Oceanography Committee

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Report of the

Workshop on the Transport of Cod Larvae

Hillerød, Denmark

14–17 April 2002

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

Palægade 2–4 DK–1261 Copenhagen K Denmark

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1 OVERVIEW

1.1 Introduction

Cod (*Gadus morhua* L.) are widespread over most shelf seas of the North Atlantic where the annual mean temperature is between about 2 and 15°C. Adult fish migrate, often over distances greater than 1000 km, to join spawning aggregations. The eggs are slightly buoyant and are transported with the water masses in which they are spawned. The larvae and early juveniles remain pelagic for the first 3–5 months of life, during which time they may be carried long distances away from their spawning site (for example from spawning on Hamilton Bank,ee Figure 1.1). In some cases spawning occurs in areas where transport is slow or there is a gyre which retains the eggs and larvae close to the position of spawning (for example from spawning on Flemish Cap - see Figure 1.1).

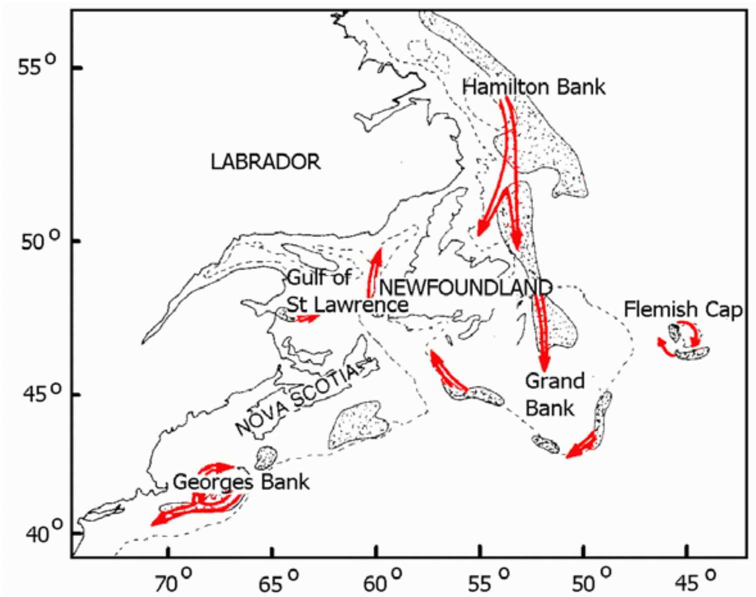

Figure 1.1 Spawning areas (stippled) and main patterns of egg and larval transport (arrows) of cod in the NW Atlantic

The drift of cod larvae has significant implications for both the dynamics of individual cod stocks and for fisheries management practices in several regions of the North Atlantic. For example, the larvae of Icelandic cod regularly drift west across the Denmark Strait toward Greenland (Figure 3.3). When environmental conditions are suitable off West Greenland, these cod thrive and subsequently return to Iceland to spawn. This return migration, estimated at 50 million fish per year, each weighing around 2.5 kg, during the 1970's (Shepherd and Pope, 1993), can result in large uncertainties in the assessment of the Icelandic stocks. Transport of cod larvae is also thought to affect recruitment, although not necessarily across stock boundaries, in several other areas of the North Atlantic including in the Gulf of Maine, Labrador, NE Arctic and Baltic.

The ICES Working Group on Cod and Climate Change (WGCCC) therefore decided to hold a workshop to explore transport processes and their role in the life histories of the affected cod stocks. The use of circulation models to explore the physical processes that lead to the variability in transport of larvae needs to be developed and comparisons made between different regions and stocks. In addition, attempts were to be made to determine whether larval transport indices, derived from model results and observations, can be used to improve assessment models.

The aims of the workshop were to:

- examine the coupling of circulation models with early life history models to determine the physical and biological processes responsible for the transport or retention of cod larvae;
- develop, if possible, interannual transport indices based on physical variables that reflect the magnitude of the larvae drift or retention;
- attempt to incorporate these indices into the cod assessment process; and
- collate and synthesize existing direct and indirect observational information about egg and larval transport for all stocks and years. [Direct information is egg and larvae surveys while indirect information includes unusual distribution and migration in later life, elemental analysis of otoliths, genetic identification, and meristic characters.]
- evaluate the effects of variations in transport during early life on subsequent recruitment

The workshop dealt with interannual variability in transport within a stock as well as transport across stock boundaries. Rapid advances in circulation models at a variety of scales have improved the prospect of developing scenarios for changes in circulation under different conditions of climate change. There are also improving prospects for operational now-casting and forecasting of circulation.

1.2 Terms of Reference

Council Resolution 2C13 (C.Res. 2001/2C13) gives the Terms of Reference for the workshop:

A Workshop on the Transport of Cod Larvae [WKTCL] (Co-Chairs: J. Quinlan, USA, B. Aadlandsvik, Norway and M. St. John, Germany) will be held in Hillerød, Denmark from 14–17 April 2002 to:

a) couple circulation models with early life history models to determine the physical and biological processes responsible for the transport or retention of cod larvae;
b) develop, if possible, interannual transport indices based on physical variables that reflect the magnitude of the larvae drift or retention;
c) attempt to incorporate these indices into the cod assessment process; and
d) collate and synthesize existing direct and indirect observational information about egg and larval transport for all stocks and years. [Direct information is egg and larvae surveys while indirect information includes unusual distribution and migration in later life, elemental analysis of otoliths, genetic identification, and meristic characters.];
e) evaluate the effects of variations in transport during early life on subsequent recruitment WKTCL will report by 15 May 2002 for the attention of the Oceanography Committee

1.3 Preparations for the workshop

Contributions for the Workshop were solicited from both participants and non-participants, in the form of Working Documents (WD), which were made available via the ICES/GLOBEC website for some time prior to the meeting. The Working Documents were categorised under four principal Topics (listed below), although in several cases documents were relevant to more than one topic. A total 18 papers, presentations and abstracts was made available in this way and will be included with the final version of this report. They can be downloaded from the ICES/GLOBEC website at http://www.ices.dk/globec/workshops/transport.

A database containing a variety of material, including figures of spawning areas and drift patterns, tables with time series of stock information and a selection of published papers for each area was made accessible via the ICES/GLOBEC website. These were used during the electronic discussion and correspondence which preceded and followed on from the meeting.

1.3.1 Topics

Four Topics were identified as a means of structuring the presentations and discussion:

1. Background information on stock structure, spawning and transport: geography, oceanography; observational time series for all stocks and years

2. Modelling physical/biological processes responsible for transport and retention: coupling circulation, behaviour and life history models

3. Consequences of observed variability in transport for stock dynamics

4. Incorporating information about variable transport into stock assessments: perturbations, probabilistic approaches, using scenarios, development of transport indices.

1.3.2 Workshop structure and working procedures

The agenda for the workshop is given in Appendix 7.1 and the participants are listed in Appendix 7.2. Contributors who did not attend are listed in Appendix 7.3. The workshop was divided into three sections. On the first day participants made individual presentations, based on the Working Documents (in Appendix 7.4). These were grouped by Topic, each with an introduction, and followed by a general discussion on the presentations for that Topic. On the second day, the participants broke into groups to discuss the four Topics. Discussion was aimed at synthesizing the information on each Topic and developing conclusions and recommendations related to the terms of reference. On the third day, four geographical breakout groups (NW Atlantic, NE Atlantic, Iceland/Greenland, Baltic) discussed the material available for each area and continued the discussion of the Topics. All breakout groups reported at a plenary session and all were asked to address the following questions, with rankings where appropriate:

- What are the most important processes for transport of eggs and larvae for each of the regions? Please rank.
- What are the critical limitations on our ability to model the transport of eggs and larvae in each region? Please rank.
- Revisit: Are there examples of transport affecting recruitment?
- What recommendations should come from the workshop concerning future work on transport? (These should be for work that could be completed within the next few years) Please rank.
- What similarities and differences are there between different stocks around the North Atlantic?

Conclusions and recommendations based on the workshop presentations and the discussion of the breakout groups were developed. In one case, additional analyses were conducted using the data posted on the website. The workshop concluded with a plenary session discussing the reports of the breakout groups in relation to the terms of reference.

2 REPORTS OF DISCUSSION ON TOPICS

Report of Discussion on Topics

Primary Issues Influencing Cod Transport

Breakout groups on the second day were tasked with identifying processes, common across regions, which would be potentially important to larval transport. These groups were also asked to specify particular conditions that might make one region differ from the next. The Workshop addressed the following four questions:

- What are the physical and biological processes responsible for the transport and retention of cod larvae?
- What further information is required to improve the models of transport of cod larvae?
- What is the evidence that the transport variability is important in determining recruitment variability of cod?
- What indices of transport should be estimated?

An initial discussion centered on what is arguably little demonstrable evidence of a relationship between transport and recruitment. The Workshop concluded that the basic need was to provide an understanding of a process that was affecting a stage of the early life history. It is entirely possible that the lack of a simple relationship between measures of transport and recruitment may be due to the complexity of the interaction or is simply owing to an inability to identify those physical processes determining the impact of transport on pre-recruit stages.

The suite of factors potentially determining the overall effect of transport on dispersal of cod eggs and larvae is quite large. Biological variables include: the stage of development (eggs, larvae, age), individual buoyancy, diurnal vertical migration (vertical migration assumed important in sheared environments), ontogenetic vertical migration, egg development time (temperature dependence), growth (temperature and food dependence), mortality (in relation to food, predators and possible condition), habitat availability (where the larvae settle), the ability of larvae to delay settlement, the timing and location of spawning and the size structure and condition of the adult population (through effects on offspring quality). Physical variables that could be considered include: light intensity, temperature, wind forcing, freshwater budgets, turbulence (horizontal and vertical), frontal structure, sea level gradients, hydrographic fields and surface heat flux. Unfortunately, this exhaustive list does not present an effective way forward in making a comparative analysis across systems in which cod occur. Significant insight could be achieved by providing an accurate description or model of six basic elements: 1) wind forcing, 2) density field, 3) tidal cycle, 4) a description of the growth process (e.g., in relation to temperature and food availability), 5) ontogenetic changes in vertical location and habitat choice, 6) spatial and temporal distribution of spawning.

The second question was addressed by considering the information needed to provide advice to managers on the interannual variations of cod egg/larval distributions and drift patterns. The Workshop concluded that physical models could be improved with: 1) better information on the temporal resolution of the atmospheric forcing and density fields, 2) better model resolution (e.g., to achieve the physical development and maintenance of fronts), 3) better development and availability of long-term data for validation and forcing to provide an indication of long term variations in transport and 4) linkage between open-ocean and regional models to provide for the occurrence of local perturbations caused by open-ocean processes. With respect to biological processes, four elements were identified: 1) information on variations in spawning location and timing, 2) information on the distribution of early stages in space and time, 3) initial and boundary conditions with respect to biological elements and 4) identifying the source(s) of mortality and their variation in space/time (which can be as important to the outcome of the transport process as the physical forcing.).

In addressing the third question, a distinction was made between the consequences of inter- and intra-stock transport. If inter-stock transport (i.e., transport across existing stock boundaries, in which the transported fish survive and may migrate back to their spawning origin when mature) is a regular feature then one may question whether the accepted stock boundaries are in fact appropriate. The Iceland-Greenland stock complex is an example where such inter-stock transport occurs. In other cases pelagic transport may take fish across a stock boundary to an area where they do not survive, with obvious effects on recruitment. The fate of larvae transported away from Georges Bank may or may not lead to mortality. If they are transported away in warm Gulf Stream rings then they do not survive, but if they are carried into the mid-Atlantic Bight in colder shelf water then they may do so and migrate back as mature fish. Intra-stock transport can also be shown in some cases to affect growth and survival rates, for example the transport of cod eggs and larvae into the Barents Sea; and the transport of larvae into shallow regions of the Baltic. In all of these examples, variability in forcing that alters the intensity or direction of transport can have an impact on population production.

The final question was dealt with briefly due to time limitations. Indices of transport were broadly classified as model derived or data derived. The former relies on confidence in the validity of the model being used to estimate transport, but in this category, the Workshop noted three possible indices: 1) volume transport (at a point or section); 2) distance travelled (in terms of mean and variance); and 3) patterns of settlement. Data derived estimates of transport could be based on 1) altimetry, 2) CTD or ADCP calculations of volume transport and 3) wind based estimates.

North Atlantic Oscillation

The Workshop examined the potential implications of the NOA for transport in key regions of the North Atlantic. The NAO is an alternation in the pressure difference between the subtropic atmospheric high-pressure zone centered over the Azores and the atmospheric low pressure zone over Iceland. The NAO is globally one of the most robust modes of recurrent atmospheric behaviour. It is the dominant mode of atmospheric behaviour in the North Atlantic sector throughout the year, but it is most pronounced during winter and accounts for more than one-third of the total variance in sea-level pressure.

A high or positive NAO index is characterised by an intense Icelandic Low and a strong Azores High. The increased pressure difference results in more frequent and stronger winter storms crossing the Atlantic Ocean in a more northerly track. The reduced pressure gradient of the low-index or negative NAO-phase leads, on the other hand, to fewer and weaker winter storms crossing on a more west-east pathway. Variability in the direction and magnitude of the westerlies is responsible for interannual and decadal fluctuations in wintertime temperatures and the balance between precipitation and evaporation over land on both sides of the Atlantic Ocean. The relationship between the state of the NAO and the temperature, wind, and precipitation patterns is particularly strong in Northern Europe (Ottersen *et al.*, 2001).

The North Atlantic Oscillation may cause variability in Barents Sea (BS) oceanography and ecology through the following mechanisms (Figure 2.1). A high (positive) NAO phase is connected to increased westerly winds over the North Atlantic. This affects BS water temperature by increasing the volume flux of relatively warm water from the southwest, cloud cover and air temperature. Increased BS water temperature influences growth and survival of cod larvae both directly, through increasing the development rate, and indirectly, through regulating the production of nauplii of their main prey - the copepod *Calanus finmarchicus*. Increased inflow from the zooplankton rich Norwegian Sea further increases availability of food for the cod larvae. High food availability for larval and juvenile fish results in higher growth rates and greater survival through the vulnerable stages when year-class strength is determined (Ottersen and Stenseth, 2001).

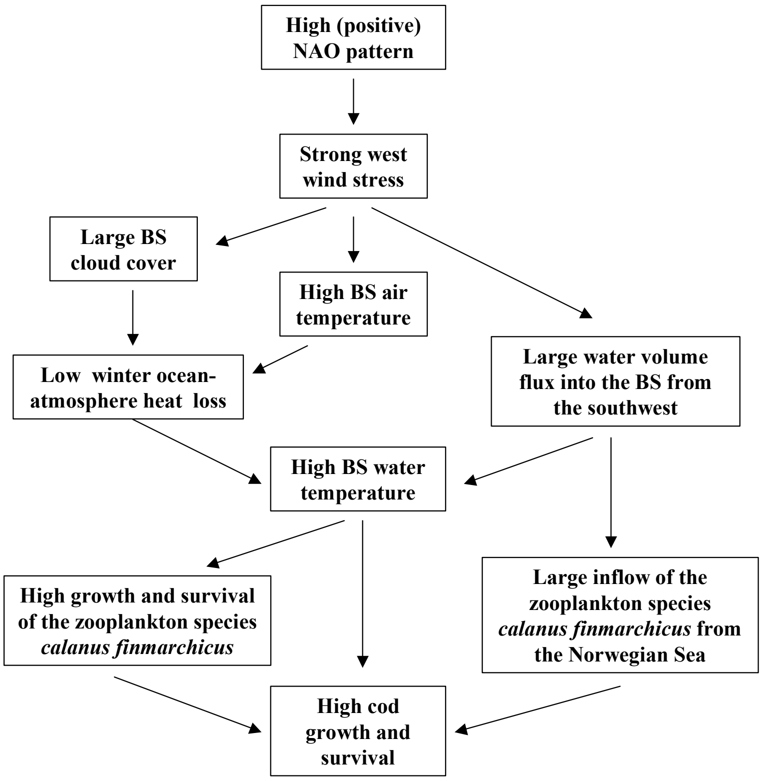

Figure 2.1. A conceptual model linking the NAO to recruitment of Northeast arctic cod.

A high NAO index also leads to an increase of oceanic inflow into the North Sea, which again is connected with increased SST and windiness in the region (Figure 2.2).

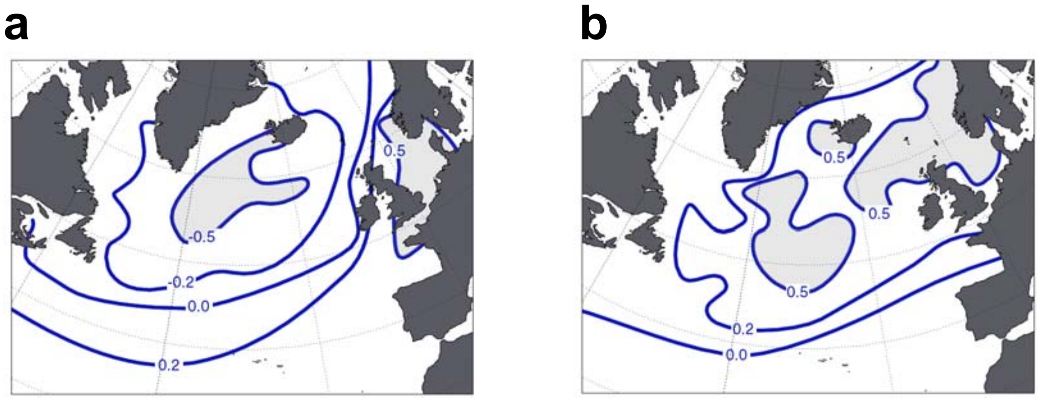

Figure 2.2. Correlation between the NAO winter index and (**a**) winter sea surface temperature (SST) and **(b)** winter scalar wind for the period 1950–95. From (Ottersen and Stenseth, 2001).

