Appendix D

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Modelling transport of cod eggs and larvae from Iceland to Greenland waters for the period 1948–2001

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Abstract

Transport of cod eggs and larvae from the Icelandic spawning grounds to the Greenland waters is studied for the period 1948–2001 using model based particle tracking. Surface currents are taken from a regional nested ocean model (MICOM) of the North Atlantic, forced by NCAR/NCEP data and with a resolution of 20–25 km in the Denmark Strait region. Random walk diffusion is added to the drift model and diffusion coefficients are taken proportional to the fluctuation velocities obtained from surface drifter statistics for the 1990s.

The hypothesis, originally suggested by Hansen and Buch (1986), that the strong year classes of offshore West Greenland cod mainly stem from the Icelandic spawning grounds as a drift of cod larvae and eggs, is tested. Large variability in the drift trajectories is seen from year to year, but we are not able to reproduce the observed high and low year class sizes at age-3 Greenland cod (YC) as a drift from the Icelandic spawning grounds towards Greenland. However, we can also not reject the hypothesis as the modelled ocean currents has some limitation (Ribergaard and Sandø, 2004, in prep.).

We test the ideas of Buch et al. (2004), that the large-scale climatic conditions, as expressed by the North Atlantic Oscillation index (NAO) have a strong influence on the hydrographic conditions at West Greenland and thereby the drift from Iceland towards Greenland. Model experiments of years with high and low NAO index do surprisingly not show similar differences. This suggests that the NAO index alone can not explain the variability of the drift of cod larvae and eggs.

We found that the actual position of the spawning sites largely affects the final position of the larvae. Therefore, we speculated if the exact position of the main spawning ground at Iceland could have changed in the past, or alternatively, if another site had delivered cod larvae in years of high YC. This has to be investigated further using observations.

The mean drift from the Southwest Iceland shelf is derived from surface drifters drogued at 15 meters, and statistics is made of their final positions. In the Denmark Strait near 66°N the drifters branch into either the Polar Water (PW) or the Irminger Water (IW) component of the East Greenland Current (EGC), or they continue north of Iceland within the North Icelandic Irminger Current. The percentage ending up at

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East Greenland is higher than found by Astthorsson et al. (1994) using observed 0-group abundance of cod, but similar if we disregard the drifters in the PW component of the EGC. This suggests that most of the cod larvae ending up in the PW component of the EGC do not survive, whereas the survival rate is much higher in the IW component of the EGC.

Keywords: Particle tracking; drift modelling; surface drifters; cod larvae; West Greenland cod; spawning ground; oceanography; East Greenland Current; Irminger Current.

Introduction

The surface waters in the Irminger Basin consists of two different water masses advected into the area from outside:

- Warm and saline Irminger Water which originates from the North Atlantic Current.
- Cold and low-saline Polar Water which originates from the Arctic Ocean

The surface circulation in the Irminger Basin is largely guided by the topography. On the western side of the Reykjaness Ridge the Irminger Current (IC) flows northward. South of Denmark Strait it branches into two currents. One proceeds northward through the Denmark Strait and turns eastward north of Iceland as the North Icelandic Irminger Current (NIIC), while the other flows westward towards East Greenland and then southward along the continental slope as the Irminger Water component of the East Greenland Current (EGC). From north, cold and low-saline Polar Water is transported southward through Denmark Strait by the EGC. South of Denmark Strait the Polar Water and the Irminger Water component of the EGC flow side by side. As the two branches flow around Cape Farewell they combine when the Irminger Water subducts under the low-salinity Polar Water of the West Greenland Current.

The South East and West Greenland shelves are important fishing grounds, and the marine ecosystem is characterised by relatively few dominant species, which interact strongly (Pedersen and Kanneworff, 1995; Rätz, 1999; Pedersen and Zeller, 2001). Ocean currents that transport water from the polar and temperate regions affect the marine productivity in the Greenland shelf areas, and changes in the North Atlantic circulation system therefore have major impact on the distribution of species and fisheries yield (Pedersen and Smidt, 2000; Pedersen and Rice, 2002; Buch et al., 2004).

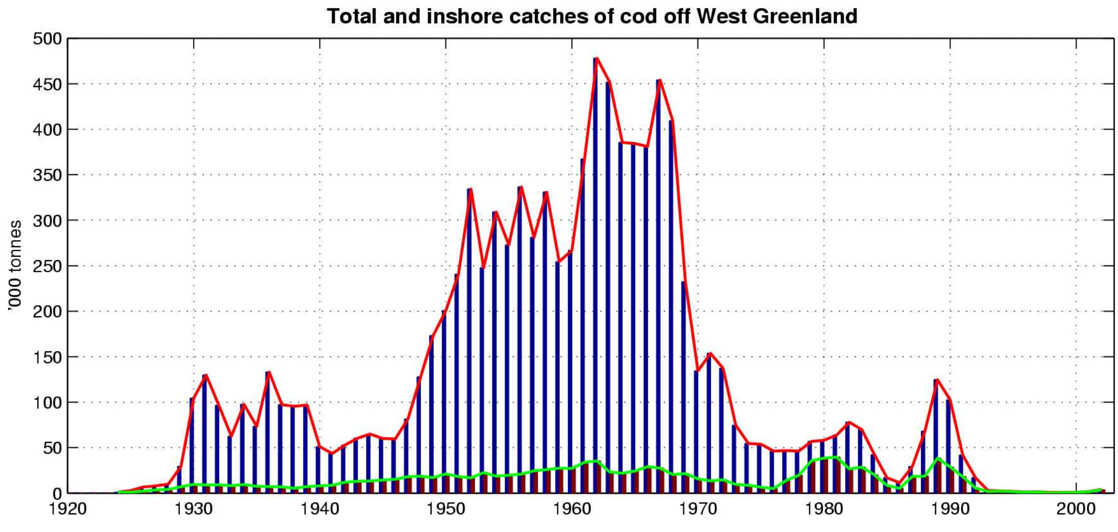

Figure 1. Total annual catches in 1000 tonnes of cod off West Greenland (blue bars and red line) for the period 1924–2002. The inshore catches are shown by red bars and the green line. (Data from ICES, 2003)

At Greenland there are different cod stocks (Wieland and Hovgård, 2002). Offshore the Atlantic cod (*Gadus morhua*) predominates, whereas Greenland cod (*Gadus ogac*) is common in West Greenland but is found only in fjords and in coastal areas from about 60°N to 73°N. Inshore Atlantic cod shows almost no migration between different fjord systems, whereas offshore Atlantic cod shows alongshore migration (Storr-Paulsen et al., 2004). In this paper we focus on the offshore Atlantic cod.

Spawning locations are observed both at West Greenland west of the fishing banks mainly at 200–600 m and at East Greenland along the offshore slope in the range 170–400 m in relative warm Irminger Water (Hermann et al., 1965; Wieland and Hovgaard, 2002 and references therein). At Iceland Atlantic cod spawn off the southwest coast below water depths of 35 m.

