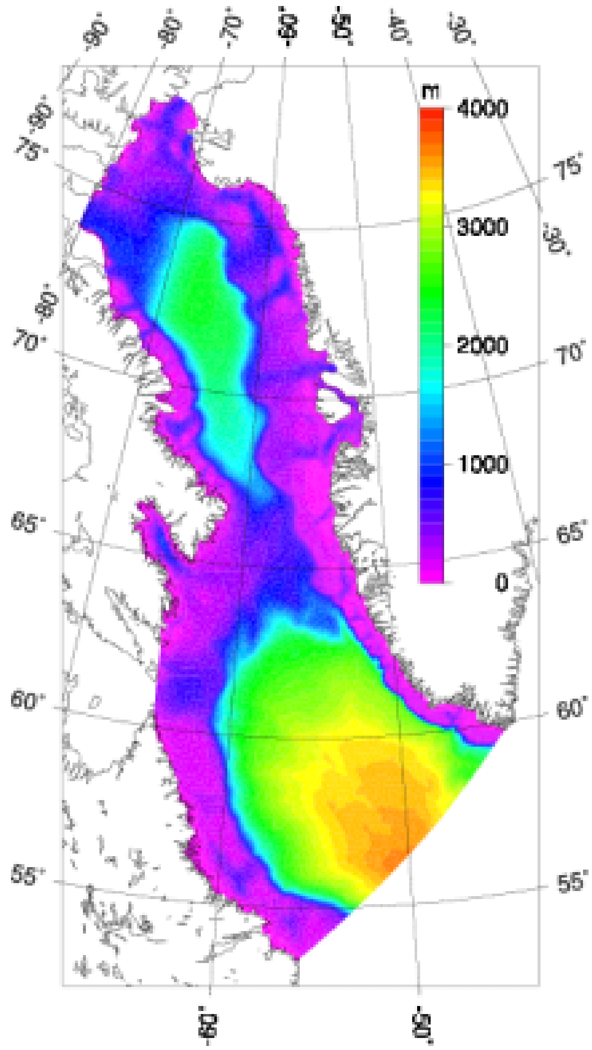

Figure 1. Bathymetry of study area.

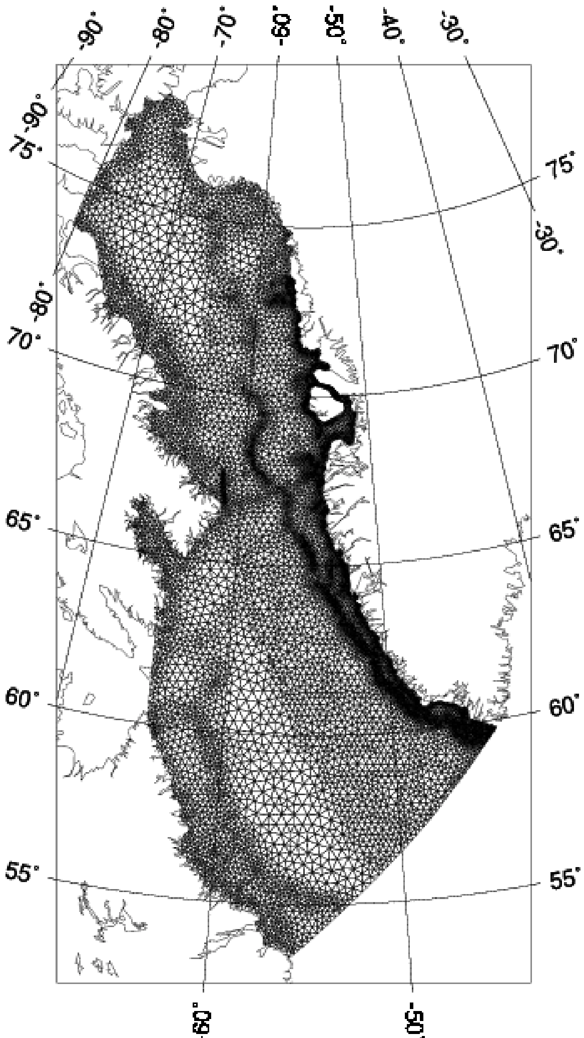

Figure 2. Computational mesh used in modelling.

The finite element ocean models Fundy (Greenberg et al., 1998) and Quoddy (Lynch et al., 1996) are applied for the diagnostic and prognostic hydrodynamical simulations. The computational mesh (Fig. 2) exploits the finite element method having a varying resolution from 2.4 km to 38.4 km with the higher resolution on the shelf and steep slopes off Greenland.

The initial temperature and salinity are obtained from observations and interpolated to the model mesh. As expected, the circulation in the diagnostic simulation (not shown) is strongly following the bathymetry, with some baroclinic effects.

The modelling task is planned to proceed as follows. The diagnostic result is feed into the prognostic model as initial field, and the summer season 2000 is forced by the actual wind provided by the atmospheric model (Sass et al., 1999) run at the Danish Meteorological Institute. The circulation fields from the prognostic simulations are archived in suitable time intervals (1-3 hours). Finally, the circulation fields are used for driving an advection-ecological model for the shrimp larvae.

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Transport of *Calanus finmarchicus* on the Scotian Shelf: the roles of the Gulf of St. Lawrence, slope waters and the Labrador current

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Introduction

As part of the GLOBEC-Canada program, we have developed a physical-biological model for the Gulf of St. Lawrence (GSL) and Scotian Shelf (SS) by linking a life-history model of *Calanus finmarchicus* to a three-dimensional (3D) ocean circulation model that predicts 3D temperature, salinity and flow fields. The main objective of this model is to describe the effects of temperature and circulation on the distribution and abundance of *C. finmarchicus* in Eastern Canadian waters, but the focus of this paper is on the SS. Briefly, the circulation model is CANDIE, a three-dimensional, fully-non-linear, z-level ocean circulation model (Sheng et al., 1998) which has been applied successfully in various studies, including wind-driven circulation over an idealised coastal canyon (Sheng et al., 1998), the non-linear dynamics of the Gaspé Current (Sheng, 2000), and seasonal circulation over the Northwest Atlantic Ocean (Sheng et al., 2001).

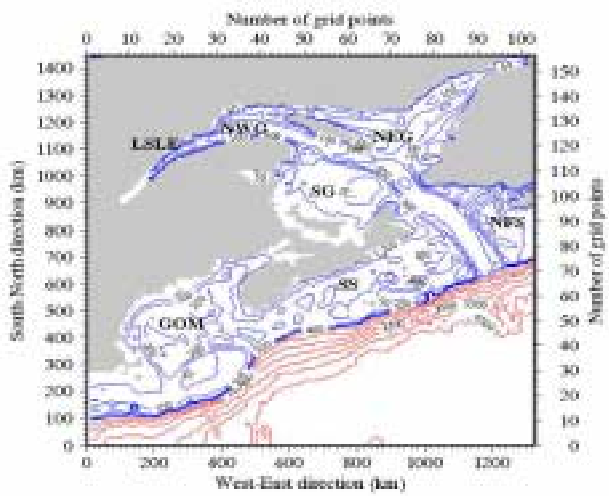

Figure 1. Map of the study area with the bathymetry (blue lines for depth < 500 m, red lines for depth > 500 m) and localisation of the sub-areas discussed in the text : LSLE for Lower St. Larence Estuary, NWG for north-west Gulf of St. Lawrence, NEG for north-east Gulf, SG for south Gulf, CG for central Gulf, LC for Laurentian Channel, SS for Scotian Shelf and GOM for Gulf of Maine. Higlighted are boundaries across which fluxes calculations were made.

In the present study, CANDIE was applied to the eastern Canadian shelf region from 55°W to 72°W and from 39°N to 52°N (Fig. 1) and was run in diagnostic mode with the 3D seasonal mean climatology of temperature and salinity constructed by Sheng et al. (2000). We used a stage-based approach similar to the model of Lynch et al. (1998) to describe the life history of *C. finmarchicus*. The main differences between the life-history model used in this paper and the one used by Lynch et al. are that the present model includes stage-specific swimming behaviour (Zakardjian et al. 1999) and that the life history of *C. finmarchicus* is driven by an optimal window for reproduction outside of which the population waits for favourable conditions in a resting/quiescent phase. The model includes a true diapausing stage with its own vital rates, allowing a complete November to November one year simulation of the population dynamics of *C. finmarchicus*. In addition, the model also includes seasonally-varying egg production and stage-specific mortality rates.

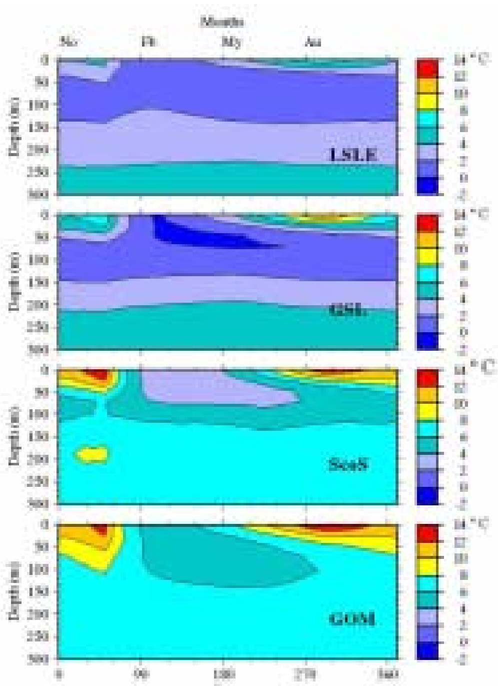

Figure 3. Seasonal trends of the vertical distribution of temperature in then upper 300 m for the Lower St. Lawrence Estuary (LSLE), central Gulf of St. Lawrence (GSL), Scotian Shelf (SS) and Gulf of Maine (GOM).

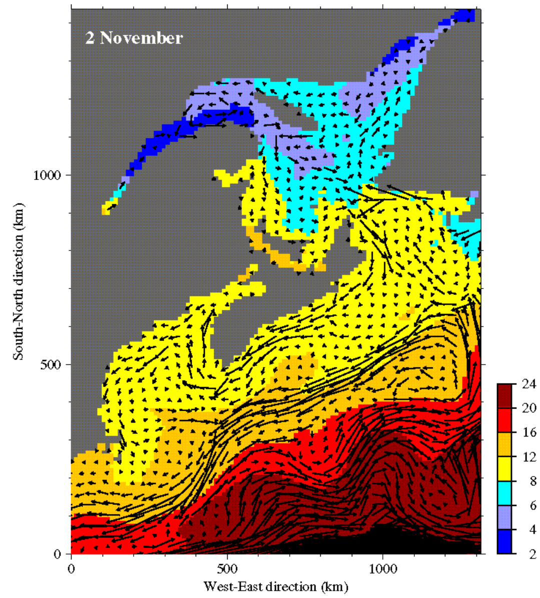

Figure 2. Surface circulation and temperature as simulated by CANDIE in early November.

General patterns of the hydrography and circulation from CANDIE

Figure 2 shows the model temperature and velocity fields produced by the physical model at the top model level in early November as an illustration of the many important circulation features in the region produced by CANDIE, including the Gaspé current, a year-round cyclonic gyre over the north-western GSL, south-eastward outflow through the western Cabot Strait, south-westward flow on the SS with relatively strong coastal and shelf break jets and the north-eastward flow of the Gulf Stream. Figure 3 presents time-depth distributions of temperature in the upper 300 m for the lower St. Lawrence Estuary (LSLE), central Gulf of St. Lawrence (CG), Scotian Shelf (SS), and Gulf of Maine (GOM), respectively. The figure illustrates the gradual establishment of upper ocean stratification in spring and summer, and the relatively rapid establishment of cold, weakly stratified waters in fall and winter.

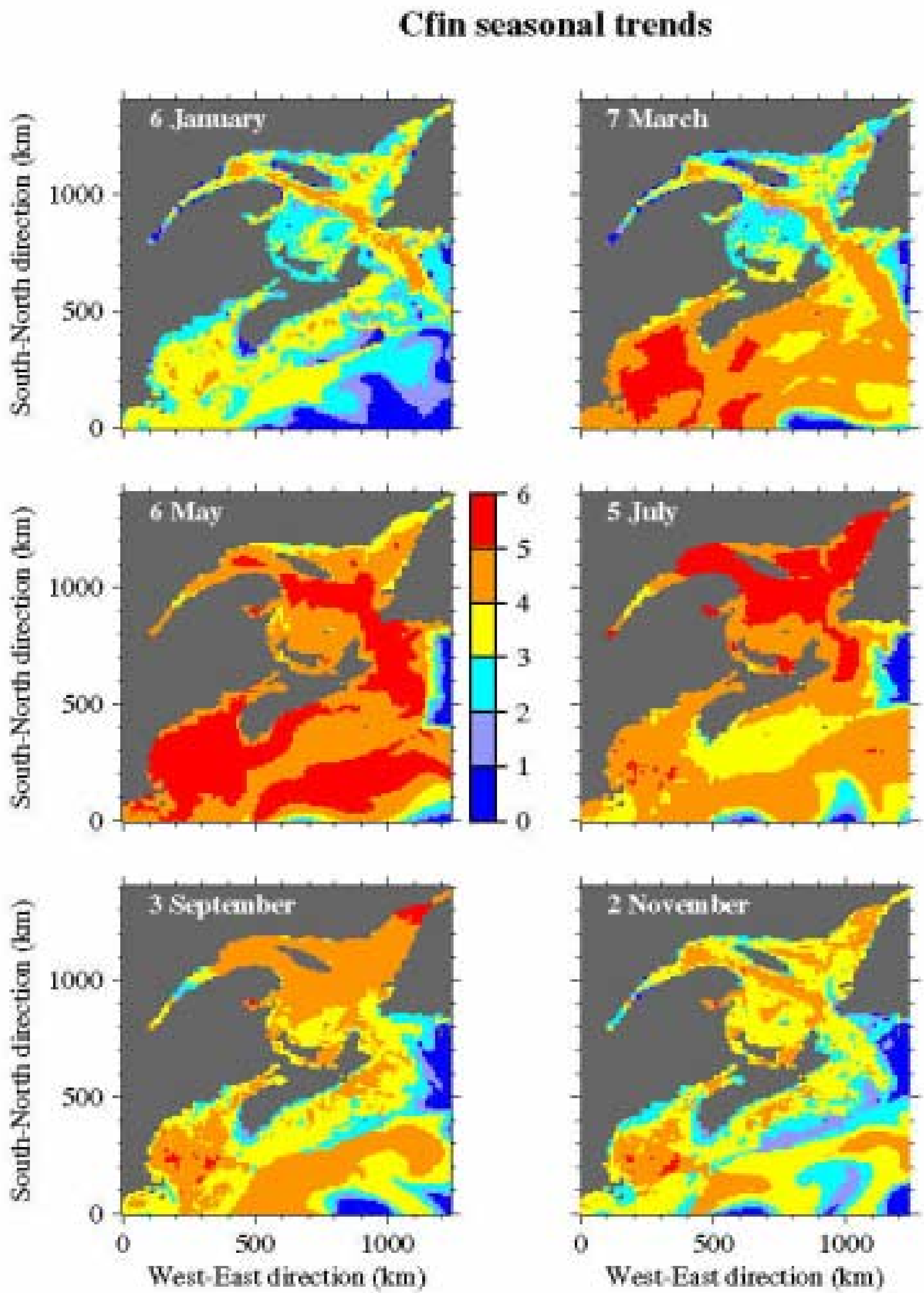

Figure 4. Seasonal trends of the total *C. finmarchicus* population showed as the log10 of depth-integrated abundance for simulation.