Early stages of *Calanus* are the main food resources for larvae and early juveniles of cod throughout the North Atlantic and thus may regulate recruitment. Fromentin and Planque (1996) found a significant correlation between the NAO index and two major copepod species in the North Sea, *Calanus finmarchicus* and *C. helgolandicus*. Four types of mechanism were proposed to explain the observed link between the NAO and *Calanus*: reduction in the volume of Norwegian Sea Deep Water where the over-wintering population resides, variations in the transport of individuals from the Faeroe-Shetland channel into the North Sea, changes in food availability (phytoplankton production), and alteration of the competitive balance between *C. finmarchicus* and *C. helgolandicus*.

Although the manner in which the NAO influences most cod populations is via sea temperatures, this is not so in the Baltic Sea. The Baltic is the largest body of brackish water in the world. Cod spawning takes place in the deep basins, where the volume suitable for successful cod spawning is regulated by oxygen and salinity levels, which determine the survival rates of eggs, larvae and juveniles (Bagge and Thurow, 1994). In recent years, the Bornholm Basin has been the only spawning area in which conditions were suitable for cod egg development (MacKenzie *et al.*, 2000). Several authors have demonstrated the connection between inflow of oxygenated and saline water from the North Sea and year-class strength of the Baltic cod stock. Dickson and Brander (1993) summarise the factors that have been suggested to promote effective inflow and conclude, citing many different studies, that the main cause is persistent westerly winds. Haenninen *et al.* (1999) point to the important impact of the NAO on salinity levels, through influencing both westerly winds, and thus major inflow events, as well as river runoff. Ultimately, the NAO, through salinity, regulates both the pelagic and demersal ecosystems in the Baltic.

3 NORTHWEST ATLANTIC STOCKS

3.1 Overview

A number of individual stocks are managed on the Northwest Atlantic Continental Shelf (Figure 3.1). The relative importance of the transport-related physical processes (atmospheric forcing (winds), buoyancy forcing, offshore forcing and tides) varies over this range. In the northern areas from Labrador to the Gulf of St. Lawrence, buoyancy – manifest as freshwater discharge from rivers and ice melt – is important early in the season and wind stress tends to be greater and more variable than in the south. In the Gulf of Maine high tides and strong tidal currents lead to strong tidal residual flows especially around banks. Reduced stratification in shallow areas through tidally-generated vertical mixing and the presence of tidal fronts are present on Georges Bank. Stratification is still critically important around the outer edges of bank systems. Offshore forcing through the presence of Gulf Stream rings impact the outer reaches of the continental shelves from the Grand Banks to Georges Bank.

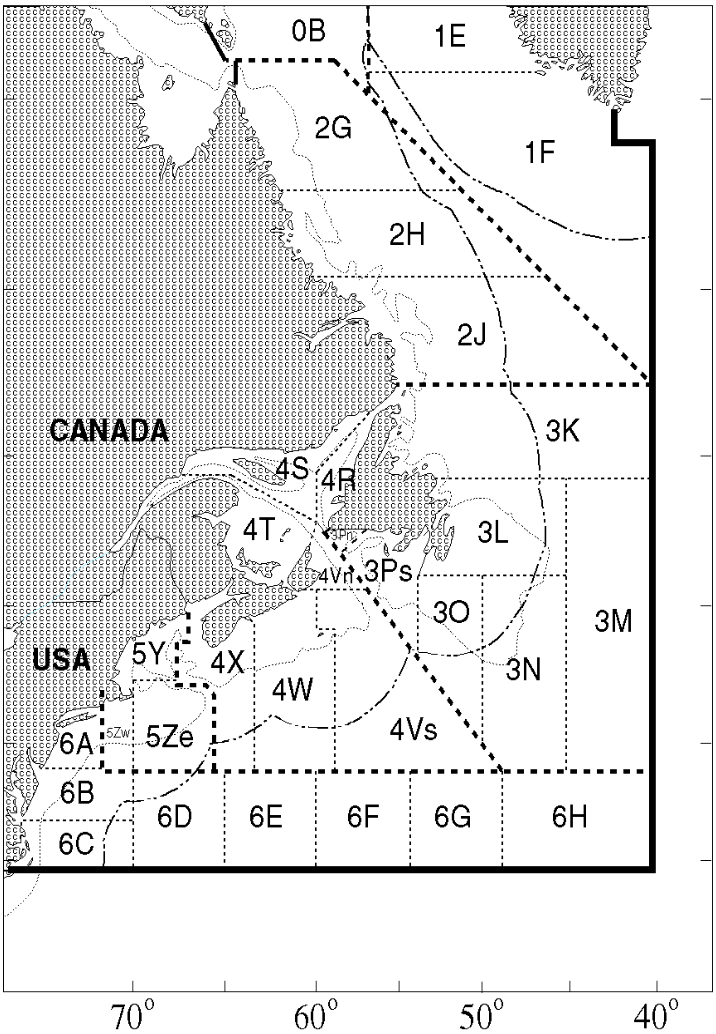

Figure 3.1. NW Atlantic Stocks Georges Bank (5Z); Browns Bank/BoF (4X) [Gulf of Maine]; Eastern Scotian Shelf (4VsW); Southern Gulf (4T); Northern Gulf (4Rs4Pn); Grand Banks (3NO); N Newfoundland/S. Labrador* (2J3KL); Northern Labrador (2GH); Flemish Cap (3M).

There is some evidence that stocks in this region are interconnected through larval drift and are not totally independent populations. The residual current patterns, drifter trajectories and numerical approaches involving particle tracking in circulation models all suggest the possibility of a degree of connectivity between these stocks. While the genetic information is ambiguous, tagging, meristic characters (vertebral counts) and initial otolith geochemistry all imply stock discreteness at the adult stage. The consensus of the Workshop was that connection between individual stocks in the region through larval drift probably does exist, but that it may be spatially limited – exchange occurs between stocks that are hydrodynamically near one another. What is not clear from the present studies is whether the larvae that are transported downstream to other stock areas survive to contribute to those stocks. Low survival of these larvae might arise due to their timing not being coincidental with the required food source or perhaps during a period of high predation.

3.2 Important Processes

Spring ice melt in the north can increase stratification anywhere on the continental shelf. This buoyancy driven stratification may result in a bloom occurring before the water column is thermally stratified. Stratification can break down through wind mixing and there are implications for larval transport, growth and survival in these dynamics. Depending on the duration of stratification and the density of eggs or other early life history stages, transport in surface layers may be influenced by wind variability.

Other fresh water inputs into the system include the Gulf of St. Lawrence. This discharge may contribute to stratification on the shelf, but the water is well mixed by the time the flow reaches the area of Browns bank.

Flow into the Gulf of Maine arises in two main sources: the Scotian Shelf and the Slope Water entering through the Northeast Channel. Smith *et al.* (2001) have found that the ratio of Scotian Shelf to Slope Water entering the Gulf of Maine has experienced significant persistent shifts that might impact hydrographic structure and circulation in the Gulf of Maine. Additionally, Loder *et al.* (2001) have identified major decadal-scale variability in both water properties and seasonal currents in the Scotian Shelf and Gulf of Maine and have suggested that these represent hydrographic regime shifts in the region. It is likely that plankton (here intended to include cod) community structure and distribution respond to and reflect the observed hydrographic variability in the system.

Finally, if transport from one area to another is to be successful, conditions at the destination must be conducive to larval survival and settlement. Obvious requirements may include things such as suitable bottom types, temperatures, salinities or oxygen levels. Less obvious are dynamics involving the production cycle and community structure at the destination. Production does not occur synchronously over this entire region. If the production cycle is shifted forward, immigrating larvae may be at a competitive disadvantage relative to resident populations. In some sense, the characteristics of the destination may not match larval requirements for growth and survival and the effect will be a loss. This may be the case for larvae transported from Browns Bank to Georges Bank in the Northwest Atlantic – production cycles on Georges are shifted forward relative to those on Browns. Timing may be very important and we should investigate if and when this may occur.

3.3 Critical Limitations

The general biological impediments to adequate modeling of the transport of cod larvae on the Northwest Atlantic continental shelf are related to defining the vertical distribution of eggs and larvae and the timing and location of spawning. Also important in determining their ultimate fate are the spatial and temporal variability in mortality (including predation), the dynamics of growth (determined duration of the larval period), and the effects of temperature on these rates, Currently, these seem to be universally applicable limitations to modeling cod stocks.

Transport processes may move larvae away from spawning areas to nursery or settlement areas where a different set of processes can further structure year class characteristics. Information on the distribution of nursery areas is rare. Even rarer are how these locations may have changed through time, which might provide clues to transport dynamics and could lead to management practices (changes in location, timing, intensity or gear used in fishing) which could protect important habitat.

Understanding of cross-shelf transport in the Newfoundland areas (2J3KL, 2GH), and how the larvae carried by the outer branch of the Labrador Current can make it to the inner shelf requires improvement. A better understanding may be derived from studies of the cross-shelf transport of *Calanus,* which also involves transport between the inshore and offshore branches of the Labrador Current.

Gulf Stream ring activity is correlated with recruitment in all cod stocks on the outer reaches of the shelves from southern Labrador to the Scotian Shelf, with the presence of rings impacting negatively However, present models of the shelf are not coupled to the dynamics of the open ocean. This is a several limitation of the models.

3.4 Examples

Evidence of a relationship between variability in current speed and recruitment for cod on the Newfoundland and Eastern Scotian Shelves - Cod eggs and larvae occur principally in the surface layer. As a result, any measure of the surface circulation within a region could serve to provide an indication of the speed and variability of the potential drift of animals within the region. To determine whether the level of variability in transport was associated with general patterns in recruitment variability of cod stocks on the Newfoundland Shelf and Eastern Scotian Shelf, information on variability in surface drifters (without drogues) released in the region was collated from a technical report by Sanderson (19XX). The International Ice Patrol released the majority of the drifters during winter and early summer. For each stock region, the average speed and variability in estimated current speed was calculated based on a spatially weighted average. Recruitment data for the period ending in the mid-nineties was gathered from the regional assessment documents to estimate the overall coefficients of variation in recruitment as well as the recruits/SSB (spawning stock biomass) for the stocks in 2J3KL, 3NO, 3M, 3Ps, 4VsW. Both coefficients of variations were strongly correlated with the average variability in current speed within each region although there was no correspondence with the mean current speed (P. Pepin, unpublished data). Overall, the relationship suggested that variability in transport could be affecting variations in early life survival.

Evidence for the effect of offshore transport by Gulf Stream rings on cod recruitment - Myers and Drinkwater (1989) examined the effects of Gulf Stream warm-core rings on recruitment of groundfish stocks in the Northwest Atlantic. The stocks were those occupying the outer half of the shelf from the southern Grand Banks to Georges Bank. For each of the 17 stocks they developed a stock-specific ring index depending upon the number of rings in the vicinity of the stock during the period the eggs and larvae are in the water and the distance of the rings off the shelf. Data series were short consisting of from 8–20 years of data, depending upon the stock. They found a negative relationship between the stock-specific ring indices and recruitment for 14 of the stocks. The probability of 14 of 17 stocks being negative was statistically significant at the $p = 0.05$ level, although individually, only 2 of the stocks were statistically significant. Of the 17 stocks examined, 5 were cod (Georges Bank, 5Z; Browns Bank, 4X; eastern Scotian Shelf, 4VsW; southern Newfoundland, 3Ps; and southern Grand Banks, 3NO) and of these 4 were negatively correlated. The only one that was not was the Georges Bank stock. The recruitment tended to be low when the ring index was high (more rings closer to the shelf) whereas when the ring index has low, recruitment could be either high or low. This was interpreted as few rings close to the shelf during the period when the eggs and larvae were in the water was a necessary but not sufficient condition to obtain high recruitment. The hypothesis was that the close proximity of the rings to the shelf led to entrainment of the shelf water into the slope water region. The groundfish larvae in these shelf waters would be carried offshore where they would be lost to the population, due either to mortality from thermal shock or starvation, or because they could not get back onto the shelf once they were ready to settle. There is observational evidence to show that cod entrained into the slope water can die from the thermal shock (Colton, 1959). Fish larvae entrained offshore by Gulf Stream rings have been shown to be in reduced condition relative to those that remained on the shelf, although this was for redfish and not cod (Drinkwater *et al.*, 2000).

3.5 Recommendations

The breakout group for Northwest Atlantic Continental Shelf stocks produced six recommendations. All were aimed at improving our understanding of transport and settlement and were designed to be achievable within about two years:

1. **Nursery Areas** – Several models predict the transport of larvae over wide geographic regions, including across stock boundaries. Whether these areas coincide with nursery areas is often unknown but could be tested.

   Recommendation: Trawl survey data should be examined to develop maps of the distribution of the early juvenile stages of cod (especially in regions 2J3KL to 5Z) and these areas should be compared with model output of potential settlement areas were available.

2. **Transport Indices** – There has been some successes in the development of indices relating variability in circulation or transport to recruitment in the system (see section 4) and it is recognized that this work should be updated. The group also felt that one of the possible reasons for a lack of statistical relationships between transport and recruitment is the lack of transport indices.

   Recommendation: A suite of stock-specific transport indices should be developed and examined in relation to recruitment time series.

3. **Vertical Distribution** – The buoyancy of eggs determines their vertical position in the water column and ultimately affects the distance it is transported and its track.

   Recommendation: A literature review be conducted to determine the ranges of egg density of cod over all stocks in the North Atlantic. Is the egg density relatively constant between stocks and hence the depth depends upon the density structure of the water column?

4. **Exchange from Western Greenland to the Northern Labrador Stock (2GH)** – Larval surveys during NORWESTLANT in the 1960s suggested the possibility of the transport of cod larvae from West Greenland to northern Labrador Shelf. Dickson and Brander (1993) suggested that wind conditions in 1957 were conducive to transport from Western Greenland to the Northern Labrador Stock region and recent analysis of cod larvae distributions and drogue tracks (see Section 3.2.3.2) provides further indirect evidence.

   Recommendation: The working group recommends further examination of the historical data to determine the possible extent of larval exchange from Western Greenland to the northern Labrador.

5. **Transport Signals in Survey Data Time Series** – There are indications in both the Greenland-Iceland stocks and those on the Scotian Shelf that transport from one stock region to another does occur and can be identified in survey data. This phenomenon may have significant implications for the assessment of the affected stocks.

   Recommendation: We recommend an examination of stock abundance data to look for evidence of increases or decreases within the age range of returning migrants, which might be indicative of early life transport between adjacent stocks.

6. **Modeling Efforts** – Circulation modeling has advanced to the point where quite realistic flow fields are being produced routinely. However, these techniques have not been applied to the problem of connection between stocks on the Northwest Continental Shelf.

   Recommendation: Develop of a large-scale model of NW Atlantic to examine interconnections between stocks in this region. This effort is already in its infancy in two separate research efforts in the United States and Canada.

7. **Other Biological Processes** - Several biological factors and processes (mortality, growth, effects of temperature, predators) warrant further investigation to provide a more realistic understanding of transport processes. However, no specific short-term objectives were recommended.

4 STOCKS AT ICELAND AND GREENLAND

4.1 Overview

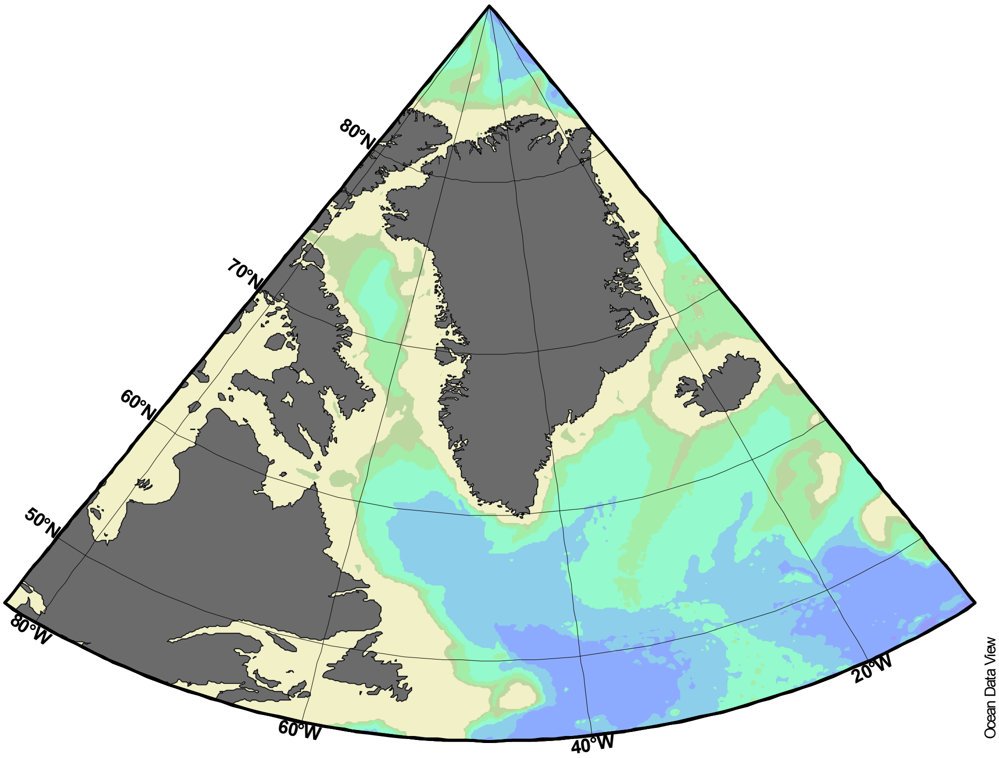

Figure 4.1. The "Iceland-Greenland-System"

The "Iceland-Greenland-System" is largely defined by two major oceanic regions, the Irminger Sea/Denmark Strait/Iceland Sea and the Labrador Sea/Davis Strait. Warm Atlantic Water is advected from a branch (the Irminger Current) of the North Atlantic Current which is topographically guided to Iceland by the Mid Atlantic Ridge. This current bifurcates in the Denmark Strait with a small branch continuing along the west coast of Iceland to the north Icelandic shelf area where it then continues along the shelf towards the east. This branch carries pelagic juvenile cod from spawning grounds south of Iceland to the nursery grounds on the shelf north of Iceland.