The total annual catches of cod at West Greenland since 1924 are shown in Figure 1. In the 1920s the cod fishery started at West Greenland after a general warming of the northern hemisphere (see Dickson et al., 1994; Buch et al., 1994; Horsted, 2000 and references therein). West Greenland cod fishery peaked in the 1960s, but in the late 1960s a collapse lead to a transition from cod to shrimp fishery which affected the human population centres and the economy of West Greenland (Hamilton *et al.*, 2000, Hamilton et al, 2003). After the collapse the catches of Atlantic cod at West Greenland never regained a high level, despite two small improvements caused by strong year classes in 1973 and 1984; by 1992 the cod was essentially gone.

Already in the 1950s, Hermann (1953) suggested a positive relationship between the cod year-classes and the temperature conditions off West Greenland. This was further investigated by Hermann et al. (1965) who found the relationship to be significantly linear correlated for temperatures above 1°C measured at the top of Fylla Bank in June. For lower temperatures, the cod year-classes were at a constant low level. Brander (1994a, 1995) found that temperature is responsible for most of the observed differences in growth between several cod stocks in the North Atlantic.

The temperature decrease after the late 1960s resulted in poor conditions for cod at West Greenland, seen as a reduced growth, and the cod was migrating southward out of the area. By analysing the structure of the cod stock Buch and Hansen (1988) concluded, that the actually collapse in cod fishery in the late 1960s is caused by a general failure in recruitment. The intensive fishery in the 1960s reduced the cod stock substantially, but it would have been stabilized on approximately 180,000 tonnes if the recruitment was kept on the 1952–1963 level. In reality, the recruitment failed while the fishing mortality was high which lead to a doubling of the rate of decline of the total spawning stock biomass. Theoretical considerations on transport time combined with German and Icelandic surveys indicate, that the recruitment of cod at West Greenland could be highly dependent on the drift of cod larvae and young fish from Iceland and less dependent on the local spawning at West Greenland. It was therefore suggested, that it is the changes in the oceanographic conditions in the Irminger Sea that drive the large fluctuations in the West Greenland cod recruitment rather than the local temperature.

Catches of haddock show similar variations as catches of cod at West Greenland, but as haddock do not spawn successfully at West Greenland, they must have drifted to Greenland from Iceland as larvae and it is therefore a useful tracer for this drift. By using catches of haddock Hovgård and Messtorff (1987) and later Dickson and Brander (1993) also suggested the collapse in the West Greenland cod stock mainly to be caused by a less frequent inflow of young cod from Iceland since the early 1960s.

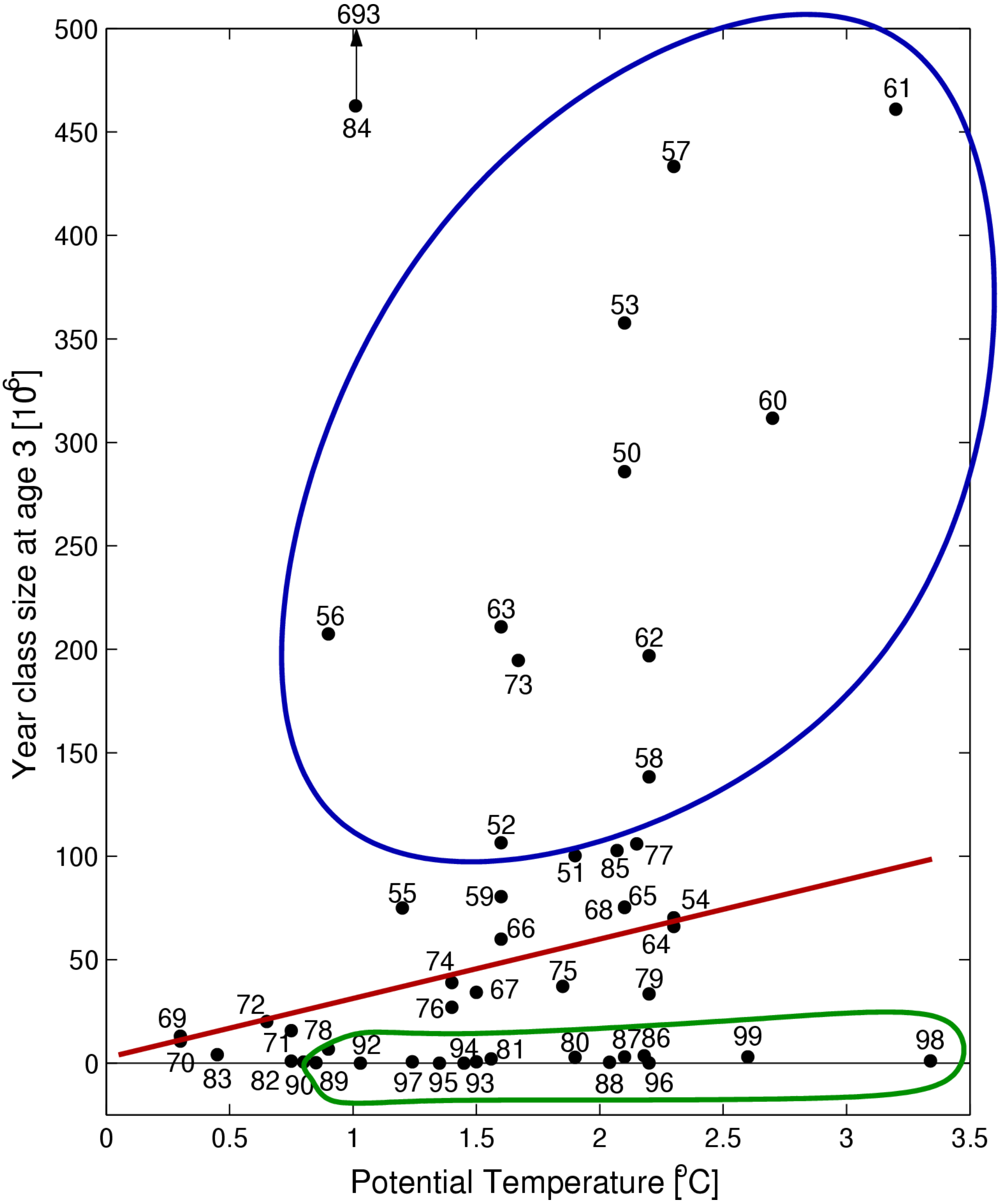

Figure 2. Year class size at age 3 West Greenlandic cod (year class size at age 3 of Greenland cod, in tonnes) as function of the mid June temperature on top of Fylla Bank (0–40m) for the period 1950–1999. Note, the 1984 year class is outside the y-axis. See text for explanation of the red line and the blue and green ellipses. For the description of the dataset see the data chapter.