Simulated *C. finmarchicus* life-cycle and abundance

The physical-biological model was initialised with an initial population of CV in diapause that are homogeneously distributed on the shelf, i.e., waters with depth less than 1000 m, on 28 October, a time when all the sub-populations in the study region are in diapause. But, as the simulated CV_d are able to swim toward their deep preferential depth, they rapidly concentrate in deeper areas (see 6 January in Fig. 4). The predicted seasonal variation of the mean abundance (Fig. 4) and stage structure (Fig. 5) are consistent with the general knowledge of the *C. finmarchicus* life cycle in the region. The CV_d exit from diapause and molt to a first adult generation G_0 which start to spawn in

January in the GOM, February on the SS, late March in the SG (southern GSL), April in the NWG (north-western GSL) and May-June in the LSLE and NEG (north-eastern GSL), respectively (Figure 5). The maximum abundance of *C. finmarchicus* is reached in March-May in the GOM, April-June on SS, in May-June for CG and later (June to August) Northward in the GSL (Fig. 4-5). The active season for *C. finmarchicus* ends with the increase of the CV stocks in diapause and disappearance of the younger copepodite stages in June-July in the GOM, July-August in the SS, August in the SG and CG, and August-September in LSLE, NWG and NEG, respectively. Figure 5 also shows a second adult generation (G_1) produced at the end of the first-year reproduction events in these sub-areas. Only a small fraction of this second generation, however, reproduces due to their late appearance. Hence, recruitment of diapausing CV's was made up mostly by the G_1 generation.

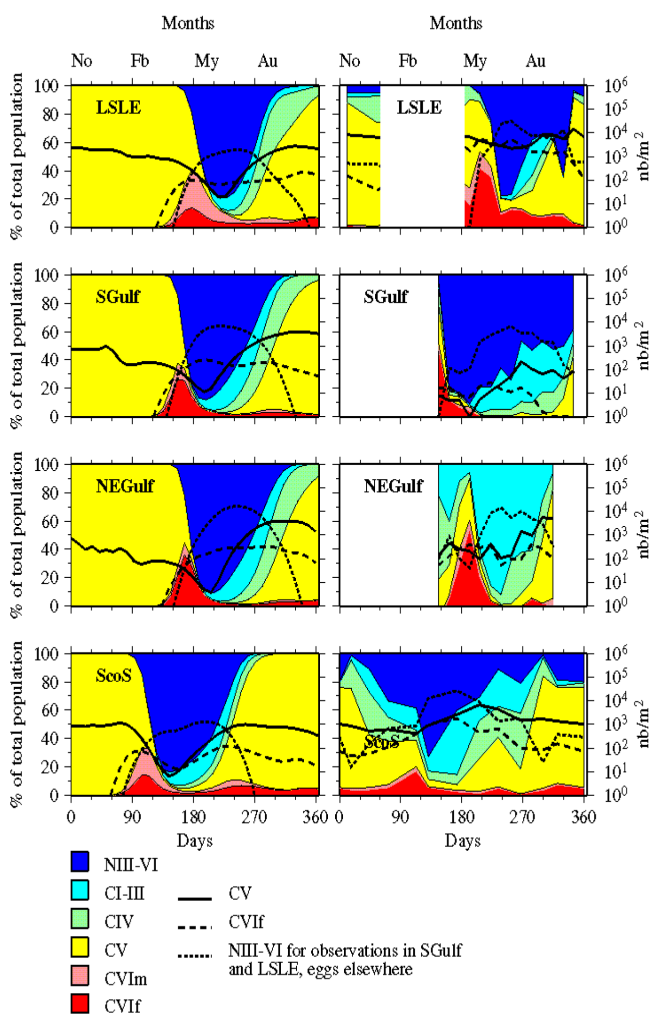

Figure 5. Comparisons of simulated mean abundance and stage-structure for sub-areas of the CANDIE domain with observations in the Lower St. Lawrence Estuary (LSLE), Northwest Gulf of St. Lawrence (NWG), Northeast Gulf (NEG) and Scotian Shelf (SS). Log absolute abundance (legends in bottom) is shown for stages NIII-NVI, CV and adult females. Stage-structures are expressed as percent of the population from nauplii III to adults with legends shown in bottom.

A comparison of the model results with observations from the LSLE (Plourde et al., 2001), GSL (Filteau and Lacroix, 1953; Starr, unpublished results; Starr et al., 1994) and SS (McLaren et al., 2001) indicates that the simulated life cycles of *C. finmarchicus*, particularly the seasonal trends of the stage-structure, agree reasonably well with observations (Fig. 5). Hence, the model predicts the right orders of magnitude of the observed CV and CVI_f abundance during the production season and is able to retrieve the initial over-wintering stocks after a one year simulation in the shelf region.

The physical-biological model also predicts the evolution through the winter of relatively high *C. finmarchicus* abundances in the deep waters off the SS and GOM. This area was initially empty of animals and is sowed by the immigration at depth of the initial CVd population that drifts eastward down to the south-east boundary of the model and offshore (Fig. 6). A significant portion of these diapausing CV which originated along the shelf-break or in the deep areas of the GSL and LC becomes trapped in this offshore region due to re-circulation between the Labrador Current and the Gulf Stream. After arousal, females ascend to the surface layers and are dispersed northward to the slope-water region, where water temperatures are favourable for rapid growth of the G_1 generation .

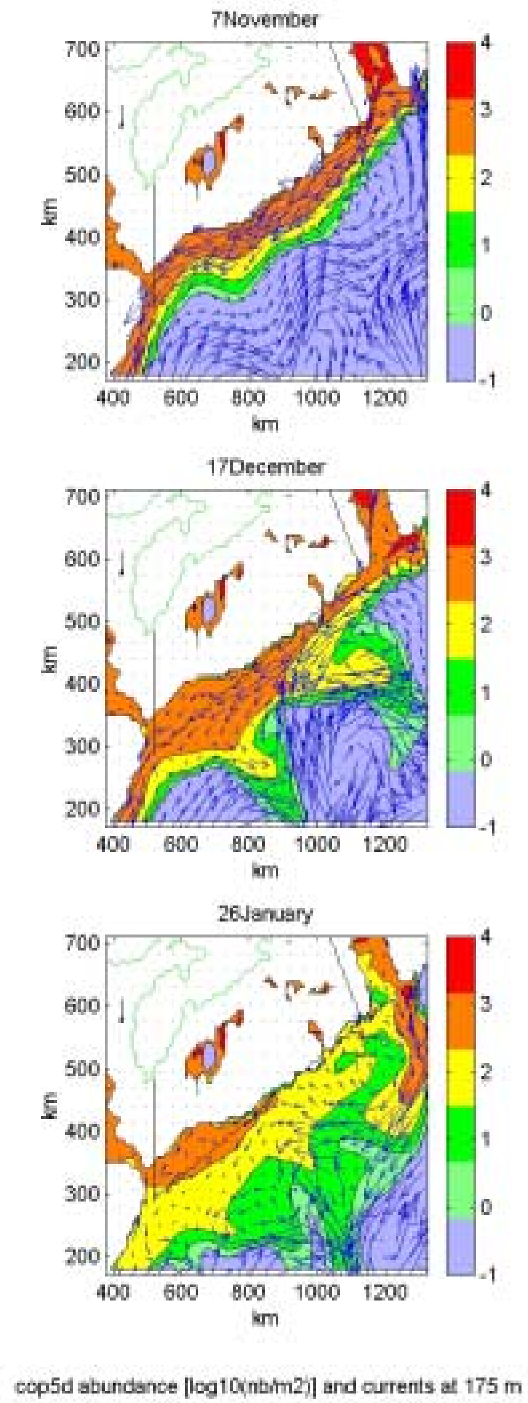

Figure 6. Depth-integrated CVd abundance and deep circulation at the beginning of the simulation showing the export of the shelf-break stock to the offshore waters. Abundance are shown as $\log_{10}$(nb. m^{-2}).

Flux computations

To demonstrate the importance of horizontal transport in the local *C. finmarchicus* dynamics over the shelf seas, we calculated the horizontal fluxes of animals across ten boundaries in the region. They include the LSLE/NWG, NWG /CG, NEG/CG, SG/CG, CG/LC, eastern LC, southern LC, LC/SS, southern SS, and

SS/GOM boundaries. To determine the importance of the horizontal fluxes to the depth-integrated abundance, we calculated the time-mean total cross-boundary fluxes during the first year and compared them with the annual mean total net local production in each area (Table 1). Note that the total net production is defined as the difference between the total eggs production and total mortality (all stages).

Table 1. Relative magnitude of yearly cumulated boundaries' fluxes by references to areas' net productions over the year.

	LSLE	NWG	NEG	SG	CG	LC	SS
LSLE/NWG	+0.182	-0.020					
NWG/CG		+0.016			-0.007		
NEG/CG			+0.183		-0.109		
SG/CG				+0.176	-0.08		
LC/CG					+0.002	+0.024	
East LC						+0.259	
South LC						-0.024	
LC/SS						-0.651	+0.615
South SS							+0.279
SS/GOM							-0.684
Balance sheet	+0.182	-0.004	+0.183	+0.176	-0.194	-0.392	+0.213

We found that the annual mean net fluxes across the LSLE/NWG boundary plays a very minor role in the NWG annual mean production budget (2.0%), but a very important role in the LSLE budget (18.26%). For all regions, except the NWG, the annual mean cross-boundary net fluxes contribute between 15 and 55% to the local production budgets, with the largest contributions in the CG, LC and SS areas (24-55%). It can be concluded, therefore, that the ocean circulation in the region plays a very important role in determining local *C. finmarchicus* abundance, mainly on the SS and in the LC which act as buffer areas between the GSL, slope waters and GOM. In particular, the model exhibits south-westward fluxes of *C. finmarchicus* from the Newfoundland Shelf to the Scotian Shelf across the LC/SS boundary and marked south-westward transport for both surface-dwelling and deep–dwelling *C. finmarchicus* from the Scotian Shelf to the Gulf of Maine via the shelf-break and Nova-Scotia currents.

Circulation and *C. finmarchicus* dynamics on the SS

C. finmarchicus exported from the GSL would mainly originate from the CG but they comprise only a small portion of the local production (Table 1) and have little impact on the LC population. The LC appeared more dependant on advection from the Labrador Sea and Newfoundland Shelf, which account for 18.6 % of the local budget despite the rapid disappearance of the eastern stock in the model. Hence the role of the Gulf of St. Lawrence appears to be limited. This is mainly due to the sheared circulation in Cabot Strait where stage-specific vertical distribution imply stage-specific differential transports that compensate for each other and lead to a low yearly-cumulated value. Any *C. finmarchicus* originating from the GSL into the LC would be rapidly advected on to the SS as the flux from LC to SS is the dominant pattern in that area accounting for about 65 % of LC net production. This eastward transport is also dominant for the SS which exports about 68 % of it local net production to the GOM. In both cases all stages would be advected. These results are in agreement with previous finding Herman et al. (1991) and of Sameoto and Herman (1991), although the GSL does not appear to be the primary source for the *C. finmarchicus* SS population. Observations of significant transport from the SS to the GOM have also been reported , which can occur directly via the Nova-Scotia current (Meise and O'Reilly, 1996).

A new feature shown by the simulation is that both the LC and SS showed marked exchanges at their south boundary due to the shelf-break jet which is fed by the Labrador Current. The LC seemed to export nauplii and early copepodites in May whereas the flux is mainly an import on the South SS boundary at the same time. This indicates that the transport of *C. finmarchicus* from the LC to the SS can also occur via the shelf-break current that may capture *C. finmarchicus* south of LC and transport them on to the central SS. By contrast, deep-dwelling stages (CIV-V, CVd and males) are imported from waters south of the shelf both into the LC and the SS slope waters. Based on observations of *C. finmarchicus* abundance and stage distributions and TS characteristics of the near-surface waters, Head et al. (1999) argued that such transport of *C. finmarchicus* from the shelf-break or offshore areas to central and western regions of the SS does indeed occur.

This leads us to consider finally the very abundant population that develop in the slope water in the model. Little is known about the slope-water population of *C. finmarchicus* but our simulated population is not unrealistic, since some previous study have shown the presence of *C. finmarchicus* in the slope-water south of New England (Miller et al., 1991; Ashjian et al., 2001). *C. finmarchicus* have been observed as far southwest, as the Mid-Atlantic Bight (Judkins et al. 1979; Lane et al., 1994), where populations proliferate following cold winter (Grant,1988). In addition, late copepodites and adults are sometimes found at depth in the Gulf Stream (Wishner and Allison, 1986; Ashjian and Wishner, 1993). These animals are mainly resting CV and adults that have followed the deepening of the 4-6° C layer (Wishner and Allison, 1986) and they may not be able to encounter conditions favourable for development for a long time, if at all, as long as they are entrained in the Gulf Stream. For *C. finmarchicus* remaining in the slope waters, conditions may be more favourable, but to our knowledge, this slope water population has not been observed in an active phase of reproduction.

One reason for this might be that the occurrence of conditions favourable for *C. finmarchicus* in the slope water may be irregular or transient . For example, *C. finmarchicus* has more affinity for moderately cold waters whereas the slope water south of Newfoundland and SS is known to be subject to marked inter-annual variability linked to the dominance of the warmer slope water jet or the colder Labrador current (Pickart et al., 1999). Another reason might be that the branch of the Labrador current that follows the shelf-break may carry low abundances of *C. finmarchicus* , which would cut off the slope water population from the shelf population (Fig. 7). On the other hand, however, while relatively little is known about the life-history and abundance of *C. finmarchicus* in the south-east Labrador Sea, overwintering abundances of *ca*. 10,000 m^{-2} have been observed at depth near the shelf-break in the western central Labrador Sea (Oct. 1996, E. Head pers. comm.) and high (>100,000 m^{-2}) abundances of young stages have been found in the near-surface layers over deep water close to the NE and SE of the Grand Bank (July, 1995, E. Head pers. comm.). Thus, the role of the Labrador Current as a source of *C. finmarchicus* to the slope waters south of the SS, especially in cold years when the influx of Labrador Current water is high, remains unclear and requires more attention in future.