The main branch of the Irminger Current is diverted towards Greenland. The warm water meets and mixes with Polar Water in the Denmark Strait region and east of Greenland. Both the Atlantic and the Polar water masses then flow to the southwest along the East Greenland continental slope forming intense meanders. After rounding Cape Farewell, the southern tip of Greenland, the cold water is confined to the surface waters on the shelf, whereas the warm current component is located in the offslope region. Branches of this warm water component diverge to the west before they meet the shallower regions of the northern Labrador Sea and flow anti-clockwise to the Labrador slopes.

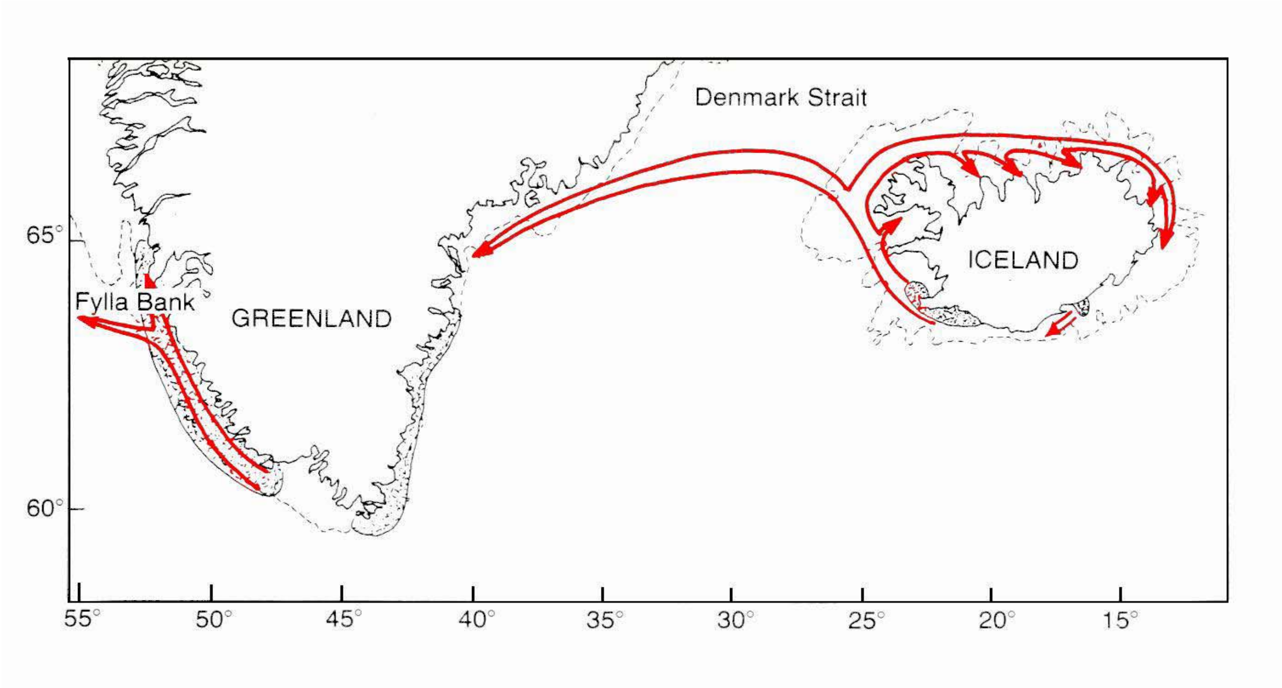

Figure 4.2. Spawning areas (stippled) and main patterns of egg and larval transport (arrows) at Iceland and Greenland

Cod abundance in Greenland offshore waters fluctuated considerably in the second half of the 20 th century, with different components involved: cod from spawning at East and West Greenland as well as cod of Icelandic origin. Furthermore, local cod populations exist in West Greenland fjords and inshore waters.

During the 1950s and 1960s spawning populations at East and West Greenland were abundant and in addition larval drift from Iceland to Greenland waters occurred regularly. In the 1970s and 1980s SSB of cod at Greenland was low and the only two strong year classes were mainly of Icelandic origin. Cod almost disappeared from Greenland waters at the end of the 1990s and so far no substantial recovery has taken place in either East or West Greenland offshore waters (Anon. 2002, Figure 4.3).

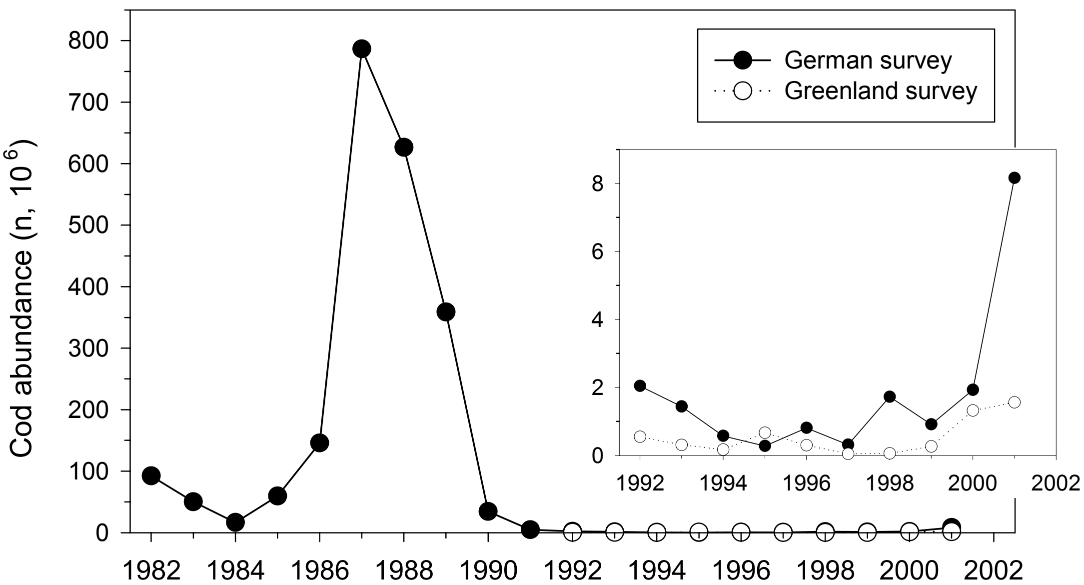

Figure 4.3. Cod abundance indices for West Greenland offshore waters from bottom trawl surveys conducted in autumn by Germany and Greenland (Anon. 2002).

4.2 Important Processes

4.2.1 Location, timing and duration of spawning

Cod spawn on the main grounds south of Iceland (see Figure 4.2) from the end of March to the beginning of June, with a peak from the middle to end of April (Begg and Marteinsdottir 2000b). Variations of about one to two weeks around the peak spawning date have been related to female size (Marteinsdottir and Björnsson (1999). On smaller spawning grounds west, north and east of Iceland cod may spawn later than on the main, south coast grounds (Begg and Marteinsdottir 2000b, Marteinsdottir *et al.* 2000)). There is insufficient information to determine whether the distribution of spawning has changed in time or space.

In Greenland offshore waters cod spawn along the offshore slope of the shelf between 62°N and 66°N at East Greenland, and on the banks south of 64°N at West Greenland. Highest egg concentrations were found at Southeast and Southwest Greenland in the 1960s (Wieland and Hovgård, 2002). There is little information about the location of spawning during the 1950s and 1960s. The drastic decline of spawning stock biomass (Anon. 2001) at the end of the 1960s and low larval abundance (Wieland and Hovgård, 2002) indicate a low spawning intensity during the 1970s and 1980s, and virtually no spawning occurred in East and West Greenland offshore waters in the 1990s (Anon. 2002).

Spawning cod are found during a prolonged period (late March to early June) in Greenland offshore waters (e.g., Jonsson 1959, see further references in Wieland and Hovgård 2002) and eggs surveys during the 1960s showed a mean date of peak egg abundance of April 20 with a standard deviation of 25 days (Wieland and Hovgård 2002).

4.2.2 Size, location and variability of nursery areas

Nursery areas for Iceland cod extend from the west coast to the shelf north of Iceland and continue along the east coast until they reach the Iceland Faroe Front off the southern part of the east coast. The south coast may also be a potential nursery area, but juvenile cod do not occur there, perhaps because they cannot be transported or retained there during the pelagic life stage.

Eggs and larvae from the spawning grounds south of Iceland also drift over to Greenland with the Irminger Current as it bifurcates in the Denmark Strait. This bifurcation probably determines the proportion of larvae which are transported to the nursery grounds north of Iceland or over to Greenland. The strength of the flow of the Atlantic Water to the north Icelandic shelf also determines how far east the larvae will drift. In 2001 for example, 0-group cod were found from the westfjord peninsula and all the way along the north and the east coast, the largest concentrations being found close to the coast, (Sveinbjörnsson and Hjörleifsson, 2001). Begg and Marteinsdóttir (2000b) showed that the distribution of 0 group cod is very variable and that the nursery areas differ from one year to another. The mean distribution from 1970–1998 is shown in Figure 4.5.

The temperature at 50 m depth in the ocean around Iceland in spring and summer (Figure 4.4) gives an indication of the temperature the larvae experience during the drift to the nursery areas. There are however large interannual variations in the temperature especially on the shelf north and east of Iceland.

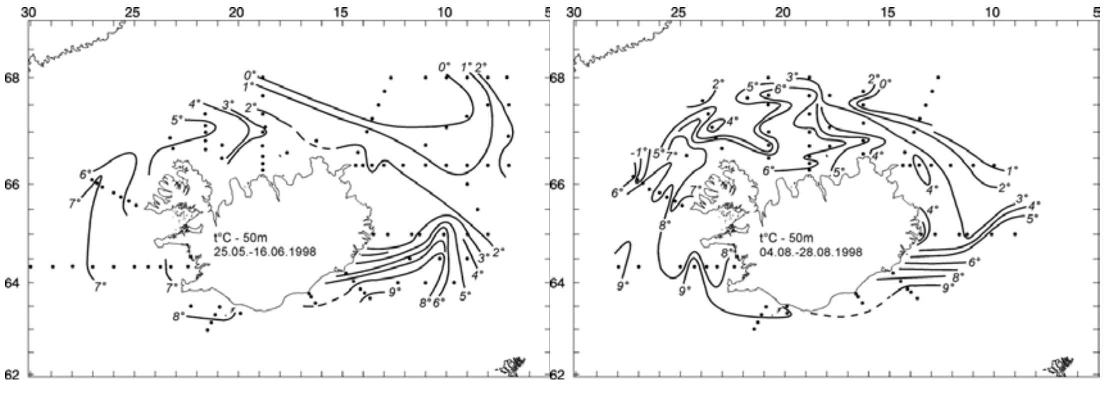

Figure 4.4. Temperature at 50 m depth around Iceland in June and August 1998.

Concentrations of pelagic juvenile cod off East Greenland seem to follow mostly the path of the 500 m isobath (Figure 4.5). To estimate the oceanographic variability along this swath, CTD profiles as obtained during the annual German bottom trawl survey during autumn to this region, may be used. They are the only available data source on subsurface oceanographic properties, which are sampled in a consistent manner. The data set starts in 1982. This information can be used to assess interannual variability in this region. As an example, the complexity of a 20 km swath of the vertical thermal field is illustrated in Figure 4.6. Further analysis may be performed by using the respective oceanographic data set from the Institut für Seefischerei, Hamburg, Germany. Observations in autumn 2001 reveal the basic difference between the East Greenland and the West Greenland thermal fields: Due to a meandering front between the cold Polar Waters of the East Greenland Current and the off-slope warm waters of the Irminger Current, the path along the 500 m isobath cuts through warm and cold water domains. These characteristics, which emerge from the right part of Figure 4.6 (East Greenland) reach down to the seafloor. The left side of Figure 4.6 shows the West Greenland thermal properties along the shelf slope region. Here, the entire bottom waters are warm and the surface waters are governed by cold Polar Waters.

Pelagic juvenile cod thus experience either changing thermal fields if they cross water mass boundaries, or are transported within the warm water parts of the meanders.

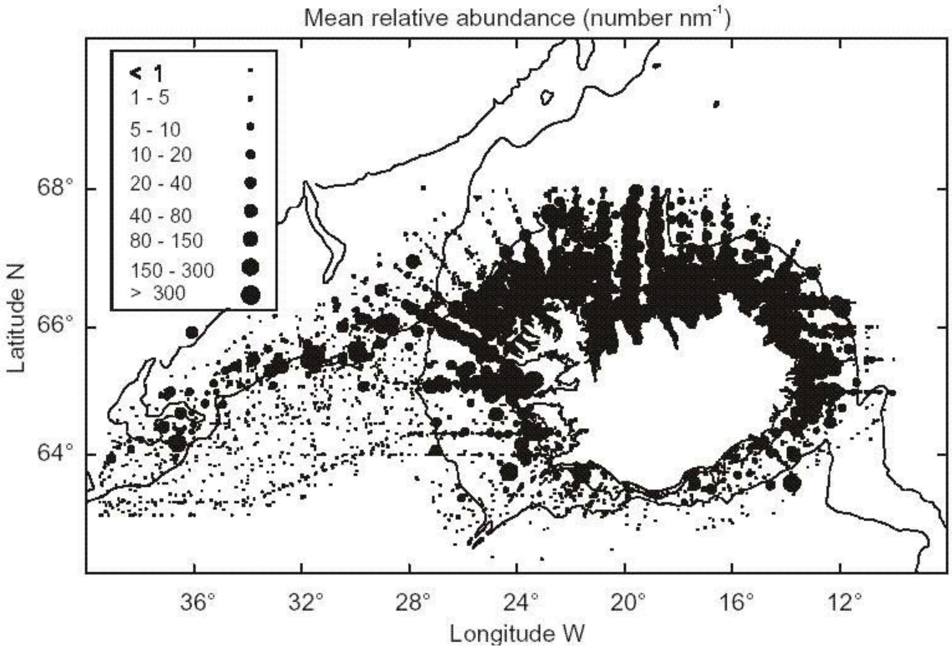

Figure 4.5. Mean (1970–1998) spatial distribution, relative abundance (number nm-1) of pelagic juvenile cod (from Begg and Marteinsdottir, 2000a).

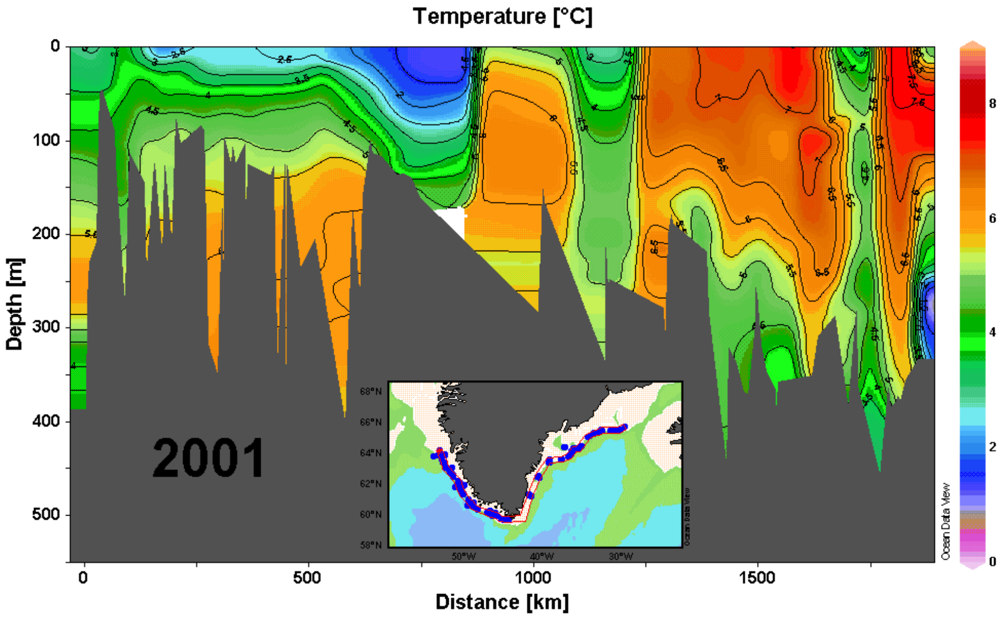

Figure 4.6. Vertical distribution of temperature along the Greenland continental slope during German autumn survey 18 October–12 November 2001).

4.2.3 Size and buoyancy of eggs

This is dealt with by Marteinsdottir and Begg, (MEPS 235,235–256), and in the latest STEREO report.

4.2.4 Duration and distance of pelagic transport

Peak spawning off the south coast of Iceland is in mid to late April. Settlement to the bottom begins in September, therefore the pelagic stage last for 5 months or more.

Begg and Marteinsdótttir (2000a) studied the relationship between several environmental parameters and the abundance of 0-group cod. They found that the amount of freshwater on a section west of Iceland (a coastal current index) was the principal factor affecting spatial distribution, abundance, size and spawning origins of pelagic juvenile cod, as well as recruitment. The coastal current index has been thought of as a transport index in that an increase in the freshwater along the coast induces a stronger geostrophic current and thus leads to a more effective transport of the larvae to the nursery grounds north of Iceland. However, the freshwater content might also be the result of favorable wind conditions in the area, inducing more melting of snow and more precipitation and may therefore be a co-varying effect of a mechanism for enhancing transport of larvae, rather than the cause.

Variation in atmospheric forcing is probably the largest contributor to variability of the ocean circulation. Therefore there is a need to study the effect of different forcing on timescales of a few days to interannual variability, and there is still a need for further investigation of other more direct transport indices. This could be constructed from direct current measurements of the flow of Atlantic Water to the area north of Iceland.

Surface drifters close to the southern Icelandic cod spawning grounds west of the Reykjaness Ridge can either flow anticlockwice around Iceland or cross Denmark Strait ending up in either the East Greenland Current or the Irminger Current (Figure 4.7). The reason is most likely due to the local wind conditions at the time when the drifters are close to the Strait.