Hansen and Buch (1986) found a linear temperature dependence between the year class size at age-3 (YC) of the local offshore cod stock recruitment off Greenland and the temperature on top of Fylla Bank station 2 (reproduced and updated in Figure 2). In some years this relation however fails as the YC was by far too high. They relate years of extreme YC to drift of cod larvae from Iceland to Greenland. Assuming that year-classes with distribute mainly off Southeast and Southwest Greenland originates from Iceland, they found the year classes, 1956, 1961, 1963 and 1973 to be Icelandic recruits. They argued, that the year-classes 1953, 1957, 1960 and 1962 also might be of Icelandic origin. In some years, including 1973 and 1984, Astthorsson et al. (1994) found a considerable fraction of the Icelandic cod larvae drifting across the Denmark Strait from 0-group survey.

Following the ideas of Hansen and Buch (1986) Figure 2 can be interpreted as follows:

- The red straight line shows a linear dependence with YC strength increasing with temperature. The years close to this line are believed to reflect recruitment from offshore West Greenland cod stock being closely related to the marine environment reflected by the temperature in the area.
- The years falling inside the blue ellipse have an extremely high YC, well above the linear temperature-YC dependence line (red). These strong YC are believed to be a result of drift of Icelandic cod larvae and eggs from the Icelandic spawning grounds to Greenland. All the years falling into this group are from the 1950s and early 1960s as well as 1973 and 1984. The cod landings (Figure 1) were record high in the 1950s and especially in the 1960s – exactly the period where the drift from Iceland gives strong YC at Greenland. It is known that the strong YC in 1973 and 1984 are a result of drift of Icelandic cod and the effect of these strong year classes are seen few years later in the cod landings.
- The years falling into the green ellipse are all years from the mid 1980s and the 1990s when the Atlantic cod stock at West Greenland was extremely low or almost non existing since 1992. Therefore the local recruitment was very low, as there were nearly no local cod to spawn. In the same period the drift of recruits from Iceland was low or absent.

Recently Stein (2004) reported high abundance of cod around East and West Greenland during the 2003 autumn survey. He suggests this to be related to the recent several of years of warming in West Greenland waters, which favoured the environmental conditions in these waters for cod. He suggested that it is the warming over time rather than inter-annual variations that seems to be relevant for the abundance of juvenile cod in Greenland waters. Stein and Borovkov (2004) modelled recruitment variations during the second half of the 20th century using time-series of several climatic variables as well as cod recruitment and spawning biomass. They conclude that advective factors were the dominant factor for cod recruitment at Greenland.

Buch et al. (2004) relate the strength of the North Atlantic Oscillation (NAO) to the climate variability at West Greenland in the second half of the 20th century, reflected in both hydrographic data, sea ice data, atmospheric data and biological data. They argue that the surface currents were altered during high NAO phase, resulting in a weakened Irminger Current and thereby decreasing heat transport to the West Greenland Fishing Banks in line with the ideas of Blindheim et al. (2001). At high NAO index, cold air masses from Canada and the Arctic flow over the Davis Strait and the Labrador Sea resulting in local cooling at West Greenland. Moreover, the weakened Irminger Current results in a decreased drift of cod larvae from the Icelandic Spawning grounds to West Greenland. All together this explains the major part of the dramatic collapse in the Greenland cod stock in the late 1960s, but other mechanisms such as overfishing must be taken into account.

Stein and Lloret (1995) tested the possibility of a link between water mass stability and strong YC at West Greenland. They found a link between low stability and strong YC in the warm period before 1970, but afterwards no significant correlations were found. They suggested that in the cold period after 1970, advection of Irminger Water to the West Greenland area may explain the variability of recruitment.

Rätz (1999) suggested the failure of recruitments of cod in the late 1990s, when the temperatures got warmer, could be due to significant by-catches in the expanding shrimp fishery combined with over-fishing on the spawning cod stocks. Malmberg and Blindheim (1994) questioned whether the failure in recruitment of Icelandic cod in the early 1990s, when the hydrographical conditions was improving, was due to a critically small spawning stock. They argue that overfishing has taken place on the Icelandic spawning grounds, as the decline in the cod spawning stock was higher than the decline in recruitment, which again was higher than the decline in the catches.

Astthorsson et al. (1994) found a significant linear relationship between the zooplankton biomass southwest and west of Iceland and the 0-group cod abundance. Malmberg and Blindheim (1994) suggest that the survival rate of cod larvae lie in the feeding conditions in the nursery area. Whereas the spawning of cod eggs at the Icelandic spawning grounds is fixed in time from year to year, the spawning of *Calanus finmarchicus* is dependent on temperature, with a difference of up to 6 month between cold and warm years. Brander et al. (2001) found, that interannual variability in *Calanus* egg production has significant effect on cod recruitment at Iceland and in the Irish Sea. They suggest that local wind forcing exert an effect on the survival of cod larvae, caused by the match between plankton production and larval feeding.

Several of theories exist on the large variations in the number of cod in West Greenland waters. However, the decline in the West Greenland cod catches during the 1960s is most commonly believed, in large part, to be a response to climate variability. Changes in climate are thought to have led to both the center of the cod fishery moving south during the 1980s and the decrease in size-at-age, as well as a reduced drift of juvenile cod from Iceland to Greenland (Buch and Hansen, 1988; Hovgård and Buch, 1990; Riget and Engelstoft, 1998; Rätz et al., 1999; Horsted, 2000). Using long timeseries Dickson et al. (1994) conclude, that it seems unlikely that the two known earlier cod periods at West Greenland in the 19th century could have occurred without a wind-induced strengthen of the Irminger Current which transport heat and cod larvae from Iceland to West Greenland.

Here we focus on the advective drift of cod larvae from the Iceland spawning grounds to the Greenland waters from 1948–2001 using a drift model driven by currents from a regional nesting of a global ocean hydrodynamic model. We test the hypothesis (1) that the extreme YC at West Greenland is caused by a drift of recruits from Iceland and (2) that the changes in recruitment at West Greenland is related to climate changes reflected in the NAO index.

Firstly we model the drift using monthly mean ocean currents for the period 1948–2001 and compare the statistics with statistics derived from surface drifters and from the literature. Secondly each individual year is modelled using currents from a nested Ocean General Circulation Model (OGCM) forced by daily NCAR/NCEP wind fields. Finally, we model the drift using monthly mean currents during high and low NAO indices and for high and low YC years.

When using a simple drift model, we assume that the cod larvae and eggs are transported passively by the ocean currents as particles. Thereby we can test if strong YC of cod mainly are a result of advection of cod larvae from the Icelandic spawning grounds. Further we are able to track the water mass characteristics of the surrounding water at any time. Thereby we are in principle able to add a temperature dependence on the survival of the cod larvae by assuming a death rate proportional to the temperature.

We ignore several factors such as direct catches and by-catches by the fishery, the amount of available food e.g. zooplankton such as calanus finmarchicus, migration of cod, species interaction, local spawning at Greenland and yearly differences in both the timing of the spawning and the larval abundance. These are all processes that need further investigations.

1. Data and methods

1.1. Catch data

Annual catches of cod used in this paper are from ICES (2003). Year class size at age-3 is estimated using Virtual Population Analysis (VPA) for the period 1925–1981 (from Horsted, 2000). For the period 1982–1999 the age disaggregate abundance indices were used (from ICES, 2003). No corrections due to catchability were done. Therefore, as the trawls used on the surveys favour larger fish, the YC is most likely underestimated, but the error is believed to be less than 20 percent (Kai Wieland, Greenland Institute of Natural Resources, personal communication). These data have been used to construct Figure 1 and Figure 2.