Conclusions

Several features concerning the impact of the circulation on *C. finmarchicus* dynamics in eastern Canadian waters, and particularly on the SS, emerged from our model results. The first is that the Gulf of Saint Lawrence may be auto-sustainable The second is that the role of the GSL in the overall dynamics of *C. finmarchicus* on the SS is probably limited, but it may be essential for the seeding of the eastern shelf. The third is that much of the SS *C. finmarchicus* production is exported to the GOM and the offshore. In addition, the model shows that export of the initial shelf break CVd stocks seed the slope waters and permit the development of a vigorous offshore stock that may interact later with the SS stocks. There may be a vigorous *C. finmarchicus* population in the slope waters, but it may develop early and be short-lived in warm years and develop later and be more persistent in cold years. This would be consistent with the findings of E. Head (pers. comm.) who in April found less abundant, but more developed populations, along and beyond the shelf-break in a warm year (1999) than in a cold year (1998). The relative importance of this population as shown by our simulation merits further attention in future research. These results also underline the role of the Labrador current which is not essential for the SS stocks but which may control the exchange between the SS and the surface slope waters and favours the along shelf-break transport of *C. finmarchicus*. Future refinements of the model, both in the circulation and ecology, will allow us to fine-tune these initial conclusions. In addition, however, more observations are also needed in critical areas such as the south Labrador Sea and Newfoundland shelf, the slope water and central GSL, particularly regarding the vertical distribution of *C. finmarchicus* in strongly sheared areas such as Cabot Strait or along the shelf break.

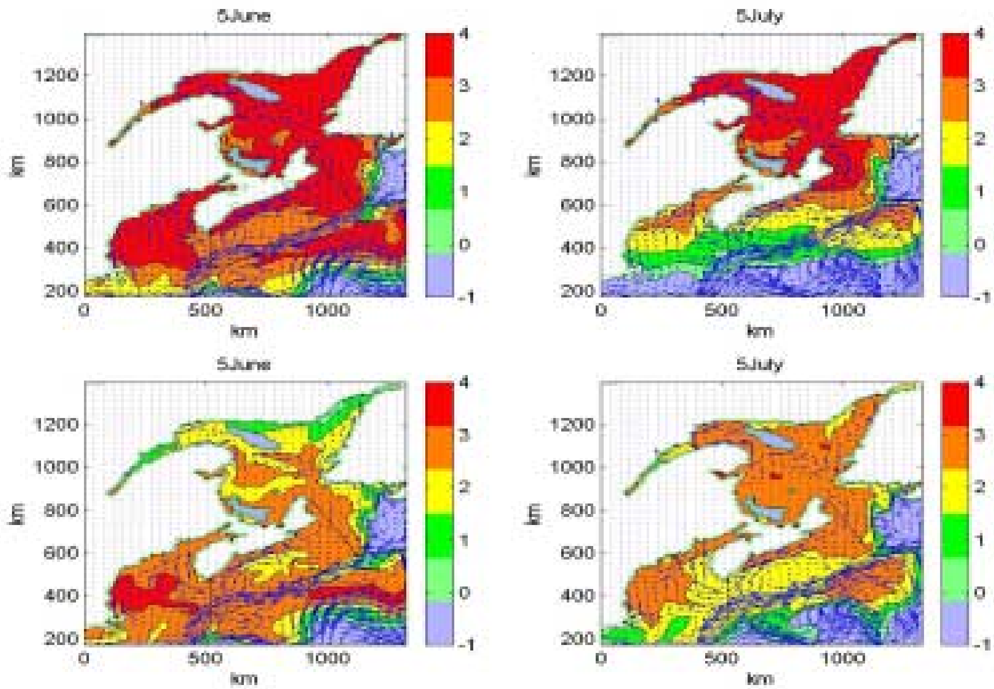

Figure 7. Surface (upper panels) and 25 m depth circulation (bottom panels) and eggs and CIII depth-integrated abundance in June-July on the Scotian Shelf. Abundance are shown as $\log_{10}$(nb. m^{-2})

Acknowledgments

This work is a contribution to the GLOBEC-Canada program and was supported by grants from the Natural Sciences and Engineering Research Council and Fisheries and Oceans Canada. Many thanks to E. Head who kindly revised this mansucript.

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Interannual variaibility of Calanus finmarchicus on Georges Bank and in the Gulf of Maine: Results from the GLOBEC study

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Spatial and temporal changes in abundance and distribution of *Calanus finmarchicus* in the Gulf of Maine and on Georges Bank are presented for the period 1995-1999.

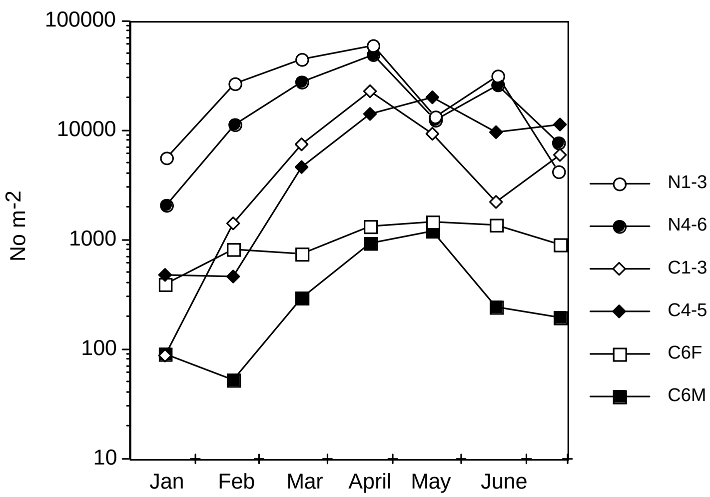

Figure 1. Mean abundance of *Calanus finmarchicus* on Georges Bank during the years 1995-1999. Nauplii data are from 20 pump staions on each cruise while copepodite data are from approx 38 1 m^2 MOCNESS tows.

Reproduction began in late December/early January in the Gulf of Maine and the new generation was advected onto the northern edge of Georges Bank at this time. This G1 generation had completely spread across the bank by March. Maturation of this first generation begins in March and one or more generations follow it. Mean abundance on Georges Bank was very similar between years. Temperature differences of about 1°C between 1995 (warmer) and 1996 (colder) resulted in an earlier development of the first generation during 1995 than during 1996, but a significantly greater peak abundance during 1996. This affect was carried over into the second generation.

Size analysis of the G0 C6 females suggests that there are interannual differences in the relative contribution of spring spawned (larger) and summer/fall spawned (smaller) animals to this stock.

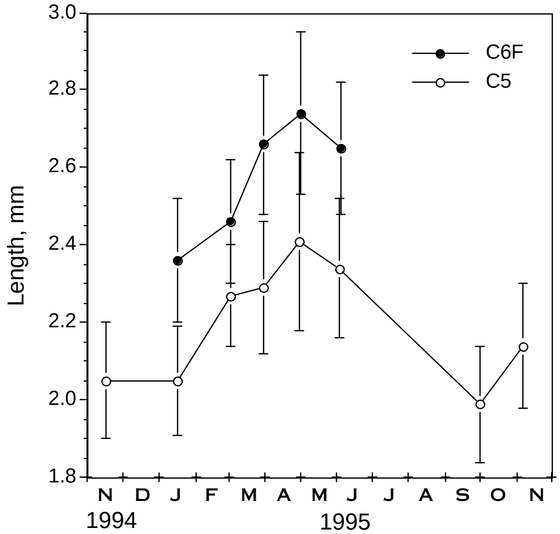

Figure 2. Mean and standard deviation of prosome lengths (mm) of C5 and adult female *Calanus finmarchicus* collected from the Georges Bank.

Possible effects of climate change on this, and on *Calanus* population dynamics on Georges Bank, were discussed.

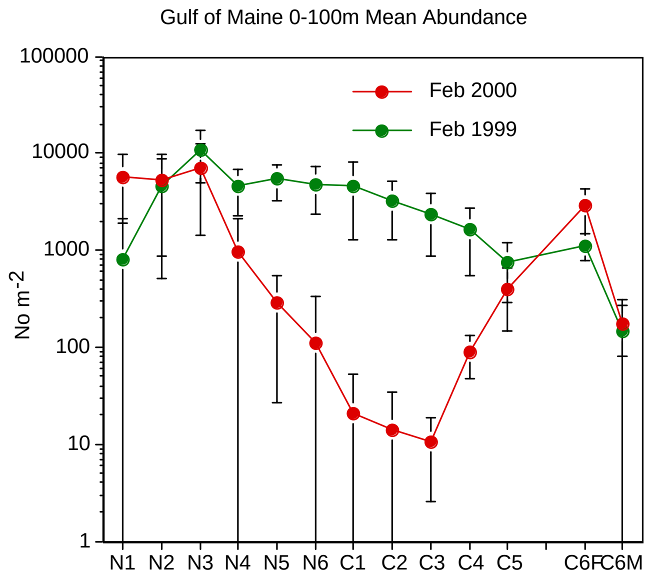

Figure 3. Mean 0-100m abundance *of Calanus finmarchicus* along a transect in the eastern Gulf of Maine between Penobscot Bay and the NE Peak of Georges Bank in late February 1999 and 2000. During 1999 a phytoplankton bloom was occurring across the central Gulf and *Calanus* egg production rates and growth rates were high, while during 2000 phytoplankton was very low and *Calanus* food-limited.

The Canadian SOLAS Research Network

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This presentation was an overview of the Canadian SOLAS Research Network plans for 2001 through 2005. The scientific focus of the Canadian SOLAS research effort largely reflects its integration with the International SOLAS Program and its stated objective of addressing 'the key interactions among the marine biogeochemical system, the atmosphere and climate, and how this system affects and is affected by past and future climate and environmental changes'. Specifically, the fifteen individual Canadian projects, supporting 43 principal investigators, will support a science program with the following objectives:

1. Determine, during different seasons, the spatial distribution of trace gases production in major biogeochemical provinces of the northwest Atlantic and subarctic Pacific, and the impact of trace gases on the atmospheric chemical and physical properties and on climate.
2. Determine the influence of Fe on the production of trace gases in the SAP and their impact on the atmospheric chemical and physical properties and on climate.
3. Significantly increase our capacity to estimate trace gas emissions from whole oceanic basins using remote sensing.
4. Significantly increase our capacity to model ocean-atmosphere exchange over regional and seasonal scales.

Two major expeditions are planned: An Fe-addition in the subarctic Pacific where Fe limits primary production (2002) and an integrated study of a tagged patch of water in the northwest Atlantic during the spring bloom (2003). Data collected to address these objectives include measurements of gas exchange dynamics, water column structure, trophic structure and physiological markers of the plankton community, rates of growth and elemental fluxes among key food-web components, remote sensing of ocean colour, and ultimate integration of field data into coupled ocean-atmosphere models.

ANIMATE -Atlantic Network of Interdisciplinary Moorings and Time Series for Europe

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The North Atlantic is the open ocean region that has the largest significance for Europe in a climatic, economic, and societal sense. It is here where the processes responsible for Europe´s climate are rooted It is here where most of the fishing takes place and where major shipping routes run. Its boundaries are used for offshore exploitation, and more. Also from a global viewpoint, the North Atlantic plays a key role in climate and ocean issues, because of critical processes like the North Atlantic Oscillation (NAO), the forcing of the thermohaline circulation, and the uptake of greenhouse gases into the deep ocean (a major sink for CO_2) in the subpolar North Atlantic. Natural and anthropogenic changes interact within the physical, geochemical, and ecological balance of the ocean, here the North Atlantic; they need to be observed and forecasted as the basis for research and policy actions.

For addressing the above issues, sustained ocean observing systems are required that collect information from the ocean in a systematic, routine fashion, both in a focussed mode for critical or representative regions and in a wide-spread survey-like approach. The EU-funded project ANIMATE (Atlantic Network of Interdisciplinary Moorings And Time Series for Europe) proposes to improve European scattered and uncoordinated ocean observing infrastructure for repeat/time series measurements, in order to develop an initial network of sustained moored stations for ocean CO_2 and carbon cycle measurements in the eastern North Atlantic. Ocean CO_2/carbon observations are imperative for understanding, monitoring and predicting the oceanic uptake of anthropogenic CO_2. Existing infrastructure is upgraded/replaced with autonomous, state-of-the-art moored equipment for relevant CO_2, physical and biological measurements, at three stations in key regions in the eastern North Atlantic (Fig 1).

The Atlantic Zonal Monitoring Program

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The Altantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing DFO's capacity to understand, describe, and forecast the state of the marine ecosystem and to quantify the changes in the ocean physical, chemical and biological properties (Therriault et al. 1998). A critical element of the AZMP involves an observation program aimed at assessing the variability in nutrients, phytoplankton and zooplankton. Zonal (NW Atlantic) environmental monitoring is the minimal, ongoing collection and analysis of ocean data required to obtain a quantitative description leading to an understanding of the variability of the biological, chemical and physical characteristics of the region.

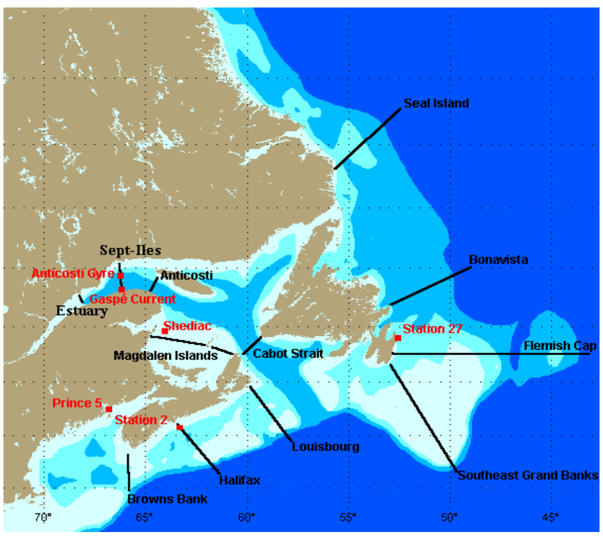

Figure 1. Sections and times series stations sampled by the AZMP.

The design of the program was based on the following considerations derived from preliminary analysis:

- It is impractical and too costly to provide complete coverage over the entire zone;
- With a limited sampling program, the variance in temperature, salinity, oxygen and nutrients at seasonal and longer time scales can be measured despite the presence of high frequency background variability;
- Hydrographic sections can provide quantitative assessments of water mass variability, transport and fluxes of heat and salt, and possibly nutrients;
- Large-scale coherence in the variability of planktonic organisms exists, but significant short-term fluctuations in abundance at time scales shorter than seasonal are also important.

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (fixed point stations, cross-shelf sections, and groundfish surveys) in each region (Laurentian, Maritimes, Newfoundland) sampled at a frequency of bi-weekly to once annually. The specific components consist of [1] high-frequency temporal sampling at six accessible sites to monitor finer time scale dynamics in representative areas; [2] limited section sampling; [3] resource surveys and other ship-of-opportunity sampling to acquire seasonal data on sections in the while Atlantic region; [4] this is completed by CPR surveys and remote sensing information, as well as other types of available data.

