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# REPORT OF THE WORKING GROUP ON COD AND CLIMATE CHANGE

**Lowestoft, U.K., 7-11 June 1993**

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**Other GLOBEC-INT documents currently available are:**

No. 1 Report of the first international GLOBEC planning meeting. Ravello, Italy, 31 March-2 April 1992

No. 2 Report of the first meeting of the international GLOBEC working group on Population dynamics and Physical Variability. Cambridge, UK, 1-5 February 1993

No. 3 Report of the first meeting of the international GLOBEC working group on Sampling and Observational Systems. Paris, France, 30 March-2 April 1993

Copies of these may be obtained from GLOBEC-INT Secretariat. Address in Appendix 1.

# 1. SUMMARY

The Working Group met for the first time in Lowestoft from 7-11 June 1993 to address the terms of reference set out in Section 2. Thirty-five scientists took part and the fact that this was a joint ICES/GLOBEC group widened the geographic and scientific boundaries of the meeting.

## 1.1 Objectives and Framework

The question being investigated by the Working Group - the effect of climate variability on cod stock fluctuations - is simply stated, but involves many different scientific disciplines and scales of investigation. These range from the effects of small-scale turbulence on encounter rates between fish larvae and their prey, to large-scale effects of interdecadal changes in windfields on circulation and transport of heat and young fish. In spite of the complexity of the processes by which variable physical forcing may affect cod stocks, the effects of climatic variability can be detected for several stocks. For example periods of low temperature are observed to result in stock decline at the northern limits of cod distribution (Barents Sea, Greenland); particular hydrographic and wind conditions result in unusual transport of eggs and larvae (Iceland-Greenland) or flush out deoxygenated basins where cod spawn (Baltic). These examples combine empiricism, a growing understanding of ocean/climate variability and detailed knowledge of processes during the life history (mainly early life history) of cod. They give grounds for believing that the question is not intractable and that we may be able to predict at least the broad direction of changes in cod abundance under different physical regimes.

The Global Ecosystem Dynamics (GLOBEC) approach (see Section 3) provides a conceptual framework within which studies at different scales can be nested. It is obvious from the reports of work in progress or in planning (see Section 4) that a great deal of research which is relevant to Cod and Climate Change is already underway, even though it was not primarily designed with that in mind (for example studies of copepod dynamics and cod recruitment). The challenge for this Working Group (see Section 2) was to identify themes and approaches which strengthen and facilitate the scientific programmes being followed at individual or national level and to propose and initiate work which can be carried out more effectively at regional or international level, within ICES and GLOBEC.

## 1.2 Unifying themes

A number of unifying themes discussed in the report (mainly in Sections 4, 5 and 7) can be grouped roughly in relation to the scale of physical processes (large, intermediate, small). Large-scale processes range from global to regional (e.g. Georges Bank, the North Sea) and include long-term changes in atmosphere and oceanic dynamics, which affect cod stocks through changes in heat and transport. Intermediate scale processes include eddies, rings and fronts, which have effects due to localised aggregation, retention and enhancement of plankton production. Small-scale processes include water column stability and turbulence, which affect plankton production and encounter rates. We have tried to identify key interactions between physical and biological processes at all these scales in order to strengthen the rationale for physical oceanographers and biologists to work together from an early stage in developing models and observation programmes.

The need to consider cod in the context of the ecosystem is considered in Section 6. Although variability in cod stocks is the principal issue, there are good reasons for including other species in the investigation when their dynamics interact with cod or if they are more sensitive indicators of ecosystem change than cod.

## 1.3 Recommendations and conclusions

We have recommended three special workshops to be held in 1994 to plan and carry out retrospective analyses of physical and biological data, including considering the case for setting up a Cod and Climate database and to investigate the effects of intermediate scale physical processes. Other recommendations (see Section 8) propose topics for research which should be considered as themes for future workshops or joint sessions of committees at ICES meetings. There are also a number of proposals for specific action in relation to existing programmes (e.g. the CPR) or the initiation of new regional programmes (e.g. see Section 7.8.1).

Finally, as regards the Working Group itself the consensus of the meeting was that the work of the group could be carried forward effectively by the special workshops in 1994 and that the Working Group should meet next in 1995 to review progress and carry out further coordination, if required.

## 2. TERMS OF REFERENCE

C. Res. 1992/2:7

A Working Group on Cod and Climate Change will be established under the chairmanship of Dr K Brander (UK) with expertise in biological oceanography, hydrography, and fisheries biology, and representatives of the Working Groups on Recruitment Processes and Shelf Seas Oceanography and will meet in Lowestoft, England, UK for 5 days in June/July 1993 to:

(a) review planning and progress of Cod and Climate Change research;

(b) taking account of Cod and Climate Change documents (Docs. C.M.1990/G:50 and CM 1991/G:78) and ongoing planning of regional studies, identify elements that, if common to all regional studies, would serve as a unifying theme and enhance comparison;

(c) review recent advances in models of global and Atlantic climate variability, consider how results from these models might be used as boundary conditions for regional models, and plan a specialised workshop on the subject if such a workshop is necessary.

(d) examine possible ways of explicitly incorporating numerical population models of species of particularly interest with spatially resolved ecosystem models, in which other species are represented by a relatively small number of aggregated functional groups;

(e) consider additional opportunities for regional studies and, if appropriate, initiate planning;

(f) make recommendations, with terms of reference, for future meetings of the Working Group and/or more specialised workshops, in order to advance the goals of the Cod and Climate Change programme.

The Working Group will report to the Inter-Committee Recruitment Group before the 1993 Statutory Meeting, with reference to the Biological Oceanography, Hydrography, and Demersal Fish Committees.

C. Res. 1992/3:1

ICES will sponsor a "Cod and Climate Change" (CCC) programme of research as a North Atlantic component of the IOC/SCOR-sponsored international GLOBEC (I-GLOBEC). The purpose of the programme will be to:

(a) promote interdisciplinary research on the response of pan-Atlantic cod populations to climate variability and long-term change;

(b) provide unifying themes for regional investigations of the relationship between cod and their environment;

(c) enhance linkage between ICES and the broader marine science community.

## 3 PLANNING AND PROGRESS OF COD AND CLIMATE

### 3.1 Background and strategy

ICES and GLOBEC have joined together to develop an innovative program to advance the understanding and prediction of variability in fish recruitment both in the short term (annual forecasts) and in the long term ('climate effects'). Cod was chosen to serve as the candidate species for this exercise because (1) its biology is relatively well-known and supported by ample data bases, (2) it has a pan-Atlantic distribution and (3) its abundance and distribution have been shown to be sensitive to specific past examples of environmental variability (e.g. Appendix 2). These considerations provide Cod and Climate Change with the possibility of developing new capabilities in predicting fish recruitment from a better understanding of the interaction of physical processes and population dynamics.

These aims are consonant with GLOBEC's mission which is "to understand the effects of physical processes on predator-prey interactions and population dynamics of zooplankton and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change" (GLOBEC-INT Report No. 1).

The rationale for this mission is based upon the principles: (1) physical processes are the most important source of biodynamic variability in the ocean and (2) trophodynamics sensu latu are the major source of variability and stability in the population dynamics processes and the way these processes are integrated over the ecosystem, resulting in biological productivity.

GLOBEC is focusing on zooplankton because of the considerable research opportunity and as a complement to other global programmes which are oriented toward phytoplankton and biogeochemistry such as JGOFS. The fundamental science of GLOBEC is seen to have important applications in understanding the variability of fish recruitment; developing a better understanding of grazing control, an important global change issue; and providing new insights on how anthropogenic substances affect the community metabolism of the upper ocean.

An emerging philosophy in the GLOBEC community is that an endeavour as complex as GLOBEC needs an organising theme to focus effort and to tabulate and organise the complex of results. The development of this organising theme involves inter-relating the fundamental process studies directly with numerical models and sampling and observation systems. In this context, GLOBEC planning has purposely taken a broad point of view which is essential to find the right 'questions'; at the same time the emphasis on numerical modelling and sampling, and observation systems is intended to guide cost-effective ways for exploring these questions.

GLOBEC is now beginning to focus on particular details of the broad ecosystem questions and developing tangible next steps forward. The choice of zooplankton was made, for example, because studies on zooplankton present important research opportunities and comprise a vital complement to other programs such as JGOFS which are concentrating on phytoplankton. While focusing on zooplankton, however, GLOBEC science cannot afford to ignore fish, phytoplankton or the small heterotrophs (to the extent that these are considered different than zooplankton). This is because the population dynamics of zooplankton depends on the population dynamics of phytoplankton and mortality of zooplankton depends on fish and other predators. At the same time the population dynamics of large zooplankton needs to take account of large zooplankton progeny which are trophodynamically associated with the so-called microbial loop.

The total systems approach of GLOBEC is made further distinct by focusing on the population dynamics of particles as opposed to chemical flux issues.

In developing tangible next steps forward leading to studies of the major ecosystem types, significant opportunities have arisen to apply the GLOBEC methodology to specific proof of concept settings. One such setting involves the North Atlantic where we believe that a more fundamental understanding of the ecosystem can lead to a material improvement in our understanding and capability to predict grazer dynamics and cod recruitment.

In particular the ICES/GLOBEC Cod and Climate Program is evolving toward the development of a systems framework linking fundamental biological processes/numerical models/and sampling and observation systems.

In developing the framework this report considers fundamental biological questions; the physical foundations for these questions; the criteria for models and the development of sampling and observation systems.

### 3.2 Planning future development of the Cod and Climate Change programme

Themes and proposals for the development of the Cod and Climate programme are to be found throughout this report and the means for coordinating and guiding the programme are discussed at the beginning of Section 7. It will be evident from the reviews of work in progress (Section 4) that a wide array of investigations, which are more or less closely related to the aims of Cod and Climate, is already in progress throughout the North Atlantic.

Major new research programmes in the US and Norway have been established to carry out regional GLOBEC studies, with Cod and Climate as part of their remit. A Canadian Cod and Climate Working Group has been compiling a cod atlas - a fisheries oceanographic description of cod stocks in the NW Atlantic. Elsewhere work has been going on at an individual level, with a number of studies which are relevant to Cod and Climate, but whose aims are more specifically related to aspects of the recruitment processes in cod. Inevitably there is a high degree of overlap between the interests of Cod and Climate and studies of recruitment processes, although the latter is only one aspect of the former.

ICES has played a part in coordinating and catalysing the work on Cod and Climate which is underway. The reports of the Study Group on Cod Stock Fluctuation and the synopses of stock and biological information prepared by them and by the Recruitment Processes Working Group have helped to clarify many of the biological issues and set out the case for explicit physical/biological modelling. The ICES Symposium on Cod and Climate in Reykjavik (in August 1993) has also been a strong stimulus for new investigations of old data and for new approaches. A brief overview of the Symposium is given in Appendix 6. The active future role of ICES, in collaboration with GLOBEC, needs to be considered carefully at this time and the present report is intended to contribute to that debate.

ICES provides a forum for meetings where regional programmes involving several countries can be discussed and initiated. An example of this is the proposed programme on factors influencing recruitment variability of Baltic cod (Section 4.5.8) and another may be the proposal for coordinated ichthyoplankton surveys of the North Sea (Section 7.8.1). These are programmes which could not be carried out by any one country and in which there is a major collective interest. Some of the difficulties in considering these as potential ICES coordinated programmes arise because ICES is not a funding body and has limited staff and facilities to carry out a coordinating role.

We have put forward numerous specific proposals and recommendations in this report with the aim of developing joint research activities between biological and physical oceanographers within ICES, GLOBEC and the wider academic community. In many cases, observed variability in cod populations seems to be strongly influenced by quite specific climatological and hydrographic events and we can therefore identify key processes for more detailed investigation. It is worth beginning to consider the ways in which results from such studies (e.g. the effect of Baltic inflow on recruitment) may be incorporated into fisheries management strategies and to solicit the advice and support of ICES assessment scientist for this work.

As regards the future of the Cod and Climate Working Group itself, the meeting did not consider that there was a strong case for meeting annually, but identified a number of areas in which progress could be made during the next year. Some of these topics are recommended as subjects for special workshops (e.g. the BACKWARD FACING Workshop, Section 7.5.5, which would address specific questions on retrospective data analysis in relation to climate change; a workshop on effects of intermediate scale processes on cod recruitment.)

### 3.3 The structure of the report

Sections 3-8 of this report address the six terms of reference (given in Section 2) in order. Thus Section 3 (this section) reviews planning and progress. Section 4 gives more detail on existing and proposed national and regional programmes, with the aim of identifying unifying themes and topics which may benefit from international cooperation, inter-regional comparisons and further development within the ICES and GLOBEC communities. Section 5 records a lively, useful, but unresolved discussion on the relationships between physical models at different scales and the treatment of boundary conditions. It provides a list of 25 'regional' physical models, which could or are being applied to the physical/biological questions being addressed.

Section 6 considers the need to incorporate specific (*Calanus*, cod) population dynamics within a spatially resolved ecosystem framework and proposes some tractable biological questions and approaches. Section 7 carries forward many of the issues raised in Sections 3-6, in order to provide proposals for future work. We have tried to avoid repetition of material from earlier sections and have concentrated on bringing out the cross links between different areas of interest and the implications for further work. Section 8 draws together the recommendations made in all parts of the report.

## 4. REVIEW OF REGIONAL PROGRAMMES AND IDENTIFICATION OF COMMON, UNIFYING THEMES

### 4.1 Introduction

This section of the report includes the reviews, presentations and discussion from which we attempt to provide a unifying scientific core for the Cod and Climate Change programme. The discussion led directly to consideration of additional opportunities for regional studies, which are set out in Section 7. Given the diversity of approaches and the breadth of the subject area being addressed, it is neither surprising nor disheartening that a range of activities was identified and that participants accorded these different priorities. The group were also well aware that many of the issues discussed had already been considered in previous documents, particularly ICES CM 1990/G:50; CM 1991/G:78 and Coop. Res. Report 85.

### 4.2 GLOBEC and the Cod and Climate Change programme

Prof. Rothschild reviewed the aims and organisation of the Global Ecosystem Dynamics programme (GLOBEC); its supporting agencies (ICES, SCOR, PISCES, IOC) and the working groups of International GLOBEC. He highlighted the influence of physical processes on predator/prey interactions and the relation of population dynamics of zooplankton to ocean ecosystems. The intent of GLOBEC is the application of a common research framework to specific ecological provinces and fishery regimes in order to unify the study of biological questions at various levels with the appropriate physical driving mechanisms.

Biological questions would involve study of copepod diet and nutrition, vital rates, and the intersection of life history and migration with the production cycle of cod larvae. These processes could be modelled in a physical framework incorporating forcing on the large (climate), intermediate (fronts, transient eddies etc.) and small scales. The models would be driven by observations; it is important to consider what sampling and observation systems would be needed to supply model requirements for data. The complex nature of biological-physical coupling at the intermediate scale was pointed out, consequently these models are not far advanced.

Some of the oceanographic/fisheries community are sceptical about the utility of the proposed hierarchy of coupled physical models and about the predictive capability of large-scale physical-biological models. Following a discussion about presentation of the programme the conclusion was that it should not be viewed as a prescription for forecasting cod and climate change, but rather as a template and justification for long-term study of the issue. This long-term study includes formulation of specific biological-physical models for interpretation of process-oriented studies and regional or mesoscale models for interpretation of long time series. The programme expresses the long-term expectation that advances in knowledge of specific physical-biological linkage at various scales will ultimately yield understanding of relationships between cod and climate. It was considered important that the ICES/GLOBEC Cod and Climate programme take this long-range perspective and support a unified physical-biological approach.

### 4.3 Climate variability and cod population dynamics

Dr Dickson presented an overview of climate variability and cod population dynamics using four related indices: (a) cyclonicity over the central North Atlantic; (b) high pressure at Greenland; (c) the North Atlantic Oscillation; (d) the number of Westerly days over the British Isles. The analysis highlighted the influence of the large-scale wind field on advective transport, larval drift, inter-stock exchange, and catch variation in the North Atlantic. Long-term changes in the windfield may alter persistent properties, such as salinity (the Great Salinity Anomaly), but may also change the predisposition for the occurrence of occasional events such as Baltic inflow or anomalous transport of eggs and larvae. They may also alter the frequency of short-term events, such as strong winds causing mixing of the water column during critical periods of the life history.