1.2. Hydrographic, wind and mean sea level pressure data

Both the mean (0–40 m) temperature at top of Fylla Bank and the NAO timeseries were taken from Ribergaard and Buch (2004). NAO is here defined as the pressure difference between Ponta Delgadas, Azores, and Reykjavik, Iceland minus the mean pressure difference for the period 1961–1990. Wind data from the central Denmark Strait and mean sea level pressure for the North Atlantic were taken from the NCAR/NCEP climatology (http://www.cdc.noaa.gov).

1.3. Surface drifter data

Satellite-tracked surface drifters drogued at 15 m are used for validation of the transport in the Denmark Strait region. The set of drifter data included available drifters for the 1990s. The basic data set is available from the Drifting Buoy Data Assembly Centre at http://www.aoml.noaa.gov. For our analysis we used only those parts of the position time series when a drogue was attached to the drifter, accounting to 167 drifters (Figure 3). The distribution of data is not homogeneous neither in time nor in space. Most of the drifters in the Icelandic waters and in the Irminger Sea are from WOCE efforts during the second half of the 1990s. The Lagrangian nature of the measurements contributed to the inhomogeneous data distribution. Also, there are very few data in the East Greenland Current, especially in the Denmark Strait and further north, due to the presence of ice in this area.

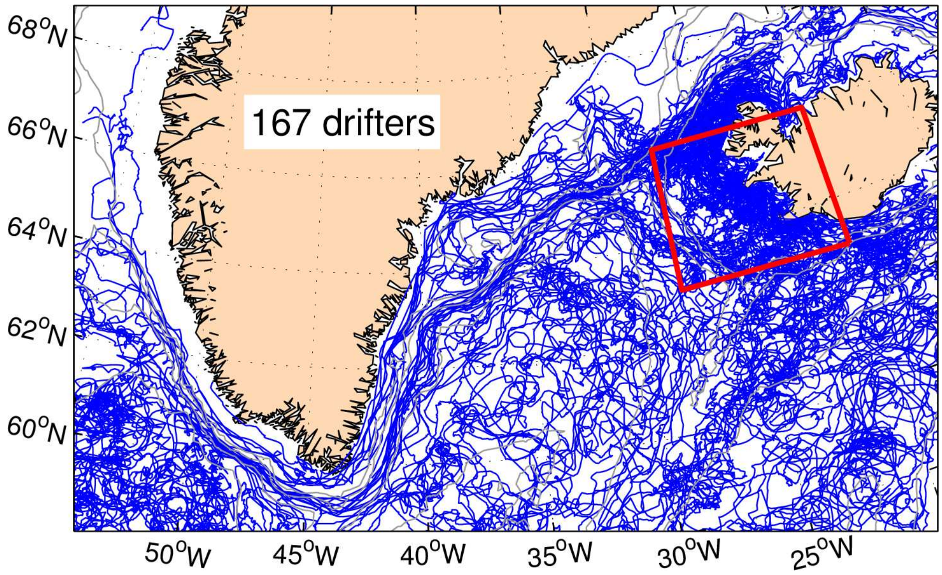

Figure 3. Low pass filtered trajectories of all drifters used from the 1990s. All drifters passing the red box southwest of Iceland.

To remove tides and eddies from each drifter track, a filter was applied with a cutoff period of 18 days (Jakobsen et al., 2003 for details). A by-product of this filter is the fluctuation velocity (the high frequency part) which is used to calculate the horizontal distribution of diffusion (Figure 4). The fluctuation velocity is mapped in 1° latitude times 2° longitude boxes, a scale well above the internal radius of deformation, and the boxes are shifted by half the box size in each direction. The resolution is then about 50 km, but somewhat smoothed since the boxes overlap.

1.4. The hydrodynamic model

The model system applied in this study is the ocean global circulation model (OGCM) MICOM (Bleck et al., 1992), fully coupled to a sea-ice module consisting of the Hibler (1979) rheology in the implementation of Harder (1996), and the thermodynamics of Drange and Simonsen (1996). It is a combination of a single-layer model of the oceanic mixed layer, based on a simple closure of the turbulence kinetic energy equation (Gaspar, 1988) and a three-dimensional isopycnic coordinate model of the stratified oceanic interior. The mixed layer (ML) has temporal and spatial varying density, while the interior layers have fixed potential densities. The specified potential densities of the sub-surface layers were chosen to ensure a realistic representation of the major water masses in the North Atlantic-Nordic Sea region (Furevik et al., 2002).

In the horizontal, the model is configured with a local orthogonal grid mesh with one pole over North America and one pole over central Europe (Bentsen et al., 1999), which gives a horizontal resolution of 20–25 km in the Nordic Seas. The bathymetry is interpolated from the ETOPO5 data base (Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth, NOAA, National Geophysical Data Center, Boulder, Colorado, 1988). It is corrected and adjusted in areas of special interest and importance such as in the Gibraltar Strait and at the Greenland-Scotland Ridge to ensure that the dense water masses are able to exit at the right depths.

In the regional model, the ML temperature and salinity fields are relaxed towards the monthly mean climatological values of Levitus and Boyer (1994) and Levitus et al. (1994). The relaxation time scale is set to 30 days for a 50 m thick ML and the relaxation is reduced linearly with the ML exceeding 50 m. If the relaxation to the climatology is too strong, the model is not able to reproduce the observed amplitude and phase shifts during the modelling period due to the fixed seasonal properties of the climatology. The applied relaxation is rather weak, allowing for seasonal to inter-annual variations in the simulated ML properties.

Daily mean NCAR/NCEP re-analysis (Kalnay et al., 1996) fresh water, heat and momentum fluxes are used to force the system by applying the schemes of Bentsen and Drange (2000). The model is initialized and nested with interpolated model data from a global version of MICOM (Furevik et al., 2002; Bentsen et al., 1999) and run for the period 1948–2001.

The model performance has been validated for the Northwest Atlantic waters by Ribergaard and Sandø (2004, in prep.). For the surface waters they conclude that:

- The modelled extent of multi-year-ice (storis) is much too low, which direct affects the temperatures at West Greenland and indirectly changes the baroclinic currents.
- Velocities within the East- and West Greenland Current are much too low in the model compared to velocities derived from surface drifters. Contrary, the Irminger Water component of the EGC has slightly higher velocities and is situated further offshore in the model.
- Surface currents are generally underestimated by the model as the surface currents are taken as the vertical mean of the mixed layer, which can be several hundreds of meters during winter.
- The salinity variations at Fylla Bank are poorly represented in the model, while the temperature variations are much better reproduced. In the model, there is no sign of the “Great Salinity Anomaly” in the late 1960s, but the two following cold periods in the 1980s and 1990s are easily seen. The air-sea exchanges appear to be well represented in the model whereas the advection processes are less well represented in the Irminger Basin / Labrador Sea area.
- Modelled transport through Denmark Strait of:
  1. Irminger Water within the Irminger Current compares well to observations. It is stable but slightly lower transports than reported in the literature. However, the salinity is much to low in the model.
  2. Polar Water within the East Greenland Current seems to be slightly to low. The “Great Salinity Anomaly” in the late 1960s does not show up but the variability seems to be fairly ok in amplitude.