A description of the seasonal patterns in the distribution of phytoplankton (microscopic plants) and zooplankton (microscopic animals) provides important information about organisms that form the base of the marine foodweb. An understanding of the production cycles of plankton, and their interannual variability, is an essential part of an ecosystem approach to fisheries management. The variables routinely collected as part of the AZMP activities include: temperature and salinity; sea level; ice and freshwater runoff, meteorological data; nutrient concentration (nitrate/nitrite, phosphate, silicate); dissolved oxygen ; chlorophyll *a* concentrations; phytoplankton – dominant species composition; secchi disk and water transparency; zooplankton biomass; zooplankton – dominant species composition; fish and invertebrate species composition, distribution and abundance.

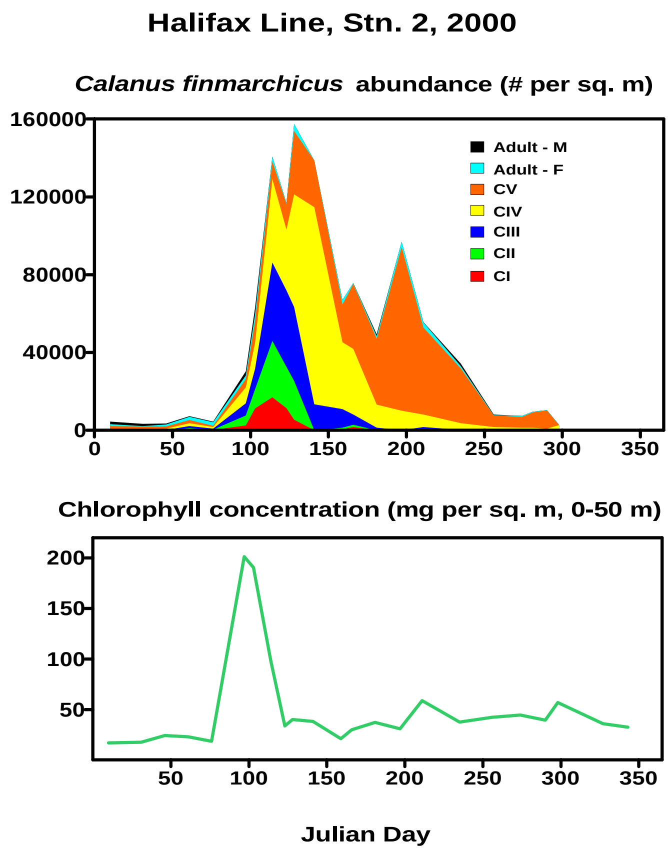

Figure 2. *Calanus finmarchicus* abundance, by stage, and integrated chlorophyll concentration (0-50m) at AZMP Time Series Stn. HL2.

The data from the AZMP are intended for wide distribution and complete accessibility. The program provides single window access to physical, chemical and biological data as well as to information and products generated under the monitoring program. To ensure compatibility of the information collected in the three regions, the program follows coordinated and standardized procedures for QC/QA, processing and archiving.

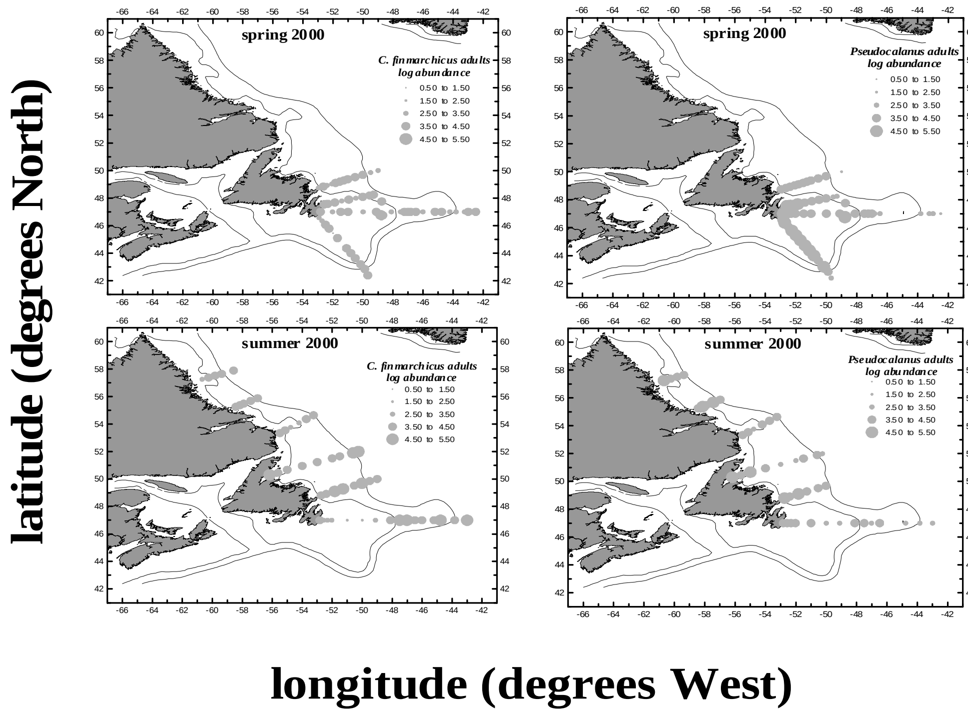

Figure 3. Abundance of *Calanus finmarchicus* and *Pseudocalanu*s spp. adults on the Newfoundland and Labrador Shelves in spring and summer 2000.

The information collected as part of the AZMP provides the basis for the continued assessment of environmental conditions in the Atlantic region as well as the ongoing collection of baseline information that can be used in the development of research initiatives.

<u>Reference</u>

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Basin-Scale Calanus Models

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Basin-scale *Calanus* models must describe an organism living mainly in deep ocean basins, which generates only 1-3 new generations per year. Questions of species persistence and abundance distribution must therefore be addressed on a multi-year timescale.

For the N.E. Atlantic, Bryant et al. (1998) have shown that most deterministic tracks originating within the domain leave it within two years and virtually none remain beyond five years. Speirs & Gurney (2000) have shown that diffusive mixing is the key to long-term persistence in such circumstances.

The data with which our models will be compared will generally be either synoptic maps or point time-series describing stage-resolved abundance, so they must predict density fields. This combination of requirements precludes the use of Lagrangian methods, because the ensemble size needed to produce adequate density estimation over multi-year timescales is prohibitive (Fig 1.).

Figure 1. Predictions 20 weeks after a two-point release.

The clear implication of this is that we need to use an Eulerian method but this introduces its our technical difficulties because we need to solve the generalised McKendrick-von Foerster equation

$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = -\mathbf{mf} - \frac{\partial}{\partial \mathbf{q}}(\mathbf{gf}) - \nabla.\mathbf{J}\ .$$

This represents the process of development as a pure advection along the development axis. Conventional numerical methods stabilised discretizations of such formalisms by introducing numerical diffusion – solution whose inappropriateness we can see by considering the case where the development index q is simply age (Fig 2).

Figure 2.

The Problem

Conventional methods stabilised by numerical diffusion

The Solution

Discrete method with appropriate Δt – Gurney et al. (2001)

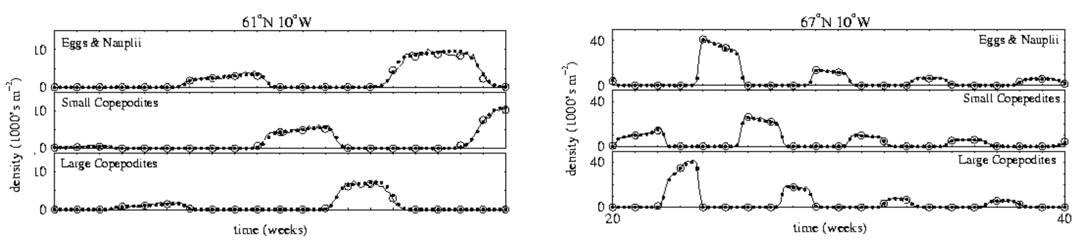
In non-spatial modelling this is a well-known problem with an equally well-known solution (de Roos 1997). However, the de Roos E.B.T. technique does not generalise to the spatial case. For spatially uniform development, an easy solution is to use a discrete-time method with update intervals chosen so that members of one development class at one increment are obligate members of the next class at the next increment.

Gurney et al (2002) have shown that this methodology can be extended to cases where the development rate is spatially and temporally variable provided that one can choose a single development index whose rate of change in not dependent on its current value. We then simple update locally at appropriate intervals and perform mixing updates at (relatively infrequent intervals.

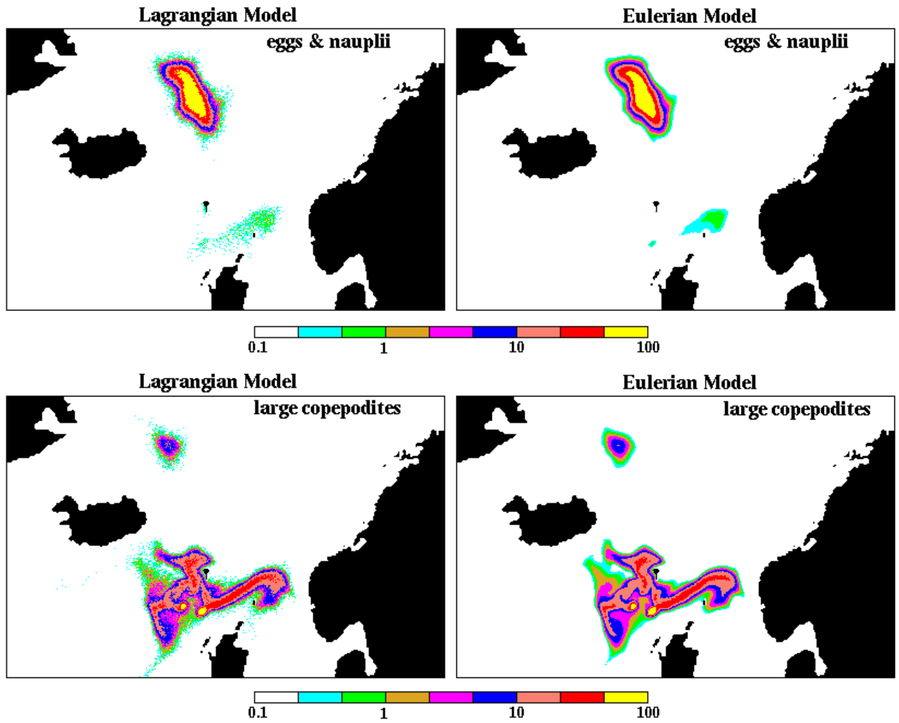
We tested the medium term predictions of an implementation of a Calanus model for the N.E. Atlantic using this methodology against those of a conventional Lagrangian ensemble (Fig 3).

Figure 3. Tests of N.E. Atlantic *Calanus* model against a Lagrangian ensemble.

Time series at two stations

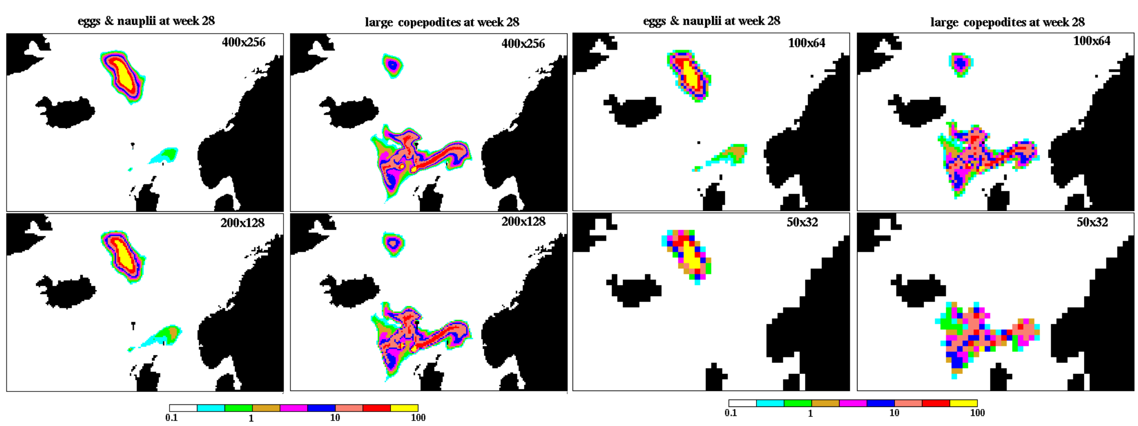


Spatial patterns at week 28, after two-point release at week 12



A key property of the discrete-time/space formalism described by Gurney at al (2001) is its remarkable resiliance against reductions in resolution (Fig 4)

Figure 4. Model predictions at 400x256, 200x128, 100x64 and 50x32.



Resolution reductions produce highly geared pay-off in terms of run-speed, because the direct reduction in cells to be processed is accompanied by (obligate) increases in mxing update increment and by (non-obligate) decreases in the required development resolution. The effects are shown in Table 1.

Table 1: Run Times
(sec/year)

Lagrangian	400x256	200x128	100x64	50x31
50,000	*30,000*	*470*	*30*	*1.2*

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Regime Shifts and Long-term Climate Impacts on the Marine Ecosystem

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How the ecosystem will react to long term changes in climate is of ongoing concern. Yet few regions have long records judged on climatological scales. The Continuous Plankton Recorder (CPR) is one of the longest, dating from the late 1940s, but has been restricted to well-established shipping routes. In many regions, driven by human commercial interests, fish catch records exceed the history of marine biological studies.

The relationship between the climate system and the environment is complex, in part due to non-linear processes in both systems and to the presence of both natural and measurement noise. Different analytical approaches attempt to reduce such complex systems to their simplest form so that we can gain understanding of the underlying mechanisms. Deriving physical climatic indices is one way to reduce large scale, changing atmospheric patterns to a single parameter. The North Atlantic Oscillation (NAO) index dates from the 1850s and its use has provided useful insights into both marine and terrestrial biophysical interactions. Such indices are parameterisations of the system and should not be confused with an underlying mechanism or driving force.

Since climate-ecosystem links are non-linear, an alternative index approach is to work with that non-linearity. To extract a non-linear physical signal, a "bulk parameterisation" of ocean processes, which matches the way bio-systems have already responded to their environment. Climate studies regard the atmosphere as having no short-term memory. Without a memory the land-atmosphere system cannot remember what happened last year. Each year the ocean stores heat and releases that heat over a number of years. So the ocean is considered to act as the memory for the land/atmosphere system. Hence if "memory" in land signals is regarded as the "reminder or feedback" from the oceans this enables us to associate repeated or persistent signals in seasonal air temperatures with long-term, bulk, ocean processes.