When landings were at their individual maxima, sometime between the mid-1950s and mid-1980s, six cod stocks (Iceland, Greenland, Labrador, Faroes, Barents Sea and Baltic) supported a total catch of around 3.5 Mt/a. By the end of the 1980s landings had dropped to about one-third of that total, driven down by an unsustainable level of fishing, but also due in part to the impacts of a changing climate. An extended abstract of the paper by Dickson and Brander is given in Appendix 2.

4.4 Summary of the discussion of national cod and climate related research programmes

During the discussions, common elements that would serve as unifying themes were identified and are given in Table 1.

Norwegian studies are seeking to identify and quantify important factors and mechanisms causing variability in the ecosystems of the Nordic seas. Discussions centred on species specific responses to climate change (cod vs capelin), windfield variation in particular regions of larval drift, and reciprocal changes in east/west Atlantic cod stock responses to basin-scale climatic variability in the North Atlantic. A catalogue of existing large-scale physical and coupled physical/biological models is required. These models should provide insights on critical variables relevant to cod, particularly the assessment of events occurring at spawning and larval drift locations and times, and the propagation of windfield effects through the food chains.

Canadian studies have focussed on the NE Newfoundland Shelf, the Scotian Shelf and the Gulf of St Lawrence. These studies examine almost all aspects of the cod production system, including spawning, drift, growth, survival, recruitment distribution and migration and the various physical and biological influences at small and large scales. Relative to other regional studies, Canadian research has a greater emphasis on climate effects on juvenile and adult cod stock distribution patterns, as well as multi-species changes in fish stock composition.

In addition to the work on the effects of climate variability reported in Appendix 2, United Kingdom studies are examining the life cycle of *Calanus finmarchicus* with emphasis on overwintering distribution and survival (including physical/biological modelling), studying distribution of cod and haddock eggs in the northern North Sea, and modelling the North Sea ecosystem. Discussion evolved around the importance of previous year abundances of adult *Calanus* and cod year class formation, age/size related cannibalism effects on recruitment, and apparent long-term changes in cod spawning locations and abundances relative to haddock. A study relating timing of cod spawning around the British Isles to timing of plankton production has been completed.

US GLOBEC studies on cod and haddock are being conducted on Georges Bank. Emphasis is being placed on effects of turbulence, stratification (direct and indirect effects), storms, eddies and predatory fish distributions on cod and copepod population dynamics. Physical dynamics modelling is well underway. Model simulations involving seeding of biological particles (i.e. cod eggs) at different depths and locations on the bank have been conducted. Future model runs will include time-dependent behaviour of cod as well as attempts to imbed the regional physical model with larger scale circulation models. Coupled biological/physical field studies are scheduled to begin in 1995.

Danish studies on physical/biological influences on growth and condition of 0-group cod in the North Sea are focussed on frontal dynamics and small-scale turbulence. It appears that diatom based food-webs result in better condition of 0-group cod, thus linking their growth and condition to frontal production. This linkage may help to identify a key mechanism whereby climate change can affect recruitment.

Additional studies are examining turbulence effects on encounter rates in cod and herring. Ways to estimate turbulent dissipation rates economically and effectively (e.g. instrumentation, proxy variables), and other issues related to larval feeding behaviour in turbulent environments (e.g. capture success, dynamics of prey distributions), were discussed.

Studies in Japan are directed at walleye pollock and Pacific cod production in Northern Japan and Hokkaido regions. These species exhibit contrasting life histories and will form the basis of comparative studies. Core projects include WPEC (Walleye Pollock and Euphausiid and Copepods) and HUBEC (Hokkaido University Sub-Arctic Ecosystem Dynamics and Climate) and involve zooplankton-micronekton dynamics, fish species replacement mechanisms, trophodynamics of the Pacific Sub-Arctic gyre and general ecosystem dynamic studies.

Table 1. Common elements and unifying themes for research programmes

| |
|---|
| **Models**<br><br>Large-scale North Atlantic model-transport and heat flux<br>Atlantic circulation models: what they produce, which may be useful to cod and climate<br>Modelling activity on banks and shallow seas – comparisons among sites<br>Real-time physical modelling and data assimilation; linked with *in situ* larval tracking |
| **Physical processes**<br><br><u>Small-scale and stratification</u><br><br>Stratification having direct (aggregation) and indirect (via food chain) effects<br>Effects of turbulence<br><br><u>Fronts</u><br><br>Cross-frontal mixing<br>Role of fronts in production and aggregation<br><br><u>Wind</u><br><br>Windfield in region of larval drift and how it changes with time<br>Event-driven processes, e.g. effects of storms<br><br><u>Climate</u><br><br>Climate effects through the food chain |
| **Stocks, their distribution, and sources and sinks**<br><br>Distributional patterns of juveniles and adults<br><br>Interchange between stocks<br>Distribution of spawning<br>Sources, sinks, retention |
| **Whole ecosystem considerations**<br><br>Species composition (and replacement) of ecosystems<br>Overwintering strategies of *Calanus* and inflow/outflow<br>Annual outputs which may indicate positive or negative effects on stock forecasts; proxy predictions |
| **Genetic consideration**<br><br>Genetic influence on behaviour, physiology, and survival |
| **Hindcasting**<br><br>Retrospective analyses including other species |

## 4.5 National and Regional Programme Summaries

### 4.5.1 *Norway*

#### 4.5.1.1 MARE COGNITUM

MARE COGNITUM is a national/regional GLOBEC programme for research on marine ecology of the Nordic Seas. The science plan for the programme has been developed over the last 1½ years in parallel and through interaction with the developing plans of GLOBEC International.

There are two traditional lines of research which are of particular importance for conducting a regional GLOBEC Programme of the Nordic Seas. One tradition is the fisheries investigations which have developed a high capability of studying and quantifying fish abundance. This capability can now be turned to full use in marine ecology by allowing quantification of fish components of large marine ecosystems. The second tradition is the experience of conducting broad national marine ecological programmes, such as PRO MARE (PROgram on Marine ARctic Ecology), which was undertaken from 1984 to 1989, and MARE NOR (North-Norwegian Coastal Ecology Programme), which was started in 1990 and will continue to 1994.

The overall goal of the MARE COGNITUM programme is to identify and quantify the most important factors and mechanisms causing variability in the ecosystem of the Nordic seas, with the aim to predict fluctuations in ocean climate, plankton production and fish stock production. The programme will emphasise the influence of zooplankton production on fish stocks, and how ocean climate influences the production and the underlying linkage. The overall goal is specified in 20 objectives under 3 main categories.

A. Ocean climate: To identify and quantify the most important mechanisms responsible for variability in ocean climate.

B. Resource ecology: To describe the structure and function of the ecosystem in the Norwegian Sea and quantify chief mechanisms regulating the effect of climate variation on production and size of fish stocks, e.g. herring and cod.

C. Carbon cycle: To quantify the importance of the biological carbon pump for the Nordic Seas and as a sink for atmospheric $CO_2$.

National pilot projects will be carried out in 1994 parallel to the work with finalising the implementation plan of the programme. The full-scale programme will start in 1995. Three phases of the programme are identified:

Phase I, 1993-94 Large-scale description.

Phase II, 1995-97 Diagnostic and focused process studies.

Phase III, 1998-2000 Validation and supplementary process studies.

Efforts shall be made to expand the national programme to a regional one for the Nordic Seas with participation particularly from the nations which have responsibility for the management of the biological resources, namely Denmark, Faroe Islands and Iceland, as well as from other countries such as Germany and the United Kingdom, which are actively conducting research in the Nordic Seas.

Reference: MARE COGNITUM. Science plan for the research on marine ecology of the Nordic Seas (Greenland, Norwegian, Iceland Seas), 1993-2000. A regional GLOBEC programme with contributions also to WOCE and JGOFS. Bergen, Norway, May 1993. 162 pp.

4.5.1.2 The role of freshwater outflow

The role of freshwater outflow as a factor linking changes in the global energy budget (climate) with planktonic production and year-class strength of cod spawning in north Norwegian coastal water is presently under study by the Nordland College, Bodo.

The abundances of several zooplankton species, sampled for a decade in overwintering habitats in the Vestfjord area, north Norway, were correlated with sea surface temperature and salinity in the previous production season, and year-class formation in north-east Arctic cod in the following spring. Thus, the Vestfjord area may be useful for monitoring of biological productivity in the Norwegian coastal current and, eventually, forecasting of cod year classes. However, year-class formation in north-east Arctic cod is probably not related to *C. finmarchicus* wintering in this area, but rather with those wintering outside the shelf.

More information will be extracted from the database to explain prey-predator relationships which interfere with the climate signals manifest in the food-web. 0-group strength will be related to extended data series on freshwater outflow and coastal hydrography to see how persistent the relationship may be.

The monitoring programme will be continued to extend time series and it is intended to do field studies on the role of the coastal current front in relation to summer phytoplankton production and reproduction of zooplankton, in particular *C. finmarchicus.*

4.5.1.3 Growth and survival of cod larvae and fry of different stocks of Atlantic cod

A project was started under the Cod and Climate Change programme to study growth and survival of different stocks of cod larvae from startfeeding through metamorphosis under equal environmental and nutritional conditions. The experiments are carried out in enclosures fed zooplankton (80-250 mm) at ambient temp (5-7°C). A cod population with a genetic marker is used as an internal standard for control of variation between parallel enclosures.

A broodstock of Arcto Norwegian cod and broodstock of west coast coastal cod have been established. Maternal effects are standardised by selecting female fish at the same size and stage in the spawning process.

A total of 12 enclosures (5,5$m^3$) were established and stocked with 500 larvae from each of 6 different fish of the Arcto Norwegian cod stock and 6 fish of the coastal cod stock. To each bag were added 500 larvae from one fish of the genetic marked cod. Preliminary results indicate a better survival rate for the Arcto Norwegian cod stock larvae than for the coastal cod stock larvae.

4.5.2 *United Kingdom*

4.5.2.1 Overwintering of *Calanus finmarchicus* off the NW European shelf

*Calanus finmarchicus* constitutes the major component of the herbivorous zooplankton biomass in the NW European shelf seas (northern North Sea and west of Scotland shelf), where it forms prey for many species of larval and juvenile fish. However, in the winter the species is virtually absent from the shelf waters. It has been proposed that in the autumn *C. finmarchicus* enters a dormant state in which animals sink or migrate into deep water and ultimately are carried across the shelf break to spend the winter in cold water at depths > 600 m. Backhaus and Harms (1991) proposed a scheme whereby the interaction of the vertical migration of *C. finmarchicus* with the continental shelf edge circulation enables overwintered animals to emerge from the depths in the spring and re-invade the shelf by surface Ekman transport. The interaction of overwintering *C. finmarchicus* with a deep counter flow along the continental shelf margin (Norwegian Sea water flowing southwards) was further proposed to effect a degree of population closure. These hypotheses are being investigated through field data collection and modelling by collaborators from the University of Hamburg, the Marine Laboratory, Aberdeen, the Danish Institute for Fisheries and Marine Research and Sintef (Norway).

4.5.2.2 Spawning distribution of cod and haddock in NW European shelf waters

Few data exist on the distributions of eggs and larvae of gadoid species in the northern North Sea and west of Scotland area, where the only recent published investigations (of haddock) were carried out during the period 1952-57 (Saville, 1959), with a preliminary report on cod spawning by Raitt (1967). In view of this lack of knowledge, the Marine Laboratory, Aberdeen undertook a wide-scale survey of plankton on the NW shelf and northern North Sea in April 1992. Approximately 200 stations were visited, four depth layers being discretely sampled at each station. Analyses of the distributions and abundances of cod and haddock eggs and larvae, and comparisons with the historical data from the 1950s period, reveal some striking similarities and differences. Further analysis of the material is underway, in particular the catches of eggs of other species, growth rate variability of sandeel larvae from otolith microstructure, and comparisons with CTD, chlorophyll and nutrient data collected at each station.

A study of the location and timing of cod spawning around the British Isles south of 56°N, relating it to the timing of plankton production, is in press (Brander, 1993).

4.5.2.3 Ecosystem analysis and modelling - the ERSEM project

ERSEM (the European Regional Seas Ecosystem Model) is a comprehensive ecosystem model which dynamically simulates the large-scale cycling of organic carbon, oxygen and macro-nutrients N, P and Si over the seasonal cycle in the North Sea. The model consists of an interlinked set of modules, describing the biological and chemical processes in the stratified or non-stratified water column and in the benthic system, forced by light, temperature, advection and diffusion. The hydrodynamic and vertical mixing driving data are provided by a general circulation model of the NW European shelf. ERSEM was developed with EEC funding with the cooperation of nine European institutes. The initial stage of the project terminates in July 1993. The second stage of the project is programmed to run until the end of 1995, with the objectives of extending the ERSEM model to include the processes controlling the long-term, large-scale dynamic functioning of the North Sea. These processes must be included to make sense of the life-cycle dynamics of the higher trophic levels whose life-spans cover many years.

A major component of the ERSEM project has been the compilation of field measurements of the organic and inorganic constituents of the North Sea ecosystem for both calibration and validation purposes, and as boundary condition data. In the first instance, the aim has been to thoroughly document the years 1988 and 1989 in the North Sea. However, increasingly, data assimilation has extended back in time to earlier years, and this will be essential when long-term simulation runs come to be carried out. Already, this exercise has highlighted some intriguing aspects of statistics of within-year spatial and temporal variability in the pelagic system which may have consequences for understanding of larval fish dynamics.

4.5.2.4 Effects of a changing windfield on cod stocks of the North Atlantic

Progress with this study is reported in Appendix 2.

4.5.3 *United States*

US GLOBEC is a research initiative organised by academic and government oceanographers and fisheries scientists to address the question of how changes in the global environment may affect ocean physics, and how changes in physical processes may in turn affect the distribution, abundance, production and mortality of zooplankton, fish and other marine animals.

The goals of US GLOBEC are (1) to predict the effects of climate change on the population dynamics of marine animals through a fundamental understanding of the mechanisms that control variations in animal abundance in time and space; and (2) translate this new understanding into assessments and predictions of the impact of climate change on marine ecosystems. The first ecosystem selected for study will be the pelagic ecosystem associated with Georges Bank.

With climate change, physical variability and animal population dynamics as foci, the research programme can be divided into four parts:

1. A five-year study of circulation, hydrography and plankton abundance (chlorophyll, copepods, larval fish) to provide fairly detailed information on inter-annual variability in temperature, salinity, circulation, copepod, cod and haddock recruitment (1995-99) on Georges Bank. This study will involve moorings and monthly shipboard surveys.

2. Detailed study of key processes.

   (a) physics of water column stratification, and the effects of stratification on vertical distribution and growth rates of copepods and larval fish (1995);

   (b) advection and loss (sources and sinks) of planktonic animals to/from the Bank; population retention mechanisms; influence of storms and warm-core rings on loss of animals (1997);

   (c) cross-frontal mixing; leakage from the Georges Bank gyre; small-scale turbulence studies (1999)

   (d) effects of predation by mackerel and invertebrate predators on copepod and larval fish populations;

3. Development of coupled physical-biological models to formalise our understanding of the effects of physical processes on population dynamics.

4. Retrospective analysis of MARMAP, CPR and satellite SST and CZCS data, for Georges Bank, Gulf of Maine and Scotian Shelf.

5. Application of new technologies to rectify the problem of being unable to study physical and biological processes on the same time and space scales:

   (a) high-frequency acoustics;

   (b) imaging optics (video cameras).

This research programme addresses four of the unifying themes identified by the Cod and Climate Working Group:

1. Effects of winds, especially storms, on larval drift. Approached both through modelling as well as field studies.

2. Climate effects as transmitted through the food chain. One may postulate that increased $CO_2$ will result in a warmer, wetter North Atlantic – this would lead to increased stratification and possibly changes in food chain structure. Stratification has a direct effect on plankton in that zooplankton may be concentrated within the upper mixed layer and/or the pycnocline. Stratification has an indirect effect on biology in that mixed water columns are characterised by dominance of diatoms, and stratified columns, small flagellates. Copepod growth rates and species composition may be affected by changes in water column structure due to differential ability of copepod species to ingest and utilise different phytoplankton species. The Georges Bank study will compare species composition and growth rates of copepods in mixed and stratified water columns.