Further information on the model setup and performance can be found in Ribergaard and Sandø (2004, in prep.).

1.5. Particle tracking model

The modelling of particle transport is driven by the input current field. The quality of the particle trajectories is therefore limited by the quality of this field. An understanding of the strengths and weaknesses of the calculated current field is a prerequisite for a proper interpretation of the particle transport.

We use the finite element drift model used by Ribergaard et al. (2004). The drift model solve the advection-diffusion equation for a passive tracer C given by

$$\frac{\partial C}{\partial t} + \vec{\nabla} \bullet (\vec{u}C) - \vec{\nabla} \bullet \left(k\vec{\nabla}C\right) = 0 \qquad (1)$$

where t denotes time, k horizontal diffusion and $\vec{u} = (u, v)$ is the horizontal advection velocity.

For the turbulent diffusion a random walk model is used. The basic idea is that the ensemble mean of the square of the particle displacement $\vec{x} = (x, y)$ satisfies

$$\frac{d < \vec{x}^2 >}{dt} = 2k \qquad (2)$$

For each particle the solution of equation 2 at timestep n+1 is on the form

$$\vec{x}_{n+1} = \vec{x}_n + R_n \sqrt{\frac{2k\Delta t}{r}} \qquad (3)$$

where R_n is a random number with mean $< R >= 0$ and standard deviation $< R^2 >= r$. We choose R as uniformly distributed between -1 and +1, in which case r=1/3.

Following Visser (1997) and Spagnol et al. (2002), the solution of equation 1 is

$$\vec{x}_{n+1} = \vec{x}_n + \vec{u}\Delta t + \nabla k_{\vec{x}_n} \Delta t + R_n \sqrt{\frac{2k\left(\vec{x}_n + \frac{1}{2}\nabla k_{\vec{x}_n} \Delta t\right)\Delta t}{r}} \qquad (4)$$

where the diffusion, k, is allowed to vary in space. The two first terms on the right hand are the solution for pure advection with no diffusion. The forth term is the random walk diffusion similar to equation 3 but as the diffusion varies in space, the diffusion is estimated at a distance $\frac{1}{2}\nabla k_{\vec{x}_n} \Delta t$ offset $\vec{x}_n$. The third term is an additional advective term that tends to transport particles towards regions of increasing diffusivity. Without this term, the particles will concentrate at regions of low diffusion which is obviously incorrect (e.g. Visser, 1997).

The drift model was run with a time step of 300 seconds. Horizontal diffusion was taken proportional to the fluctuation velocities obtained by surface drifters for the 1990s (Jakobsen et al., 2003). The diffusion fields in the x and y directions are shown in Figure 4. High values are seen on both the East and West Greenland shelf, in the eastern Labrador Sea between 60°N and 62°N and in the North Atlantic current. Low values are seen all around Iceland. Areas without data are substituted with mean value for the whole area. This does not affect the results, as the gaps are mostly in the Davis Strait, in the Baffin Bay and on the Canadian shelf and thus far away, downstream of the spawning areas for Icelandic cod and the focus of this paper.

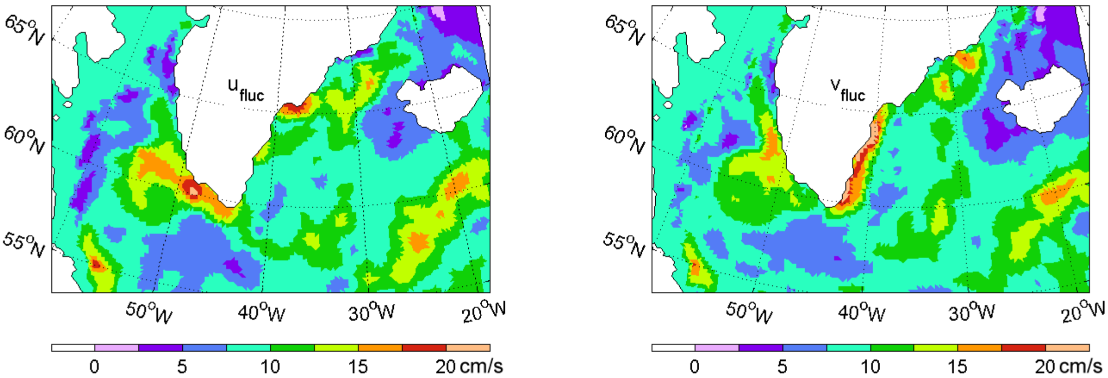

Figure 4. Zonal (left) and meridional (right) fluctuation velocities. The velocities are derived from statistics from surface drifters drogued at 15 m in the 1990s (see Jacobsen et al, 2003). Areas without data (mostly in the Davis Strait, in the Baffin Bay and on the Canadian shelf) are given the mean value for the whole area.

1.5.1. Spawning locations and development of cod eggs and larvae

Today, the main spawning grounds for cod around Iceland are in the southwest corner (Marteinsdottir et al., 2000b, Figure 5b). It is believed that cod found in the Denmark Strait area near Greenland has drifted from these spawning grounds with the northern and western branch of the Irminger Current. Hatching time is estimated to peak around mid May, which may vary about half a month (Begg and Marteinsdottir, 2000b). The time of spawning is estimated to be approximately 15 days before hatching. Additional spawning takes place in fjords west, north and east of Iceland with later spawning times clockwise around Iceland (Marteinsdittir et al., 2000b ; Begg and Marteinsdottir, 2000b).

In the present experiments spawning is chosen for a 60 days period from the 1st of April as a normal distribution with peak at day 26 (Figure 6b). At each spawning location 200 particles were released. Only spawning southwest and west of Iceland is included.

Marteinsdottir et al. (2000a, 2000b) divide the spawning sites into 3 categories separated by depth: inshore below 75 m, "in between" in the range 75–100 m and offshore on the continental slope in waters deeper than 100 m, but all inside the 200 m depth contour (see Figure 5). As the focus for this experiment is the drift of Icelandic cod larvae towards Greenland, we only consider the offshore spawning ground.