Using this concept a new index technique, called MONACLE, has been derived which emphasises the non-linearity in a time series as well as allowing noise to be an integral part of the any feedback mechanism. It can be shown that the approach works for different historically dominant fish catches around the North Atlantic. Regime shifts in both regional index and fish catch match and occur on variable 20-70 year time scales. This approach allows us to question whether such regime shifts represent periods when the ocean-climate system undergoes changes resulting in environmental "stress". On the Eastern-North Atlantic side land stations have over 300 years of atmospheric records providing an index which shows a higher level of variability in both the 1700s and the 1900s, with far less variability in the 1800s. Currently we can only speculate on whether similar temporal pattern occurred in the Western-North Atlantic.

UK Plans For Globec Work In The Nw Atlantic

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Introduction

The UK Natural Environment Research Council (NERC) Marine Productivity Thematic Programme is an initiative modelled on the GLOBEC principles, which sets out to discover how climate fluctuations affect secondary production in the ocean. The Programme includes a North Atlantic basin scale modelling component and a field campaign focusing on the sub-arctic Irminger/Labrador gyre. The interest in the Irminger Sea arises because 1) it is a locus of high secondary production which supports major North Atlantic fisheries in the fringing shelf seas, 2) the zooplankton community is dominated by a few key species thereby simplifying the scientific task, 3) the physical oceanography has been clearly affected by changes in the state of the North Atlantic Oscillation (NAO) index since the 1960's, and 4) a major plankton-oceanography study of the region was carried out in 1963 providing an outstanding database for a revealing comparative analysis with the data we shall collect in 2001-2003. An added advantage of concentrating on the Labrador/Irminger Seas is that considerable understanding of the circulation and water mass properties of this region has been developed as a result of the WOCE programme. The general approach is to focus on key zooplankton species of the region (the copepod *Calanus finmarchicus*, and the euphausiids *Thysanoessa longicaudata* and *Meganyctiphanes norvegica*), and conduct research to understand how their life-cycles and population dynamics interact with the physical oceanographic system they inhabit.

Why should we choose to focus on *C. finmarchicus*, *T. longicaudata* and *M. norvegica*?

These particular species have been chosen because 1) they are characteristic of the sub-arctic North Atlantic, 2) they have a historical relationship with climate indices in particular the NAO and, 3) they play a key role in the pelagic food web of the sub-arctic North Atlantic (Parsons and Lalli, 1988). The major international fishery in the Irminger Sea (40-60,000T) targets redfish, *Sebastes mentella,* and stomach analyses show that copepods and euphausiids form the major part of their diet (Gonzalez *et al*., 2000). An acoustic survey in 1999 gave an estimate of the redfish stock size at around 600,000T (Sigurdsson *et al*., 1999). Baleen whales, squid, salmon, and blue whiting also feed directly on both euphausiids and *C. finmarchicus* (Macauley *et al*., 1995). Norwegian spring spawning herring undertake an annual oceanic migration to Iceland tracking the development of the *C. finmarchicus* bloom across the Norwegian Sea (Misund *et al*., 1997), whilst both *Calanus* spp. and euphausiids form a significant component of the diet of most fish species in the North Atlantic shelf seas at some time in their life (Sundby, 2000). Compared to the North Pacific, the sub-arctic North Atlantic food web is characterised by a relatively inefficient microphytoplankton – macro-copepod plankton community with significant annual loss of phytodetritus to the meso- and bathypelagic zones (Parsons and Lalli, 1988). The inefficiency of the North Atlantic food web is thought to be principally due to the weak coupling between the annual cycle of primary production and the life cycle of *C. finmarchicus*, the dominant herbivorous copepod of the region in terms of biomass.

Hypotheses concerning the connection between climate and species abundance

A characteristic feature of the space-time dynamics of mesozooplankton and micronekton species demography, which is not apparent from bulk biomass data, is that the different life-cycle stages 'bloom' not only at different times, but also at different locations. The conclusion is that there is a strong space-time dimension to the life cycle which is important for the persistence of populations. The hypothesis underpinning this project is that climate fluctuations lead to disruption of this space-time dimension, which manifests as changes in abundance and demography. The key questions are – what are the physical and ecological controls on the space-time dynamics of the life-cycles of the target species, how have decadal time scale fluctuations in climate affected this coupling, and what are the consequences for the pelagic food web?

Regarding *C. finmarchicus*, modelling and observational studies have shown that the space-time dimension can arise as a consequence of interactions between seasonal/stage-dependent vertical migrations and the three-dimensional circulation regime of the oceans (Backhaus *et al*., 1994). Climate related changes in circulation (specifically the deep overflow of Greenland-Iceland-Norwegian (GIN) Seas water into the Atlantic) have disrupted the space-time dimension of the *C. finmarchicus* life cycle in the NE Atlantic (Heath *et al* 1999a). Evidence suggests that this at least partly accounts for the decline in their abundance in the region since the mid-1960's, which has been detected by the CPR surveys and is inversely related to the NAO index. It has been hypothesised that the opposite has happened in the NW Atlantic – increased deep water formation in the Labrador Sea has led to an increase in *C. finmarchicus* abundance in the Labrador/Irminger gyre (Greene and Pershing, 2000). However, there is also a possibility that trophic factors (changes in the timing, magnitude and distribution of the production of the lower trophic levels ("bottom-up control"), or changes in predation loading ("top-down control")) have contributed to these basin scale changes in abundance. Assessing the relative contribution of physical and trophic factors will be one of the goals of this project.

Aims of the project

Our aims are to discover how the population structures of *C. finmarchicus*, *T. longicaudata* and *M. norvegica* are maintained, how they respond to basin-scale physical forcing, and the consequences for the structure of the pelagic food web. To accomplish this we shall collect and analyse biological and oceanographic data from 4 broad scale surveys of the Irminger Sea and its connections with the Labrador Sea and Iceland Basin during 2001-2002, and compare and contrast these with data from the International Commission for North Atlantic Fisheries (ICNAF) NORWESTLANT surveys of the region in 1963. Our surveys will be carried out over an annual cycle of winter, spring, late summer and winter, in order to elucidate the connections between the life-cycles of our target species, the physical oceanographic regime, and the spatial and temporal patterns in prey and predators.

BACKGROUND TO THE WORK PROGRAMME

Summary of the circulation regime in the Irminger/Labrador Sea/ Iceland Basin

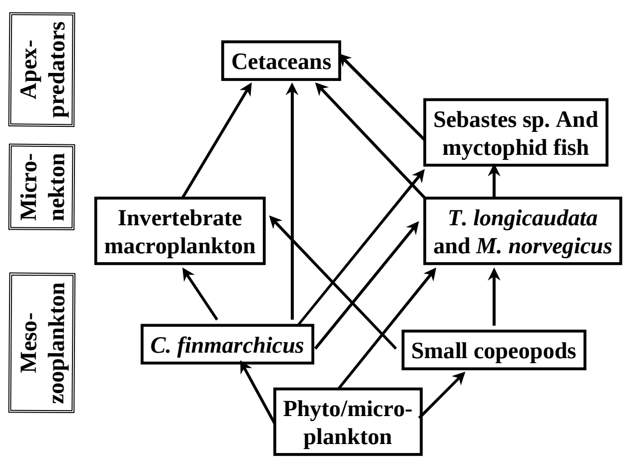
A recent Lagrangian description of the present day circulation at mid-depth in the Irminger/Labrador Sea comes from PALACE floats which indicate a recirculation cell with a series of sub-basin scale cyclonic gyres, one of which is off the east coast of Greenland (Lavender *et al*, 2000). While northward flow in this tight gyre close to Greenland has not been observed before, there is evidence for two other pathways from the Labrador Basin (eg Pollard *et al*, 1999). One is directly northeast up the western side of the Mid-Atlantic Ridge, the other enters the Iceland Basin at the Charlie Gibbs Fracture Zone, then returns in a tight Sub-Polar Gyre round the southern tip of the Reykjanes Ridge. Both these paths continue north up the western flank of the Reykjanes Ridge. A major physical objective is to quantify the transport in these 2-3 branches. The distribution of *C. finmarchicus* may itself prove to be a useful tracer for determining the importance of the Iceland Basin route, and whether there is any pathway from the northern Iceland Basin down the eastern flank of the Reykjanes Ridge as many transport schematics suggest.

There is considerable variability to the strength of convection and the circulation on decadal timescales. Convection in the Labrador Sea periodically ceases, notably in the late 60's, the 80's and most recently in the late 90's, with changes to the thickness and properties of the Labrador Sea Water (LSW) (see e.g. Dickson *et al*. 1988, Lazier, 1995, and Rhein *et al*. 1999). The signal in water mass properties of the LSW has been observed to rapidly enter the Irminger Sea on a timescale of 6 months (Sy *et al*. 1997).

Recently it has been conjectured that deep convection occurs periodically in the Irminger Sea itself (Pickard and Lavender, 2000). Changes in the pattern of convection in either the Labrador or Irminger Seas will presumably affect the circulation pattern, although there is no direct observational evidence of such changes.

The strength of the deep western boundary current flowing southward off south-east Greenland also undergoes large variations on decadal timescales (Bacon, 1998). This is presumably connected in part to variations of convection in the Greenland Sea (see e.g. Schosser *et al*., 1991), but also possibly to the interaction of the North Atlantic Current and the flow through the Charlie Gibbs fracture zone (Schott, pers. comm.).

The sub-arctic pelagic food web



New production by phytoplankton is channelled through large copepods and micronekton to the fish and apex predators in the sub-arctic food web. There is considerable information on the diet of redfish in the Irminger Sea (Gonzalez *et al*., 2000) on account of its commercial importance, but much less on predator-prey relations in the plankton. In this project we shall use the ratios of key fatty acids as biological markers of diet and plankton food web structure, and for linking variations in predator condition to productivity and oceanographic regimes (St. John and Lund, 1996; Graeve *et al*., 1994). Diatoms have a characteristically high ratio of the fatty acids C16:1(n-7) to C16:0 compared to other algal classes. Chrysophyceae, Haptophyceae and Dinophyceae are detectable by the presence of the C18:4(n-3) fatty acid. The ratio of these fatty acids in herbivorous zooplankton has been used to indicate their reliance of different algal groups, whilst low concentrations of 18:4(n-3) and 20:5(n-3) and high ratios of 18:1(n-9)/(n-7) indicate a more carnivorous diet. By this means, Falk-Petersen *et al*. (2000) concluded that *T. longicaudata* is probably more carnivorous than its congeners *T. raschii* and *T. inermis*.

The phyto/microplankton

Temporal and spatial coincidence between the annual phyto/microplankton bloom in the sub-arctic and the life cycle of the key mesozooplankton is critical for the flux of carbon through the food web. There is compelling evidence that the annual production of *C. finmarchicus* and other mesozooplankton and micronekton species, is governed by survival at a few key stages in the life cycle. In *C. finmarchicus*, one of these stages is the transition to first feeding during naupliar stage 3 (Hirche *et al*., 1999; Niehoff *et al*., 1999). Mature female *C. finmarchicus* can sustain moderate rates of egg production at relatively low levels of food abundance, but unless the stage 3 nauplii encounter high concentrations of suitable food they cannot survive. Similarly, as copepodites approach the end of stage 4 they must feed intensively to develop gonads if they are destined to mature and spawn within the current year, or accumulate wax ester storage lipids if they are destined to enter diapause (Jønasdøttir, 1999). Thus, concurrent with sampling of zooplankton demography, the project will need to collect data on the quality (functional and chemotaxonomic groupings) and abundance of phytoplankton and microzooplankton, which are the potential prey of the target zooplankton species. In addition to these instantaneous indicators of the abundance and composition of the mixed plankton assemblage, we will assess the spatial variability of new and export production from changes in inorganic and organic nutrient concentrations derived from high resolution vertical profiles.

C. finmarchicus and the mesozooplankton

Most of our understanding of the basin scale spatial and temporal dynamics of *C. finmarchcicus* and other mesozooplankton taxa in the North Atlantic derives from the CPR surveys (Planque and Batten, 2000). However, for all their value, these data provide poor stage resolution, are semi-quantitative, and restricted to the upper 10m of the water column. Fundamental to a better understanding of the coupling between life-cycle process and physical oceanography is the collection of high quality 3-dimensionally resolved, taxon-specific demographic data with concurrent physical measurements, and data on the physiological state of developmental stages in relation to the environment (eg. EU-ICOS and TASC projects in the NE Atlantic: Fish. Oceanogr. 8 suppl. 1, 1999; ICES J. Mar. Sci., 57, 2000; Canadian studies in the Labrador Sea (Head *et al*., 2000), and the US-GLOBEC Georges Bank programme (eg. Durbin *et al*. 1997)). In the case of *C. finmarchicus*, since the population may spend up to 50% of the annual cycle at 400-2500m depth in resting state, information on the associations between wintering life-cycle stages and deep circulation patterns is critical. In this project we shall use sampling technology developed in ICOS and TASC to obtain detailed depth resolved samples and data, and measurements of lipid content and composition as indicators of condition.

For *C. finmarchicus* lipid content may partly dictate the endurance and depth of the diapause phase (Visser and Jønasdøttir, 1999), and thus contribute to overwinter survivorship. Surviving post-diapause females (referred to as generation 0, (G0)) arriving at the surface in spring seem able to subsidise egg production from the residue of their winter lipid reserves, and hence sustain low rates of egg production even at apparently unsustainable exogenous food concentrations, at least until the residual reserves are exhausted (Richardson *et al*., 1999). At some locations, and in some years, it is possible that a significant fraction of the G1 copepodite recruitment arises from this lipid subsidised egg production. Lipid content in relation to stage, time and location is therefore an important diagnostic of both the history and reproductive prospects of *C. finmarchicus*, as well as their quality as food for predators.

The micronekton

Euphausiids, other micronekton and squid have been shown to be a major part of the diet of fish and cetaceans in the sub-arctic North Atlantic, and yet their distributions and abundances are only poorly known because they are difficult to sample quantitatively with nets. In fact, the open ocean abundance of *M. norvegica* is a matter of some debate. However, developments with hydroacoustic sampling technology now enable the biomass of these taxa to be estimated from ship-based transect surveys (eg. MacLennan and Simmonds, 1992; Brierley *et al.* 1998, Lavoie *et al.* 2000). Several hydroacoustic surveys have been carried out in the Irminger/Labrador Sea area for redfish (*Sebastes mentella*) stock assessment (Sigurdsson *et al*., 1999) and these have reported an extensive series of 38kHz scattering layers between 250 and 500m depth (Magnusson, 1996). Sampling with a 2.5 m^2 frame trawl during the EU-TASC project indicated that euphausiids and mesopelagic fish were the major constituents of similar layers in the Iceland Basin. Redfish are distributed mainly in the upper 500m and are widespread around the Reykianas Ridge and the eastern Irminger Basin, and feed heavily on both euphausiids and *Calanus*.