3. Overwintering strategies. One US GLOBEC project studies experimentally the effect of photoperiod and food quality on entrance to, and exit from, diapause by *Calanus finmarchicus*. Study of sources of populations to Georges Bank in 1997 will consider timing of entrance and exit from diapause of *Calanus finmarchicus* in the Gulf of Maine. This will be studied through both shipboard surveys and use of moored acoustics.

4. The role of fronts in production and aggregation This will be addressed during each of the three process studies, in 1995, 1997 and 1999.

### 4.5.4 *Canada*

The major research programmes in Canada that are relevant to cod and climate research are the Northern Cod Science Programme (NCSP) sponsored by the Department of Fisheries and Oceans (DFO), and the Ocean Production Enhancement Network (OPEN) sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC). Each of these programmes is conducting physical and biological research directly relevant to cod stocks on the north-east Newfoundland Shelf and the Scotian Shelf, and, in addition, DFO has established a Cod and Climate Change Working Group and a Scientific Review Committee called the Fisheries Oceanography Subcommittee, the latter dealing specifically with influences of environmental variability on production of commercially-exploited species such as cod. Recent DFO sponsored studies on cod in the Gulf of St Lawrence have also been initiated. Each of these initiatives will be briefly reviewed.

#### 4.5.4.1 Canadian Cod and Climate Change Working Group

The Canadian CCC WG was formed in 1991 to coordinate its planning with the ICES CCC programme. The working group involves government and university fisheries scientists and physical oceanographers. A major activity of the working group is the fisheries oceanographic description of cod stocks in the NW Atlantic (a so-called 'cod atlas'). This involves determination of the stock-specific seasonal distributional patterns of cod at various life stages and the seasonal description of the regional hydrography and circulation.

These descriptions have largely depended on the collation, editing and analysis of historical data bases from groundfish surveys, tagging studies, hydrographic studies, etc. Collectively, this initiative will provide the foundation for future cod-related research programmes as well as serve to identify information gaps. Analysis of historical trends and fluctuations in the Canadian cod stocks will be the focus of contributions to the CCC Symposium in Reykjavik.

#### 4.5.4.2 Northern Cod Science Programme (NCSP)

The following lists research primarily dealing with the influence of environmental variability on cod population dynamics being conducted at the Canada Department of Fisheries and Oceans, Northwest Atlantic Fisheries Centre in St John's, Newfoundland, primarily under the auspices of the Northern Cod Science Programme. The NCSP initiative began in 1990 and expected completion is in 1995. This list does not include all NCSP initiatives.

(a) Biological processes

**Indicators of Ocean Climate Change (Paranjape):** Establishment of temporal and spatial patterns of distribution of plankton on Newfoundland Shelf areas in relation to physical environment and development of a biological data base (historical and 'new' data) for use in estimating the response of the pelagic communities to the changes in ocean climate.

**Larval Transport (Pepin, Helbig, Anderson, Colbourne, Dalley)**: Reconstruction of the spawning distribution of cod based on reconstruction of egg and larval drift and assessment of the potential significance of shelf regions and inshore bays as retention or nursery areas for larval cod. This study is linked with shelf and coastal-bay-scale physical modelling.

**Early Life History (Dalley, Anderson, Dawe)**: Assessment of spatial and temporal variability in catchability and abundance of juvenile cod among gear types and habitats and relationships among areas of juvenile distribution, preferred habitats, growth, condition, feeding ecology, some aspects of mortality, and stock structure.

**Inshore Cod Migration (Rose)**: Development of a migration model of cod in NAFO 2J3KL and quantitative assessment of physical and biological factors influencing distribution and abundance and migratory patterns and processes. This study is tightly linked with shelf-scale physical modelling.

**Northern Cod Stock Structure (Taggart)**: Genetic (nuclear DNA) assessment of putative 'stock' and 'population' structure of northern cod and quantitative description and analysis of historical cod-tagging data base (1993-present) focusing on 'stock' movements within and among the 2J3KL region.

**Cod Food and Feeding (Lilly, Carscadden, Bishop)**: Analysis of cod feeding, condition, and prey field focusing on the distribution of important prey, and the manner in which cod distribution, condition, and migration is attuned to long-term patterns in the distribution of major prey. This is primarily a retrospective study with 'nowcasting' implications.

**Physiological Indicators of Stress in Cod (Kiceniuk)**: Assessment of historical trends in lipid levels in cod livers and a determination of the utility of C-reactive protein levels as environmentally induced stress indicators in cod.

(b) Oceanographic processes

**Oceanographic Research (Narayanan)**: A detailed description of the circulation and water mass characteristics of the northern cod region, based on all available data. A description of the climatic variability in the oceanographic conditions and the atmospheric forcing including a comprehensive climate and ocean current data base for use in delineating environmental effects on population biology and dynamics of northern cod.

**Near-shore Oceanography (Colbourne)**: An analysis of all available oceanographic data collected by the NCSP plus the historical environmental data along the coast of Newfoundland to enhance the environmental data base, particularly during the period of northern cod inshore migration.

**Technology Advancement (Helbig)**: Assessment of capabilities of long-range and short-range, high frequency, groundwave radar and other remote sensing technologies to provide physical oceanographic data useful to regional scale-dependent fisheries research.

4.5.4.3 Ocean Production Enhancement Network (OPEN)

One of the objectives of Canada's Ocean Production Enhancement Network (OPEN) is to investigate processes which control the survival, growth, reproduction and distribution of Atlantic cod. The cod-related research began in 1990, terminates in 1994, and is divided into six modules of research teams focusing research on recruitment processes, physiology, distribution and migration, ocean dynamics, marine genetics, and marine technology development (the potential of a second research has for 1994-98 is currently being explored). The following lists research efforts directed toward cod at various life stages and locations. The titles, principal investigator(s) and project outlines are listed in Table 2.

**Cod Recruitment Processes**: Research is being directed at cod eggs and larvae on the Western Bank of the Scotian Shelf at monthly intervals (1990-93) and during the real-time tracking of a larval cohort over a period of 20 days. Additional laboratory-based studies are being used to supplement the field-orientated research. The evolving characteristics of larval survivors are being determined through measurements of their phenotype (morphometrics), the birth-date frequency distribution (otolith-derived), genotype (through DNA micro-satellite probes), biochemical condition (analysis of triacylglycerol levels), feeding success (stomach analysis in relation to prey-field), and behavioural attributes (through controlled experiments). The majority of the measurements are made on the same individual larvae in the laboratory and field studies and are assessed in relation to environmental conditions. The obvious over-resolution of field sampling and selected measures was intentionally designed to adequately test existing hypotheses and assumptions.

**Cod Physiology**: The research objectives are focused on the physiological energetics underlying the dynamics of fish production and survivorship; namely, activity physiology, growth and cold adaptation. Specific studies are directed toward stock-related metabolic sensitivities to temperature fields and variations and age/size related seasonal production of anti-freeze proteins.

Table 2 Cod-related research being conducted in the Ocean Production Enhancement Network (OPEN)

| Investigator(s) | | Ocean Production Enhancement Network (OPEN) RESEARCH FOCUS |
|---|---|---|
| Fortier, L. | Laval U | Birth-date frequency distribution of cod |
| Leggett, W. C. | McGill U | Phenotypic correlates of survivorship in cod larvae |
| Frank, K. T.<br>Taggart, C. T. | BIO<br>NWAFC | Lipid content and survival of larval cod |
| Taggart, C. T.<br>Doyle, R. | NWAFC<br>Dalhousie U | Genotype-dependent survival in larval cod |
| McLaren, I. | Dalhousie U | Larval cod survival and zooplankton dynamics |
| Brown, J. | Memorial U | Behavioural ecology of larval cod |
| Boutilier, R.<br>Kerr, S. | Cambridge U<br>BIO | Heritability of bioenergetic processes in cod |
| Fletcher, G. | Memorial U | Cold water adaptation in Atlantic cod: physiological ecology of cod |
| Rose, G. | NWAFC | Large-scale density distribution of Atlantic cod |
| Sanderson, B. | Bureau of Meteorology Res. Ctr., Melbourne, Australia | Particle trajectories and ocean diffusion |
| Thompson, K. | Dalhousie U | Cod larvae tracking on the Scotian Shelf |
| Greatbatch, R. | Memorial U | Circulation and density field on the Newfoundland-Labrador Shelf and Slope – modelling |
| deYoung, B. | Memorial U | Circulation and density field on the Newfoundland-Labrador Shelf and Slope – observations |
| Doyle, R. | Dalhousie U | Cod gene-probe development |
| Bowen, A. | Dalhousie U | Ocean probe (oceanographic technology development) |

BIO = Bedford Institute of Oceanography
NWAFC = Northwest Atlantic Fisheries Centre

**Distribution and Migration**: The goal of the cod distribution and migration research is to account for the observed patterns of cod migration and recruitment in northern cod on the Newfoundland Shelf through observation and coupled oceanographic and migration modelling.

**Ocean Dynamics**: The focus of the ocean dynamics research is on the development of various oceanographic models that are directly applied to the related cod research being conducted on the NE Newfoundland Shelf and the Scotian Shelf. On the Scotian Shelf, the main effort is on combining numerical models and observations so that real-time circulation patterns could be used to track larval cod cohorts. On the Newfoundland Shelf, the efforts are directed to integrating data analysis results and modelling with observations (assimilation models) on cod distribution and migration, as well as on modelling the large-scale climatological mean circulation and the development and application of stratified shelf circulation models.

**Marine Genetics**: Research in marine genetics is concentrated on developing various types of nuclear DNA probes for identifying individuals, populations and stocks of cod for application to related research efforts on survivorship, physiology and distribution.

**Marine Technology**: The marine technology research is directed at using new technology to address 'old' fisheries oceanographic problems. Efforts have been on enhancing the accessibility of information on the physical state of the ocean in an immediately usable form and on timescales that are relevant to the biological research.

4.5.4.4 Fisheries Oceanography Subcommittee (FOS)

FOS activities related to cod and climate change have dealt with assessing the role of environmental variability in the recent decline of northern cod. Anomalous cold water conditions prevalent throughout the geographic range of northern cod since 1983 appears related to the wintertime atmospheric circulation, and specifically an intensification and/or westward shift in the strength of the Icelandic low which generates relatively strong north-west winds from the Labrador Sea. Inter-annual variability in cod recruitment is highly correlated with summer salinity; poor year classes are associated with low salinities (and high sea ice) and vice versa. Several co-occurring groundfish species have exhibited recent declines in concert with northern cod, whereas the biomasses of some invertebrate stocks have recently increased. In addition, other Canadian cod stocks, such as those resident in the Gulf of St Lawrence and the eastern Scotian Shelf, have been declining, suggesting a possible influence of large-scale environmental factors.

4.5.4.5 Gulf of St Lawrence cod programme

DFO, Quebec region, initiated a programme on cod and environmental change in 1993. The programme focuses on understanding declines in N. Gulf of St Lawrence cod stocks that have occurred over the past 10 years. It is considered that part of the cause of the decline in cod productivity is due to the effects of environmental change on cod growth and recruitment. The guiding hypothesis is that changes in environmental conditions in the northern Gulf have negatively influenced a number of aspects of cod life history, including modification of distribution and migration patterns, reduction of individual reproductive output, and decrease in condition (with consequent increases in mortality) of larvae and juveniles.

Programme research that has direct application to cod and climate includes:

1. Study of the environmental change in the northern Gulf of St Lawrence.

    (a) Analysis of historical data sets. Validation of date (temperature, salinity, dissolved oxygen) from 1960 on file at MEDS and analysis of temporal trends.

    (b) Establish a limited number of monitoring stations in the northern Gulf. Station locations include sites in the Strait of Belle Isle and in Cabot Strait, for analyses of exchange with Labrador and Atlantic water, respectively.

    (c) Development of a numerical circulation model for the Gulf of St Lawrence.

2. Description of the spatial-temporal distribution of life stages (eggs, larvae, juveniles) of cod in the northeastern Gulf. It is hypothesized that recent changes in biochemical composition of eggs of northeastern Gulf cod, brought on by effects of environmental change on adult reproductive effort, have resulted in a significant proportion of eggs developing and hatching in the cold (0°C) intermediate layer. Larvae hatch there and remain associated with the cold water until juvenile 0+. This results in a general lowering of condition and growth rates of all early life history stages. Field studies are being conducted to establish spawning sites, measure biochemical composition of eggs and larvae, and determine vertical distribution of eggs, larvae and juveniles in relation to the cold intermediate layer.

3. Laboratory study of the foraging behaviour and competence of cod larvae, in conjunction with field study described in (2). Experiments using silhouette video photography to (a) compare indices of larval condition with indices of larval cod foraging and escape responses and (b) evaluate the hypothesis that larval cod foraging abilities and susceptibility to predation are related to temperature and to egg quality.

4. Linkage between growth rate, energy reserves, and survival probability of cod juveniles and adults in the Gulf of St Lawrence. A study involving field collection and experimental manipulation in the laboratory to test the following hypotheses:

    (a) Recent environmental change in the N. Gulf has resulted in a reduction in growth rate and a shortening of the growth season;

    (b) Energy reserves of cod in autumn are lower at lower environmental temperatures;

    (c) Reduction of growth rate and energy reserves results in higher mortality during periods of starvation and sexual maturation.

#### 4.5.4.6 Canadian GLOBEC

A science plan for Canadian GLOBEC is in preparation, resulting from the Canadian GLOBEC workshop held in Fredericton on 5-7 June 1993. Three regional studies are under consideration: (1) at a site off Newfoundland, a study of cod recruitment processes in relation to the breakup and the subsequent spring production, (2) a study of the advective-estuarine system coupling the St Lawrence Estuary with the Scotian Shelf via Cabot Strait and (3) a bank-scale study of physical biological coupling off the coast of Vancouver Island.

### 4.5.5 *Denmark*

Danish Institute for Fisheries and Marine Research

Research initiatives in Denmark are focused on the determination of biological and physical processes influencing growth and condition of 0-group cod, a clarification of how climatic variability influences these biological and physical processes, and the incorporation of these findings into stock assessment and management programmes.

#### 4.5.5.1 Research in 1992-93

The field components of the research were directed at a) the distribution of 1-5 cm cod in relation to frontal systems in the eastern North Sea during May, b) the condition of individual fish using the ratio of storage/structural lipids, c) food web utilisation using tracer lipids, and d) stock assessment advancements in the North Sea, Skagerrak, Kattegat and Baltic.

The laboratory components of research are focussed on experimental and modelling studies of small-scale turbulence on feeding and swimming behaviour of larval cod, exploration and verification of food web tracers (lipid composition of algae, copepods and cod etc.) in relation to mixed and stratified water masses and the suitability of North Sea bloom algae for growth and condition of larval cod.

4.5.5.2 Future research

A continuation of North Sea research on biological/physical processes influencing growth and condition of 0-group cod (possible focus on larval phase) is envisioned, along with retrospective data analyses to identify long-term climatic influences on frontal production (precipitation, solar heating, duration and intensity of storms, wind stress etc.). Experimental and modelling studies of small-scale turbulence on feeding and swimming behaviour of larval cod are planned.

The Baltic (AIR) programme, a 3-year joint programme with participation by Germany, Sweden, Finland and Denmark, is described in Section 4.5.8. (EC funding negotiations are in progress.)

4.5.6 *Japan*

Pacific cod *Gadus macrocephalus* and walleye pollock *Theragra chalcogramma* are both traditionally and commercially important in the northern Japan. Recent annual catch of walleye pollock in northern Japan varied from 600,000 to 800,000 tonnes, which is ten times of that of Pacific cod. Our studies of the spawning characteristics in captivity revealed distinct differences between the two species in spawning pattern, spawning behaviour and egg type. Walleye pollock release pelagic eggs as do Atlantic cod and haddock, while Pacific cod lay demersal eggs. Female Pacific cod release whole eggs in a single spawning on the sea bottom, while female walleye pollock spawn serially for about a month. Spawning of walleye pollock is limited by suitable water masses, while that of Pacific cod is limited by suitable substrata and suitable water masses. This indicates that reproductive success of Pacific cod is more fragile than that of walleye pollock.

4.5.6.1 WPEC programme in Japan-GLOBEC

The core project of Japan-GLOBEC was proposed tentatively as:

1. Zooplankton and micronecton dynamics focussing on phytoplankton grazers and prey of pelagic fish.

2. Replacement mechanisms of dominant pelagic fish species in the northwestern North Pacific.

3. Trophodynamics of Pacific Sub-Arctic gyres in relation to long term variations of pelagic fish populations and ecosystems.