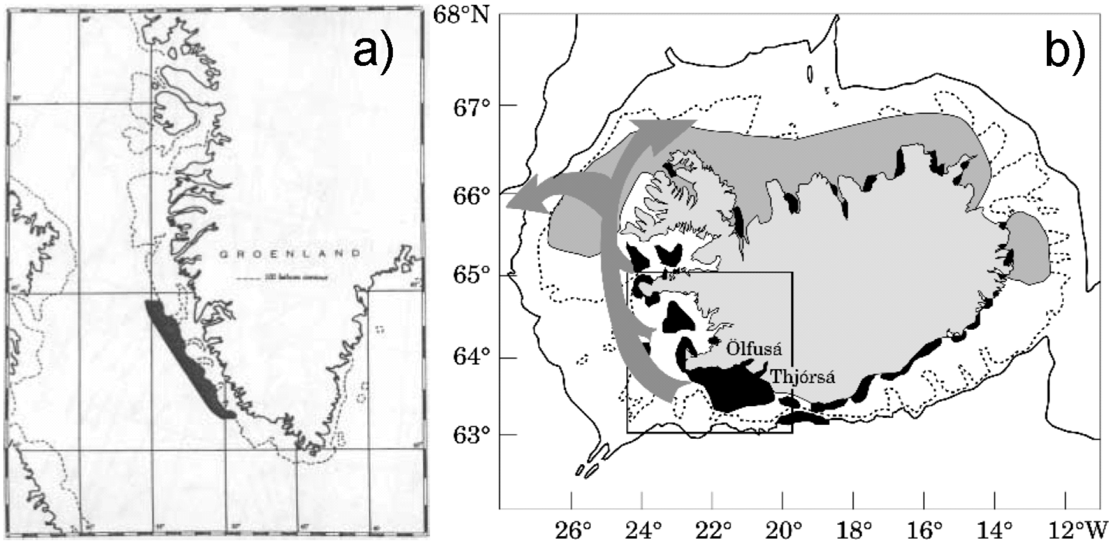

Figure 5. a) Spawning grounds at West Greenland according to Hermann et al. (1965). The depth contour is 100 fathom equal to about 180 m. b) Spawning grounds around Iceland (in black) according to Marteinsdottir et al. (2000b). The main spawning grounds are in the southwest corner. Depth contours are 200 and 500 m.

However, there is insufficient information to determine whether the distribution of spawning at Iceland has changed in time or space (ICES, 2002). Greenland offshore cod spawns in the relative warm Irminger Water close to the continental shelf break at water depths 170–400 m on the east coast and mainly at water depths 200–600 m on the western side (Hermann et al., 1965 ; Wieland and Hovgård, 2002 and references therein ; Figure 5a). These spawning depths are much deeper than those reported from Iceland by Marteinsdottir et al. (2000a, 2000b). However, the water mass south and southwest of Iceland are Irminger Water, except for a narrow coastal current diluted by fresh water runoff. Therefore, from a hydrographic point of view the spawning takes place in Irminger Water both at Iceland and Greenland.

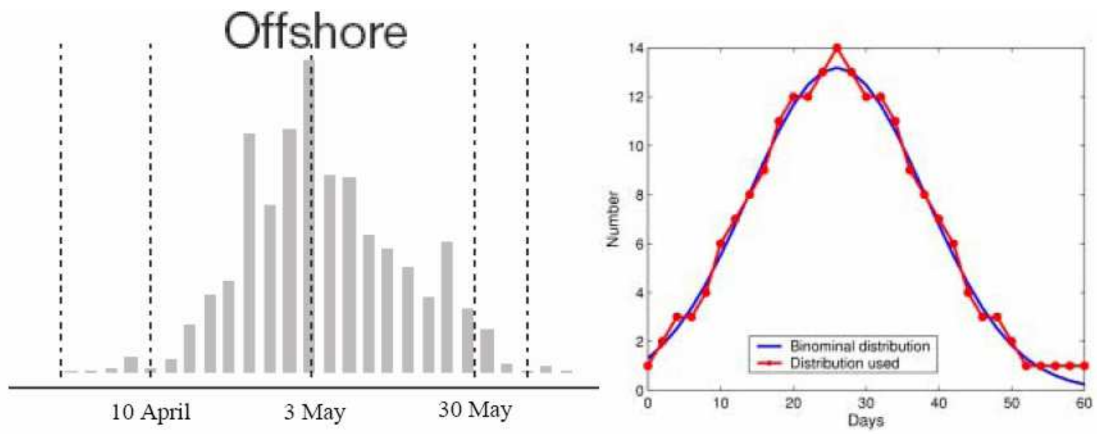

Figure 6. Spawning distribution for the main Spawning ground (left, modified from Begg and Marteinsdottir, 2000b) and spawning distribution used for the drift model (right, red dots). Day 0 is set to 1st of April. Number of particles released each day is given as the y-axis (sums up to 200).

For the idealized experiments using monthly mean currents for high and low YC and NAO, 229 spawning locations were chosen southwest and west of Iceland, from the shallow waters close to land to the continental shelf break close to the 500 m depth contour (Figure 7). For simulations of the individual years six spawning locations are chosen southwest of Iceland, all at model depths at about 220 m on the continental shelf (circles in Figure 7). This depth is about the lower limit for spawning at Iceland according to Marteinsdottir et al. (2000a, 2000b). We expect that the outermost spawning locations are the ones with the highest probability for ending up at Greenland, which is the focus in this paper. Therefore we disregard the spawning locations closer to land.

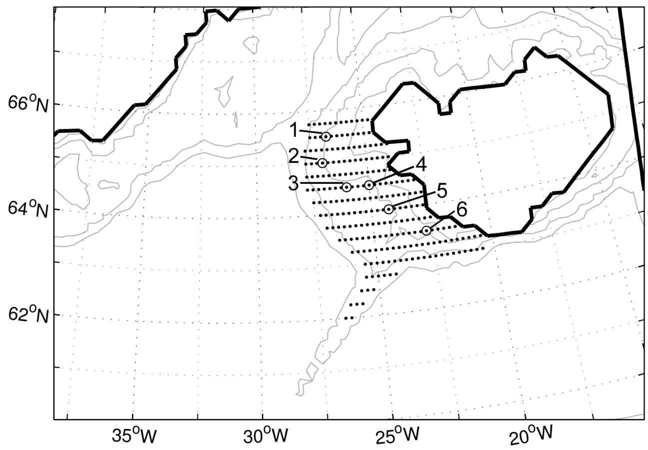

Figure 7. Spawning locations for the simulations using monthly mean currents for high and low NAO and year class size at age-3 west Greenland cod. 229 start positions at all. The 6 circles denote the spawning position used for each individual year 1948–2001. Model depth contours shown for 100, 200, 500 and 1000 m.

1.5.2. Defining standard high and low NAO and YC years

The years are divided up into years of high and low YC based on observations (Figure 2). Then monthly mean currents from the MICOM model are calculated and used as input to the drift model. Similar procedure has been done for high and low NAO years.

YC years are divided into two categories:

- High YC years: (YC >= 100 tonnes): 1948, 1950, 1951, 1952, 1953, 1956, 1957, 1958, 1960, 1961, 1962, 1963, 1973, 1977, 1984, 1985.
- Low YC years: (YC <= 50 tonnes): 1967, 1969, 1970, 1971, 1972, 1974, 1975, 1976, 1978, 1979, 1980, 1981, 1982, 1983, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999.