Both of the target euphausiids have been reported to feed on *C. finmarchicus* (Bamstedt and Karlson, 1998), and myctophid fish have been observed actively selecting copepodite V stage *C. finmarchicus* (Sameoto, 1989). Hence, it seems likely that much of the predation pressure on *C. finmarchicus* is concentrated in these scattering layers. The layers differ in their seasonal and diel vertical migration patterns, suggesting that the constituent taxa are separated vertically. Key questions pertaining to *C. finmarchicus* mortality are 1) when and where do these scattering layers coincide with the 3-dimensional distribution of *C. finmarchicus*, and 2) is there any interaction between the vertical distributions of predators and prey (Kaartvedt, 1996; Dale *et al*., 1999), or are they simply dictated by physical constraints?

Cetaceans

Cetaceans include some of the oceans' major consumers of secondary production, and their distribution is predicted to reflect spatial and temporal patterns of productivity (Jacquet *et al*., 1996). Currently, quantitative data on cetacean distribution in the NE Atlantic are available from only a few systematic surveys (eg. Sigurjonsson 1985; Buckland *et al*., 1992) and no systematic cetacean survey in North Atlantic has simultaneously collected physical and biological oceanographic data. In the past, efforts to determine spatial and seasonal patterns in the cetacean distribution have also been constrained by the need to conduct visual surveys during daylight and calm sea conditions. Recently, the use of passive acoustic monitoring to detect cetacean vocalisations has transformed the scope for cetacean surveying, and we have successfully used these techniques during multi-disciplinary oceanographic programmes in the N.E. Atlantic. One of the components of the project will use a combination of passive acoustic and visual surveys to collect data on cetacean distribution. Using this approach, we will be able to collect parallel data on these apex predators during the RRS Discovery's winter and summer oceanographic cruises.

Comparative analysis - the NORWESTLANT data set.

In 1963, during the era of lowest NAO indices in the 20th century, the International Commission for the Northwest Atlantic Fisheries (ICNAF) co-ordinated a major oceanographic, plankton and fisheries study of the Irminger and Labrador Seas (NORWESTLANT) (ICNAF Special Publication No. 7, 1968). Three surveys of the region were carried out (31 March – 9 May, 1 May – 18 June, 30 June – 3 August), and the sampling covered detailed physical oceanographic measurements, phyto/microplankton, zooplankton (focussing specifically on the demography of *C. finmarchcicus*, *T. longicaudata* and *M. norvegica*, for the same reasons as in our proposal), fish larvae and cetaceans.

Oceanographic conditions in the Irminger Sea at the end of the 1990’s were substantially different from those in 1963. Sea ice extended south along the east coast of Greenland as far as Cape Farewell throughout the NORWESTLANT survey period. High phytoplankton biomass (>5 mg chl m^{-3}), and the bulk of surviving early copepodite stages of *C. finmarchicus* and furcilia stages of *T. longicaudata* were distributed in a narrow band along the ice edge. In contrast, during the late 1990’s the area extent of sea-ice cover reduced to minimum observed values since at least the mid-20^{th} century. Deep-water overflow across the Greenland-Scotland Ridge has also significantly reduced in the intervening years, affecting the potential overwintering habitat for *C. finmarchicus*. During the 1990’s alone there has been a pronounced warming of the upper 200m of the water column, with marked consequences for the distribution of redfish, which occupy a temperature range of 3.4-5.7EC (Sigurdsson *et al*., 1999). We therefore hypothesise that the spatial structure of the food web, patterns of *C. finmarchicus* ascent from overwintering, and the spatial patterns of *C. finmarchicus* and *T. longicaudata* recruitment in the Irminger Sea in 2001-2003, will differ significantly from that in 1963, in a manner that can be explained in terms of the circulation, water mass distribution and sea-ice cover.

WORK PROGRAMME

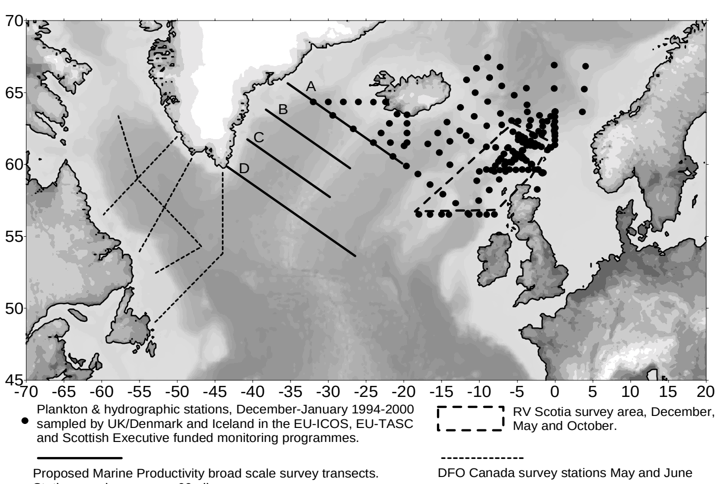
Overview of the Programme structure

The Programme is structured as 7 interconnected projects, each with separate leaders, but integrated together by the overall mission of establishing the coupling between oceanography, zooplankton species demography, and the food web structure, and comparing the present-day system with that observed in 1963.

Survey dates and vessels

The RRS Discovery has been requested for the following periods: **Cruise 1**: 1 November-18 Dec 2001; **Cruise 2**: late April - early June 2002; **Cruise 3**: August - early September 2002; **Cruise 4**: November - Deccember 2002.

Draft survey plan and sampling regime



The two winter cruises (1 and 4) will be fully devoted to broad scale survey work. During the spring and summer cruises part of the time will be devoted to process studies. We anticipate that the broad scale survey component of each cruise will collect samples from 35 stations at 60 nautical mile intervals along the survey transects (closer spacing near the mid-Atlantic Ridge and shelf edge). Each station will entail a lowered deployment of WOCE standard hydrographic equipment plus hydro-acoustic and ADCP systems, followed by three towed deployments of different net samplers. Although the time available for broad scale survey work in the spring and summer is less than in the winter cruises, we can anticipate better weather conditions. We have estimated 40% downtime due to weather in the winter, and 10% in spring and summer.

Other vessels will also be conducting hydro-plankton and hydro-acoustic surveying in the North Atlantic during 2001-2003. From the UK, RV Scotia will be sampling in the NE Atlantic during December 2001, and provisionally May 2002, October 2002, December 2002, May 2003 and October 2003. From Canada, the Department of Fisheries and Oceans (DFO) routinely conduct surveys of the Labrador Sea in May/June. We already have arrangements in place to collaborate with these agencies in a pan-Atlantic analysis based on the combined data sets. The Discovery transects have been positioned to interface with their programmes and to capitalise on the existing database from the EU-TASC project.

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Ecology of *Calanus finmarchicus* in Icelandic waters and the Irminger Sea

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Iceland is located in the northern part of the North Atlantic at the junction of two great submarine ridge systems, the Mid-Atlantic Ridge and the Greenland-Scotland Ridge (Fig. 1). The ridges have important influences on the ocean circulation and the distribution of water masses around Iceland, as they constrain flow between the relatively warm waters of the North Atlantic and the colder waters of the Nordic Seas. South of Iceland the water is mainly relatively warm Atlantic Water which flows towards the south coast with the North Atlantic Current, whereas north of the country the water masses are formed by mixing and local modifications of warm Atlantic waters originating from off the south coast and cold Polar and Arctic Water carried from the Arctic Ocean by the East Greenland and East Icelandic currents, respectively (Fig. 1). In the Irminger Sea the circulation is cyclonic and it connects to the Subpolar Gyre in the northwestern North Atlantic.

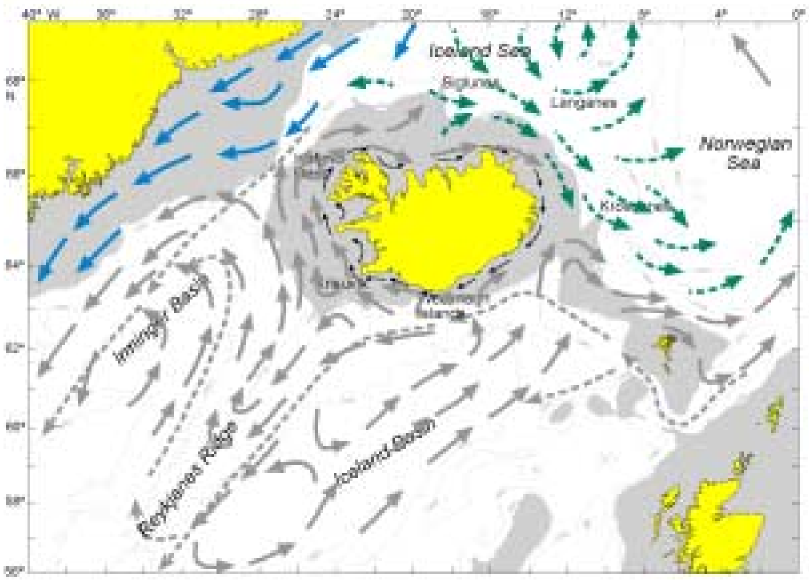


Figure 1. The main ocean currents around Iceland. The currents in the upper layers are redrawn from Valdimarsson and Malmberg (1997), and the main overflow paths over the Greenland-Scotland Ridge from Hansen *et al.* (1998). Grey arrows: Atlantic Water; black arrows: Polar Water; black broken arrows: mixed water; grey broken arrows: main overflow paths.

Long term zooplankton monitoring has shown that in spring the biomass of total zooplankton is highest in the Arctic East Icelandic Current northeast of Iceland, and on the shallow banks off the southwest coast (Astthorsson and Gislason 1995, Astthorsson et al. 1983, Beare et al. 2000) (Fig. 2A). The reason for the high biomass values in the northeast is the high abundance of the large Arctic species (*Calanus hyperboreus* and *Metridia longa*) that are transported to the region from the north by the East Greenland and East Icelandic Currents. Thus the high biomass in the oceanic area northeast of Iceland partly reflects immigration rather than local production. On the other hand the relatively high zooplankton biomass on the shelf southwest of Iceland may reflect the higher secondary productivity in the frontal area between the Coastal Water and the Atlantic Water (Astthorsson and Gislason 1995).

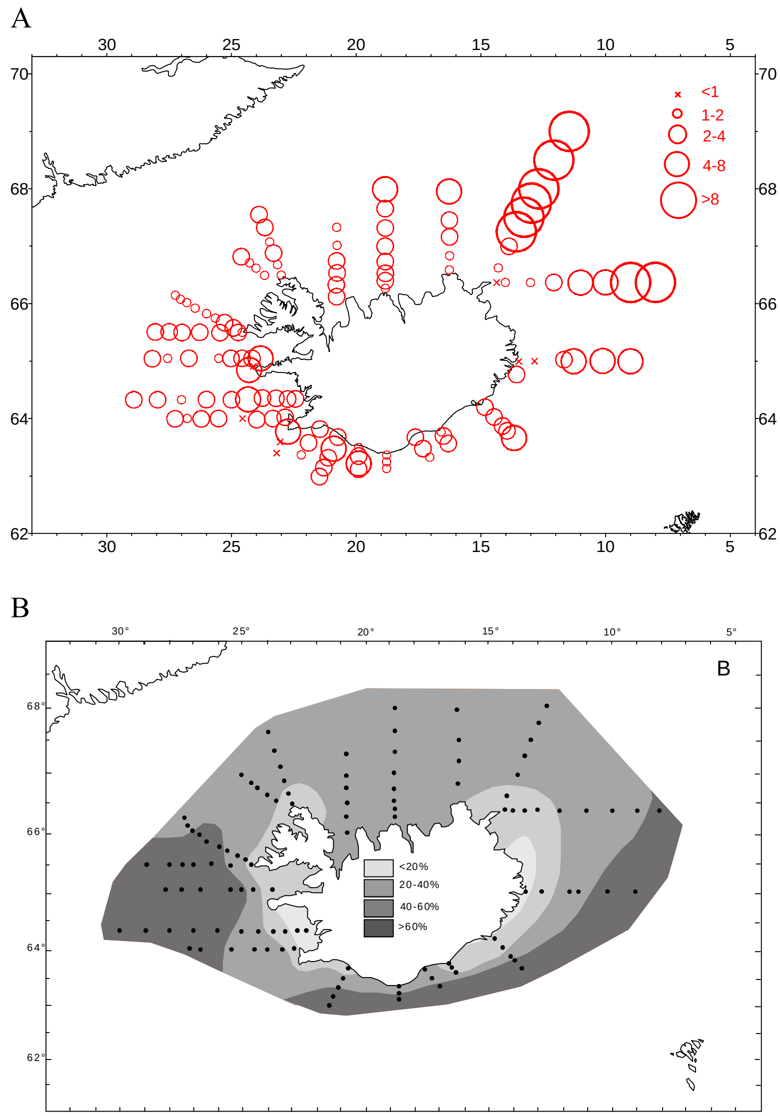


Figure 2. Average zooplankton biomass (A) and average percentage frequency of *Calanus finmarchicus* (B) around Iceland in May-June 1960-1999.

Calanus finmarchicus is a key species both in the Atlantic waters south and west of Iceland, including the Irminger Sea, and in the mixed Arctic-Atlantic waters north of the island (Astthorsson et al. 1983) (Fig. 2B). In spring the percentage of *C. finmarchicus* increases towards the Norwegian Sea, the Iceland Basin and the Irminger Sea. In these areas it generally constitutes >60% of the zooplankton by number (Fig. 2B).

In the Atlantic Water South of Iceland, there are basically two peaks in both total numbers and total biomass during the summer, the former in May-June and the latter in July-August (Gislason and Astthorsson 1995, 1996, Gislason et al. 2000) (Fig. 3).