4. Ecology and ecosystem dynamics in the Southern Ocean (Antarctic Ocean ecosystem).

The workshop on WPEC (Walleye Pollock, Euphausii and Copepods or Climate) aimed to clarify the present problems on the dynamics of marine ecosystem in the North Pacific Sub-Arctic water focussing on the linkage between the key species (walleye pollock, euphausii and copepod) and the climatic change. In this workshop, a life cycle table of walleye pollock for research direction in the WPEC programme was proposed (see Appendix 3). Mortality in the early life stage and its relation to the prey and predator are a focus of the research.

The working group meeting of HUBEC (Hokkaido University, Subarctic Ecosystem dynamics and Climate) as a member of WPEC discussed physical, chemical and biological interactions and the responses to the spring bloom in the early life stage of Pacific pollock, sampling and observation systems, population dynamics and numerical modelling. The effect of climate change on the early life stage of walleye pollock is being addressed through the match/mismatch hypothesis and the transport and aggregation hypothesis.

4.5.7 *Latvia*

The Latvia Fisheries Research Institute (former USSR Baltic FRI) cod and climate change related investigations and available databases include:

1. assessment of commercial fish stocks, providing fishery prognosis and regulatory measures. Collected data include:

- seasonal research trawl surveys since 1985 with research vessel in January (young fish survey and pre-spawning stock investigations). March-April (young fish survey and spawning stock survey) and November-December (young fish survey). Besides that until 1986 in some years additional surveys in June and September were performed. Until the introduction of fishery zones in the Baltic, surveys covered the area east of Bornholm (sd 25-32). After 1977 seven profiles were maintained in former USSR fishery zone. Each profile covers the depths from 10m to 100m (120-150m in spawning time) with interval about 10m. Each survey contains about 30-60 hauls. In 1992 and 1993, due to financial difficulties, only the more important surveys in March-April were continued.

- cod feeding investigations (1963-until now). The cod stomach database contains about 37,000 samples from all seasons in total.

2. Oceanographic monitoring with main aims of short and long term oceanographic forecasting and providing information for fish stock assessment. The historical monitoring database covers the periods to the present, from 1958 for Gulf of Riga and from 1962 for the Baltic Proper. Sampling of oceanological parameters includes temperature, salinity and oxygen content.

3. Ichthyoplankton, zooplankton, and benthos investigations (since end of 50's until now) mostly based on standard stations and oceanographic monitoring.

It is clear that fish surveys (for cod in spring period), oceanographic monitoring and ichthyoplankton surveys will continue in future.

4.5.8 *Germany*

Baltic Sea

Within the frame of a case study on the reproductive ecology of cod in the Bornholm Basin started in 1987, the Institute for Marine Research in Kiel is concentrating on the following objectives:

- Fecundity of cod
- Horizontal/vertical distribution and abundance of cod eggs and larvae
- Mortality of eggs related to hydrographic conditions
- Predation mortality on early life stages caused by potential predators
- Feeding ecology of cod larvae

Sampling is done in cooperation with the Danish Institute for Marine Research and the German Federal Research Board for Fisheries on 4 to 5 cruises annually, covering the spawning period from March to August. The fecundity of cod is investigated by counting oocytes from subsamples of randomly collected ovaries from cod of different size groups before individual spawning has started. To describe the horizontal distribution and abundance of cod eggs and larvae, an ichthyoplankton survey covering the Bornholm Basin is carried out regularly. Sampling is done with a Bongo net on a fixed station grid in combination with hydrographic measurements. The vertical distribution of eggs and larvae in relation to the hydrographic situation is monitored by using a multiple opening/closing net. Drift experiments and successive ichthyoplankton surveys are conducted in appropriate time intervals to estimates the total egg mortality from the decrease in the abundance of different egg stages. Since 1990, experimental studies have been conducted to describe the developmental success of cod in relation to different combinations of temperatures, salinities and oxygen concentrations. Stomach sampling of sprat and herring as potential predators on early life stages of cod is performed in combination with the above described ichthyoplankton surveys. Analysis of stomach contents of cod larvae in relation to the available prey of zooplankton from the ichthyoplankton surveys derived by using a Babybongo and a small meshed liner in the multiple opening/closing net should enable a description of feeding strategies and prey preferences.

Related to the reproductive ecology of cod in the Baltic, the Institute of Baltic Sea Fishery Research is concentrating on following objectives:

- Timing of spawning activity and fecundity of cod
- Distribution and abundance of ichthyoplankton
- Growth, distribution and abundance of 0-group cod

In cooperation with the Institute for Marine Research, the fecundity and the distribution of ichthyplankton is investigated in the western Baltic Sea, whereas 0-group cod related research is conducted in both areas, i.e. the western and the central Baltic. The timing of spawning activity in relation to the age structure of the stock and hydrographic processes as well as the individual fecundity dependent on the age, size, weight and condition is analysed. The distribution and abundance of ichthyoplankton is mapped by covering a station grid with a Bongo net. Hydrographic measurements were performed concurrently. Concerning 0-group cod, most effort is presently spent on methodological problems of qualitative sampling, i.e. the use of different active and inactive gears as well as hydroacoustic methods are tested.

Greenland

Within the frame of a study focussed on the interaction of marine fish species in West Greenland waters, the Institute for Marine Research in cooperation with the Greenland Fisheries Research Institute and the German Federal Research Board for Fisheries has investigated the predation on early life stages of different marine fish species by potential predators and the drift of larvae and 0-group fish in the West Greenland current since 1989.

Stomach sampling has been conducted in different times of the year, giving most emphasis to the autumn season to estimate the consumption of 0-group fish drifting around Cape Farewell and further north along the West-Greenland coast (NAFO Div. 1B-1F). Sampling of ichthyoplankton with a multiple opening/closing net in summer and of 0-group fish with an Isaacs Kidd Midwater Trawl and a pelagic Krill-trawl in autumn were carried out on NAFO hydographic standard sections.

However, no indication of an offshore cod spawning activity and no significant in-flow of 0-group cod from East-Greenland has been detected, resulting in a poor recruitment in the most recent years. After the drastic decline of the cod stock from 1988 to 1991 the West-Greenland offshore spawning stock is close to extinction and also the spawning stock off East Greenland seems to be on a very low level. Thus, future recruitment to both stocks will depend mainly on the larval and 0-group drift from the Icelandic spawning areas. This drift is monitored by the Icelandic Institute for Marine Research in the areas around Iceland and off East Greenland.

During the annual bottom trawl survey carried out by the Institute for Sea Fisheries in autumn, sampling of 0-group fish and stomachs of identified predators will be continued in the next years. On these cruises covering the East and West-Greenland shelf south of 67 N examining the status of the cod stock, the distribution and migration of cod in relation to the hydrographic situation is described. Furthermore, long-term trend analysis of meteorological and oceanographic influences on cod reproductive success and stock development is carried out by the Institute for Sea Fisheries.

4.5.9 *Germany, Denmark, Sweden, Finland*
*International Air Programme (EC)*
*Factors influencing recruitment variability of Baltic cod*

The objectives of this programme, whose funding is presently under negotiation, are to elucidate the dominant biotic and abiotic processes affecting the developmental success of the early life stages and the maturation of Baltic cod; to incorporate these processes into recruitment and dynamic multi-species assessment models in order to enhance prediction of future stock fluctuations due to environmental perturbations and fisheries management directives; and to evaluate the feasibility and possible effects of stock enhancement programs on stock and recruitment.

The cod stock in the Central Baltic is of major social and economic importance in the countries bordering the Baltic Sea. Following an increase in stock size and landings in the beginning of the 80's, the stock is presently at its lowest level on record. The drastic decline appears to be caused by a substantial reduction in the reproductive success during the last decade while high fishing pressure continued to remove large numbers of adults from the population. The present study will examine the mechanisms governing long-term trends in the recruitment and their implications for fisheries management. The project will investigate three closely linked components within an internationally coordinated multi-disciplinary research programme:

(a) Trend analysis: Long-term trends in physical/biological variables and stock recruitment will be analysed to identify the main factors influencing the reproductive biology and recruitment success of Baltic cod.

(b) Process analysis: Biotic and abiotic processes and interactions will be analysed in respect to their effects on survival and maturation of juvenile cod, adult fecundity, quality and viability of spawned eggs and rates of development, drift and mortality of the early life stages.

(c) Modelling: Results from the first two components will be utilised for incorporating 0-group cod into multi-species assessment models and for improving predictive models on future cod recruitment.

Improved understanding of the recruitment processes as obtained during this research project will enable more efficient fisheries management strategies with reference to environmental changes; it will also allow to identify prerequisites for successful stock enhancement programs and provide the biological basis for assessing their economic value.

## 5. GLOBAL, ATLANTIC AND REGIONAL MODELS - BOUNDARY CONDITIONS

Our terms of reference require us to review recent advances in models of global and Atlantic climate variability, consider how these models may be used as boundary conditions for regional models, and plan a specialised workshop on the subject, if necessary. Discussion during the meeting showed that this was an active area of research and we benefited from the presence of two participants from UK universities. Several participants provided written contributions to the discussion, which reflect differences in approach and in the priority accorded to basin scale modelling.

### 5.1

The meeting acknowledged the need for basin-scale modelling of the North Atlantic in the Cod and Climate Change context for several reasons:

- Regional models need realistic dynamically consistent boundary conditions produced by basin-scale models.
- The fluctuations of North Atlantic cod stocks are linked to large-scale ocean climate processes, particularly the stocks along the lower boundary temperature range. These large-scale ocean climate processes are linked to the large-scale volume/heat flux of Atlantic water into the Nordic Seas and Arctic water along the coast of Greenland into the Labrador Seas and the coast of Canada. An example of these phenomena is the mid-seventies anomaly.
- The wind pattern itself, which influences the recruitment to cod stocks, is large scale, and influences also the large-scale circulation (e.g. Greenland High, Iceland Low).
- To address the interaction between the Icelandic stock and Greenland stock one must consider the advection/transport of larvae on a larger scale than regional.

There was a general opinion that Cod and Climate Change should strengthen the contacts with the basin-scale modelling programs rather than develop their own basin-scale models. Cod and Climate should emphasise the development of regional models of relevance coupled to biological and physical processes.

### 5.2

Cod and Climate Change needs interaction with large-scale modellers in order to study mechanisms and causes of particular **identified** phenomena of interest. One example is the use of nested dynamical models to investigate frontal structures and dynamics. It is not sufficient in such local models just to have 'open' boundary conditions. One needs specific input signals, at the boundary of the nested models, which have been generated in a consistent dynamical way by a larger-scale outside model. A regional model with merely 'open' boundary conditions will not tell one anything about variability of frontal position/meandering etc. It is the varying influence of the larger-scale model, providing time-dependent, consistent, external forcing to the regional nested model, which will generate information on frontal position, steepness, etc. This is just one example.

Table 3 Numerical ocean models of relevance to CCC

| MODEL | AREA | PROCESSES | AUTHOR |
|---|---|---|---|
| **NORWAY** | | | |
| 3-D level model<br>20 km grid nesting down to 4 km.<br>Source: D Slagstad | North Sea - Norwegian Sea - Barents Sea | Physics + Thermodyn.<br>Phytoplankton<br>Zooplankton | D Slagstad<br>SINTEF/Trondheim |
| 3-D level model<br>20 km grid nesting down to 4 km.<br>Source: Mellor & Blumberg<br>(Princeton Ocean Model) | North Sea | Physics<br>Phytoplankton | J Berntsen<br>Inst. Mar. Res./Bergen |
| | North Sea | Physics<br>Drift of sandeel larvae | J Berntsen<br>Inst. Mar. Res./Bergen |
| | Norwegian Sea-Barents Sea | Physics<br>Drift of cod larvae | B Ådlandsvik<br>Inst. Mar. Res./Bergen |
| | Northeast Atlantic | Physics | E Martinsen<br>Norwegian Meteorological Inst./Oslo |
| 3-D isopycnal model<br>20 km grid nesting down to 4 km.<br>Source: J Oberhuber | North Atlantic-Arctic Basin | Physics + Thermodyn. | T Aukrust/Nansen Center/Bergen |
| **UK** | | | |
| 3-D isopycnic model<br>1° and $^{1}/_{3}$°<br>Source: Bleik | North Atlantic - Nordic Seas | Physics and Air/Sea Interaction | A New<br>Rennell Centre<br>Southampton |
| 3-D level model<br>50 km<br>Source: Cox: GFDL | Nordic Seas | Physics Thermodyn. | D Stevens<br>UEA, Norwich |
| 3-D level model<br>5 km<br>Source: Cox: GFDL | Iceland - Faeroe ridge region | Physics including frontal dynamics | S Maskell<br>Univ. Exeter |
| 3-D spectral invert ?<br>Source: POL | European Shelf and regional | Physics | Proudman Lab<br>Bidston |
| 3-D level<br>1°, ½°, ¼° versions*<br>Source: GFDL | World Ocean | Physics | P Killworth<br>IOS Wormley |

* Under construction

Table 3 continued

| MODEL | AREA | PROCESSES | AUTHOR |
|---|---|---|---|
| **CANADA** | | | |
| Semi-spectral primitive equation Source: Haidvogel *et al.* | Scotian Shelf | Physics<br>Larval drift | K R Thompson<br>Dalhousie Univ<br>Halifax |
| Diagnostic Shelf model | Scotian Shelf | Physics<br>Cod larval drift | K R Thompson<br>J Y Sheng<br>Dalhousie Univ<br>Halifax |
| Barotropic wind-driven model<br>Source: Davies | Scotian Shelf | Physics<br>Cod larval drift | K R Thompson<br>Dalhousie Univ<br>Halifax |
| Data assimilation of 3-D numerical model<br>Tide, wind, density, currents | Scotian Shelf | Physics<br>Cod larval drift<br>Real time tracking | K R Thompson<br>D Griffith<br>Dalhousie Univ<br>Halifax |
| Prognostic evolution | Newfoundland Shelf | Physics<br>Cod larval drift<br>Adult cod migration | R J Greatbatch<br>B de Young<br>Memorial Univ<br>St John's |
| Diagnostic shelf model | Newfoundland Shelf | Physics<br>Cod larval drift<br>Adult cod migration | R J Greatbatch<br>B de Young<br>Memorial Univ<br>St John's |
| Coastal baroclinic with1-D mixing | Newfoundland Shelf | Physics<br>Phytoplankton | R J Greatbatch<br>B de Young<br>Memorial Univ<br>St John's |
| Reduced gravity | Coastal embayments of Newfoundland | Physics<br>Phytoplankton | R J Greatbatch<br>B de Young<br>Memorial Univ<br>St John's |
| 3-D advection/diffusion | Newfoundland | Physics<br>Cod eggs/larval drift | B de Young<br>R J Greatbatch<br>Memorial Univ<br>J Anderson NWAFC/St John's |
| Advection/diffusion | Coastal embayments of Newfoundland | Physics<br>Cod eggs/larval drift | J Helbig<br>P Pepin<br>NWAFL<br>St John's |

Table 3 continued

| MODEL | AREA | PROCESSES | AUTHOR |
|---|---|---|---|
| **CANADA** | | | |
| Reduced gravity | Coastal embayments of Newfoundland and Quebec | Physics<br>Phytoplankton | R J Greatbatch<br>B de Young<br>Memorial Univ<br>St John's<br>G Ingram, McGide |
| Statistical model 1945-1990 | Scotian shelf, gulf of Maine | Sub-surface, temp. variability | B Petrie<br>K Drinkwater<br>BIO/Halifax |
| **US** | | | |
| Semi-spectral primitive equation model (SPEM); 3-D | Georges Bank | Physical transport, air-sea inter. stage structured populations, food chains, esp.<br>*C. finmarchicus* | Gawarkiewicz, Chapman, Davis, Chen |
| Finite element, 3-D | Georges Bank | Physical transport, larval drift, active particle tracking | Lynch, Werner, Lough, Loder, Greenberg, Page, Perry, Sinclair,<br>W Smith, P Smith |
| Finite elements, 3-D; analytical | Georges Bank; The Shelf Break | Physical transport; tidal front, stratified flow, abrupt changes in topography | Cushman-Roisin, Lynch |
| Tidal; 3-D | Georges Bank | Tidal forcing; rectification retention, etc. | Beardsley, Chen |
| GERMANY | | | |
| 3-D baroclinic | NW European shelf | Larval dispersal (herring, sprat)<br>River water dispersal<br>Contaminant dispersal<br>Ecosystem model forcing (ERSEM)<br>Calanus dispersal/ over-wintering | Backhaus, Pohlmann<br>Univ. of Hamburg |

Large-scale/medium-scale physical modellers must be aware of the types of data that biologists have, or that can be deduced from their physical and biological observations. There may well be room for mutual benefit. Good liaison between large-scale modellers and physical-biological regional-scale models could be extremely valuable to each. Anomalies of 'local climate' - e.g. the great salinity anomaly - might be better explained by running computer experiments. These are the conditions of greatest interest to us. Presently, large-scale modellers are looking to nest (interactively) finer resolution local area models within their large-scale models. These local areas at present are areas that are dynamically interesting (containing fronts or sill overflows, for example). There may be some interest by large-scale modellers if other areas are suggested, perhaps for reasons of biology, especially if the suggestions come with some data! Perhaps some 'sensitive areas' of use to our studies could be explored. There may be other useful cross-fertilisations. Biological phenomena may contain oceanographic data that the modellers are unaware of.