NAO years are divided into two categories:

- High NAO years: (NAO >= 5 hPa): 1954, 1961, 1967, 1972, 1973, 1974, 1976, 1983, 1984, 1989, 1990, 1992, 1993, 1994, 1995, 1999, 2000
- Low NAO years: (NAO <= -5 hPa): 1955, 1956, 1958, 1960, 1962, 1963, 1964, 1965, 1966, 1969, 1977, 1979, 1985, 1996, 2001

These years are used to construct the "standard current" representing high and low YC and NAO. However, by making monthly means, we smooth out all variations on timescales less than one month. Thereby, any timescales less than a month are disregarded in these experiments. The limitation of this assumption is discussed later.

2. Results and discussion

2.1. Statistics of the drift towards Greenland based on surface drifters

In this chapter we use drifters for estimating the transport of cod larvae from the Icelandic spawning grounds with special focus on the transport towards Greenland.

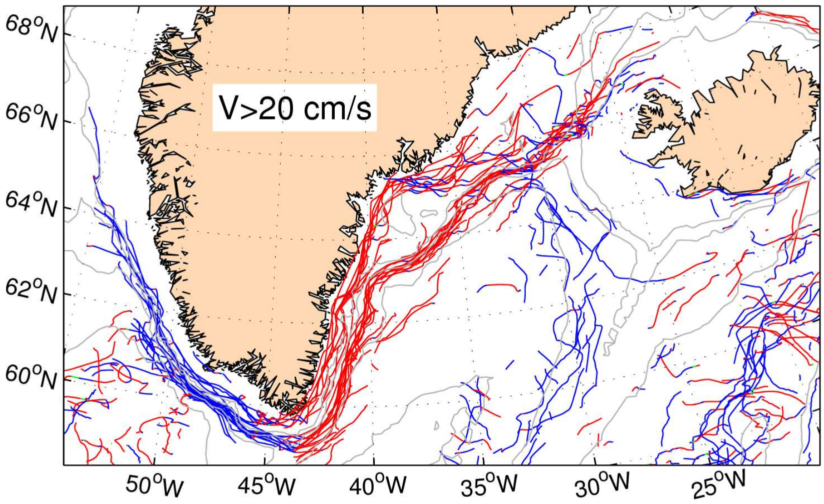

Figure 8. Trajectories of 18 days low pass filtered drifters drogued at 15 m with drifting velocities exceeding 20 cm/s. Blue: northward drift. Red: southward drift. Green: zonal drift.

The main surface currents can be seen from the low pass filtered drifter trajectories (Figure 3) but more easily if only drifters with high velocities are plotted (Figure 8). It is obvious that the mean flow is highly barotropic as the drifters mainly follow the isobaths. However, in the Denmark Strait at about 66°N, a fraction of the drifters turns west and south joining the EGC (blue in Figure 8). This cross-current is most likely responsible for the major part of the Icelandic cod larvae ending up in Greenland. As these drifters cross the 500 m depth contour at two different locations when crossing the strait, this flow can not solely be barotropic, but either partly baroclinic or more likely affected by baroclinic eddies formed in the front between the Polar Water and the Irminger Water and affected by Ekman drift forced by northerly winds.

South of the Denmark Strait, the main core of the Polar Water is easily seen sitting on the shelf in mean (low pass filtered) as the Polar Water component of the EGC close to the coast distinct from the component transporting Irminger Water. This is most noticeable at the Ammagssalik Basin at about 65°N, where the two branches diverge guided by the topography. As the EGC rounds Cape Farewell the Irminger Water starts to subduct the Polar Water (Pickart and Torres, 2001) and the branching in trajectories is diminishing.

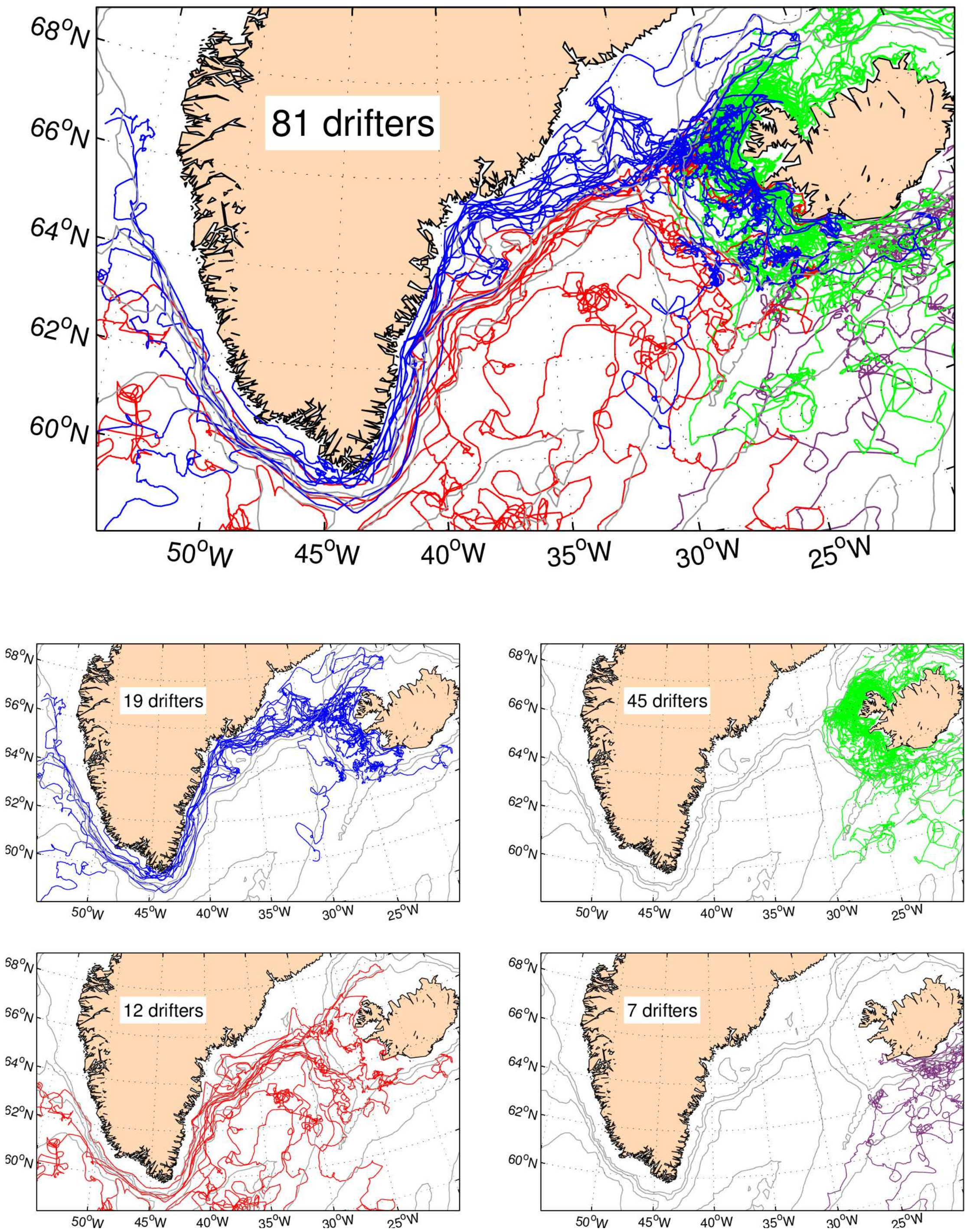

Figure 9. Low pass filtered trajectories of surface drifters drogued at 15 m in the 1990s. Only drifters passing close to the southwest Iceland shelf are considered defined by the red square in Figure 3. In top all drifters are displayed with different colours according to their final position and below the four groups are printed alone. Blue: Cross the Denmark Strait and continue in the East Greenland Current closest to the Greenland coast. Red: Cross the Denmark Strait and continue in the Irminger Water located at about the 500–1000 m depth contour. Green: End north of Iceland. Purple: flowing eastward south of Iceland. Depth contours shown: 500, 1000, 2000, 3000 m.