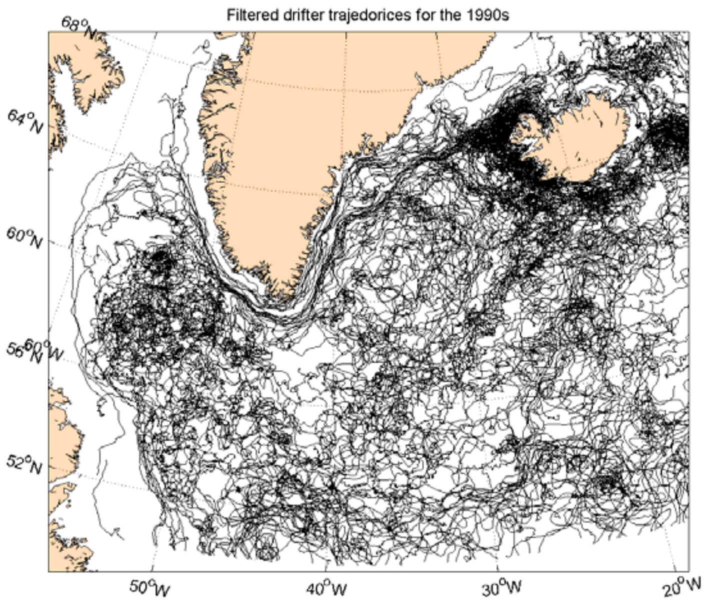

Figure 4.7. Trajectories of drifters drogued at 15m in the 1990s. The drifters has been detided and filtered for eddies.

Based on 15 m drogued drifters from the 1990s, an objective mapped mean velocity field is calculated (Figure 4.8). All drifters have been filtered for tides as well as eddies (for details see Jakobsen *et al.*, 2002). The resulting mean velocities within the East Greenland Current are of the order of 40 cm/s (~35 km/day) and in the Irminger Current of the order of 30 cm/s (~25 km/day). These current estimates are most likely a lower limit for the actual mean current within the core of the respective currents because of averaging. Given these current speeds, the transport time for a particle having crossed the Denmark Strait to reach the tip of Greenland is in the order of a month. However, a rough and preliminary analysis of flow patterns from the HAMSOM North-East Atlantic Model (EU- TASC, EU-STEREO) suggests that the dispersion of cod eggs and larvae can be due to seasonally changing wind fields which cause

significant differences in the surface circulation south-west of Iceland. Note the mean circulation cell just southwest of the tip of Greenland recirculation Irminger Water. Maybe this cell can play a role for the transport of cod.
Available literature should be analysed for direct sub-surface current measurements on the East Greenland shelf and slope region. Moored current meter measurements were performed from 1971 onwards. There are near seafloor measuremen from the Overflow 1973 expedition, and from follow up programmes like MONA (Monitoring the Overflow into the North Atlantic). Further information on direct current measurements performed in the pelagic domain along the East Greenland slope region should be explored.

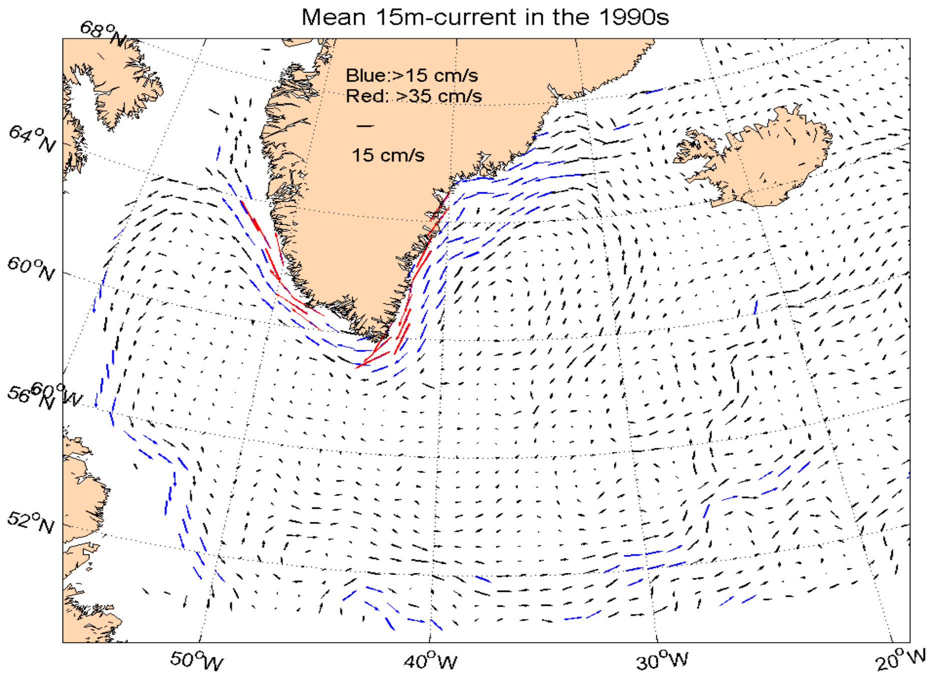

Figure 4.8. Objective mapped mean velocities based on 1m drogued drifters in the 1990s; drifters detided and filtered for eddies.

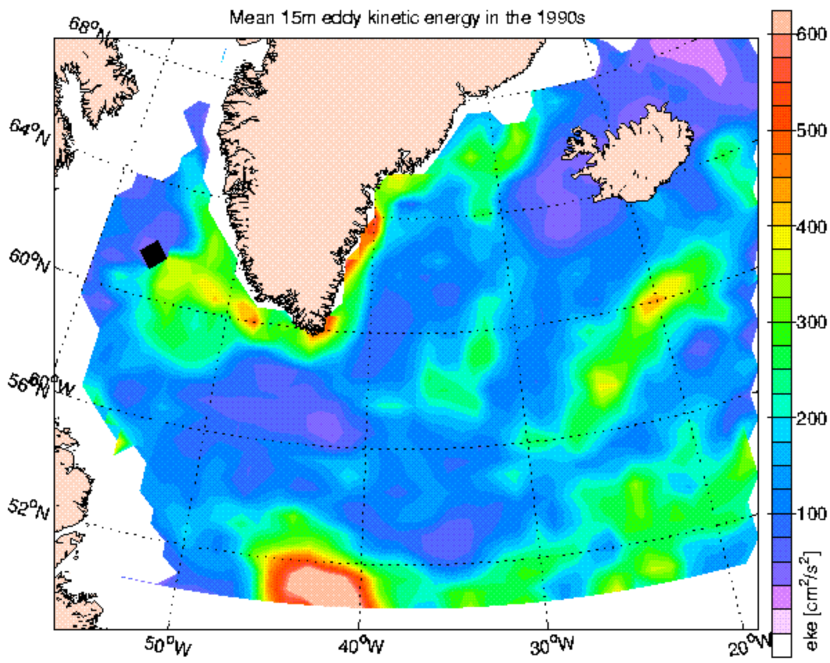

Figure 4.9. Eddy kinetic energy based on 15m drogued drifters in the 1990s.

4.2.5 Temperature experienced during pelagic stage

Survival of cod larvae depends on temperature; therefore it is necessary to identify the water masses in which they occur during the pelagic stage. Although the core of the East Greenland Current and the Irminger Current are well separated in mean (Figure 4.6), the area is dominating by eddies. This can clearly be seen in the calculated eddy kinetic energy (EKE) field, showing high values at the East Greenland Shelf in the order of 350 cm^2/s^2 (Figure 4.9). A cod larva being transported southward in the Irminger Current branch may be affected by the much colder Polar Water transported by the East Greenland Current through eddy activity. This can be seen e.g., from the autumn cruise 2001 (Figure 4.6).

The temperatures experienced by pelagic juvenile cod have been estimated by Begg and Marteinsdottir (1999), who divide the area around Iceland into northern and southern sectors. After spawning on the main grounds off the southwest coast between March and May the pelagic stages are transported clockwise around the coast in temperatures of between 4 and 8.4 ^{o}C until they reach about 65^{o}30'N, where they either remain in the Icelandic coastal current and continue around the northwest and north of Iceland or branch westward towards Dohrn Bank and Greenland in the Irminger Current. Temperatures in the Irminger Current probably remain similar to those experienced south of Iceland, but decline by about 1^{o}C going across the Denmark Strait. Temperatures in the coastal waters north and east of Iceland range between -1.65 and 5.6^{o}C. Begg and Marteinsdottir (op.cit.) provide information on the interannual variability in temperature experienced by pelagic juveniles in northern and southern Icelandic waters for the years 1970–1998 for the period from April to August (Figure 4.10).

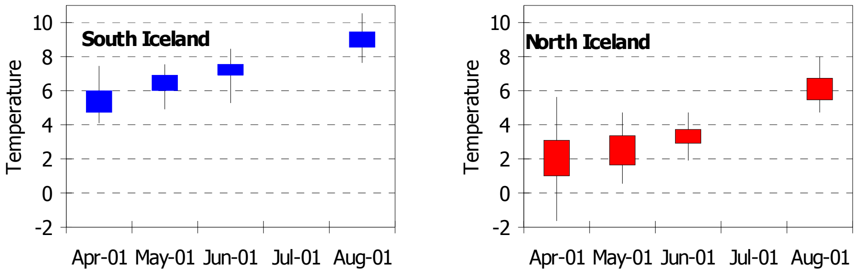

Figure 4.10. Interquartile range and extremes of temperature experienced by pelagic juvenile cod. Estimates for 1970-1998 from Begg and Marteinsdottir 1999.

4.3 Examples of transport across stock boundaries?

4.3.1 From Iceland to Greenland

Transport of pelagic juvenile cod to Greenland from the spawning grounds southwest of Iceland occurs in most years. The route which this transport follows can be seen from the distribution of pelagic juvenile fish, which matches drifter trajectories and the flowfields (Irminger Current) from hydrodynamic models for the area (see Figures. 4.5 and 4.8). Pelagic juvenile surveys have taken place since 1970 and the proportion of the total number of pelagic juvenile cod which are taken in area 8 (Figure 4.11, Denmark Strait) is an indication of the variability of pelagic transport of cod from Iceland to Greenland (see Figure 4.12, four missing years are marked 0).

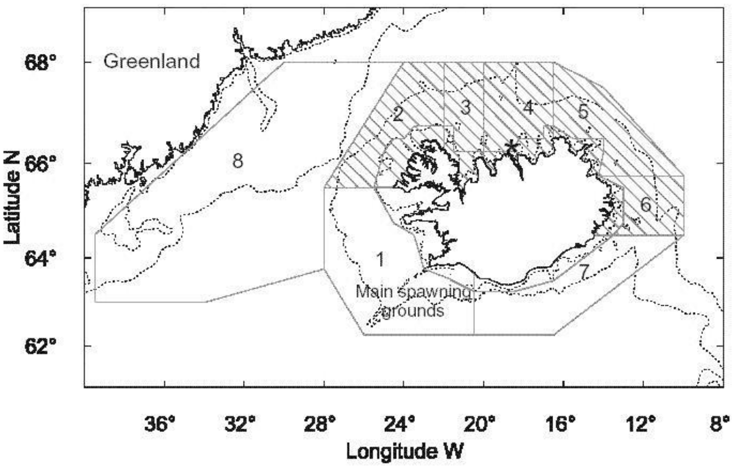

Figure 4.11. Areas where pelagic juvenile cod were taken.

The average for the period 1970–1998 is 17%. Thus transport of pelagic juvenile cod is a regular occurrence, with at least 5% of all Icelandic larvae being transported towards Greenland in 21 out of the 26 years of surveys. The fate of the juvenile cod after the period of the pelagic surveys may of course vary in different years, however there are two additional sources of evidence indicating that they contributed regularly to recruitment at Greenland, at least up to 1989, which is the last year for which recruitment is estimated by VPA, and after which recruitment has been very low:

1) The abundance of pelagic juvenile cod in the Denmark Strait (area 8 in Figure 4.11) and of 0-group cod in the Dohrn Bank-East Greenland area correlates well ($r^2 = 0.69$ and 0.88 respectively, 16d.f.) with subsequent estimates of year class strength for Greenland.
2) There is a return migration of mature fish from Greenland to Iceland in most years (Shepherd and Pope, 1993; Schopka 1993, 1994).

In conclusion it is evident that transport of pelagic juvenile cod from Iceland to Greenland has been a regular occurrence and that before 1985 they survived and migrated back to Iceland as mature fish. An investigation of the conditions affecting their survival is essential in order to draw conclusions about the likelihood that they will once again provide a major input to the cod stock at Greenland and also benefit the Icelandic stock on their return. The numbers of pelagic juvenile cod in the Denmark Strait has been above average since 1997 (Figure 4.13), but although the abundance of cod at Greenland taken by the German and Greenland surveys has been increasing since 1997, the absolute abundance remains very low (Figure 4.3).

The question whether the re-establishment of a viable offshore spawning stock at Greenland depends on immigration from Iceland was discussed briefly. There is very little direct evidence for or against this, but it was thought likely that Icelandic immigrants do contribute to the Greenland offshore spawning stock.

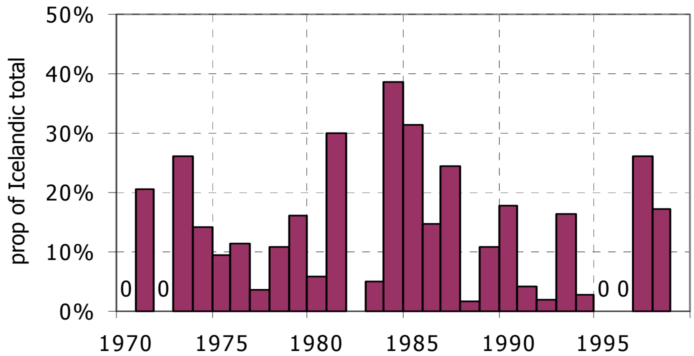

Figure 4.12. Proportion of pelagic juvenile cod in Denmark Strait.

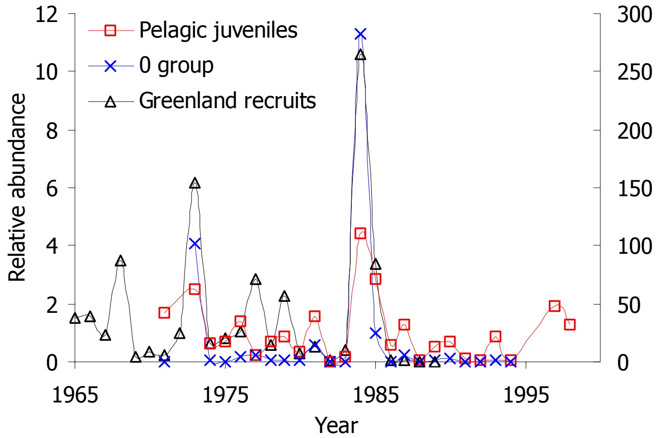

Figure 4.13. Abundance of cod in Denmark Strait and recruitment at Greenland.

4.3.2 From Greenland to the Labrador Shelf

Given the current depleted state of the "Northern" cod (NAFO 2J3KL) the question of transport of pelagic juveniles from Greenland to the Labrador shelf was also raised. The evidence that this occurs was reviewed by Dickson and Brander (1993). Direct evidence comes from tagging studies and from larval distribution. A new summary of the latter is given in Working Document 8 (Wieland and Hovgaard 2002, Figure 4.14). The main larval concentration during June-July of the years 1959–1960 and 1961–1970 was centered in the Davis Strait and extended to the northern edge of the Labrador shelf. Using the current velocities shown in Figure 4.8, this distribution could reach Hamilton Bank (54°N) by about September.

Indirect evidence of transport from West Greenland comes from distributions of pelagic stages of other species, from vertebral counts of cod and from anomalous mortalities, which indicate return migration of maturing fish. The transport of cod of course requires that there be a source population, but at present the West Greenland offshore stock is extremely small and therefore unlikely to contribute significantly to the rebuilding of the "Northern" cod.

4.4 Variability of recruitment and SSB

The variability of recruitment (R) and spawning stock biomass (SSB) for the stocks at Iceland and Greenland can be judged and compared with other stocks in Table 4.1. Recruitment to the Icelandic cod stock is less variable (CV 39%) than any of the other twenty stocks, whereas for the Greenland stock (CV 136%) it is higher than any other. SSB at Iceland is considerably more variable (CV 56%) than recruitment.

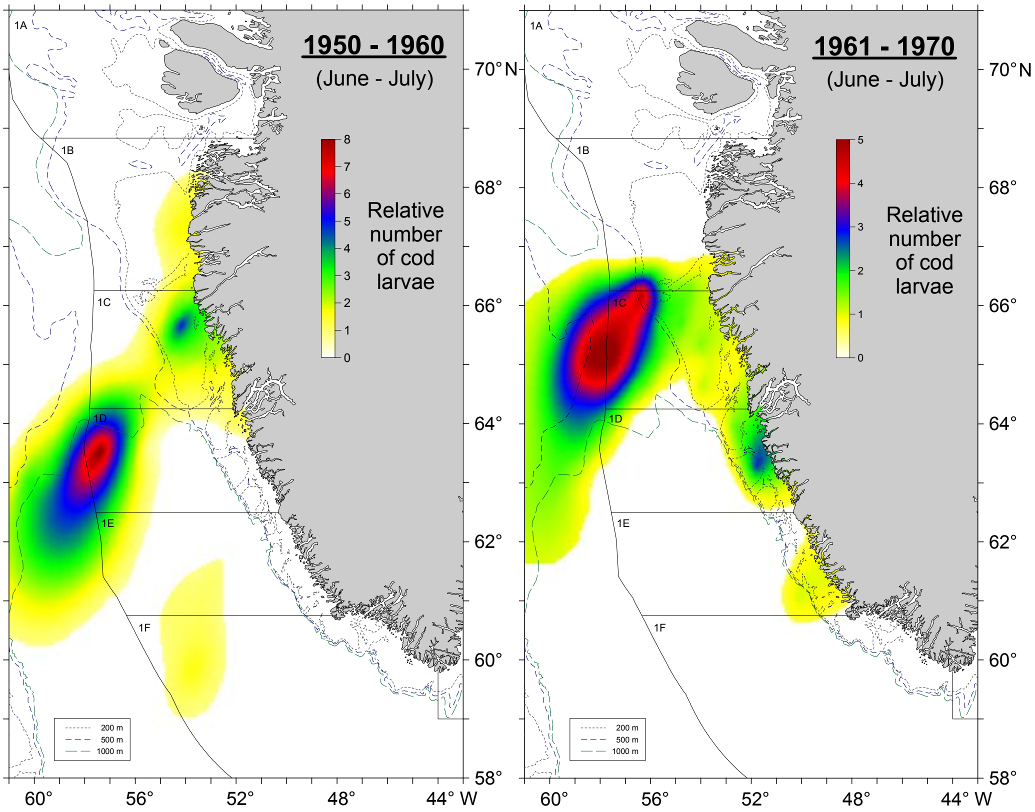

Figure 4.14. Average distribution of cod larvae off West Greenland 1950–1960 and 1961–1970.