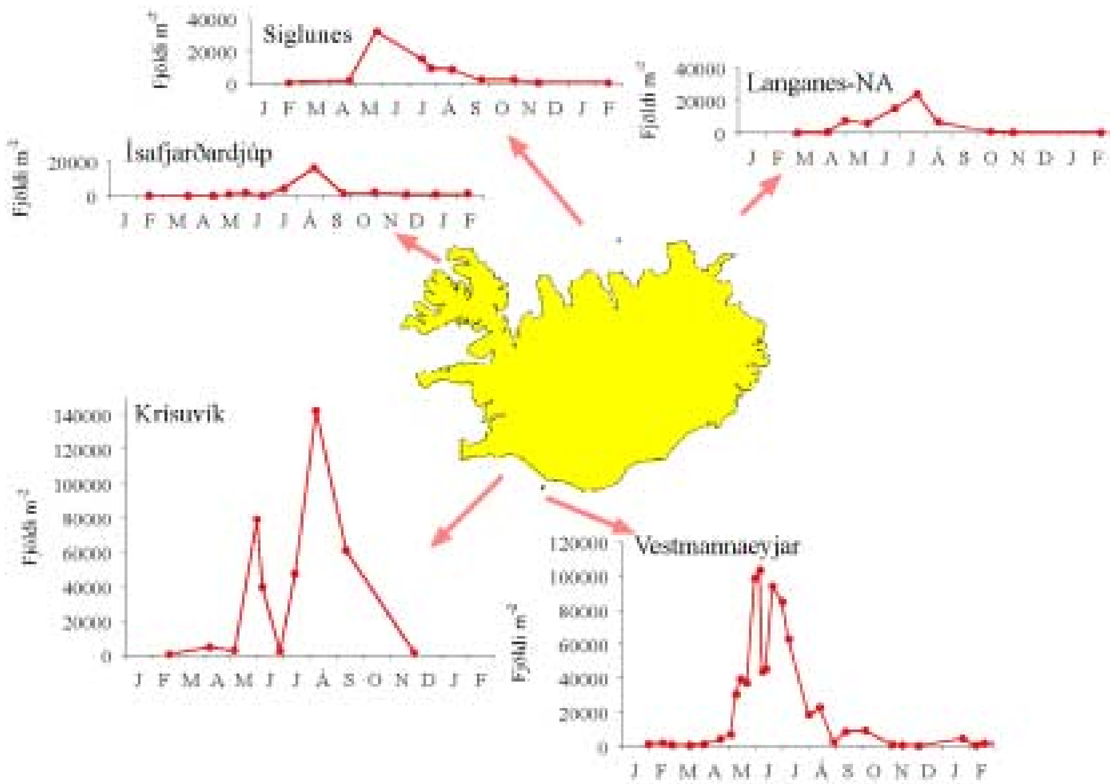


Figure 3. Seasonal variations in the abundance of *Calanus finmarchicus* at locations around Iceland (numbers m^{-2}, 0-100m). From Astthorsson and Gislason (1992, 2001) and Gislason and Astthorsson (1996, 1998, 2000)

In the Subarctic Water north of Iceland the seasonal variations in both numbers and biomass of zooplankton are characterised by low winter values and one maximum during the summer (Astthorsson and Gislason 1992, 2001, Gislason and Astthorsson 1998). These seasonal changes generally reflect the different life cycles of *Calanus finmarchicus* in these environments, with a part of the stock having two generations in the waters south of Iceland and only one off the north coast. The reason for the observed differences in seasonal dynamics of *C. finmarchicus* in the different environments around Iceland is most probably related to the different temperature regimes in these environments, with temperatures in the surface layers during summer being much higher south of the country (~6-9°C) than in the north (~1-5°C). However, other factors, such as feeding conditions, predatory impact and advection may also be playing a part.

Southwest of Iceland *Calanus finmarchicus* overwinter at 200->2000m depth, mainly as copepodite stages C4 (~14%) and C5 (~85%), while few females are also found (~1%) (Fig. 4) (Gislason and Astthorsson 2000). Migration up to the surface takes place during March, April and May, and in June the density of animals is highest in the uppermost 100 m of the water column. Mating probably takes place while the animals are migrating up to the surface. Oceanic stocks are then advected onto the shelves to produce a new generation. The southern and western shelves are probably mainly colonised from the south, i.e. from the Iceland Basin, while import from the Irminger Sea may also be important, especially onto the western shelf (Gislason and Astthorsson 2000).

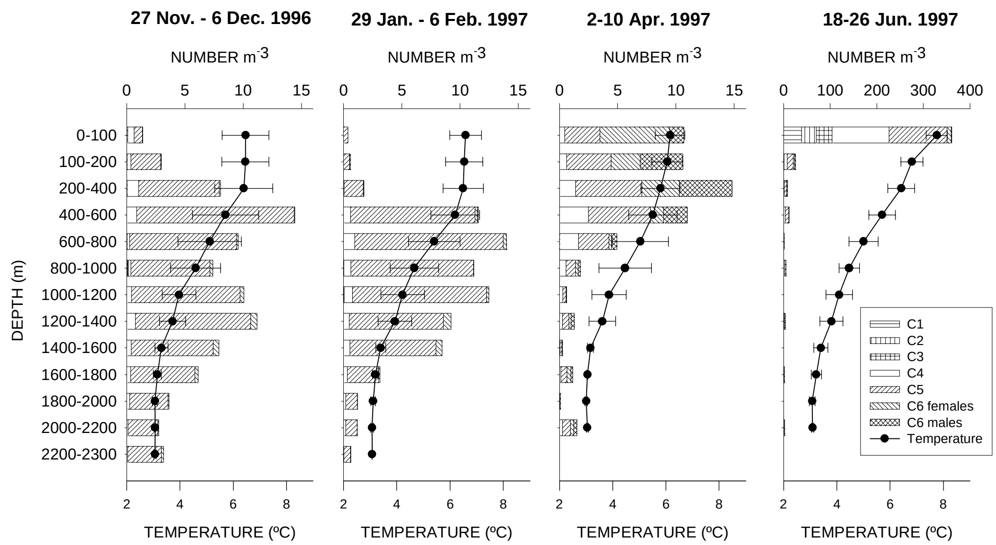


Figure 4. Vertical distribution of *Calanus finmarchicus* (numbers m^{-3}) during 27 November-6 December 1996, 29 January-6 February 1997, 2-10 April 1997, and 18-26 June 1997. The values are means from 5 stations in the Irminger Sea. Temperature profiles obtained by simultaneous CTD casts are also shown. Horizontal lines on the temperature plots show standard deviation. Note the change in horizontal scales between April and June. From Gislason and Astthorsson (2000)

In the Irminger Sea overwintering animals are found in association with Atlantic Water, Intermediate Water and Labrador Sea Water (Gislason and Astthorsson 2000) (Fig. 5). The presence of animals in the Intermediate Water and the Labrador Sea Water indicates that the stocks in the Irminger Sea partly originate from the Labrador Sea. In the Iceland Basin overwintering animals are mainly found in association with Atlantic Water and Intermediate Water (Gislason and Astthorsson 2000).

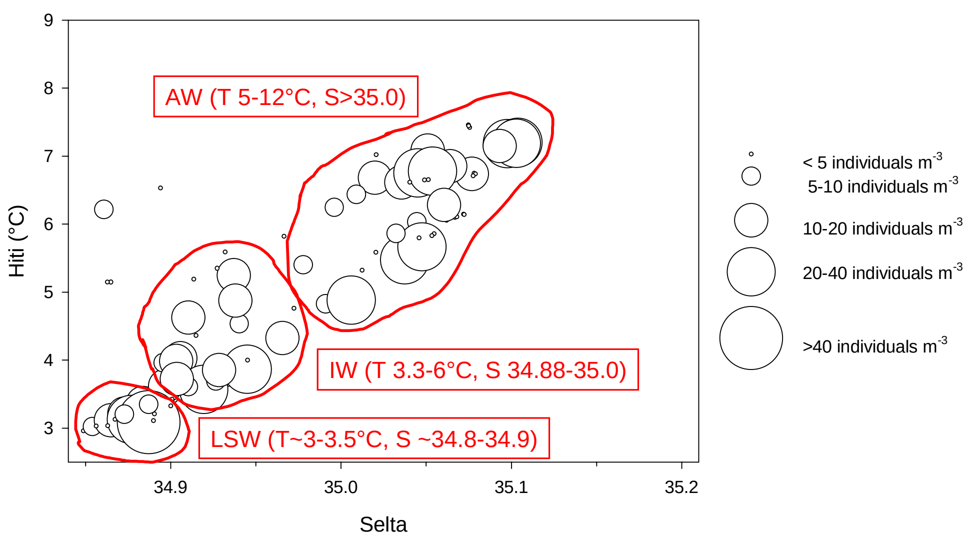


Figure 5. Distribution of *Calanus finmarchicus* in the Irminger Sea in relation to temperature and salinity during 27 November-6 December and 29 January-6 February 1997. AW: Atlantic Water; IW: Intermediate Water; LSW: Labrador Sea Water.

The spring spawning of *Calanus finmarchicus* is closely coupled to the development of the phytoplankton. Thus, due to the similar timing of the spring bloom in the Atlantic water south of Iceland and in the Subarctic waters north of the island, and in spite of the much higher spring surface water temperatures in the former region (~6-9°C) compared to the latter (~1-5°C), the spring spawning of *C. finmarchicus* starts at similar time in both areas (e.g. Gislason and Astthorsson 1995, 1998).

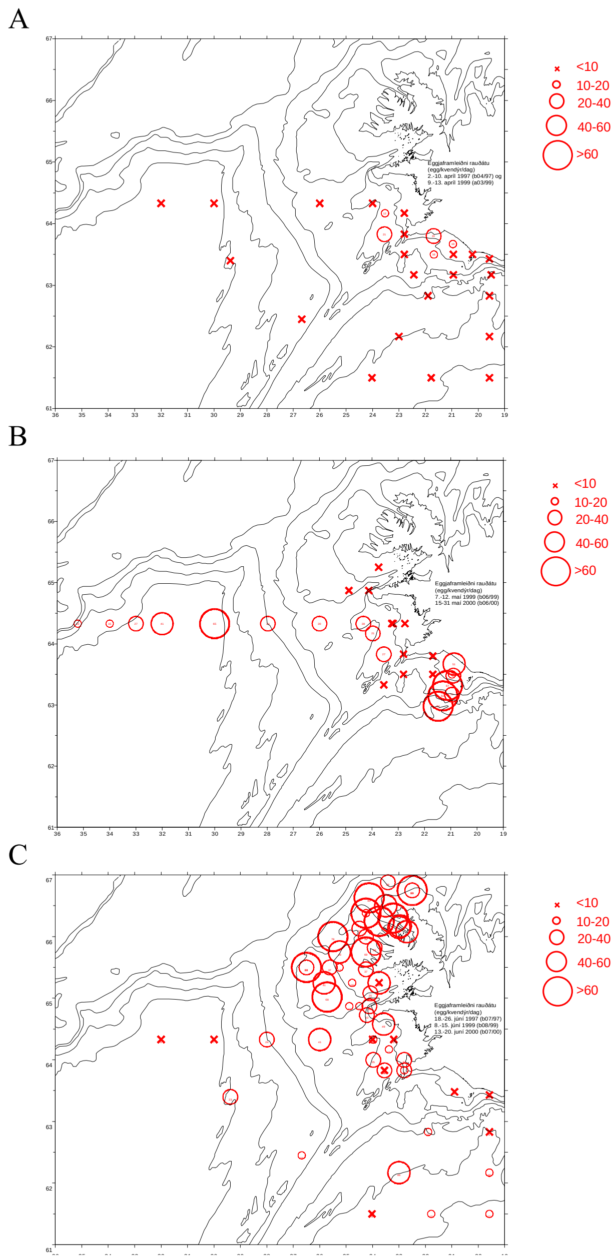
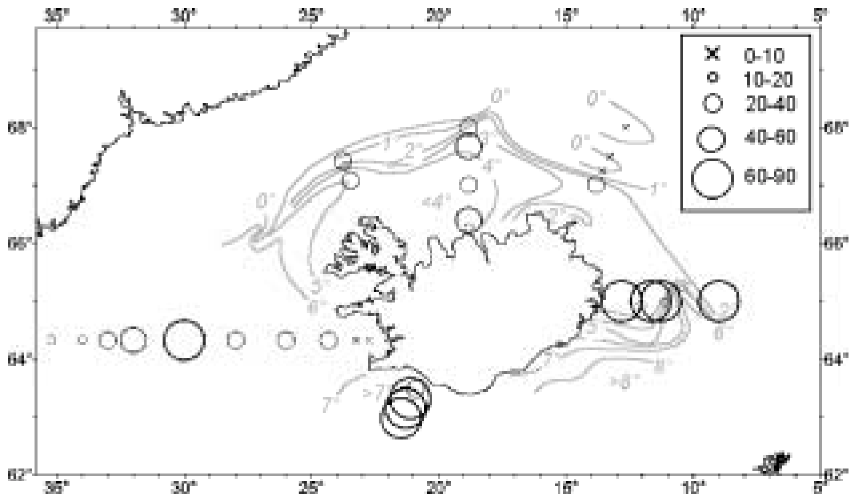


Figure 6. Individual egg production rates of *Calanus finmarchicus* (eggs female^{-1} day^{-1}) in April (A), May (B) and June (C). The data are from 1997 and 1999 (April), 1999 and 2000 (May); and 1997, 1999 and 2000 (June).

On the shelf *Calanus finmarchicus* started to reproduce in April, while in the offshore area reproduction began in May (Gislason and Astthorsson 2000) (Fig. 6). On the shelf, egg production rates were lower in April (<10-20 eggs female^{-1} day^{-1}) than in May and June (<10->60 eggs female^{-1} day^{-1}). Further the areas of highest egg production rates along the west coast had shifted from south to north during this period, following the general current pattern in the area. In the Irminger Sea, the egg production rates were higher during May (10->60 eggs female^{-1} day^{-1}) than in June (<10-40 eggs female^{-1} day^{-1}) (Fig. 6).

A



B

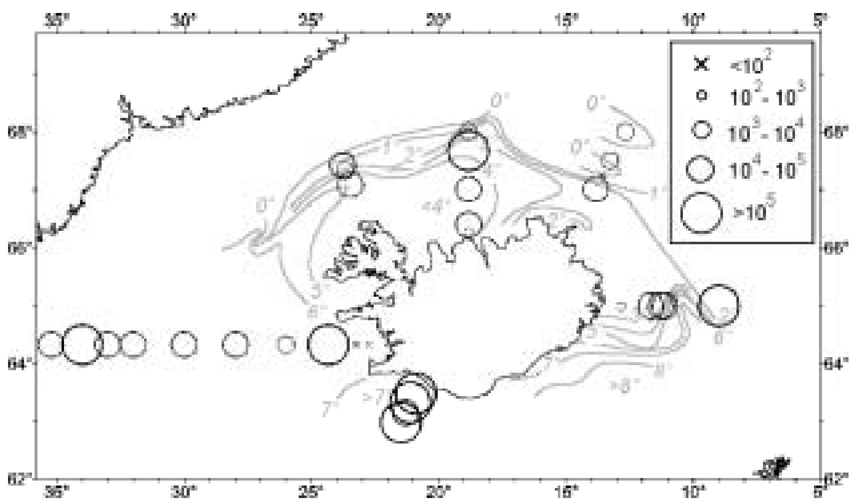


Figure 7. Individual egg production rates (eggs female^{-1} day^{-1}) (A) and population egg production rates (eggs m^{-2} day^{-1}) (B) of *Calanus finmarchicus* during 15-31 May 2000. The gray lines show sea temperature (°C) at 50 m depth.

Results from a survey that was carried out around Iceland in May 2000 show that then individual egg production rates were highest in the frontal areas east of Iceland, in shallow waters off the south coast, and in the central parts of the Irminger Sea (>60 eggs female day) (Fig. 7). In the cold Arctic East Icelandic Current (<1°C) individual rates were very low (<7 eggs female^{-1} day^{-1}). In terms of production of the whole population the rates were highest in the frontal areas north and east of Iceland, in shallow waters off the south coast, and in the central parts of the Irminger Sea (10^4->10^5 eggs m^{-2} day^{-1}). Although individual females in the East Icelandic Current were producing few eggs the population production was nevertheless relatively high (10^3-10^4 eggs m^{-2} day^{-1}), because of relatively high numbers of spawning females. However, the hatching rates of the eggs and the survival of the larvae are unknown.