5.3

Investigators developing regional models of the Georges Bank system have identified outputs that would be desired from the latest global climate (coupled atmosphere-ocean models). Specifically, the expected regional wind patterns (mean speed and direction, storm frequency), regional changes in ocean and atmospheric temperature, and the regional changes in freshwater input (precipitation) to the coastal system are the parameters of primary interest - particularly on a seasonal basis. These parameters would be needed to utilise the regional models that are developed in order to evaluate the potential effects on the Georges Bank system of different climate change scenarios.

5.4

The long-term climatic signals in fish stocks, which may be due to the 18.6-year nodal cycle, the 11-year sunspot cycle and the 7-year wobble of the earth's axis, needs to be explained. This can not be addressed experimentally, other than by model simulations. The features act on a global scale which requires large-scale models to take into consideration how the global energy budget accounts for fluxes within and between large-scale atmospheric and oceanic processes. Anything less than basin-scale models seem inappropriate for the purpose, as they will not cover events like low-salinity anomalies affecting the entire North Atlantic, and unexplained regional differences like the opposite response of cod recruitment to salinity variations in the NE Arctic and Georges Bank stocks.

5.5

Despite the persuasive arguments presented above, participants cautioned that physical oceanographers will be unlikely to embark on modelling exercises without specific biological questions framed in the relevant scales (time and space)! Such questions might include:

1. How to model the overwintering circulation at depth, ascent, and on shelf transport of *Calanus finmarchicus*?

2. What are the seasonal and intra-annual changes in retentive systems and how do you embed them in regional models that incorporate:

   - density/topographic steering,
   - Taylor columns,
   - tidal rectification?

3. What were the windfield and advective changes in 1984, west of Iceland, and 1810-20, as opposed to 1820-30?

4. Finally, how might one model bio-physical interactions that lead to interstock, interarea exchange?

5.6

It appears that the principal large-scale processes so far identified which may affect fish populations, including cod, are anomalous hydrographic conditions at the regional scale, and anomalous large-scale drift currents. Basin-scale models may ultimately be useful for hindcasting and nowcasting such conditions. Prediction (forecasting) is, however, out of sight, because it is not possible to forecast atmospheric conditions on the time-scales (multi-annual) required.

At present, the basin-scale models do not seem helpful in explaining how these anomalous conditions actually affect cod populations once they are established. Since this interaction occurs at the (regional) scale of the fish stocks themselves (or less), this question may equally well be studied using real data to drive regional-scale (or smaller) models. Basin-scale models may possibly help in providing the forcing conditions in sufficient detail, and for very recent times, for which real data may not be available.

In summary, then, basin-scale models are less vital to the study of Cod and Climate, though they may be useful for some highly specific purposes. They should be assigned a lower priority in the overall programme than coupled physical/biological models at smaller scales, which are imperfectly developed so far.

Returning to section 5.1, this is not to say that the Cod and Climate programme should not maintain dialogue with those pursuing the modelling of climate and circulation at the basin or global scale, and profit from their ability to explain and ultimately predict anomalous hydrographic and circulation patterns, if and when they reach this goal. The Cod and Climate programme should, however, focus on how these anomalous conditions affect cod stocks, rather than understanding what causes them in the first place.

Participants noted that the present generation of physical models were good enough to (a) convert raw environmental data into more ecologically meaningful indices (e.g. wind into upwelling), (b) to perform sensitivity studies (e.g. effect of $\rho(z)$ on nutrient fluxes), and, (c) perhaps, to hindcast bank basin-scale variability on season-decade scales. However, forecasting the physical environment, or the coupled biological/physical environment, under different global change scenarios is not feasible within the perceived time-scale of, say, a five- to ten-year programme. The approach adopted by one group (Canadian GLOBEC) was to examine selected environmental and trophic interactions in selected systems by a combination of: (1) retrospective analyses of existing time-series data; (2) interpretative models; (3) targetted field studies (distributional and process); and (4) time-series modelling.

In the light of the consensus that development and application of the regional-scale, coupled, biological/physical models should continue, we present a table of such efforts from Canada, Germany, Norway, the UK and the US. This is not an exhaustive list; and we welcome communication about entries that may have been overlooked.

### 5.7 Recommendations

1. Continue the vigorous development and application of regional-scale, coupled biological/physical models. Strengthen the liaison between these regional-scale efforts and existing larger-scale (basin, planetary?) endeavours.

2. A detailed comparison of the relative strengths and weaknesses of the regional-scale models would profit our community. An attempt to assess the relative usefulness of several models at a single site, against a single data set, would be laudable.

## 6. NUMERICAL POPULATION MODELS AND SPATIALLY RESOLVED ECOSYSTEM MODELS

### 6.1 Model construction

Mathematical modelling of physical, chemical or biological systems is not concerned with replicating reality - rather about caricaturing reality. Just as in a caricature of a personality one should be able to recognise the subject, so in a mathematical model the aim is to caricature essential features of the system such that the result provides an explanation of recognisable distinguishing features of that system. If the model cannot be falsified with available data, then it may have some predictive capability given different external forcing scenarios.

Model construction may be considered to have at least three core activities: (a) statement of the question(s) to be addressed, (b) simplification and formulation of processes, (c) provision boundary/driving conditions. Simplification is a necessary component of modelling, designed to make the system numerically and analytically tractable and is the essence of the caricaturing process. Increasing complexity in a model may lead to decreased comprehension of the results. A major skill in modelling activity involves devising neat numerical methods of implicitly representing or caricaturing important sub-grid scale processes in the model. The term grid-scale in this context refers to the basic temporal, spatial or biological structural units of the model (e.g. distance between spatial grid points).

In the context of marine ecological models the main processes to be dealt with are dispersal and predator-prey interactions of the constituent biota. Term of reference 4 is concerned with striking the balance between the necessary simplification of processes and structure, whilst retaining sufficient detail to address questions concerning the population dynamics of particular species. The underlying assumption is that the two conditions may not necessarily be compatible.

## 6.2 Simplification of structure and processes

Simplification of structure and processes may take place at spatial, temporal and biological levels, to varying degrees, dependent upon the content of the question being addressed. In the following section the constraints on these three levels of simplification are briefly described in the context of shelf scale (e.g. North Sea, Georges Bank/Gulf of Maine) ecosystem models, since this is the underlying intent of the term of reference. The discussion of constraints is not intended to be read as a draft of obstacles to progress - more a reminder of the need for careful consideration during model construction, to be aware of the consequences of decisions, and the need for compromise.

### Temporal simplification

The biological components of most ecosystem models ignore processes occurring at time scale less than 1 day, due partly to computational constraints but also to lack of understanding of sub-daily biological processes, and the perception that the diurnal light cycle is a primary forcing function on the biology and therefore a logical time unit. Immediately, this means that biological processes on the time scale of the semi-diurnal tidal cycle are not considered explicitly but must be caricatured implicitly if it is considered that they are an essential aspect of the system in question. Clearly, the physical components of ecosystem models are very much concerned with shorter time scale processes and hence, the provision of physical forcing data to the biological component of such ecosystem models must involve schemes for temporal integration.

### Spatial simplification

The spatial resolution of ecosystem models is limited in the first instance by that of the underlying physical component, but also by computational constraints. Clearly, there must be a trade off between the biological and spatial complexity of the model. Setting the spatial resolution of an ecosystem model provides scope for clever mathematical caricaturing of the effects of sub-grid scale features (e.g. fronts, vertical stratification, particle contact scale turbulence) without recourse to complicated explicit representation. One can argue here, that there is a need to carry out explicit modelling of the sub-grid scale features in isolation in order to understand their function, before attempting to condense their effect into a larger scale construct.

### Biological simplification

The major limitation to representing biological components in an ecosystem is the lack of basic understanding of physiology and behaviour at the species and individual level. Species differentiation is specially problematic among the lower organisms, whilst lack of understanding of the role of individual behavioural variability is prevalent among high organisms. The typical consequence of these constraints is that the structural complexity of model food webs may be the inverse of that in reality. For example, there are probably a very large number of marine bacteria species, but these are typically represented by a single state variable, whilst the (probably) smaller number of fish species tend to be represented by several variables since, it is argued, the known feeding habits of fish are very diverse. This has certain consequences for the representation of prey preference dynamics in a model.

Functional grouping of organisms in ecosystem models into aggregate state variables is clearly a necessary action if one is concerned to capture the total effect of predation pressure at a particular trophic level. However, biological aggregation carries several penalties:

creation of artificial omnivores;

need for artificial stabilisation mechanisms to damp predator-prey oscillations;

parameterisation problems (should one use an archetype species or an unrecognisable 'functional average'.

Predation closure at the top of the food web is a well documented problem in ecological modelling. Basically, the mortality rate of the highest trophic level in a model food web needs to be imposed as (essentially) a driving function. Often, this is achieved by inflicting a static mortality rate on the top modelled predator to represent the rate of removal by unmodelled, unseen, even-higher predators. However this carries the penalty that the unseen predator does not react to declines in the modelled predator and continues to remove animals even at vanishingly small densities.

6.3 Treatment of numbers and biomass

There is a fundamental difference, in modelling terms, between unicellular binary fission organisms and metazoans. Binary organisms are amenable to biomass-only based representation, since the biomass per individual of a species varies only marginally. For higher organisms, biomass per individual can vary considerably over the life cycle (e.g. copepod eggs - adults; fish larvae - adults). This carries potential problems since mortality is essentially a numbers based rate, not a biomass based rate. Thus, in long-lived organisms the biomass-only approach does not preclude the conceptual possibility of numbers declining faster than biomass and, for example, a sprat assuming the body size of a whale. Thus, for higher trophic levels, it is necessary to simultaneously keep track of both numbers and biomass over time, potentially compromising the need for simplification.

MSVPA (a multispecies extension of the classical Beverton and Holt numerical population dynamics model) is a relatively well known form of model which tracks both numbers and biomass and deals with predation interactions between the constituents, in this case, fish guilds. However, growth of fish in the MSVPA is represented logistically (e.g. von Bertalanffy growth curve), hence there is no requirement for biological boundary condition data on prey other than those represented explicitly in the model. MSVPA therefore has nothing to offer on how environmental changes expressed through lower trophic levels may impact on the explicitly represented fish species (or vice versa).

The requirement for a number and biomass tracking model capable of interacting with low trophic levels requires an underlying dynamic physiological model to drive individual growth and development. Parameterisation of such a 'physiological engine' is a difficult task and there are fundamental decisions to be made at the construction stage. For example, three possible options are:

1. parameterise the engine to represent some composite of a group of functionally similar species;
2. adopt one major species to act as an archetype of a number of functionally similar species;
3. explicitly represent one (or more) species, in parallel with a simple biomass-only representation or static loading for all other functionally similar species.

An underlying assumption of the above options is that, in one way or another, it is necessary to take account of the full predation loading on any trophic level in order to capture the essence of any feedbacks between the species or taxa of primary interest and the surrounding trophic levels. Clearly, the approach adopted must depend on the questions being addressed. Consider two examples:

Example (a) One wishes to ask questions about the role of Pseudocalanus sp. in an ecosystem. First, one asks whether this species constituted the bulk of the biomass of small calanoid copepods. Very likely, the answer would be yes. In that case, an age or stage structured representation of all small calanoid copepods, parameterised as if all such copepods were Pseudocalanus (option 2) might be adequate.

Example (b) One wishes to ask questions about the growth rates of adult cod in an ecosystem (e.g. North Sea), where cod constitute only a tiny fraction of the total demersal fish biomass. An age or size structured cohort model seems appropriate. However, option 2 will not be acceptable. Option 1 is likely to be very unsatisfactory because of the very wide range of maximum sizes and feeding strategies of demersal fish. Option 3 is feasible, but still difficult to implement because the biomass-only or static loading representation of all other demersal fish will dominate over the cod cohort in the model.

In addition, if one implements an age or stage structured representation of a species or functional group in a model, then care must be taken to avoid creating artificial competition between age groups or stages, as an artefact of the degree of resource differentiation in the lower trophic level. For example, there may be problems associated with implementing a stage structure copepod model where the main food source for each stage is a single undifferentiated phytoplankton category, unless some clever implicit caricature of functional or size differentiation in the phytoplankton is also included. The extent to which biological detail at trophic levels surrounding that of interest needs to be included cannot easily be determined beforehand due to inherent non-linearities in competing predator systems. This area is a prime target for numerical experimentation to achieve the optimum balance between dynamic representation and external forcing.

Finally, there are specific problems associated with combining spatial resolution and a numbers and biomass representation. Basically, a good physiological engine should dictate that an animals' growth response to the ingestion of a particular amount of food is dependent on multi-dimensional characteristics, for example age or development stage, and present condition expressed by the ratio of reserve biomass to total biomass. Incorporating spatial resolution necessitates consideration of the dispersal of animals , and potential mixing of animals with different histories at each grid point in a model. Schemes for dealing with this problem are not readily available.

The above discussion includes some of the considerations which need to be taken into account if one wishes to include a representation of particular species within an ecosystem context. Essentially, there are trade-offs to be made between the need for simplification and the retention of sufficient detail to be able to recognise the key features of interest. At the same time, there may be a limit to which secondary details can be discarded or replace by simple forcing functions. The correct balance may only be found by experimentation. At the same time, it is of paramount importance to carefully pose the questions to be addressed by any modelling exercise.

## 6.4 Three candidate ecosystem frameworks to form the basis for cod and copepod models

In this section three types of approach to ecosystem modelling are briefly outlined, together with an indication of their potential for forming the 'underlying context' of models of particular species.

### 6.4.1 *Box-model systems*

The ERSEM (European Regional Seas Ecosystem Model), described briefly elsewhere in this report, is an example of the box-modelling approach which could form the template for supporting representations of particular species of zooplankton and fish. Briefly, biological dynamics are modelled in 15 spatial compartments covering the whole North Sea in the horizontal and vertical domains. Physical exchanges (advection and diffusion) between compartments are driven by spatially and temporally integrated output from a 3-dimensional general circulation model of the north-west European Shelf. The chemical and biological ecosystem is represented by some 50 state variables in each compartment, covering pelagic and benthic nutrients, phytoplankton, zooplankton, fish, benthos and detritus. An attempt has already been made to explicitly represent three fish species (herring, whiting and mackerel) by age structured cohort models superimposed on the main ecosystem model and operating in parallel to static loading representing the residual moralities inflicted by other planktoivorous, pelagic piscivore and demersal fish. At present, recruitment is represented simply by a driving function. Experimentation with the model has shown that body growth rates of herring in the system are responsive to changes in biomass forced through inflicted removal by fishing, suggesting that herring growth is strongly resource limited. Historical data from the North Sea show an inverse relationship between size at age 3 and stock biomass of herring over the period 1947-1991. The initial results therefore suggest that the approach is not without many of the problems outlined earlier, but is clearly feasible.

### 6.4.2 *Particle tracking systems*

Extensive work has already been carried out in several shelf seas (e.g. North Sea, Georges Bank, Barents Sea) using Lagrangian particle tracking models driven by a variety of general circulation models. So far these have been used to explore the potential for dispersal of fish larvae or copepods under different vertical distribution/behaviour scenarios. However, this approach may also have possibilities for modelling biological dynamics, by introducing categories of particles and allowing particles to interact. This approach is analogous to a 3-dimensional cellular automaton, and could be considered to be an Individually Based Model (IBM) approach. Various groups of investigators are considering such systems, but the computational problems appear to be considerable, due to the need for an extensive database of behavioural options under the various scenarios encountered by particles in the system. The approach is therefore attractive, but unlikely to yield results in the short term.