Given the low variability in recruitment of Icelandic cod and the regular occurrence of pelagic juveniles in the Denmark Strait (see Figure 4.12), one might expect a consistent level of immigrant recruits at Greenland. This has not been the case since 1989 and conditions for their survival through into the fishery probably have a strong influence.

Table 4.1. Cod population characteristics.

Stock	Life expectancy	CV of SSB	CV of recruits	Age of recruits	Years of data
Baltic E	0.96	61	61	2	35
Baltic W	0.77	35	58	1	31
Celtic Sea	1.12	37	75	1	30
Faroe	1.54	37	56	2	40
Iceland	1.32	56	39	3	46
Irish Sea	0.94	40	60	0	33
Kattegat	0.84	57	55	1	30
N. Sea	1.05	46	61	1	38
NE Arctic	1.28	79	62	3	55
Norwegian coastal	1.83	22	47	2	16
W. Scotland	1.04	48	60	1	35
Greenland	1.48	112	136	3	38
Northern (2J3KL)		96	100	1	39
S.Grand Banks (3NO)		66	119	3	43
S. Newfoundland (3Ps)		30	45	2	43

Notes:

1) These values are taken or calculated from recent assessment reports (ICES CRR 242 for the NE Atlantic stocks);
2) Life expectancy (in years) is the inverse of total mortality (i.e., 1/Z) where Z is the average over the exploited age range, as defined in the assessment reports;
3) The shading in the column showing coefficient of variation (CV) of recruits (R) indicates stocks for which this value is less than the CV of Spawning Stock Biomass (SSB).

4.5 Recommendations

1) Available flow fields should be used to run particle tracking simulations in order to investigate possible trajectories in the Denmark Strait region and the corresponding temperature evolution along those trajectories. The time frame should cover the period 15. April–1. September. In the case of “positive” trajectories (south Iceland –> east Greenland), the corresponding air pressure fields should be analysed to define transport indices for these events.
2) The distribution of juvenile cod (0- and 1-group) from the database of ISH, Germany for the area East and West Greenland should be analysed. The objective of this study should be to define nursery areas in relation to water temperature and depth.
3) Enhance the basis of knowledge about sub-surface currents in the East Greenland shelf/slope region. This should be done by literature studies and/or bottom-moored ADCP’s.
4) Transport indices, based on direct current measurements of the Atlantic inflow to the north Icelandic shelf and also including atmospheric forcing, be constructed for comparison with 0-group indexes and recruitment.

5 NE ATLANTIC STOCKS

5.1 Overview

This group dealt with three stocks, The Northeast Arctic, North Sea, and Irish Sea stocks. For all of these it appears to be of great importance that the larvae arrive in certain favourable locations at the end of their drift phase. For the Northeast Arctic this area is the Barents Sea; for the North Sea, the northern shelf slope and bank areas, and for the Irish Sea the pelagic juveniles need to reach the thermally stratified water within the western Irish Sea gyre.

5.1.1 Overview of North Sea stocks

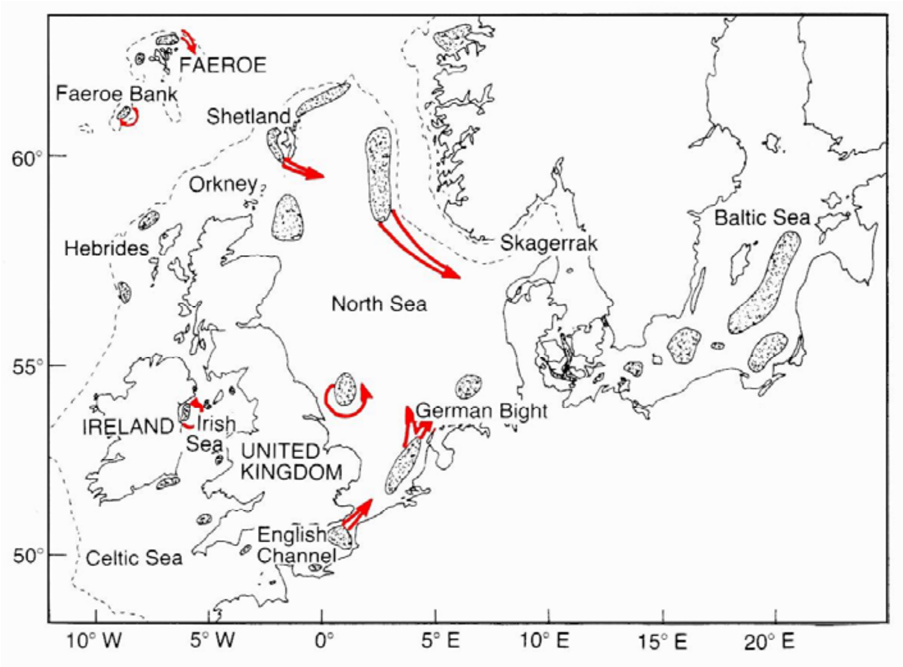

Figure 5.1. Spawning areas (stippled) and main patterns of egg and larval transport (arrows) of cod in the North Sea and Baltic.

5.1.1.1 Distribution of spawners

The location of cod spawning in the North Sea + VIa has been studied in the course of the STEREO project (EU-FAIR-CT98–4122) using groundfish data from the 1st quarter surveys, by calculating the prevalence of spawning fish in the hauls, from 1991, by ICES square (Figure 5.2, R. Hedger and E. McKenzie, University of Strathclyde unp. results). Thus, a prevalence of 1 would indicate the presence of spawning cod in all hauls, while a prevalence of 0 would indicate that no spawning was detected in that ICES square.

The distribution of spawning appears to be quite diffuse spatially. Unfortunately, the data from all years had to be grouped together, to have sufficient numbers of hauls to perform the analysis, so it is not possible to comment on the interannual variability on the basis of the current work.

5.1.1.2 Distribution of eggs

Several attempts have been made to define the spawning areas of cod in the North Sea (Figure 5.1 and 5.3). However, since no fully comprehensive ichthyoplankton surveys have ever been conducted in this region, these efforts have been based upon compilations of results from surveys of parts of the whole North Sea and on distributions of maturing adults (fisheries surveys and commercial catches).

Spawning takes place from the beginning of January through to April. The timing of spawning is related to the timing of the spring bloom and not to latitude around the British Isles (Brander 1994b). The latest spawning occurs in the Bristol Channel.

In the past a small amount of spawning has been recorded in the autumn but this is probably not significant (Brander 1994a). Spawning occurs offshore in waters of salinity 34–35 psu (Riley and Parnell 1984). In the more northern areas spawning may be associated with banks on which the spawning fish may aggregate. Early surveys were however hampered by the inability to distinguish early stage eggs of cod and haddock. The application of genetic probes recently developed at CEFAS and UEA should overcome this difficulty. The rate of egg development is mainly related to temperature (Thompson and Riley 1981). However, recent work on plaice has found that female condition can have a secondary influence on egg development rates (Fox *et al.* 2001). Insufficient experimental work has been undertaken to see if a similar effect occurs in cod.

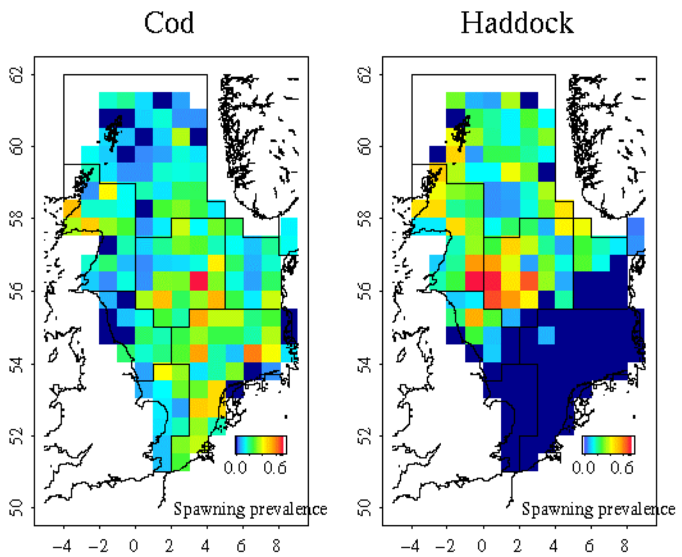

Figure 5.2. Prevalence of mature cod (running, stage 3). Determined from ground fish survey data, first quarter.

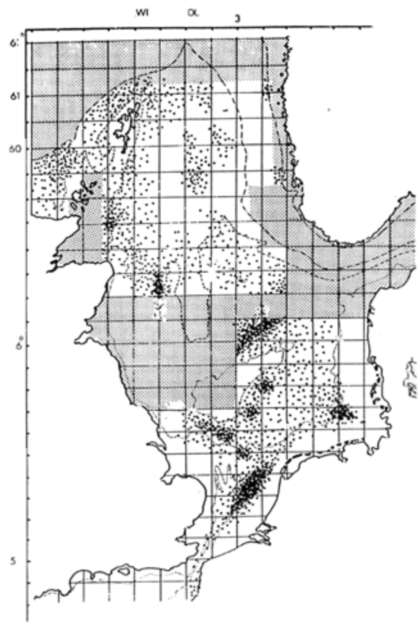

Figure 5.3. Egg distribution areas of cod in the North Sea according to Daan, (1978). He did not have data for the shaded areas.

Cod spawning off the NE coast of England was intensively surveyed in 1976 (Harding and Nichols,1987; Brander 1994b). For the southern Bight, Daan (1981) produced estimates of egg production for 1968 to 1976.

Ichthyoplankton surveys around the coast of Scotland have been undertaken by Saville (1959) in the 1950s (Figure 5.5) and by Heath (1994) in 1992 (Figure 5.6). The Saville surveys were principally concerned with haddock but Raitt (1967) re-analysed the data and presented maps for cod. Since they were unable to distinguish cod and haddock eggs the results are based upon the occurrence of late stage eggs. The 1950s surveys in March showed some cod eggs off Butt of Lewis, west of Orkney and Shetland and off the Moray Firth and east Scottish coast. By April, eggs were more

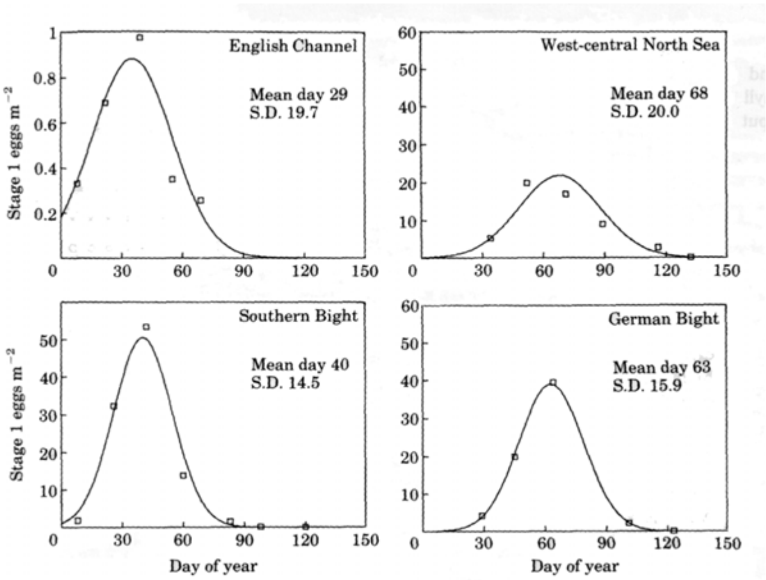

Figure 5.4. Abundance of stage I cod eggs and fitted normal distributions with mean dates of spawning and standard deviations. For the English Channel cod eggs of all stages are amalgamated because abundance of stage I eggs was too low to give an estimate (Brander 1994b).

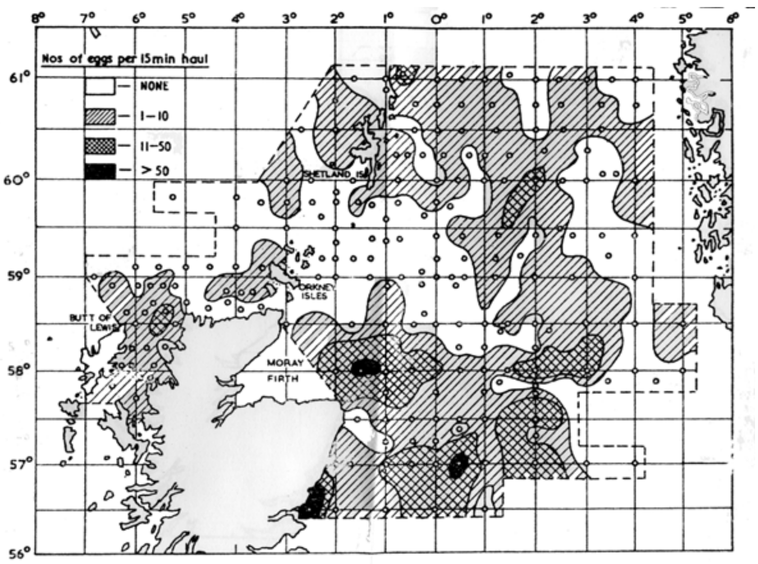

Figure 5.5. Cod egg distributions from 1950s surveys (Raitt 1967).

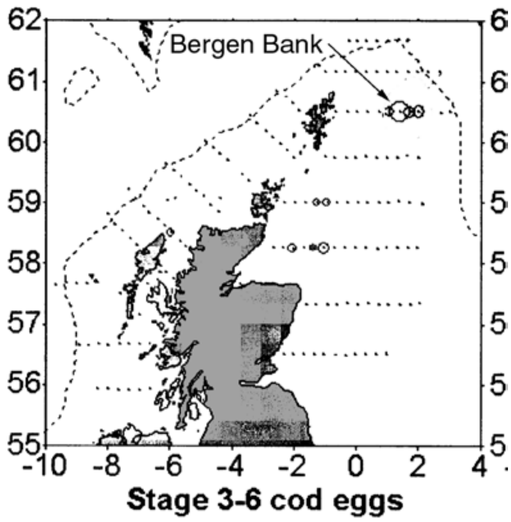

Figure 5.6. Occurrence of late stage cod eggs from ichthyoplankton surveys undertaken in 1992 (Heath *et al.* 1994).

abundant in the northern North Sea (the southern limit of survey coverage). Larvae were common across the survey area. By May the occurrence of cod eggs and larvae was much reduced (Figure 5.5).

It should be noted that based upon the proportions of late stage eggs and larvae, the majority of the eggs sampled by Heath appeared to be those of haddock (Figure 5.6).

5.1.1.3 Distribution of larvae

The larval stages of cod have been studied in the southern and eastern section of the North Sea during series of investigations during the last decade. Investigations have predominantly focused on life in the late larval /early juvenile stages, but recently information on the earlier and later stages has been incorporated. A concurrent feature in all findings of spatial distributions of cod has been a distinct overlap between larval/juvenile concentrations and frontal features. The peak concentrations of early larval stages in March coincide with the haline fronts between coastal freshwater-influenced water masses and shelf water at the southern slope of the Dogger Bank and in areas of the German Bight (Munk *et al.*, in press, see Figure 5.7a). During April –May the later stage larvae have been found in areas of tidal mixing fronts around banks, and at the shelf slope front in the northeastern North Sea and Skagerrak (Munk et al 1995, 1997, see Figure 5.7b). The cross-shelf concentration of larvae can be very distinct with more than 60% of all larvae within a narrow frontal zone of less than 10 km width (Munk, 1995).