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Slope Water Circulation and Sea Level

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The Slope Water region lies between the Gulf Stream and the continental shelf in the northwestern Atlantic Ocean. Mixtures of several source water masses form the surface and intermediate-depth waters. McLellan (1956) proposed a scheme including warm, saline North Atlantic Central Water from south of the Gulf Stream, cold, fresh Labrador Current Water, and low-salinity Coastal Water influenced by river runoff. Gatien (1976) used temperature-salinity observations from 1960 to identify two distinct Slope Water masses. The first was Warm Slope Water, equivalent to McLellan's (1956) Slope Water. Gatien (1976) found a warming trend in the Warm Slope Water from west to east close to the Gulf Stream at depths less than about 400m. This implied that the Warm Slope Water was warming through exchanges with the Gulf Stream as it flowed from west to east along the northern edge of the Stream. Gatien (1976) defined a second water mass, the Labrador Slope Water, to include all of the Slope Water deeper than 500 m plus the northern part of the shallow Slope Water in the eastern part of the region. Labrador Slope Water temperatures were colder in the eastern part of the Slope Water region, leading Gatien (1976) to conclude that this water mass is more influenced by the Labrador Current. The implication was that its flow direction was from east to west.

Hogg et al. (1986) discussed the circulation in the Slope Water region on the basis of current meter measurements. They identified a weakly depth-dependent gyre transporting 20-30 x 106 m3 s-1 (Sv). Hogg (1992) summarised direct flow measurements from the Gulf Stream and Slope Water between Cape Hatteras and the Grand Banks and produced a schematic circulation scheme for depth-integrated transport that included a Northern Recirculation Gyre.

Direct flow measurements were made at 50°W during 1988-90 in the Intergyre Exchange Experiment (IEE) carried out by the Bedford Institute of Oceanography's (Hendry, manuscript in preparation). Figure 1 shows a gridded interpretation of the mean zonal flow in the latitude range 41°N to 42°45'N

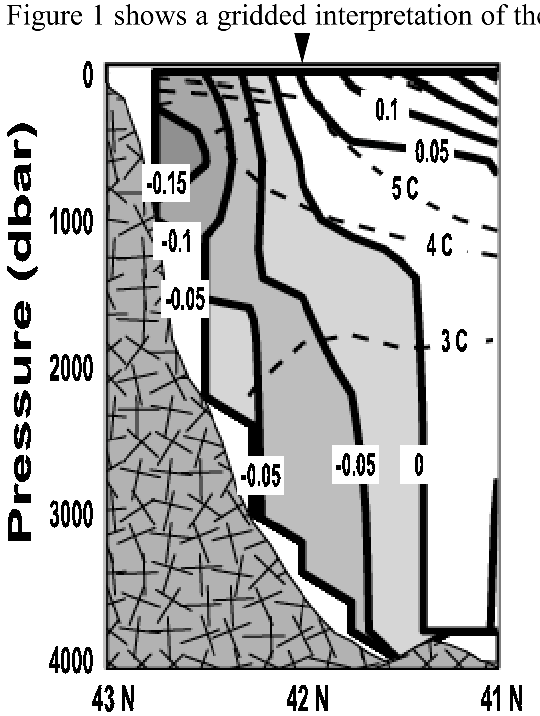
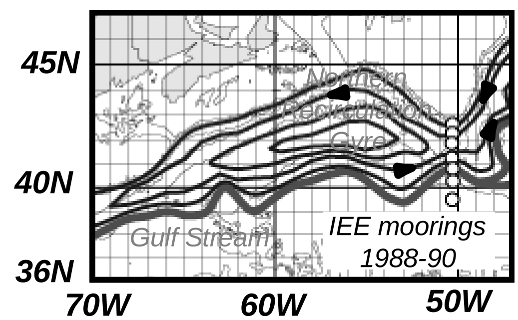


Figure 1. Conditional mean zonal flow at 50°15'W based on mapped current measurements from April 1988 to January 1990. Shaded regions represent flow to the west. Mean temperature contours are shown as dashed lines.

based on the IEE measurements. The figure is based on conditional statistics that attempt to remove the influence of warm core Gulf Stream rings. The criterion used included a requirement that the 200 m temperature at 42°N be less than 6.5°C. The conditional mean shows a weakly depth-dependent westward flow along the continental rise south of the Grand Banks. Total mean westward transport was about 20 Sv, divided into approximately equal contributions for temperatures less than and greater than 3°C. The westward transport in the 3°C to 5°C temperature range represents a substantial inflow of water which we identify with Gatien's (1976) Labrador Slope Water. Much of the Labrador Slope Water may be formed outside the Slope Water region, entering the region at 50°W as a distinct water mass. Figure 2 is a schematic Slope Water circulation at intermediate and shallow depths modified from Hogg's (1992) depth-integrated version. Figure 5 emphasises both inflow/outflow and recirculating components of Slope Water transport

Figure 2. Schematic Slope Water and Gulf stream circulation diagram. Symbols along 50°15'W show the locations of Intergyre Exchange Experiment (1988-90) current meter moorings.



Gridded maps of zonal flow at daily intervals were created by spatially interpolating the moored measurements. Geostrophic shears based on climatological hydrographic data were used to extrapolate the zonal flow maps to the sea surface. Surface zonal flows were integrated as a function of latitude to yield sea level time series, an application of geostrophic levelling. The origin for the integration was 42°45'N, the northernmost limit of the grid, where sea level variability is expected to be relatively small. Figure 3 shows the resulting sea level time series at 42°N, roughly coincident with the 3000 m depth contour and near the dividing line between zones of westward and eastward mean flow. An energetic warm core ring was responsible for the prominent peak in August-September 1989. The conditional sampling is an attempt to remove the influence of transient, non-stationary feature like this from the statistics.

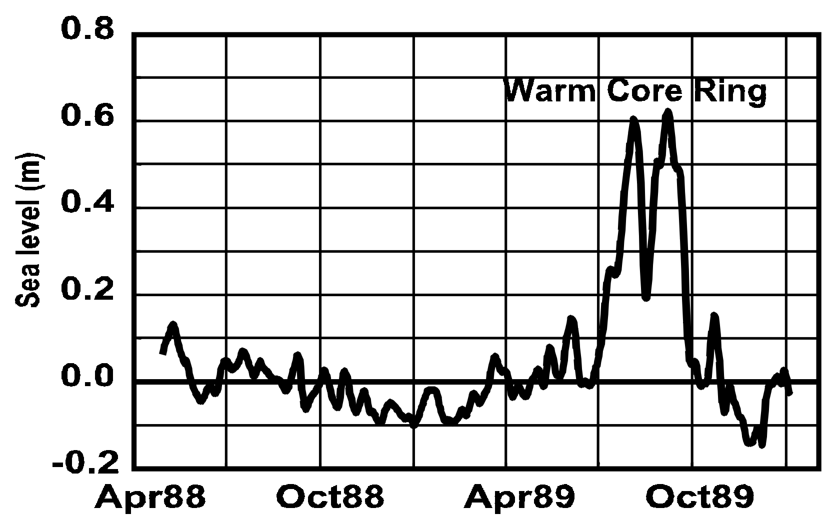


Figure 3. Sea level at 50°15'W, 42°00'N for April 1988 – January 1990 calculated by geostrophic leveling of the surface zonal flow.

Figure 4 is a scatter diagram of IEE westward volume transport at temperatures between 3°C and 5°C plotted against sea level at 42°N. The lighter-coloured symbols in the figure indicate points excluded in the conditional statistics. Conditional mean sea level was -0.04 m, compared to an overall mean of 0.05 m. Conditional mean volume transport was -13 Sv, compared to an overall mean of -11 Sv. Except for periods when warm core rings dominated the flow field, changes in transport were correlated with changes in sea level. Increased westward transport in the chosen temperature range was associated with lower sea level at 42°N. Simple layer models (Stommel, 1966) yield a quadratic relationship between sea level and volume transport. The dashed line in Figure 4 is a conditional quadratic regression constrained to pass through transport = 0 Sv at sea level = 0.1 m.

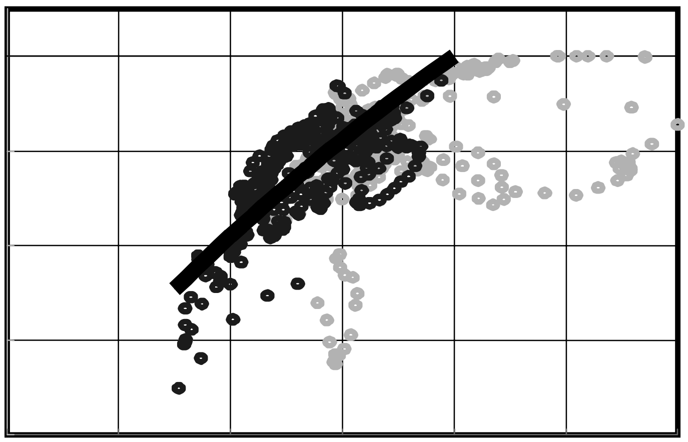


Figure 4. Scatter plot of westward volume transport at temperatures between 3°C and 5°C from maps of IEE zonal flow and temperature plotted against sea level at 42°N. The dashed line is a quadratic regression. The lighter points, identified with warm core ring events, were excluded from the fit.

TOPEX/POSEIDON altimetric data have been compiled into useful Maps of Sea Level Anomalies (MSLA) gridded products by the French AVISO group (Le Traon et al., 1998). The MSLA grid point at 42.125°N, 50.375°W is near the site of the 42°N IEE sea level time series in Figure 3. The September 1992 - January 2001 MSLA sea level anomaly time series at this point shows low-frequency fluctuations of 0.1 m, but no events comparable to the energetic warm core ring observed in the IEE measurements. MSLA sea level anomaly time series at 50.375°W, 42.875°N and 50.375°W, 42.125°N were differenced to provide an analogue of the IEE 42°N sea level time series. A temporally low-passed transport time series for the TOPEX/POSEIDON time period was calculated from the quadratic regression model using this difference time series (Figure 5). The -9 Sv mean transport in Figure 5 is arbitrary inasmuch as the mean values of the MSLA anomaly time series are zero by construction. The IEE conditional mean meridional sea level difference of -0.04 m Sv corresponded to a mean transport of –13 Sv. The transport variations are arguably more meaningful. They show a prominent interannual variability with a standard deviation of about 4 Sv.

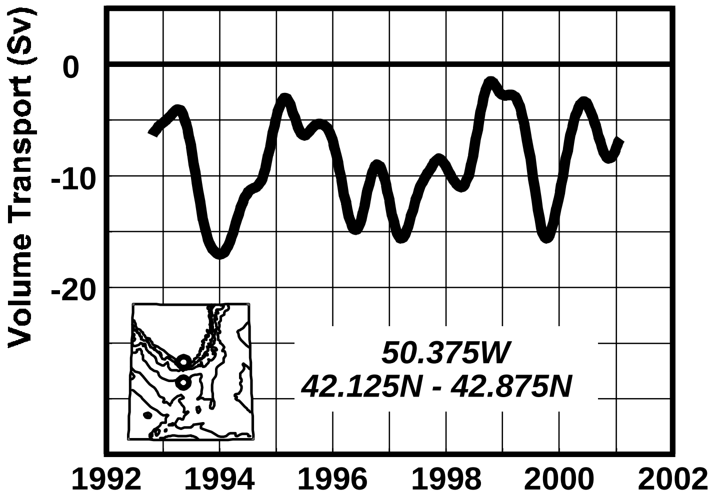


Figure 5. Westward volume transport for temperatures between 3°C and 5°C based on TOPEX/POSEIDON sea level measurements near 50°W from September 1992 to January 2001. The inset map shows the locations of the sea level time series used to construct the transport estimates.

Figure 6 shows the May 24, 1996 meridional profile of temporally low-passed MSLA sea level anomaly from 50.375° W between 41°N and 43°N. This corresponds to the 1996 relative maximum westward transport in Figure 5. The points that were spatially differenced to provide the transport estimates are highlighted.

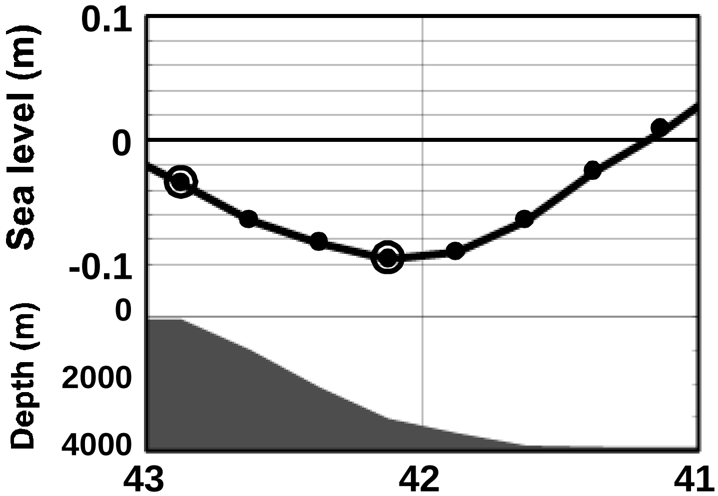


Figure 6. Temporally low-passed TOPEX/POSEIDON sea level anomaly along 50.375°W for May 24, 1996. The difference in sea level between the highlighted symbols is –0.06 m. This gives a volume transport of –14.8 Sv in Figure 5. A bathymetric profile is also shown.

These preliminary results suggest that altimetric measurements of sea level could provide a useful proxy measure of the variability of Labrador Slope Water inflows into the Slope Water system.

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The MSLA altimeter products were produced by the CLS Space Oceanography Division as part of the European Union Environment and Climate project AGORA (ENV4-CT9560113) and DUACS (ENV4-CT96-0357) with financial support from the CEO programme (Centre for Earth Observation) Midi-Pyrénées regional council.

Climate connections in the Gulf of Maine

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Situated in an oceanographic transition zone, the Gulf of Maine/Western Scotian Shelf (GOM/WSS) region of the Northwest Atlantic is especially susceptible to changes in the climate system. Recent studies suggest that a coupled slope water system (CSWS) operates in the Northwest Atlantic and responds in a similar manner to climatic forcing over a broad range of time scales. These studies further suggest that it may be possible to associate different modes of the CSWS with different phases of the North Atlantic Oscillation (NAO). Time-series data collected from the GOM/WSS region over the past half century, we show that: (i.) the CSWS mediates the effects on these ecosystems of basin-scale climatic forcing associated with the NAO, and (ii.) shifts in the state of the CSWS are associated with changes in the abundance *Calanus finmarchicus*.