6.4.3 *Size spectrum systems*

The 'Sheldon size spectrum' approach has been available for many years as a framework for assembling biomass and predator-prey relations across entire ecosystems. Essentially, the numerical abundance of taxa is assumed to decline in a characteristic way with body size across the full range of organisms in the system. Assuming fixed relationships between prey size and predator size, various predictions about higher tropic level production can be made on the basis of information about low trophic level productivity (which is more easily measured). Recently, this generic approach has received new attention in relation to the survival of target species (Beyer, 1989), survival strategies in the presence of seasonal pulses of primary production (Shepherd and Pope, in preparation), and analysis of fish predation strategies (Heath, in preparation). There would seem to be scope for developing the Sheldon size spectrum principle as a setting or context for more detailed species models, provided that spatial and temporal dynamics can also be incorporated (Paranjape and Sheldon, 1991).

6.5 Proposed core topics to be addressed by the Cod and Climate programme

Are the observed wide variations in growth rates of all life history stages of cod in ecosystems around the Atlantic rim the product of genetics, abiotic conditions, or ecosystem productivity in relation to the importance of cod in the various demersal fish assemblages?

This seems to be a highly tractable issue, involving state of the art biology investigations and modelling, and is also highly relevant to the productivity of cod populations under climate change scenarios.

Two other topics which would require international cooperation and would be suitable for the Cod and Climate programme are:

1. To export coupled physical/biological models which have been developed for one region to other regions in order to test them.

2. To apply the Sheldon size spectrum approach to several ecosystems in which cod is a major component.

## 7. CONSIDERATION OF UNIFYING THEMES AND FUTURE PROGRAMME

The review of regional programmes in Section 5 produced a Table of unifying themes. These were discussed in terms of their priority, timeliness and potential for stimulating useful cooperative work. The group kept in mind the intent expressed in C. Res. 1992/3:1 that the programme should be interdisciplinary, should bring together regional investigations around common themes and should enhance linkages with the broader marine science community.

A number of themes are developed below in order to provide the rationale for specific recommendations for future work. The form which future work may take is diverse, including:

(a) addressing common 'core science' themes;

(b) exchange of models for development, testing and validation;

(c) coordinated sampling and observation;

(d) coordinated retrospective data analysis;

(e) databases;

(f) special workshops;

(g) theme sessions for meetings;

(h) addressing specific questions to scientists in other disciplines.

In some cases we have proposed specific terms of reference and dates for special workshops, in others we have suggested that certain 'core science' themes should be developed with the longer-term aim of bringing together parallel studies in different regions. There may be some value in endorsing work which is already being planned or carried out at national level, but in the main we have limited ourselves to tractable topics which an international group such as this is better able to coordinate or carry out than individual scientists or groups of scientists within a region.

## 7.1 GLOBEC

The aims, approach and progress of GLOBEC are documented in earlier sections. It provides a scientific and organisational framework, with the Cod and Climate programme as a 'regional' component. Coordination with other parts of GLOBEC is needed to ensure that the specific interests of Cod and Climate are taken into account (e.g. in the design of sampling and observation systems) and to avoid duplication of work in certain areas. On the other hand the number of meetings now taking place at national and international level to coordinate and report on progress over a range of disciplines is already excessive and we should not add to them without very good justification.

## 7.2 Large-scale models and boundary conditions

These are discussed in section 5 and the implications for future programmes are presented there.

## 7.3 Intermediate scale processes

The working group recognised the importance of physical processes in producing, aggregating and dispersing food organisms required by various stages of cod throughout its geographic range. In particular, the working group noted that there is a gap in our knowledge of how processes which take place at intermediate scales (metres to kilometres) affect cod biology. These processes and phenomena include $h/[U]^3$ tidal mixing, shelf break fronts, eddies and rings (e.g. Taylor columns, Von Karmen vortex fields, topographically trapped eddies).

These features affect the distributions and feeding activities of cod populations both directly and indirectly, and different sizes of cod are affected in different ways by such phenomena. For example, physiological studies of adult swimming behaviour and metabolism indicated the sensitivity of cod distributions and metabolic rates to small differences in water temperature. The smaller less mobile stages of cod appear to utilise these features during the pelagic phase.

Intermediate scale physical features represent an additional research opportunity for regional studies involving both new field investigations and retrospective data analyses. This is because the locations and the annual timing of occurrence of these features are likely to shift as a consequence of changes in wind stress, solar radiation and precipitation. New combinations of meteorological variables will therefore influence the rates of biological production which presently exist at these sites, and the degree to which these phenomena aggregate the consumers, including various life-stages of cod.

In order to clarify the role and importance of intermediate scale bio/physical mechanisms (metres to kilometres) in linking cod stock variability with climatic processes a number of areas for future work have been identified. These broadly address the question whether the abundance and survival of the pelagic stages of cod can be related to intermediate scale physical features such as fronts.

Processes which may be involved include:

(a) physical mechanisms resulting in enhanced nutrient flux leading to increased primary and secondary production;

(b) the effects of physical processes on food webs and hence on transfer efficiencies to all stages of cod;

(c) influence of turbulence on larval and 0-group feeding ecology;

(d) distribution of larvae, juveniles and their prey due to migratory patterns in a variable flow field;

(e) implications of intermediate-scale physical processes for 'match/mismatch' of larvae and their prey;

(f) linkage of these processes to enhanced growth, condition and survival of all life stages of cod.

These processes mainly affect the early life history stages, but the effects of changes in patterns of intermediate scale physical features on adult cod physiology distribution and migration also need to be studied.

The recommendations which flow from this discussion concern:

(a) Establishment of a workshop to consider whether and how intermediate scale processes are important in governing cod stock fluctuations in all regions of the North Atlantic. [A proposal was received after the Working Group meeting that this workshop should have the title AGGREGATION and should meet at Charlottenlund in June/July 1994. A Grand Gathering of Recondite Ecologists Generating A Turbulent Intrusion Of kNowledge.]

(b) Continued development of intermediate scale hydrodynamic models and incorporation of key biological process. This might be a suitable topic for a joint theme session with the Hydrography Committee in two years.

(c) Analysis of commercial fishing effort distribution to infer large-scale long-term variations in spawning concentrations related to oceanographic structure under the influence of climatic variation.

A particular example of a local programme looking at biological processes in the Norwegian coastal current and its associated front is given in Appendix 4.

### 7.4 Small-scale processes

These may seem to have less relevance to studies of the effects of climate change and to require little inter-regional cooperation. Nevertheless two physical processes which may benefit from a coordinated approach are stratification and small-scale turbulence.

#### 7.4.1 *Stratification*

Stratification determines the timing and course of primary production and also the aggregation of biological particles in the water column. A regional model of primary production around the British Isles has been constructed from a mosaic of one dimensional (stratification) models and has been used to test the hypothesis that the timing of cod spawning is related to the timing of plankton production (Brander, in press). The model could be exported to other regions where tidal and wind mixing are the dominant factors governing stratification. Hindcasts can be carried out for any years for which suitable meteorological data are available.

A further model under development will attempt to relate zooplankton (cod larval food particle) production to primary production, but with an advective component. The model will allow a more rigorous test of the match-mismatch hypothesis, relating survival of larvae to timing of production of their food in different years as a function of changing meteorological conditions. Haddock larvae are also known to be sensitive to stratification. The US GLOBEC program (see 4.5.3) has very similar objectives. A suitable theme for a workshop in three years might be: testing models for hindcasting variability in cod and haddock recruitment as a function of the effect of variable meteorological conditions on stratification.

#### 7.4.2 *Turbulence*

The effect of small-scale turbulence on encounter rates and feeding is the subject of active research, and existing field data on feeding by larval fish and copepods should be used to quantify the positive or negative effects. Since it is difficult to measure turbulence routinely it would be useful to have adequate ways of estimating it through the water column from data on wind and tidal velocity.

### 7.5 Retrospective analysis

Cod stocks provide a data-rich case study for examining the effects of climate changes on marine ecosystems. The ICES Study Group on Cod Stock Fluctuations produced a synthesis of information on cod stocks (CM 1990/G:50, Appendix III). This is being updated and combined with information from the checklist of spawning and early life history characteristics compiled for the ICES Recruitment Processes Working Group into a Cooperative Research Report, which will include data from twenty-five stocks. These data syntheses are intended as a basis for comparative studies of the kind proposed by Bakun (1985) and have started to be used in this way (e.g. Appendix 2; Brander (in press)).

International GLOBEC is planning a working group (PRUDENCE) to consider the use of the historic database for GLOBEC programme aims.

There is considerable scope for further retrospective analysis of the relationships between observed variability of cod populations and their physical and biological environment. This should provide relatively rapid results concerning likely effects of climate change, as well as pointing the way for future data collection and highlighting the need to develop comparable time series of information in different systems over the long-term. The assembly of data on the various stocks and examination of hypotheses in a comparative manner in different regions of the North Atlantic basin is a suitable subject for cooperative international investigation. Climatic effects may be basin or region in scale, necessitating data from as many locations as possible. ICES is clearly the appropriate marine science agency to co-ordinate this work, since much of the data has been collected and processed within the ICES framework and/or by member states.

A workshop in 1994 would be a timely means of bringing together retrospective analyses in progress and the topics to be addressed include:

#### 7.5.1 *Review of existing large-scale studies of the relationships between cod, copepods and climate variables*

A number of empirical studies have considered the coherence in cod and zooplankton population variability across the North Atlantic and the response of cod and copepod populations to temperature and other physical and biological variables. In reviewing these, the aim would be to explore the processes which may underlie apparent relationships and to bring together available data to test these more critically.

#### 7.5.2 *Review of appropriate methods for times series analysis and geostatistical techniques*

#### 7.5.3 *Consider the need for, and issues related to, the establishment of centralised database*

A great deal of thought has already gone into this issue and it concerns not only retrospective data analysis, but also the acquisition, validation and storage of new data. Appendix 5 sets out some of the issues and lists some of the data sets which may be useful to the Cod and Climate programme. ICES already brings together annual stock information and hydrographic data.

More detailed biological data (e.g. fecundity, age of maturity) of the kind being synthesised for the Cooperative Research Report may not need to be updated as frequently, but there are considerable difficulties in standardising definitions and in obtaining biological data in comparable forms. For many purposes (e.g. comparing fecundity estimates) it is necessary to know how the estimates were made and the answer may depend on the precise question being asked (e.g. population fecundity, specific fecundity). This highlights two issues, namely (1) that the database cannot be regarded as a static set of unchanging tables and (2) that the use of the data and the questions being addressed dictate what data are included and in what form. Since the actual quantities of biological data (particularly annual fish stock data) are quite small, it may be more useful to have a data inventory and an address list of experts who can help to update and interpret data than to have a database.

7.5.4 *Review existing data sets in planning new data acquisition*

Three issues to consider here are (1) the use of existing data to select sites for instrument packages, moorings and sampling systems (2) data requirements in relation to modelling activities and how well they have been met in the past and (3) which data sets need intercalibration and standardisation.

7.5.5 *BACKWARD-FACING Workshop*

A number of specific questions have arisen from recent large-scale studies of climate effect on cod (e.g. Appendix 2). These are tractable and it is proposed they should be the subject for a special Workshop in 1994. A tentative time/location might be adjacent to the Northern Cod - OPEN Workshop in St John's Newfoundland in October 1994. The issues to be considered by the Workshop will include:

1. Climate at West Greenland during the last cod period 1820-40.

2. The 1880's migration of cod from Labrador to New England during the tilefish kill.

3. Large-scale, long-term evidence of inter-stock exchange on the Northern American, eastern seaboard (tagging, genetics, meristics).

4. 19th century cold periods in the Barents Sea and year class strength.

5. CPR redfish records, Irminger Sea.

6. Catch history in Northern Labrador and Baffin Island (2GH and OB) as evidence of inter-stock exchange.

7. The long-term history of the cold intermediate layer on the Canadian banks and their relation to large-scale climate.

8. Evidence for historic shifts in cod spawning.

The title for this Workshop materialised during an early morning walk on the beach with dog: Bob And Ken's Workshop on Archaeology of Relevant Data For Assessing Climatic Impacts on the Northern cod and Greenland.

7.6 Retrospective analysis and CPR

J. Gamble illustrated long time series generated by CPR analysis with examples from sectors in the North Sea and Northeast Atlantic. Interannual and interdecadal variability in copepod time series were clearly evident. Temporal maps of the seasonal cycle of *Calanus* show considerable interannual variation in the onset of *Calanus* abundance over the past 30 years. CPR analysis also shows the timing of seasonal phytoplankton cycles, as indicated by phytoplankton colour. A meeting in Plymouth in May 1993 addressed the important issue of proper and thorough data analysis, including multivariate time series analysis and possibilities for correlating the physical/biological data base. Interpretation of CPR time series also requires sophisticated biological understanding of species specific population dynamics and life histories for example, in factoring the seasonal ontogenetic migration of *Calanus* to the surface in spring.

Since the CPR provides the only spatially extensive long time series of the principal food species for cod (and other fish) during the period in their early life when variability in recruitment is determined, this data set is of great value in studies of Cod and Climate. The Group recommend:

1. That the CPR Survey be expanded to reoccupy North Atlantic time series routes and maintained so as to provide a continued, uninterrupted time series of upper mixed layer plankton. New instrumentation should be added to measure physical and biological variables.

2. That the opportunity be taken to design future studies around the survey, including process-oriented studies, to enhance the interpretation of CPR data and its intercalibration with other plankton population estimates.

3. That specific hypotheses be formulated which can be investigated through a more detailed investigation of existing CPR data involving the application of state of the art statistical and modelling techniques. Questions should be directed towards: regional and interannual variability in prey populations, variability in the timing and extent of ontogenetic migrations of *Calanus*, identification and statistical characterisation of anomalous event, variation in plankton populations in relation to frontal features and water mass differentiation.

### 7.7 Sampling and observation systems

The ICES/GLOBEC Cod and Climate programme is developing methodologies to link fundamental process studies (population dynamics and physical processes); sampling and observation systems; and numerical modelling. This linkage was articulated by the GLOBEC Sampling and Observational System working group (SOS). They observed the need "to link observational systems and models with a key objective of bridging scale gaps through data assimilation schemes ...". They also suggested that "sampling systems be located and maintained in regions of critical interest long enough to define critical processes in space and time. 'Over sampling' and sensor comparison are necessary at an early stage. Nested arrays of sensors are needed to establish subgrid scale parameterisations, and robust, reliable data assimilation schemes should be developed and applied for the sampling region. This effort should greatly facilitate the definition of critical variables and sampling domains. An international commitment to technology and engineering development is highly desirable" (GLOBEC-INT Report No. 3).

In thinking about the development of these sampling systems it is necessary to make the important distinction between various sampling sensors and a sampling-and-observation-system, because a system includes not only the sampling hardware, but the 'software' as well. In a system, special considerations involve the deployment of sensors (e.g. moored, towed, etc.); specifying the type of sensors (e.g. optic, acoustic, etc.); sampling theoretic and operations research; and data archival and retrieval.

C. Taggart described technologies associated with the Canadian OPEN programme, including a ship-fitted ADCP, telemetry drifters, contemporaneous data assimilation for tracking, towed V-fin instrument package including CTD, fluorescence and OPC sensors, and development of a moored version of an OPC and fluorometer. There is also the possibility of acoustic monitoring from moored arrays (presently being done by V. Holliday off California and on Georges Bank as part of US GLOBEC).

Other monitoring technologies (Sea WiFS, SEA WATCH) were discussed and information was requested. T. Powell pointed out that international programs such as Cod and Climate should actively support national monitoring efforts.

A discussion about the use of high technology within the Cod and Climate programme ensued. The choice of sites for deploying moored or towed arrays depends on the questions posed. The focus would be on monitoring climate (wind, temperature, salinity fields) using both fixed and mobile systems.