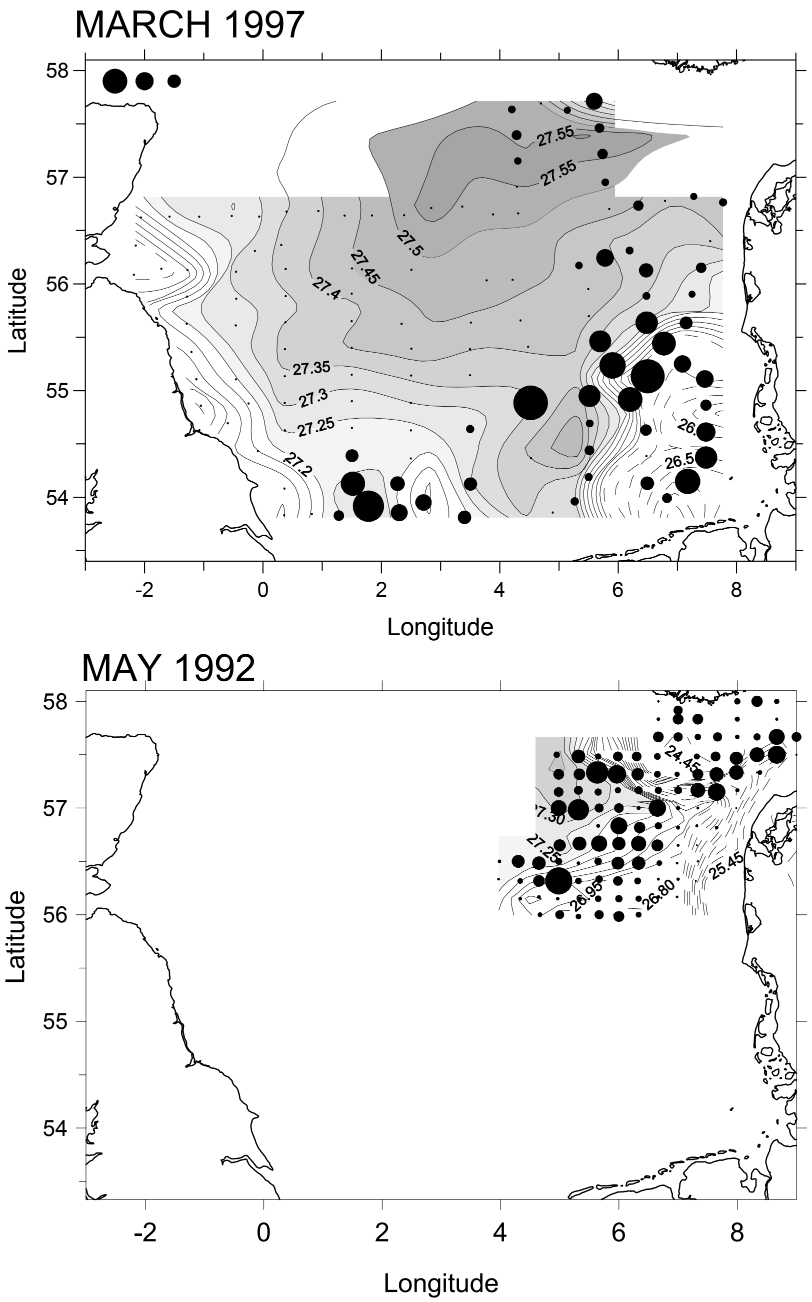

Figure 5.7. a): March 1997: Estimate of the density of newly hatched cod larvae, and illustration of surface water density (5 m depth). b) May 1992:Estimate of the density of larger cod larvae/ small juveniles, illustration of surface water density. Circles in upper left corner of Figure 3.22a illustrate densities of 2, 1 and 0.5 m^{-2}.

5.1.1.4 Settlement and juvenile life

It is known that cod probably require cryptic habitat into which to settle and that this may be a mechanism to avoid predators (Gregory and Anderson 1997, Bromley and Kell, 1999). It is therefore possible that successful settlement could be limited to relatively small areas of suitable habitat.

Following settlement from the pelagic phase in June-August (Figure 5.8) there is a shoreward movement of 0 group cod (Riley and Parnell 1984). By October the fish are found in the tidal mudflats of estuaries of the English, Dutch and German coasts. The authors suggested this movement was due to the young cod seeking areas of reduced salinity. According to Daan (1978), the main nursery grounds in the period 1965–1974 lay along the Danish-German coast with a band of lower concentrations extending over the Dogger Bank and through the central North Sea. A similar picture was produced by Heessen (1993) for the period 1983–1987 (Figure 5.9). Neither author had data on the distribution of settled young cod in the period before 1960 when the overall stock size was probably much lower than in the late 1960s.

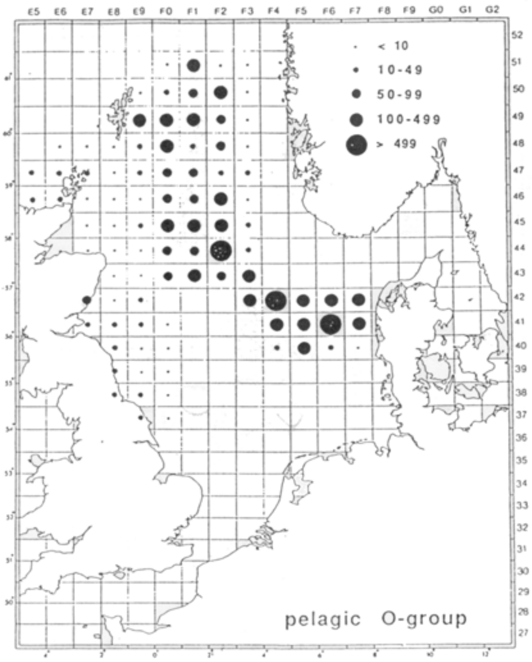

Figure 5.8. Average catches of pelagic 0 group cod averaged over June-July 1974–1983 (Brander 1994a).

More recent results from young fish surveys appear similar although there may be a suggestion of a possible reduction in distribution of 1 group fish along the Dutch coasts (Figure 5.10).

By the time the fish reach 3 years old they have moved off into deeper water and appear to be in a more constant thermal regime (Heessen and Daan 1994). Such observations accord with recent work on temperature experience of cod as determined using oxygen isotopes (Weidman and Millner 2000).

Further information is available from an analysis carried out in the course of the STEREO project (EU-FAIR-CT98–4122) using groundfish data from the 3rd quarter surveys from 1991, by ICES square (R. Hedger and E. McKenzie, University of Strathclyde unp. results). These results should be taken with caution because the sampling gear may underestimate the abundance of 0-group fish and the surveys do not cover inshore areas which may be important nursery grounds. The west coast figures are averaged over the available years (1996–99).

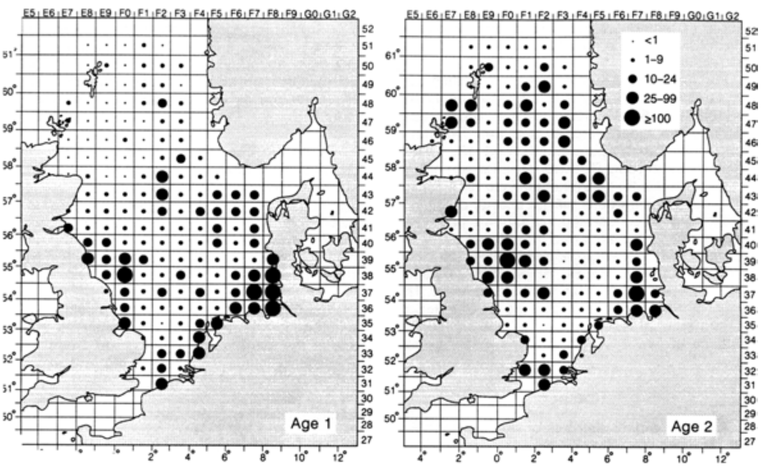

Figure 5.9. Distribution of cod, age groups 1 and 2 as mean number per hour fishing, averaged for period 1983–1987 (data from International Young Fish Survey (Heessen, 1993).

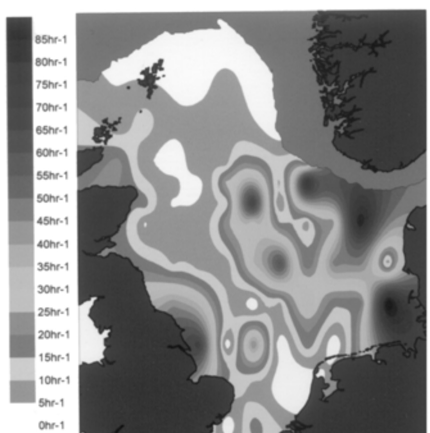

Figure 5.10. Distribution of age 1 cod in numbers caught per hour, average over 1994-1998 (unpublished data from the English Q3 groundfish survey).

The general patterns appear to remain fairly constant in time, although the distribution of juveniles is more diffuse in given years, compared to others. The distribution of 1-group cod is generally more disperse, which agrees with the general view that older juveniles migrate towards coastal areas from their original settlement grounds.

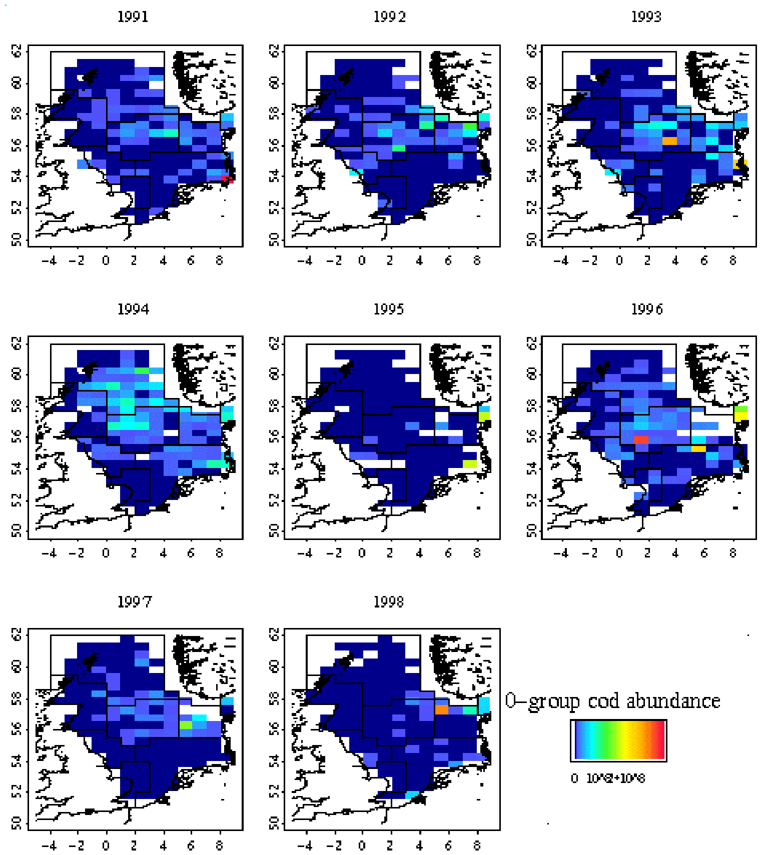

Figure 5.11. Spatial distributions of demersal 0-group cod in the North Sea (1991–1998).

Figure 5.12. Spatial distributions of demersal 1-group cod in the North Sea (1991–1998).

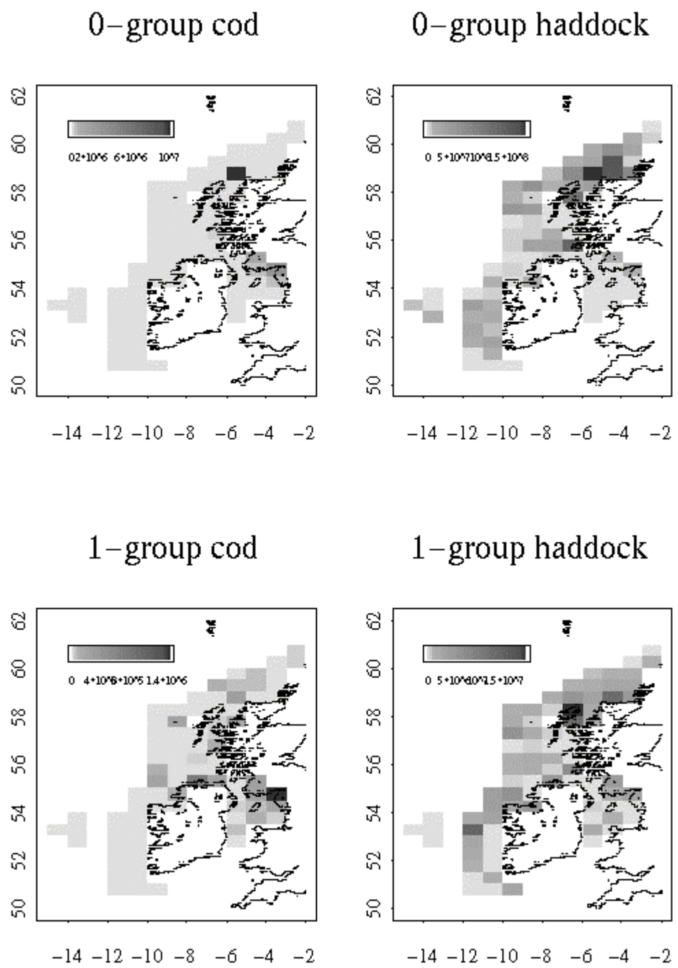

Figure 5.13. Mean spatial distribution of 0-group and 1-group cod and haddock in the West Coast of Scotland (1996–1999).

5.1.2 Overview of Irish Sea stocks

In the Irish Sea cod spawn in the coastal bights off Ireland and North Wales, and to the south west of the Isle of Man and Cumbria (Brander, 1994b; Fox *et al.* 1997; 2000). Spawning occurs in March and the peak of spawning can vary by two weeks (Armstrong *et al.*, 2001, Anon 2002). Temperatures at this period are at their annual minimum, approximately 7°C and the circulation is dominated by tidal and wind forcing.

Eggs and larvae tend to disperse from the spawning areas and the distribution is thought to be determined by an interaction of timing and duration of spawning with seasonal hydrodynamic features (Dickey-Collas *et al.*, 1997; 2000). Data on eastern Irish Sea cod are sparse. Pelagic juveniles begin to show diel migration by late May and are not found in the water column by late June (DARD unpublished data). Initial settlement in the western Irish Sea, after a pelagic phase of 2–3 months, is to the south east of the Northern Irish coast and to the south west of the Isle of Man in waters 50 to 80 m deep (DARD unpublished data). The sea in these areas is thermally stratified or frontal with surface temperatures of 12°C. By September and October the young cod are found inshore in Irish, Manx and Welsh waters and off Cumbria (DARD, CEFAS unpublished data).

The spawning stock is thought to be at a historic low (5,000 tonnes), and the age structure is heavily depleted (only 3% of adult fish are older than 3 years, ICES NSWG 2002). There is some evidence of mixing between the Irish and Celtic Sea stocks of cod (Brander 1974) although the degree of mixing is unclear and may vary between years (Marine Institute Dublin, unpublished data). Recruitment variability is similar to that in the North Sea and concurrent large recruitment events have occurred in the Celtic and Irish Seas and west of Scotland (ICES NSWG 2002).

5.1.3 Overview of NE Arctic stocks

The main habitat of the Northeast arctic cod is the Barents Sea. Mature cod migrate to the Norwegian coast for spawning. Spawning takes place from Møre in western Norway to Finnmark in the very north, with 40–50% in the Lofoten area. The eggs larvae and early juveniles are transported back to the Barents Sea by the Norwegian Coastal Current and the Norwegian Atlantic Current. This route of pelagic drift from spawning ground to area of bottom settlement is the longest for any cod stock. Five months after spawning the 0-group are spread out in the entire Atlantic watermasses of the Barents Sea and partly above the narrow shelf region off the coast of West Spitsbergen. The distribution of the pelagic juveniles within the Barents Sea has a substantial interannual variation: some years have a typical westerly distribution while other have an easterly distribution (Ådlandsvik and Sundby, 1994).

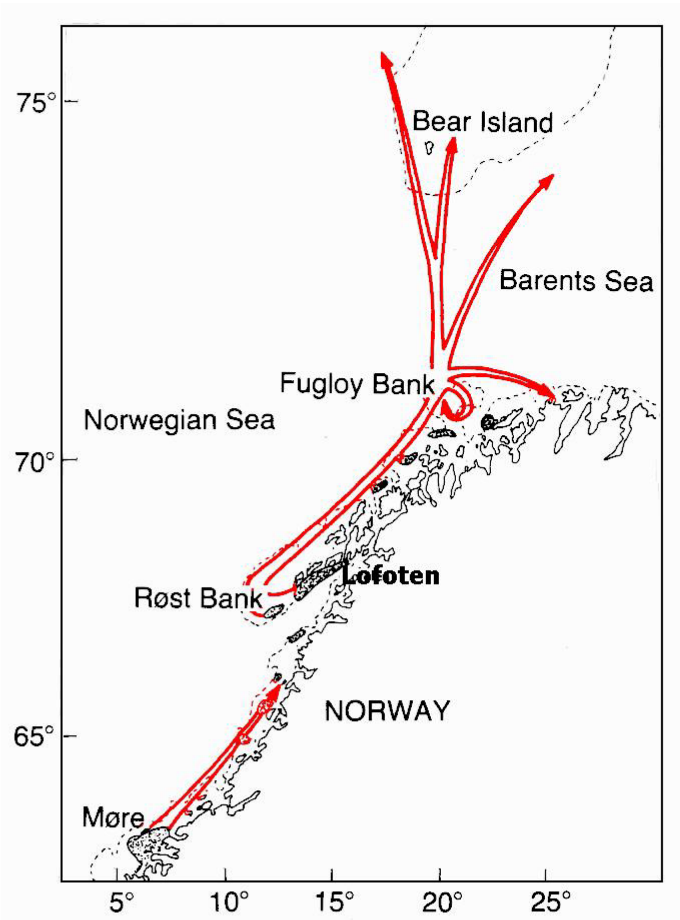

Figure 5.14. Spawning areas (stippled) and main patterns of egg and larval transport (arrows) of NE Arctic cod.

Presently, the typical maturation age is 6–7, a year less than in the 1950s. The Northeast arctic stock is the largest cod stock, with a total biomass (age 3+) spanning from 0.8 to 4 megatonnes. During the last century a substantial amount of information has been gathered, mostly by Norwegian and Russian investigations.

The main prey of the cod is capelin (*Mallotus vilotus*). Larval cod prey primarily on nauplii of the copepod *Calanus finmarchicus*. The main predators on cod, in addition to fisheries, are marine mammals, such as several species of seal and minke whales. Little is known about predation on eggs and larvae.

Temperature variability in the Barents Sea is, to a large degree, caused by fluctuations in the inflow of warm Atlantic water masses from the southwest (Ådlandsvik and Loeng 1991). A year with enhanced inflow of Atlantic water masses provide the 0-group cod (age 5 months) with a relatively warm and prey rich environment (Helle and Pennington 1999) and carries them further east in the Barents Sea (Ottersen *et al.* 1998).

5.2 Most important processes for transport of eggs and larvae.

5.2.1 North Sea and Irish Sea stocks

Transport can be broken down into a number of components. Advection moves particles from place to place whilst diffusion dilutes particles. Certain patterns of advection, which may operate on fine spatial scales, can aggregate particles. Eggs and early stages of larvae are often treated as passive drifting particles (perhaps with varying time dependent density) but later stage larvae exhibit behaviour that must be accounted for. Such behaviour includes vertical movement, directed horizontal movement. The interplay of behaviour and water movements may aggregate larvae in zones of enhanced food productivity. In turn this will also affect the advective transport that the larvae will experience. As well as allowing enhanced growth, the transport routes must deliver late stage larvae into areas suitable for settlement. There is evidence that bottom habitat required for successful settlement may be quite specific.

In tidally energetic areas like the North Sea and Irish Sea, fronts are extremely important. Early in the year these fronts tend to be due to freshwater runoff whilst later in the year thermal structure becomes more predominant. Jet flows occur along the fronts and in certain areas gyre circulations are set up. Good examples are the western Irish Sea gyre, circulation around the Dogger Bank in the North Sea and the fronts running into the Skaggerak. Ichthyoplankton surveys often indicate increased densities of fish larvae associated with these structures. It is also well known that fronts are areas of enhanced primary and secondary productivity. It therefore seems possible that the importance of these structures for survival and transport of larvae may have been under estimated.

As pointed out above, settlement also appears to be a crucial process. At this stage the juvenile fish are vulnerable to predation. Several studies have shown that the juveniles prefer to settle into cryptic habitat in response to this. Historical surveys of pelagic distributions in the North Sea show the juveniles to be confined to a restricted area north of the Dogger Bank and towards the Great Fisher Bank. By October the fish are found inshore. The behaviour at this stage has not received extensive study but tidal stream transport appears probable.

5.2.2 Northeast Arctic stock

The Northeast Arctic stock has a transport distance from spawning to settlement of up to 1500 km. While most of the post-larvae typically drift into the Barents Sea, in some years a large proportion may drift in a more northerly direction and reach west of Spitsbergen. However, the shelf area here is narrow and conditions for survival are less favourable than in the Barents Sea. Which drift route the larvae take is a direct consequence of wind-induced advection. This is thus a process of high importance for this stock.

From their first-feeding stage, survival of larvae of N-A cod is furthermore directly related to the availability of their main prey, nauplii of the copepod *Calanus finmarchicus* which overwinter in large numbers in the deep waters of the Norwegian Sea. During this time numbers of Calanus remaining in the Barents Sea and on then –Norwegian shelf are extremely low. In early spring they rise towards the surface and start to drift with the wind driven currents. This annual influx of Calanus into the Barents Sea and onto the Norwegian shelf is critically important for determining prey availability for the cod.

An enhanced volume flux of Atlantic water masses to the Barents Sea is therefore favourable for larval survival for several reasons: Higher temperatures, increased food availability, and a favourable nursery area (see WD XX).

5.3 Critical limitations for ability to model cod egg and larvae transport

5.3.1 Modelling of physical processes.

The model must have a high enough horizontal resolution to be able to resolve critical processes. This will vary between regions. For the Northeast Atlantic shelf Seas, fine-scale frontal regions are key transport features. This requires high resolution modelling. With a Rossby radius of 3–4 km, a resolution of 1 km is recommended. We are only now achieving models at this resolution over the shelf areas. However, such models impose greater demands on computing resources and on resolution of forcing functions (such as atmospheric data). This may limit the number of years that can be hindcast. To resolve tidal currents, a high temporal resolution of the stored physical fields is necessary, of the order 30 minutes. There are currently a number of different models at varying stages of development for the North Sea. Whilst to a certain degree they may differ in their scientific aims, a coordination of these activities could prevent duplicated effort. In some areas, there is also a requirement for better data on freshwater runoff. For example, for modelling studies of the Northeast arctic stock it is important to reproduce the temporal and spatial variability of the

Norwegian Coastal Current. For certain areas topographic steering of winds may be locally important. This particularly applies to modelling the Norwegian coastal regions.

For the Northeast Atlantic shelf regions there is a reasonable amount of physical measurement data to test the physical models.

5.3.2 Modelling of biological processes

The most critical limitation is the poor knowledge on processes related to mortality. In addition, biological rate processes are typically modelled as mean values, while information on variability is not represented. Data limitation is a serious problem for the development of transport models incorporating biological processes, even more so than for the physical models. This is particularly the case if we wish to deal with variability, rather than mean values. In some areas data are available, but there is little or no knowledge on the relative importance of different processes. In areas where little data is available, such as the North Sea, the use of complex models is not advisable at present. However, advanced models may be very useful tools for hypothesis testing, and for sensitivity analyses to help identify those processes that are most important and would most benefit from further field study. Laboratory experiments would also contribute towards this. In addition, the lack of adequate data is a limiting factor in the evaluation of the quality of model results.

For the North Sea the basic biological survey data required to define the location and duration of spawning are extremely limited. Recent data for locations of juvenile stages and settlement areas are similarly lacking. Certain information can be inferred from results of the regular demersal groundfish surveys undertaken by the fisheries laboratories but the gear deployed are not suitable for efficiently sampling these pre recruit stages. It will be difficult to progress modelling transport of cod early life stages in the North Sea until comprehensive ichthyoplankton surveys are initiated (see recommendations, PGEGGS).

For the Irish Sea there have been large-scale ichthyoplankton surveys undertaken in 1995 and 2000. Regular sampling of juvenile cod in June-July has also been undertaken for the last five years by DARDNI. Modelling of transport of eggs, larvae and pelagic juveniles can be undertaken using this data. Data on settlement and subsequent inshore movement of 0 group fish is lacking.

5.4 Recommendations

5.4.1 Recommendations for North Sea

1) Support be given to undertaking large scale ichthyoplankton surveys in 2004 (PGEGGS)
2) Link a comprehensive survey of pelagic 0 groups in June–July 2004 to the ichthyoplankton surveys
3) Undertake experiments and studies on settlement behaviour and habitat preference
4) Undertake studies on cod larval behaviour in relation to gradients of light, prey, and water currents

5.4.2 Recommendations for Irish Sea

1) Behaviour modelling studies on movement of larvae juveniles in relation to western Irish Sea gyre
2) Fine scale sampling across gyre structure
3) Studies of the distribution and timing of settlement in the eastern Irish Sea.
4) Studies on fate of settling juveniles
5) It must be noted that both these stocks are currently in very poor condition. Field programs requiring sampling of adult fish may experience great difficulty in finding sufficient fish at the present time.

5.4.3 Recommendations for the NE Arctic

1) Develop a biophysical modelling system for the region
2) Undertake further empirical/retrospective statistical and modelling based work to better understand what determines larval drift patterns into the Barents Sea or west of Spitsbergen.

6 BALTIC STOCKS

6.1 The Physical Environment

The Baltic Sea is a large estuary with shallow connections to the ocean, principal of these being the Danish Belt Sea. Fresh water inputs into the Baltic, on the order of 15000 $m^3.s^{-1}$ (Bergström and Carlsson, 1994), create a low salinity (~ 7 ‰) layer typically of 60–65 m in thickness (70% total volume of the Baltic Sea). Below this exists a 10 m layer termed the upper deep water pycnocline (25% of the Baltic volume; residence time circa 3 years) which overlies the deep saline waters of the Baltic (10–13 ‰; 5% total volume; residence time varies due to intermittent renew by inflows). Salinities and stratification vary significantly horizontally with salinities being lower to the north and east (e.g., Bothnian Bay) and higher to the west and south (e.g., Arkona Basin). A seasonal thermocline develops in the spring due to surface heating and is maintained due to solar inputs until the autumn. Between the summer thermocline and the halocline exists a cold intermediate layer termed the "winter water". In the autumn the thermocline coalesces with the remnants of the previous winters cold intermediate water resulting in a relatively homogeneous surface mixed layer down to the halocline.

The unique oceanographic conditions of the Baltic Sea, the resultant residence times of the various layers, coupled with the sedimentation of organic materials from terrestrial sources and surface euphotic layers, results in a build up in organic materials in the deep layer (e.g., Wulff *et al.*, 1990), which are degraded by bacteria utilising oxygen in the process.

The principal mechanism influencing the replenishment of oxygen in the deep Basins of the Baltic is the occasional inflow of saline oxygen rich waters from the North Sea (e.g., Matthaus and Franck 1992). However, other mechanisms, including wind driven advection from the Arkona Basin into the Bornholm Basin (e.g., Stigebrandt 1987), convective winter mixing down to the halocline and vertical turbulent mixing caused by wind forcing, also result in fluxes of oxygen to the deep layer (e.g., Stigebrandt and Wulff, 1987)

6.2 Potential Processes Influencing Survival in Baltic Cod.

As in other stocks, two processes, feeding success and predation, potentially influence the probability of larval survival. However, in Baltic cod, due to the prolonged spawning period (Wieland *et al.* 2000, and Figure 6.1), age and size dependent timing of spawning (Tomkiewicz *et al.*, 1998), the potential exists for eggs and larvae of differing quality to be exposed to varying environmental and predation scenarios due to;

- intra-annual variation in oxygen conditions at the depth of egg development (MacKenzie *et al.*, 1996; MacKenzie *et al.*, 2000);
- variations in predation on developing eggs by sprat and herring (e.g., Köster and Möllmann, 2000):
- temporally varying food environment (i.e., from the onset of the spring bloom to the fall bloom; Möllman In press);
- a spatially varying food environment (e.g., St. John *et al.*, 1995; Grønkjær *et al.*, 1997);
- varying larval transport (e.g., Hinrichsen *et al.*, 1997).

These processes all have the potential to influence the survival of the eggs larvae and early pelagic juvenile stages.

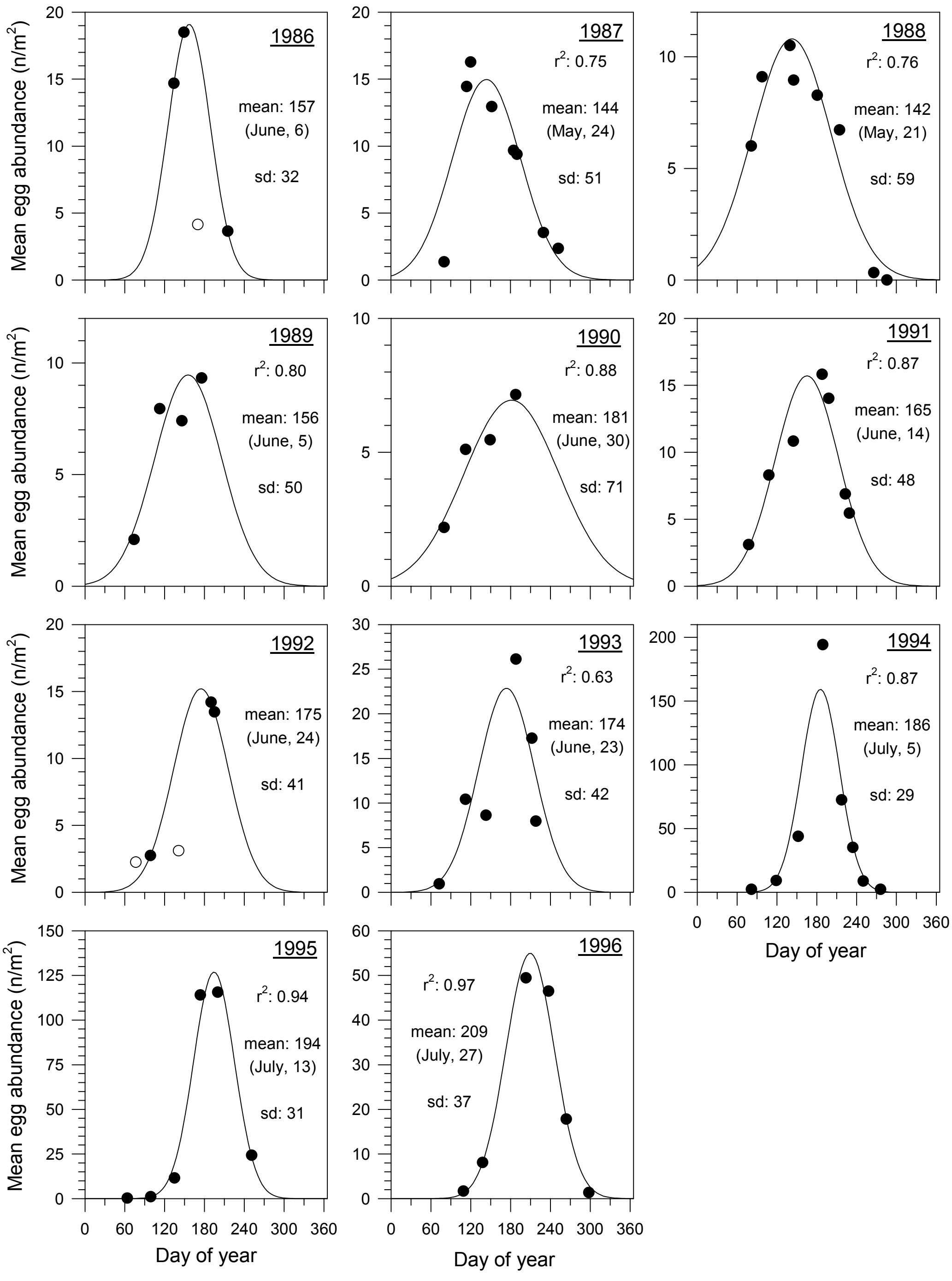

Figure 6.1. Abundance of stage IA eggs in the Bornholm Basin 1986-1995, with fitted normal distribution, estimated mean day of peak spawning and standard deviation. r^2 measures the fit to the parabolic regression with ln-transformed data. Observed values marked with an open circle were not included in the parameter estimation..

6.3 Background: Egg and Yolk-sac Larvae.

Historically there existed three main spawning areas for the eastern Baltic cod stock; the Bornholm and Gotland Basins as well as the Gdansk Deep (Figure 6.2). During recent years successful spawning of the eastern stock has been limited to the Bornholm Basin due to anoxic conditions in the other historic spawning sites (e.g., Bagge *et al.*, 1994). Consequently, reproductive success of Baltic cod is mainly dependent upon the environmental conditions presently existing in the Bornholm Basin. During the main spawning season (March to September), the Bornholm Basin is characterised by a thermocline occurring at approximately 20 to 30 m depth and a permanent halocline between 50 to 75 m (Kullenberg and Jacobsen, 1981). Neutral buoyancy and hence peak abundance of cod eggs occurs in the region of the halocline in the Bornholm Basin, with small quantities of viable eggs found in the more saline deep layer when oxygen levels permit (e.g., Mackenzie *et al.*, 2000).

Baltic cod eggs hatch after 13 to 27 days, dependent upon the ambient temperature at the depth of incubation in the

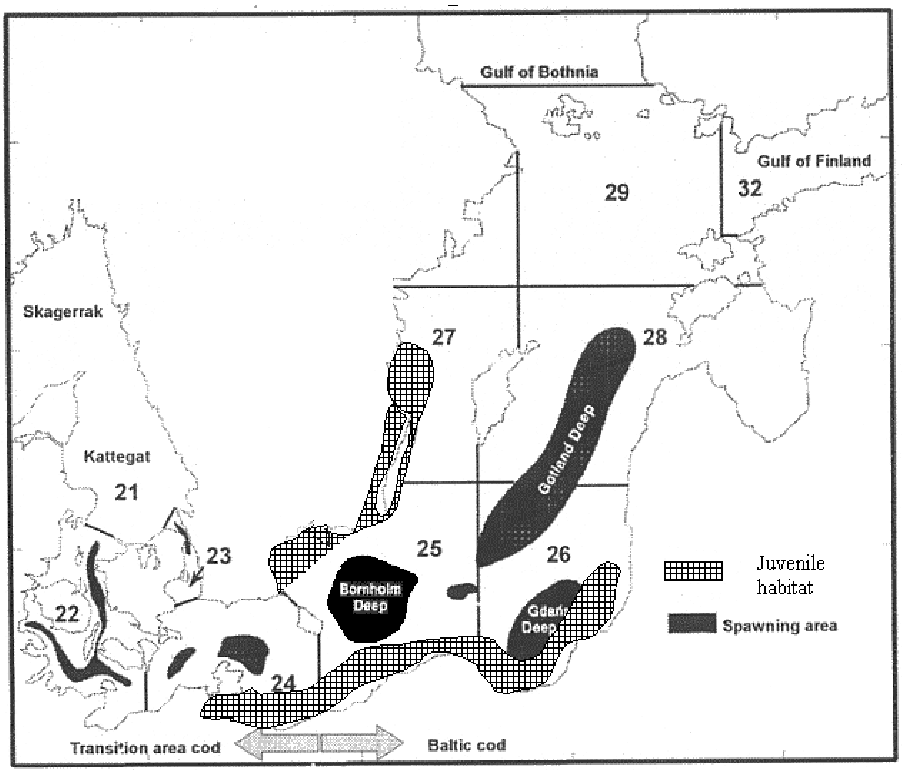

Figure 6.2. Location of historic spawning sites and nursery areas of Baltic cod (adapted from Bagge 1981).

Bornholm Basin (Wieland *et al.*, 1994). Salinity and oxygen conditions at the depth of neutral egg buoyancy are key factors influencing the survival to hatching of Baltic cod eggs, through their influence on spermatozoa mobility (Westin and Nissling, 1991), vertical distribution of eggs and hatching success (Nissling and Westin, 1991). Water in the region of the halocline can, after periods of low inflow from the North Sea, become unsuitable for the development of cod eggs. Crucial to the successful development of cod eggs is the oxygen concentration at the depth of neutral buoyancy. Wieland *et al.*, (1994) determined that the successful development of Baltic cod eggs requires an oxygen minimum of 2 $ml.l^{-1}$ below which eggs cease to develop. Neutral buoyancy for cod eggs is generally achieved at a salinity of 12.3 to 18.2 ppt (Nissling *et al.*, 1994) which typically occurs in the lower region of the halocline in the Bornholm Basin (Wieland and Jarre-Teichmann 1997), at present the site of major spawning. Egg buoyancy varies with egg size and lipid content, both of which are related to the size of female and batch number, with large females typically producing larger more buoyant eggs (e.g., Kjesbu *et al.*, 1992; Nissling and Vallin, 1996) of higher lipid content (Grauman, 1965), hence increasing the probability that their offspring will survive in marginal oxygen conditions. The utilisation of has resulted in the development of A rough index of “reproductive volume” can be derived from the oxygen minimum in conjunction with the salinity of neutral buoyancy. Variations in the volume of water suitable for the development of cod eggs can thus be compared between years (e.g., Plikshs *et al.*, 1993; Sparholt, 1996).