An impressive array of sensors already exists and is deployed and used. It is now necessary to determine how the sensors can be employed in a contemporary pan Atlantic sampling system and how they can evolve over the next decade for use in Cod and Climate studies. Because of the cost and the considerable benefit that could accrue from the deployment of such a system, the location and mode of their deployment, data transmission methods, etc. must be determined. We recommend a group of ICES/GLOBEC SOS and CCC experts meet to formulate an Atlantic sampling and observing system that is both feasible and appropriate to Cod and Climate. Questions such as rates of sampling, flow of data into numerical models, input into design of systems for Cod and Climate purposes, and identification of precise needs for information should be addressed.

It was recommended that B. Rothschild put together a statement supporting SOS recommendations and addressing the needs to the Cod and Climate programme.

### 7.8 Regional surveys

Although our data on catches and age structure of cod populations throughout the North Atlantic are comprehensive the same is not true of some very basic biological information such as the distribution of spawning and early life history stages. This basic information is fundamental for studies at all scales. Large-scale studies of effects of variable transport or temperature on the early life history obviously depend on knowing where and when these factors have their effect.

Intermediate and small scale studies give information which may lead to understanding the physical and biological control of local variability in growth and survival, but ultimately these need to be placed within the context of the total population. For example there have been several studies of juvenile cod growth and survival in the inshore area of Newfoundland, but there is still some uncertainty over the proportion of juvenile cod from the 2J3KL stock which are inshore and offshore.

#### 7.8.1 *Coordinated ichthyoplankton surveys of the North Sea*

A proposal for a series of ICES coordinated egg and larval surveys of the North Sea was discussed briefly at the 1992 Statutory Meeting and has since been developed by correspondence between potential participants. This would be a considerable international undertaking, since most of the North Sea would have to be surveyed over a period of several months in order to ensure complete coverage.

The lack of synoptic data on spatial and temporal distribution of spawning of cod (and other fish species) in the North Sea is a serious obstacle to assessing the vulnerability of the resident fish assemblage to climate change and to planning future research activities. The Working Group recommend that a coordinated series of ichthyoplankton surveys should be carried out and that the views and support of the assessment Working Groups, the Multispecies Working Group and the Ecosystem Effects Working Group should be enlisted at the planning stage.

In addition to the aims related to Cod and Climate the survey can provide useful information for other species and for assessment and environmental monitoring purposes. Results from the Continuous Plankton Recorder should be used in designing the ichthyoplankton surveys and the opportunity provided by such a large-scale survey should be used to validate and calibrate CPR results.

The CPR Survey has been conducted in the North Sea from its beginning in 1931 and has an unbroken time series since 1931. Furthermore the spatial coverage in the North Sea is more intensive than in any other region. While the CPR is not well suited to sampling fish larvae, data are available and, being internally consistent, should at least give an indication of trends in abundance and persistent patterns of distribution. It is recommended:

1. That priority should be given to an analysis of the distribution patterns of the larvae of cod, and other relevant species, sampled by the CPR Survey in the North Sea in order to look at historic trends in abundance and distribution and to provide uscful information for planning the ichthyoplankton surveys.

2. That the ichthyoplankton surveys of the North Sea be compared with CPR data.

## 8. RECOMMENDATIONS AND TERMS OF REFERENCE FOR FUTURE MEETINGS

Background information and details about the recommendations listed below can be found in the relevant sections of the report, the numbers of which are given in brackets.

8.1 The Working Group recommend that three special workshops should take place in 1994.

8.1.1 *Time series analysis, database and data acquisition*

Terms of reference to include:

(a) Review existing large-scale studies of the relationships between cod, copepods and climate variables (7.5.1).

(b) Review appropriate methods for time series analysis and geostatistical techniques (7.5.2.).

(c) Consider the need for and issues related to the establishment of a centralised database (7.5.3).

(d) Review existing data sets in order to plan new data acquisition (7.5.4).

8.1.2 *BACKWARD-FACING Workshop (7.5.5)*

Tentatively planned to take place in Canada in October 1994. The principal terms of reference will be to assemble evidence for assessing climatic impacts on cod stocks, including:

(a) Climate at West Greenland during the last cod period 1820-40.

(b) The 1880's migration of cod from Labrador to New England during the tilefish kill.

(c) Large-scale, long-term evidence of inter-stock exchange on the Northern American, eastern seaboard (tagging, genetics, meristics).

(d) 19th century cold periods in the Barents Sea and year class strength.

(e) CPR redfish records, Irminger Sea.

(f) Catch history in Northern Labrador and Baffin Island (2GH and OB) as evidence of inter-stock exchange.

(g) The long-term history of the cold intermediate layer on the Canadian banks and their relation to large-scale climate.

(h) Evidence for historic shifts in cod spawning.

8.1.3 AGGREGATION Workshop (7.3)

8.2 The Working Group identified the following questions and topics which should form part of the scientific core of the Cod and Climate programme and which could be the subject of special workshops or theme sessions in future years:

8.2.1 *Cod in relation to the ecosystem (6.5)*

(a) Are the observed wide variations in growth rates of all life history stages of cod in ecosystems around the Atlantic rim the product of genetics, abiotic conditions, or ecosystem productivity in relation to the importance of cod in the various demersal fish assemblages?

(b) Export of coupled physical/biological models which have been developed for one region to other regions in order to test them.

(c) Application of the Sheldon size spectrum approach to several ecosystems in which cod is a major component.

8.2.2 *Effects of large-scale processes*

(a) Cod and Climate Change should strengthen the contacts with the basin-scale modelling programmes rather than develop their own basin-scale models. Cod and Climate should emphasise the development of regional models of relevance coupled to biological and physical processes (5.1).

(b) Continue the vigorous development and application of regional-scale, coupled biological/physical models. Strengthen the liaison between these regional-scale efforts and existing larger-scale (basin, planetary?) endeavours (5.7).

(c) A detailed comparison of the relative strengths and weaknesses of the regional-scale models would profit our community. An attempt to assess the relative usefulness of several models at a single site, against a single data set, would be laudable (5.7).

8.2.3 *Effects of intermediate scale processes*

(a) Continued development of intermediate scale hydrodynamic models and incorporation of key biological process. This might be a suitable topic for a joining theme session with the Hydrography Committee in two years (7.3).

(b) Analysis of commercial fishing effort distribution to infer large-scale long-term variations in spawning concentrations related to oceanographic structure under the influence of climatic variation (7.3).

(c) Testing models for hindcasting variability in cod and haddock recruitment as a function of the effects of variable meteorological conditions on stratification (7.4.1).

8.3 The Working Group recommends that close links should be maintained with the specialist Working Groups of GLOBEC and specifically that:

(a) A group of ICES/GLOBEC SOS and CCC experts meet to formulate an Atlantic sampling and observing system that is both feasible and appropriate to Cod and Climate. Questions such as rates of sampling, flow of data into numerical models, input into design of systems for Cod and Climate purposes, and identification of precise needs for information should be addressed (7.7).

(b) B. Rothschild put together a statement supporting SOS recommendations and addressing the needs to the Cod and Climate programme (7.7).

8.4 The Working Group recommend that a coordinated series of ichthyoplankton surveys of the North Sea should be carried out. The views and support of the assessment Working Groups, the Multispecies Working Group and the Ecosystem Effects Working Group should be enlisted at the planning stage.

Results from the Continuous Plankton Recorder (CPR) should be used in designing the ichthyoplankton surveys and the opportunity of such a large-scale survey should be used to validate and calibrate CPR results.

Priority should be given to analysis of distribution patterns of larvae of cod and other relevant species, sampled by the CPR Survey in the North Sea, in order to look at historic trends in abundance and distribution (7.8.1).

8.5 Since the CPR provides the only spatially extensive long time series of the principal food species for cod (and other fish) during the period in their early life when variability in recruitment is determined, this data set is of great value in studies of Cod and Climate. The Working Group recommend that:

1. The CPR Survey be expanded to reoccupy North Atlantic time series routes and maintained so as to provide a continued, uninterrupted time series of upper mixed layer plankton. New instrumentation should be added to measure physical and biological variables.

2. The opportunity be taken to design future studies around the survey, including process-oriented studies, to enhance the interpretation of CPR data and its intercalibration with other plankton population estimates.

3. Specific hypotheses be formulated which can be investigated through a more detailed investigation of existing CPR data involving the application of state of the art statistical and modelling techniques. Questions should be directed towards: regional and interannual variability in prey populations, variability in the timing and extent of ontogenetic migrations of *Calanus*, identification and statistical characterisation of anomalous event, variation in plankton populations in relation to frontal features and water mass differentiation (7.6).

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APPENDIX 1

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APPENDIX 2

Effects of a changing windfield on cod stocks of the North Atlantic. Extended abstract of Dickson and Brander (in prep.)

Climate change can be described from any of a wide range of environmental variables. Here we emphasise the role of the windfield since it is the nearest point at which we can offer a unifying context for the very different case-studies we describe. The actual mechanisms by which these changes appear to have imposed their effects on cod stocks are surprisingly different in type and scale for each stock.

In the Iceland-Greenland-Labrador case, the principal mechanism is advective transport and larval drift. This case-study hinges around the role of the Atlantic windfield in stimulating the spread of warmth and larvae to West Greenland in the 1930s to 1960s via a strengthened Irminger-West Greenland Current System, and the question of whether, once established, the West Greenland stock was ever capable of sustaining a significant exchange of larvae and adults to and from Labrador.

To the suggestion of many authors that the West Greenland cod stock was mainly recruited from Icelandic waters, a suggestion supported by the use of juvenile haddock as a tracer (Hovgard and Messtorff, *op. cit.*), we add the confirmatory evidence from the work of Kushnir (1993) that during the period of warming off West Greenland, the North Atlantic windfield was configured in such a way as to boost the warm Irminger Current. This establishment of increased easterlies over the west-going Irminger was not just a small-scale local event. Kushnir's U-index registers the cyclonic or anticyclonic tendency over a large area of the central North Atlantic between 30°N and 60°N, and shows that only during the 1930s to 1960s was the large-scale Atlantic windfield dominated by a major cyclonic centre in mid-ocean, with easterlies sweeping around its northern rim across the Irminger Sea.

As to whether and under what circumstances there might have been a similar interchange further downstream between the cod stocks of West Greenland and the Labrador coast of Canada, it is clear from the outset that the possibilities of such an exchange must be limited to the three or four decades in this century when the West Greenland stock was sufficiently strong to act as a source of larvae.

Reviewing the available evidence – none of it conclusive – we believe that in only one year (1957) was there evidence for an actual, long-range, inter-stock exchange. In that year, not only were the spawning stock biomass and year-class strength of cod at West Greenland close to their absolute maximum (Hovgard and Buch, 1990;) but the anomalous airflow off West Greenland in May-July 1957 was such as to divert the bulk of this large larval production offshore into the Davis Strait, so that the 'conveyor' was at its most productive and its most direct.

Whether these larvae reached the Labrador Shelf is conjectural. Our sole evidence that an **effective** transport of cod larvae to Labrador might have taken place in that year is a sequence of high mortality estimates (F) in the 1957 year class of the Northern Cod at ages (6+) when the adults of any larval immigration would be returning to Greenland. We conclude that the climatic stimulation of larval exchange from Greenland would be rare – either in years such as 1957 when the normal current system might have been short-circuited, or in years of extreme cold when larval development might have been sufficiently prolonged to allow the young fish to reach Labrador by the normal route.

Throughout the century-long change in the cyclonicity/anticyclonicity index in the central North Atlantic, a further key index - the waxing and waning of High Pressure at Greenland - was undergoing a parallel slow evolution. As the Greenland Ridge reached its 20th century maximum in the mid- to late-sixties, it triggered four separate impacts in three Atlantic cod stocks.

First, it directed an intense and refrigerating northerly airflow across the Norwegian-Greenland Sea, especially during winter, ushering in the first post-war period of prolonged cooling in the marine environment of the Barents Sea with adverse effects on the year-class strength of the Arcto-Norwegian cod.

Second, the southward transport of cold, fresh, polar water in a swollen East Greenland Current, and its preservation through convective capping and ice formation north of Iceland (Malmberg, 1969, 1973; Dickson *et al.*, 1988), provided the initiating conditions for the Great Salinity Anomaly, which then entered the circulation of the Northern Gyre via the Denmark Strait. After a short advective time-lag, the arrival of the chill fresh conditions of the Great Salinity Anomaly in the last years of the 1960s accelerated the deterioration of the marine climate there, and continued the reduction/retraction of the West Greenland cod stock (see Blindheim and Skjoldal, *op. cit.*).

One decade later, during the last years of the 1970s, the slowly propagating signal of the Great Salinity Anomaly arrived in the Barents Sea (Dickson and Blindheim, 1984; Dickson *et al.*, 1988), accompanied by a minimum in surface and subsurface temperatures and the near-record cooling which spread across the Barents Sea shelf in the late 1970s/early 1980s can therefore fairly be described as a third **deferred** effect of 1960s pressure changes at Greenland, with much the same net effect as during the earlier direct-cooling episode of the 1960s – i.e. low growth and a succession of poor year classes.

As the winter pressure at Greenland (Figure 23) and the cyclonicity over the central North Atlantic reached their 20th century maximum intensity, the North Atlantic Oscillation dropped to its long-term minimum indicating a minimum in the strength of the mid-latitudes westerly circulation. At the 'event scale' of windiness, Holt (1991) reports that strong wind events in the north-east Atlantic showed a parallel evolution, decreasing gradually but steadily over 60 years to the 1950s or early 1960s. Since then, there has been a steadier increase in gale frequency, and a steadily increasing trend in mean wave heights across a broad swathe of the mid-latitude North Atlantic.

The response to these long-term shifts in windiness at both the large-scale and the storm-scale seems to be reflected most clearly in the gadoids of the Faroe Plateau, where Hansen *et al.* (1990) find a similarly-evolving trend in the ratio of haddock to cod in catches over almost one hundred years. Juvenile haddock exhibit such a markedly greater preference for stratified conditions as to render themselves the more vulnerable to changes in windiness as a result. A long-term increase, then decrease in the haddock:cod catch ratio at Faroe is therefore the expected result of a long-term decrease, then increase in non-directional windiness. While this case-study hinges much more on the response of the haddock than that of the cod to environmental change, this in itself is not irrelevant to the present review since it highlights by contrast the conditions which promote stability in at least one of the cod stocks under review. At Faroe the factors which seem to buffer the cod against change seem to include a small stock size, a relatively well-mixed environment as juveniles and a retentive horizontal circulation.

The case of the Baltic cod provides a final example of the way in which a stock may respond to wind-induced changes in its physical environment. If conditions at the depth and location of spawning are so fresh as to cause eggs to sink and so anoxic as to prevent their development, it becomes obvious that the success of this major stock is linked to the inflow/stagnation cycle of the Baltic Deeps. The cause of **that** is complex, yet there seems to be a growing consensus, now validated by models, that **prolonged periods of westerly wind, above a certain strength, during winter** are an essential pre-condition of major inflows. There is a sufficient correspondence between the short-term peaks in the 130-year winter index of westerly weather for the British Isles and the known chronology of major Baltic inflows to encourage that conclusion.

## APPENDIX 3

Description of life cycle of walleye pollock for direction and analysis of WPEC program

(18, Dec., 1992, Kushiro, Hokkaido)

| Description of lyfe cycle | Age | Season | Area | Water mass | Depth | Prey | Predator |
|---|---|---|---|---|---|---|---|
| Spawning | 0 | winter | off Funka Bay | winter cooling (mixing) | midwater | | (fishing) |
| Egg (1.5mm) | 0 | winter | Funka Bay | coastal Oyashio | surface | (bloom) | |
| Hatchling (5mm) | 0 | winter | Funka Bay | | surface layer | Pseudo. spp. nauplii | sagitta jerryfish |
| Larvae (6mm~) | 0 | winter~ spring | Funka Bay | | surface~ midwater | | fish seabird |
| Juvenile (~10cm) | 0 | spring~ fall | Funka Bay | summer warming<br>Tsugaru Warm Current | midwater ~bottom layer | Copepoda | fish (pollock) |
| Young (10-20cm) | age 1~2 | winter~ ~winter | shelf | cold water mass on shelf | | Euphausia | fish (cod) |
| Immature (20-35cm) | age 2~3 | winter~ ~winter | shelf | | | Canibalism | |
| Adult (35cm~) | age 3,4< | winter~ ~winter | off Funka Bay | winter cooling (mixing) | | | marine mammal (fishing) |

APPENDIX 4

Norwegian coastal current - a research proposal

The Norwegian coastal current provides an unidirectional production and transportation system, running from south towards north. Simply stated, in any food chain in this region, predators at high trophic levels are fed biomass transported from the south.

First feeding of cod larvae which eventually constitute the bulk of recruits to the north-east Arctic and stocks probably occur on the shelf outside the Lofoten Islands. *Calanus finmarchicus* females produce nauplii, which are the first prey of north-east Arctic cod larvae. Females possibly emerge from deep wintering habitats in the Norwegian Sea, drifting on shelf and northwards as their diapause terminates. This spawning generation may be the product of a parent generation spawning along the coastal current front during the previous summer.

A study of how climate effects survival and growth of north-east Arctic cod larvae should address several problems:

1. Does the food-web of north-east Arctic cod larvae depend on the Norwegian coastal current front as a system for particular high production of phytoplankton?
2. What phytoplankton is involved in the food-web?
3. What physical processes may cause interannual variations in phytoplankton biomass?
4. How does phytoplankton production affect the fecundity of *Calanus* spawning in the front?
5. What is the duration of the seasonal primary production and *Calanus* reproduction cycles?
6. How is the spawning generation of *Calanus* advected into and retained within the frontal system?
7. How is the new generation of *Calanus* retained by or dispersed from the front?
8. How are cod larvae retained by or dispersed from the front?
9. What is the relative importance of different zooplankton species in the diet of the different size groups of cod larvae.?
10. How is the survival of cod larvae related to prey-predator relationships?

APPENDIX 5

Establishing a Cod and Climate database

A key element of retrospective analysis of cod and climate data is the assembly of time-series data sets in formats accessible to the many analysts likely to participate in the exercise. If the data sets involved are simply processed indices of time-series trends in recruitment, stock sizes, temperatures, etc., then the maintenance of data is trivial. However, many of the potential analyses anticipated with these data (e.g. growth, predation, distribution, recruitment) require information disaggregated spatially and temporally. Given these considerations, then careful thought on the design of data sets is imperative.

Recent experiences of the ICES Multispecies Assessment Working Group can perhaps serve as a model of how common data sets for the eight cod stock units can be merged (Anon. 1991; 1992a; 1992b). The Multispecies Working Group assembled several sets of information pertaining to (1) factors involved in variations in cod growth rates (prey density, temperature, etc.), and (2) factors involved in average stomach content and prey species composition. In both sets of analyses, data from a wide array of cod stocks are assembled. Data were analysed at two meetings of the Working Group. Several conclusions can be drawn from the exercise.

(a) The development of data sets is critically dependent on the nature of hypotheses being tested. The group should have a firm grasp of the scientific question prior to designing data sets. This is particularly important given that answering an initial set of questions will invariably lead to additional hypotheses and tests. The data set should be sufficiently disaggregated and flexible to accommodate a hierarchical chain of inquiry.

(b) Individual data sets should be designed very carefully to ensure that there is comparability among areas. Often similar but not equivalent data are collected on the same attribute by different institutes, so careful attention to nuances in data collection and file format is imperative, particularly if a variety of analysts are going to participate in simultaneous analyses of the data.

(c) A policy on the availability of data and its use for publication should be carefully considered. The development of large disaggregated data sets will involve significant time investments of a large number of individuals. There are likely to be some sensitivities involved with widespread distribution of such data, particularly if individuals other than those creating and maintaining these data sets are likely to publish results. A policy regarding the 'rules' for access to these data, authorship and acknowledgements in subsequent papers should be worked out beforehand.

Examples of data sources available for retrospective analyses of cod population changes and indices of biotic and abiotic environmental variables for the Northeastern United States are provided below. The cod population estimates are derived from a synthesis of recruitment and stock size estimates compiled by Myers *et al.* (1990). For the environmental data an attempt has been made to provide a relatively complete list for the Northwest Atlantic region of the United States to suggest the types of information that should be identified for other areas wherever possible. These data from other locations should include series such as the Continuous Plankton Recorder Survey conducted by the Sir Alister Hardy Foundation for Ocean Science, plankton and bottom trawl surveys conducted by countries throughout the northern Atlantic region, etc. Acoustic surveys may also prove useful in the proposed analyses.

Detailed population size and life history information is available for North Atlantic cod stocks covering a broad range of environmental conditions. Myers *et al.* (1990) document time series of recruitment and spawning stock size for 22 cod populations throughout this region and these estimates are available in an existing data base structure. This information provides the basis for an empirical analysis of how cod stocks have fluctuated under variable environmental conditions.

BIOLOGICAL AND PHYSICAL DATA SETS
NORTHEASTERN UNITED STATES

1. Biological data

A. MARMAP CPR Programme

This survey consists of standard monthly transects using the Continuous Plankton Recorder (CPR) by merchant and other vessels of opportunity between (1) Massachusetts, USA, and Cape Sable, NS (1961-present), (2) New York to the Gulf Stream (1976-present), and (3) from Newfoundland to Cape May (1961-1974, 1991-present). Phytoplankton, zooplankton, and ichthyoplankton are collected on 240 μm mesh at a depth of 10 m.

B. MARMAP

The NOAA - Northeast Fisheries Science Center undertook broad scale surveys of plankton populations on the continental shelf of the Northeastern United States during 1977-87. These biomass and abundance of zooplankton species are available for this series at approximately bimonthly to monthly intervals during this period.

C. ICNAF plankton surveys

An international survey designed to estimate production of larval herring of Georges Bank and the Gulf of Maine was undertaken during the period 1971-76 using a systematic sampling design. In addition to larval herring, components of the zooplankton community were also enumerated. Sampling was conducted at monthly intervals.

D. Trawl surveys

The Northeast Fisheries Science Center has conducted stratified random trawl surveys off the northeastern United States annually in autumn since 1963 and in spring since 1968. These data provide estimates of cod relative abundance by age class. Data on interacting species are also available.

E. Soviet archival data

Biostatistical data including meristic and biological analyses, zooplankton, phytoplankton and hydrographic data from the Georges Bank and adjacent area for the period 1963 to 1978 are at ATLANTNIRO.

2. <u>Physical data</u>

| | Variables | Years |
|---|---|---|
| A. Satellite Remote Sensing Data | | |
| 1. AVHRR Full-Resolution Images | SST, water mass patterns | 1982-present |
| 2. AVHRR 1/4 Resolution Images | SST, water mass patterns | 1982-present |
| 3. CZCS | Chlorophyll | 1978-1986 |
| B. SOOP Ocean Monitoring Data | | |
| 1. New York Bight Route | SST, surf. salinity, bottom temp., water column temp. | 1978-present |
| 2. Gulf of Maine Route | SST, surf. salinity, bottom temp., water column temp. | 1978-present |
| 3. Southern New England Route | SST, Bottom temp., water column temp. | 1974-1984 |
| C. Climatological Data | | |
| 1. Marine Deck | SST | 1946-present |
| 2. NOAA Data Buoys | SST, winds | 1975-present |
| 3. NOS Tide Stations | Sea level | 1911-present |
| 4. Boothbay Harbor Records | Coastal SST | 1905-present |
| 5. Coastal Weather Stations | Air temp., winds, solar radiation | 1905-present |
| 6. Streamflow | River discharge | 1920-present |
| 7. Wind Driven Ocean Transport NODC Data) | Wind stress, Ekman transport | 1946-present |

APPENDIX 6

Overview of the ICES Symposium on Cod and Climate Change, 23-27 August 1993, Reykjavik, Iceland

*Session 1 Historical review*

Archaeological excavations of fish bones indicate that cod of 1-1.5 m were regularly taken in the 12th to 19th centuries throughout the North Atlantic. Historical records on the cod fisheries both at Iceland and in the north-east Arctic since the 16th century have shown great fluctuations which are clearly linked to changes in temperature. In cold periods catch per unit effort fell but showed an increase when environmental conditions became more favourable. This was the case for cod stocks in general until the beginning of the 1950s. Overviews of the landings of cod show that, following a highly productive period, 1950-65, the cod fisheries have subsequently suffered a protracted decline. Concomitant environmental changes would not be expected to cause a consistent decline in all cod stocks throughout their climatic range. There is evidence of climatic effects but the widespread decline in almost all stocks indicates that steadily increasing fishing mortality is the dominant factor in recent years.

*Session 3 Physical processes and models*

Session 3 was aimed at describing the overall climatic changes in the North Atlantic region and the regional responses to such changes, including possible effects on cod stocks. The presentation and the discussion focussed on the effects of wind and temperature changes. With respect to winds, it was clearly demonstrated that, although effects of slow shifts in the large-scale North Atlantic wind field were seen simultaneously throughout the area, the actual effects are different in the various subareas, due to varied regional responses. Examples of such responses relevant to cod stocks were given as follows:

— Decadal to centennial changes of the atmospheric circulation pattern (as, for example, expressed by the North Atlantic cyclonicity/anticyclonicity index) to affect the intensity of the four major cyclonic gyres in the subpolar North Atlantic Ocean: Labrador, Irminger, Iceland and Greenland Sea. This implies changes in the intensity of advection by the cyclonic current system and thus changes in larval drift pattern affecting inter-stock exchanges such as those between Iceland and Greenland. It also implies changes of the upwelling intensity within the gyres. Via the stratification this affects the intensity of deep and intermediate water formation, resulting in changes of upper layer temperatures and a change in the intensity of the polar parts and the arctic facts related to gyres. These changes also control the flux of fresh water from the Arctic Ocean within the system of polar currents, leading to pulses of cold and low saline water like the great Salinity Anomaly, which persisted for a decade in the subpolar North Atlantic.

— Changes in the windspeed (as, for example, expressed by the North Atlantic Oscillation Index) also occur on large time-scales. By enhancing the turbulence in the near-surface layers, it increases the contact rate between predator and prey. With respect to changes of directional windspeed, important effects are known on the exchange of deep waters in semi-enclosed seas (Baltic) and fjords. Direct relations between living conditions for cod and series of intense westerly winds have been shown.

— With respect to the effects of large-scale atmospheric temperature changes the effects of global warming were discussed. Since observations cannot yet conclusively distinguish between global warming and natural fluctuations, models of coupled oceans/atmosphere circulation are applied to the case of increasing $CO_2$ in the atmosphere. The results show maximal warming in the high latitudes, however there are varying regional patterns. For the northern North Atlantic there is only small to zero warming, since the salinity decrease from melting ice suppresses convection and reduces the northward extension of the North Atlantic Current.

*Session 4 Models of bio-physical processes*

The term 'biological processes' addresses a wide range of processes which have the potential of influencing recruitment and growth. From a very general point of view, the relevant physical processes and parameters in this context are limited to **temperature, salinity, light conditions, buoyancy** and **motion**. All the papers and posters in this session addressed different aspects of **motion.**

Certainly we are all aware of the importance of the dynamics (currents) for drift and dispersion of eggs and larvae (and juveniles) from the spawning areas. However, we have jut recently become aware of the importance of the currents in the microscale environment for feeding of larvae.

In recent years we have seen large improvements in numerical models simulating drift and dispersion of eggs and larvae, partly because of the model techniques, partly because of input data like spawning period, spawning site, buoyancy and vertical behaviour of the larvae. The modelling from the three regions, Georges Bank, Newfoundland shelf and the Barents Sea, shows that the mechanism for transport and dispersion is very different. Vertical distribution of eggs and larvae seems to be very important for the resulting transport in Georges Bank and Labrador cod, while in the Arcto-Norwegian cod the horizontal transport is much less sensitive to variations in the vertical distribution of the larvae. However, all three model results demonstrate the importance of wind field variations on the inter-annual variations of the distribution of the juveniles.

On the level of small-scale dynamics we now see increasing evidence of the Rothschild and Osborn theory. Modelling, field measurements and laboratory experiments show that this process is particularly important for larval fish. the increasing knowledge will have to change our present views of energy balance for larval cod. It also focusses on the importance of wind and wave climate on the recruitment processes, and on the importance of regions of high tidal mixing.

*Session 5 Biology of cod (eggs, larvae, juveniles and adults), stock identity, migration, stock structure, recruitment processes and population dynamics*

It is of critical importance to correctly identify discrete populations and associated time and space scales in order to resolve population processes. Our present predisposition to study biology at the stock or management unit level may result in oversights of wider issues and general patterns. For example, it appears that spawning takes place over a more extensive period on the Labrador and Grand Banks compared to the north-east Atlantic cod stocks. This difference may be an artifact of aggregating across spawning concentrations and years. This problem also highlights the general lack of data on cod eggs and larval distribution for the northern cod stock complex and other cod stocks throughout the north-west Atlantic. Lack of such fundamental knowledge at this and other life stages will plague attempts to make meaningful inter-stock and inter-regional comparisons.

The comparative approach is an effective means of identifying factors which influence cod production and distribution. The general distribution of cod stocks is well known and can be related to temperature, salinity, oxygen and depth. It may be useful to look for general patterns in cod growth, such as by examining the relationship between size at age across stocks and the average annual hydrographic condition. Once could also seek relationships between mean recruitment and the magnitude of certain attributes common to cod spawning grounds such as the volume of water of a critical temperature for survival or the distributional area of the eggs or larval stages. It is generally recognised that the processes which limit distribution and production could depend on the geographic location of the stock and levels of data aggregation need to be considered carefully. Caution is necessary when applying such general models to local populations because they may not accurately reflect stock-specific parameters. Clearly, a healthy blend of comparative and process-orientated studies is recommended.

Distinguishing between the effects of fishing and environmentally induced changes in stock distribution and production will be a difficult but highly important task. Several cod stocks have recently experienced declining recruitment, environmental extremes, and severe exploitation. In addition, loss of spawning components, low SSB and change in age composition due to fishing could increase a stock's susceptibility to environmental variation. It is essential that the fisheries scientific community debate the order of importance (e.g. proximal vs ultimate) of these two interacting effects.

Many studies have shown that 0-group abundance indices correlate well with year-class abundance levels leading to the conclusion that year-class strength is established during the first few months of life. These same studies,. using correlative and descriptive approaches, have shown that biological and physical factors influence distribution, growth and survival. Warm years are generally associated with higher cod production among high latitude cod stocks. One potential shortcoming of such studies is that proxies derived from available data may not adequately represent the assumed processes being modelled. The emphasis on studying factors influencing survival during the early life stages is not balanced by a similar number of studies dealing with survival processes acting on juveniles and adults. In fact, we do not know (or hazard to guess) under what set of environmental circumstances M# 0.2. Unlike the early life stages, juvenile and adult cod can select temperature and salinity condition and thereby reduce the variance in the environmental condition experienced. It may only be during extreme environmental conditions (broad-scale and persistent), when the capacity for migration or delayed maturation cannot prevent exposure to the prevailing conditions, that juvenile and adult cod may die from environmental stress.

*Session 6 Trophic relationships of cod in various ecosystems*

Trophic interaction of cod was reviewed in the Barents Sea, North Sea, Iceland, Newfoundland and Baltic ecosystems. Diet composition was similar across ecosystems in that fish were the major prey for adult cod, while crustaceans constituted the most important prey of juvenile cod. However, the particular prey species differed among each of the ecosystems. Cod is preyed upon by other fishes, by marine mammals, by marine birds, and several invertebrate species; however, in most cases, the magnitude of these impacts is unknown (or poorly known) and much more information is required before reliable quantitative estimates of predation mortality on cod can be derived.

Cannibalism may be important in some regions (e.g. Iceland and the North Sea) but not in others. Most cannibalism involves predation on younger age groups (< 3) and small-sized fish (< 40 cm)—and is most significant on 0-group and 1-group fish. Again, however, there are few reliable estimates of the intensity of cannibalism in any region. Studies of the ontogenetic changes in stock distribution (for each stock) are essential to better understand and evaluate the intensity of cannibalism and its possible significance in affecting recruitment.

Temporal and spatial changes in the abundance/biomass of the prey of cod are generally reflected in the diet composition, although there are few data on the 'suitability' of alternate prey species or the ability of cod to preferentially seek out prey species.

Statistical analysis of cod stomach content data (or any stomach contents data) is often hampered by a large proportion of empty stomachs and when stomachs have been bulked (or aggregated) before the contents have been measured/counted. However, models and procedures have been developed to accommodate/account for these in deriving statistically-reliable estimates of average stomach contents by length group (of cod)—and also accounting for other independent variables (i.e. area, depth, etc.). Procedures are also available for estimating the amount of food consumed using statistical models (such as the Gamma-Bernoulli model and GLM/GAM type models).