Late stage and hatching eggs as well as early larvae are found in the halocline and deep saline waters of the Bornholm Basin (e.g., Grønkjær and Wieland 1997). The highest abundances of young yolk-sac larvae are typically found in and below the halocline (Grønkjær and Wieland 1997). Later stages of larvae undergo vertical migration to the surface layer, where late larvae in enhanced nutritional state are found in conjunction with the peak availability of their prey (Grønkjær and Wieland 1997; Grønkjær *et al.*, In press). The successful completion of this vertical migration is deemed necessary for successful growth and survival of Baltic cod larvae due to a combination of low prey abundances and light intensities below the surface layers (Grønkjær and Wieland 1997).

6.4 Questions Posed to the Group

Rank in the order of importance, processes in the Baltic Sea which impact upon the transport and survival of the YOY pelagic stages and settling stages of Baltic cod.

1. **Variations in the Wind driven circulation.** Transport of larvae in the surface mixed layer is mainly influenced by the wind driven circulation of the Baltic (Hinrichsen *et al.*, 1997). Wind stress acting at the sea surface results in Ekman transport of the surface mixed layer with coastal jets in the direction of the wind produced along both coasts of the basin. These are compensated for by a weak return flow in the central interior of the basin (Kraus and Brügge, 1991). Results based on the analysis of the vertical distribution of cod larvae suggest that larval transport occurs in the depth range of the compensating return flow below the Ekman layer (Grønkjaer and Wieland, 1997). Observations coupled with coupled 3-D physical advection modelling and particle tracking simulations (Hinrichsen *et al.*, 1997a,b; Voss *et al.*, 1997) suggest that larvae are transported rapidly to the shallow coastal zone where they settle out as juveniles. Using the characteristics of survivors approach examining the otolith structure of surviving demersal juveniles and a coupled 3-D hydrodynamics model St. John *et al.*, (2000 *et al.*) proposed that intra annual variations in growth and survival in 1995 were a result of co-occurrence of surviving juveniles with periods of rapid transport to the shallow coastal regimes.

2. **Sites of spawning:** Studies on the horizontal distribution of cod and sprat eggs and larvae have been carried out since the beginning of the century which have identified the Bornholm Basin, the Gdansk Deep and the Gotland Basin as the major spawning grounds, at present successful reproduction of cod in recent years was mainly restricted to the Bornholm Basin (e.g., Bagge *et al.*, 1994, Figure 6.2 (Gdansk and Gotland basin). This reduction in the geographic distribution of spawning activities reduces the potential for larvae and pelagic juveniles to access all potential habitat available to newly settled juveniles.

3. **Seasonality of egg production.** The changes observed in the temporal occurrence of cod spawning (e.g., Figure 6.1) result in the exposure of larvae to periods of lower wind energy later in the year resulting in a reduction in the potential demersal habitat available.

4. **Other factors - Prey abundance.** Food of appropriate size and nutrition is key to rapid growth of cod larvae. Previous work has documented that *Pseudocalanus* copepods are an important prey item of larval cod in the Baltic Sea. Detailed spatial and temporal distribution of zooplankton is available only for 1999 (Möllmann, unpubl.). Time series data of zooplankton biomass from a few stations in the central Baltic show substantial seasonal (quarterly), interannual, and longer-term variability (Möllmann *et al.*, 2000). *Pseudocalanus* biomass declined from the early 1980s to a minimum in the early 1990s. Following a major inflow event in 1993 *Pseudocalanus* biomass has increased although it remains below the long-term mean. In addition to their direct importance as prey of cod larvae, prey availability impacts cod survival via an indirect effect operating through sprat predation. The preferred prey of sprat are cladocerans and Calanoid copepods. If they are abundant, sprat predation on cod eggs is lessened. If zooplankton are not abundant, then the predation upon cod eggs by sprat is higher.

What are the critical limitations on our ability to model transport of pelagic stages of cod in the Baltic also considering mortality?

Key to resolving the importance of transport variations for larval survival is the availability of techniques and data to verify that survival variations occur during these stages. Typically in the Baltic, as in other systems, no direct measurement of early larval and demersal pre-settling pelagic abundances are available making the testing of the larval drift hypothesis at best based on and SSB related estimate of egg production and settled juvenile abundance or at worst on age 1 or 2 group abundances. This approach can mask the influence of transport on survival as a number of other processes occurring between the pelagic juvenile stage and these later stages have impacted on survival success. Although this is the major limitation for establishing the importance transport variations, limitations also exist at present with regard to the parameterisation of the IBM models. These are as follows.

1. Resolution of true prey fields experienced by larval cod
2. Spatially and temporally resolved predation mortality.
3. Diel migratory patterns of larvae relative to light and prey conditions
4. Resolution of the optimal and marginal demersal habitats for juvenile cod and what defines this suitability.
5. The distribution of demersal habitats for juvenile cod
6. Settling flexibility of late larvae and juveniles.
7. Directed swimming wrt to the sampling and re-sampling of the demersal habitat

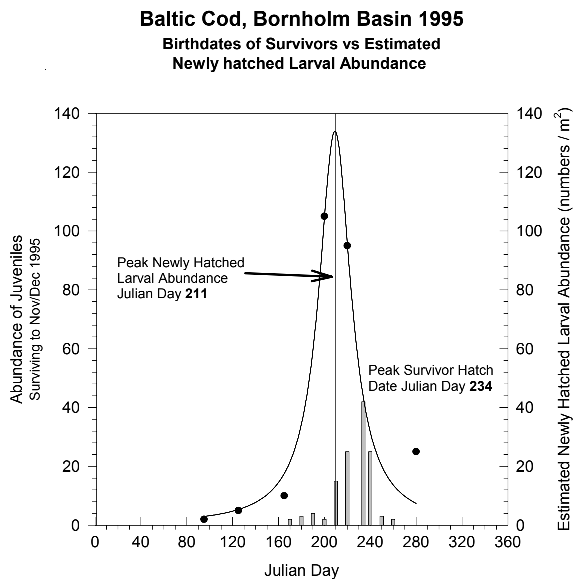

Figure 6.3. Occurrence of newly hatched cod larvae in the Bornholm basin in 1995 as estimated from egg surveys and the birth dates of surviving juvenile demersal cod captured in a December 1995 trawl survey.

Are there examples of transport variability effecting recruitment variability of cod in the Baltic Sea?

As in other systems evidence identifying the importance of transport variability on the population level is not well documented however on the level of the individual transport variations have been identified impacts on survival. (St. John *et al.*, 2000). In this study, through the utilisation of otolith characteristics such as hatch check, daily increments (identifying hatching time), increment width (indicative of otolith growth rates) and comparison with an environmentally forced 3-D circulation model of the Baltic Sea identified environmental windows and processes influencing the survival success of Baltic cod. Specifically this study identified that for the year 1995, surviving individuals came from a restricted subset of the potential survivors. Sequential sampling of the population demonstrated that offspring from large females, which produce energetically more viable and buoyant eggs and larvae, and which are transported rapidly to coastal nursery areas, are those with the highest potential to survive.

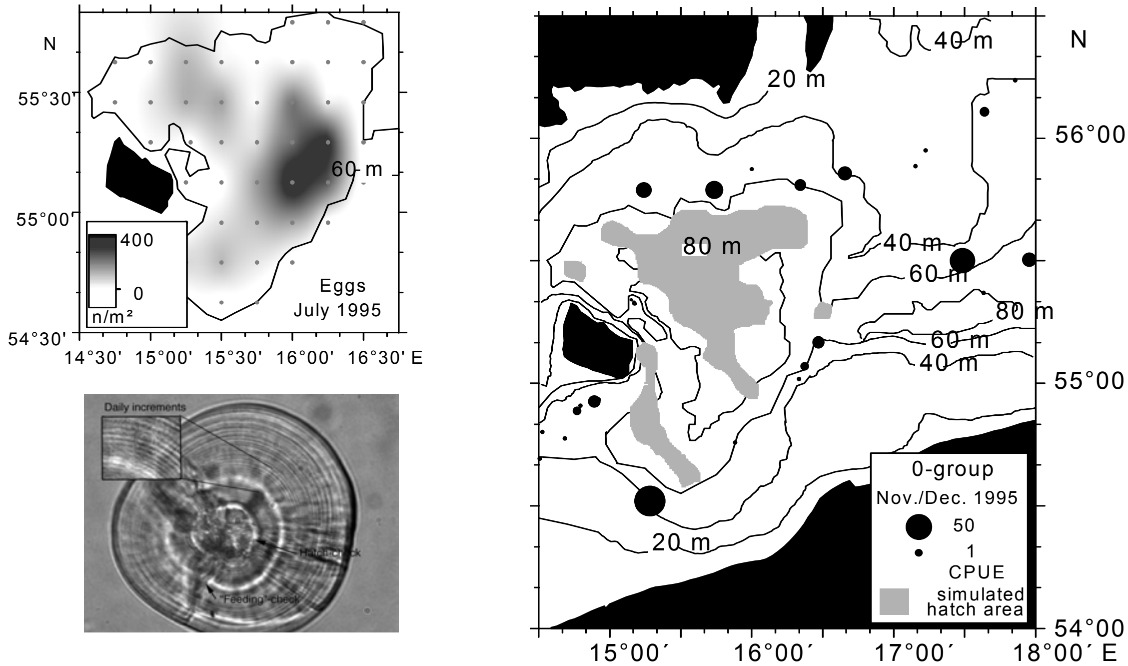

Figure 6.4. An example, hind casts of hatching areas of juvenile cod obtained in 1995 based on otolith derived hatch dates and 3-D hydrodynamic modelling are presented in comparison to hatching areas of cod eggs monitored by an icthyoplankton survey at peak spawning time.

6.5 Recommendations for Future Baltic Activities.

- Trawl and acoustic surveys to resolve the optimal and realised demersal settlement habitats;
- Field experiments to resolve changes in diel vertical migration patterns of larvae and early juveniles;
- High resolution plankton surveys with video or optical particle counters to generate spatially and temporally explicit larval and juvenile prey fields raltive to hydrodynamic processes;
- Sampling programs to resolve the spatial and temporal overlap of eggs and larvae and their predators to develop spatially and temporally explicit egg and larval mortality rates;
- The performance of laboratory experiments to resolve the effects of temperature, metabolism and prey availability on larval and juvenile growth;
- The performance of laboratory experiments and field programs to resolve processes occurring during the transition from pelagic to the demersal settling period.

6.6 What are the similarities and difference between cod stocks?

- Western Baltic Stock: January to March;
- Eastern Baltic: April to September:
  - Spawning period has changed for the Eastern Baltic stock from a historic peak in May June to peak now occurring in July August
  - Location of Spawning has it changed see Figure 6.2.;
- What is the concentration of eggs after spawning: Up to 200 eggs.m^2 in1994. However as the eggs are concentrated in a restricted strata, densities per m^3 will be much higher;
- Egg size: Size 1.15 to 1.65 mm;
- Egg Buoyancy: Neutrally buoyant at a sigmat t of 13 +/- 5;
- Duration of larval transport: 30 to 60 days;
- Temperature regime for Egg development: 2 to 10 ^{o}C;
- Larvae Temperature experience: 2 to 20 ^{o}C highly variable;
- Variability of recruitment 60 to 700 Million individuals;
- SSB: Min 135115 tonnes in 1992: Max 1035512 tonnes in 1982;

- Evidence of transport across stock boundaries: Yes transport between Eastern and Western stock occurs with a transition area proposed in the Bornholm Basin (e.g., Figure 6.2).

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8 CONCLUSIONS WITH REGARDS TO TERMS OF REFERENCE

The collective result of the workshop was a demonstration that physical transport of cod eggs and larvae has the potential to link stocks at both local and larger scales. However, the contribution of this displacement to the recruitment dynamics of local and adjacent stocks has not been quantified in most cases.

One of the immediate benefits of incorporation of transport indices into stock assessments may be the improvement of recruitment estimates. Stocks for which transport indices have been or are being incorporated into recruitment estimation include the Baltic, Iceland and NE Arctic, where they account for a small, albeit significant, proportion of the total variation.

Knowledge of the influence of transport processes will also provide important insights into long-term stock dynamics. For example, the productivity and resiliency to exploitation of adjacent stocks receiving immigrants from source populations will be dependent on the frequency and magnitude of such transport events. Special consideration should be given to conservation measures directed at source populations.

The approach to the assessment of cod stocks has generally been highly discrete with the assumption that stock dynamics are confined to processes occurring within the management unit. In the past, one important exception to this was the acknowledged connection between Icelandic and West Greenland cod, where immigration and emigration were incorporated into the assessment model. Recently, the approach to this assessment has changed and the Iceland-West Greenland stocks have been combined into a single assessment.

Particle tracking based on hydrodynamic models shows the potential for wide dispersal of offspring, well beyond the borders of the existing management units. While management unit boundaries provide a convenient means of accounting for catch and fishing effort, their biological realism is limited. The perspective developed during the workshop was that stocks should be assessed in a more connected way and that the assumption of closed boundaries, which is typical of current assessments, should be examined carefully with a view to relaxing it.

The recovery of collapsed stocks may, in fact, be dependent on immigration from other stocks and the time-scales for such re-colonization events may be quite long. In the 1920s, West Greenland was re-populated by immigrants from Iceland leading to the development of a local, offshore cod stock as West Greenland. In the Baltic, several historic spawning populations no longer exist and one can speculate whether they will reappear or not with improvements in habitat conditions. Stock recovery scenarios based on hydrodynamics models should be given immediate attention, noting that past scenarios based on intrinsic rates of population growth have been overly optimistic and highly inaccurate.

The specific tasks set out in the Terms of Reference have all been addressed to varying degrees in this report, but most require further development. The Recommendations set out below are intended to guide and prioritise this. In addition a follow-up to the Workshop was proposed in the form of a Theme Session during the ICES Annual Science Conference in 2003. This was discussed during the meeting of the Working Group on Cod and Climate Change, which followed immediately after the workshop, and a recommendation was put forward there (and is not included here)

9 RECOMMENDATIONS

The recommendation to hold a Theme Session on Transport of Eggs and Larvae Relevant to Cod Stocks of the North Atlantic at the 2003 ICES Annual Science Conference was put forward by the WG on Cod and Climate Change.

Other recommendations for future work are presented within each geographic section of the report:

Section 3.5 - NW Atlantic Stocks

Section 4.5 - Stocks at Iceland and Greenland

Section 5.4 - NE Atlantic Stocks

Section 6.5 - Baltic Stocks

ANNEX 1: AGENDA

Workshop on Transport of Cod Larvae

Hillerød, April 14–17, 2002

14 April

1400	Welcome and Introduction
1520	Plenary: Presentations and Discussion on Topics 1 and 2

15 April

0900	Plenary: Presentations and Discussion on Topics 3 and 4
1200	Plenary: Discussion of breakout group work on Topics, ToR, report and paper
1400	Breakout groups on each Topic
1700	Plenary: Discussion and reallocation of participants among groups

16 April

0900	Group work (possibly split geographically)
1400	Plenary: Presentations on group work, discussion of conclusions (related to ToR and contents of paper)
1600	Preparing report and paper

17 April

0900	Plenary: Taking stock, presentations, discussion of conclusions and how to finish off the paper and report
1030	Final group work
1130	Final Plenary, closing discussion
1400	...WGCCC starts

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ANNEX 3: WORKING DOCUMENTS

All of the Working Documents listed below are available from the ICES/GLOBEC website (http://www.ices.dk/globec/workshops/transport). They will be included in the final CD for the 2002 ICES documents.

WD 1 - Batchelder *et al.* - Spatial and Temporal Distributions of Mesozooplankton in Idealized Models of Coastal Upwelling Systems*

WD 2 - Peter Munk - Concentration of larval and juvenile cod in frontal zones of the eastern North Sea, implications for drift during ontogeny.

WD 3 - Vidar Øresland - Transport mechanisms in cod larvae and larvae of other commercial species)

WD 4 - Buckley and Lapolla - Hatch date distributionof YoY haddock (*Melanogrammus aeglefinus*) on Georges Bank: implications for modeling transport, growth and survival.

WD 5 - Skreslet - Advection of eggs related to 0-group recruitment of cod in north Norwegian fjords.

WD 6 - Ottersen and Stenseth - Consequences of interannual variability in transport for recruitment of Arcto-norwegian cod.

WD 7 - Ottersen, Helle and Bogstad -Transport during early stages impacts interannual variability in length-at-age of juvenile Arcto-norwegian cod.

WD 8 - Wieland and Hovgaard - Distribution and drift of Atlantic cod (*Gadus morhua*) eggs and larvare in Greenland offshore waters.

WD 9 - Stein and Borovkov - West Greenland Cod - Modelling Recruitment Variation during the Second Half of the 20 th Century.

WD 10 - Ottersen - Comparison of environmental influence on Arcto-norwegian and other North Atlantic cod stocks: Wind, circulation patterns and larval advection.

WD 11 - Jonsson - Flow of Atlantic water to the north Icelandic shelf in relation to drift of cod larvae.

WD 12 - Buch, Nielsen and Pedersen - On the coupling between Climate, Hydrography and Recruitment variability of Fishery Resources off West Greenland.

WD 13 - Chasse *et al.* - Modeling the drift, growth and survival of cod eggs and larvae in the southern Gulf of St Lawrence, Canada.

WD 14 - Pepin and Helbig - Distribution and drift of Atlantic cod (*Gadus morhua*) eggs and larvae on the northeast Newfoundland Shelf.

WD 15 - Hinrichsen - Larval transport, growth and survival in the eastern Baltic Sea: a coupled hydrodynamic/biological modeling approach.

WD 16 - Gallego - Bio-physical models developed in the STEREO project (FAIR-CT98–4122).

WD 17 - Young, Brown and Fernand - Observations and modelling of the seasonal circulation in the North and Irish Seas: Implications for larval transport.

WD 18 - Harms *et al.* - Modelling egg and larvae transport around Iceland and Scotland in the frame of METACOD