In Figure 9 the final position of the drifters that pass the southwest Icelandic shelf, defined as the red square in Figure 3, are shown. In total, 96 drifters pass through this box, but only for 81 drifters it is possible to locate their ending position defined as:

- Polar Water jet in the East Greenland Current (blue)

- Irminger Water jet in the East Greenland Current (red).
- North of Iceland by the North Icelandic Irminger Current (green).
- Southeast of Iceland (purple).

Slightly more than half of the drifters end north of Iceland as one expect from the drift of cod larvae. About one third drifts towards Greenland while only a few drift towards southeast of Iceland. Most of the drifters that end up at Greenland cross the Denmark Strait at about 66°N. The part that ends up in the Polar Water branch of the EGC are often originating from positions closer to Iceland than the drifters ending up in the Irminger Water branch. About two thirds end in the Polar Water branch of the EGC. When the drifters have joined the EGC in the Denmark Strait, they will stay in either the Polar Water or the Irminger Water component of the EGC until they rounds Cape Farewell. Only two drifters are found shifting in between the branches of the EGC, indicating moderate mixing between these two currents between the Denmark Strait and Cape Farewell, whereas extensive mixing takes place in the Denmark Strait as two thirds of the drifters that join the EGC choose the Polar Water branch.

Table 1. Statistics of final position of surface drifters. The colours in brackets reefers to the colour used in Figure 9. Note, both the initial position and time is different for all the drifters and the statistics is only based on 81 drifters.

Final position	**Percentage**
Polar Water branch of East Greenland Current (blue)	20–25
Irminger Water branch of East Greenland Current (red)	10–15
North of Iceland within the North Icelandic Irminger Current (green)	50–60
South of Iceland (purple)	5–10

The statistics are shown in Table 1. For real significant statistics there are too few drifters in our dataset, which also are scattered both in time and space, but at least it gives an idea of the drift in the area.

The estimated fraction of cod larvae ending north of Iceland based on the drifter data is similar to what Astthorsson et al. (1994) reported based on the Icelandic 0-group cod survey for the period 1970–1992 (their Figure 5). They also include the fraction staying at west Iceland, which we skip in our statistics. Excluding this fraction they found about 60 percent north of Iceland and 0–30 percent in the East Greenland Area. They found the Greenland fraction to be highly variable between years, but the mean is slightly more than 10 percent which is lower than our estimate based on the drifter data. However, the cod larvae that end in Polar Water have less chance of survival, caused by the low temperature and thereby slow growth, compared to the cod larvae drifting within the warm Irminger Water. Excluding this part, the statistics are much more similar, but our estimate derived from the drifters is still higher.

The cross frontal transport responsible for the drifters ending up at Greenland mainly takes place within the Denmark Strait at about 66°N. The front between the Polar Water and the Irminger Water is very sharp in the Denmark Strait, so only a small displacement is needed for a shift from one water mass to the other. Some physical factors can cause such a displacement:

- Instability in the frontal system forming intense meanders and eddies. In Figure 4 the fluctuation velocities in both directions are high in the central Denmark Strait

at the front, which is a sign of high eddy activity. The eddies act as small scale mixing (on the order of 10 km).
- Ekman transport forced by changing wind conditions over the Denmark Strait. The area is dominated by low-pressure systems which, after deepening off the east coast of North America, move into the Iceland region. This introduces highly variable wind conditions in the region. The dominating wind direction within the Denmark Strait is from eastnortheast, which gives a surface Ekman velocity towards westnorthwest and an Ekman transport towards northnorthwest (Figure 10). The mean wind direction is to some extent guided by the topographies of Greenland and Iceland which act as a deep channel for the air masses. Thereby, the strongest winds are the eastnortheasterlies or westsouthwesterlies, giving Ekman transport either towards westnorthwest or southsoutheast, respectively. However, eastnortheasterlies are by far the most common, both by number and during strong winds.

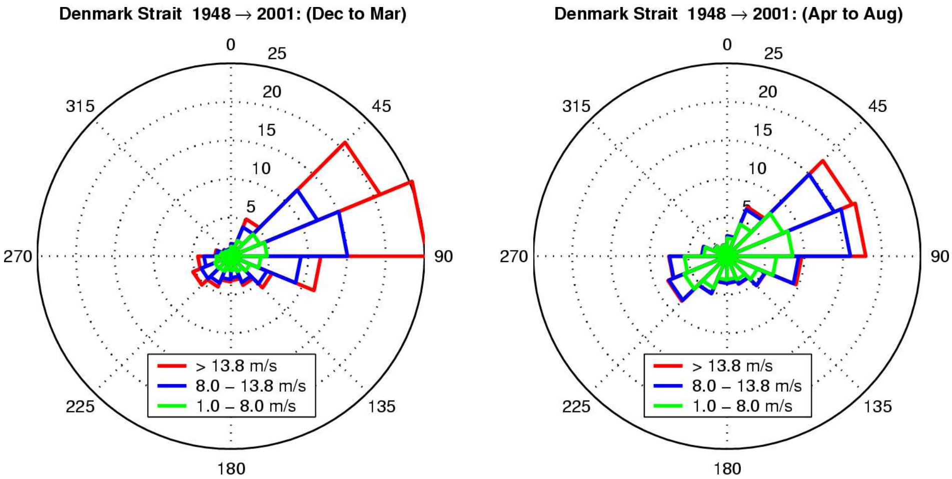

Figure 10. Wind roses over the central Denmark Strait calculated using NCAR/NCEP surface winds for 1948–2001. The radial scale is percentage. Left: December–March. Right: April–August. The direction is “wind from”, i.e. 45° means wind from northeast.

2.2. Modelled drift for the period 1948–2001

Drift simulations of cod larvae for each individual year for the period 1948–2001 are done and visually compared to the observed distribution and abundance of 0-group cod larvae for the period 1970–1998, shown in Begg and Marteinsdottir (2000b, their Figure 3). The modelled transport has large variations in between years as in the observations, but no clear match is seen between the modelled and observed distribution of cod larvae.

In Figure 11 the modelled relative abundance indices of 0-group cod are shown after 180 days at three regions similar to the regions defined for the drifter statistics earlier in this paper:
- Greenland defined as particles west of 28°W.
- North of Iceland defined as particles north of 66°N and east of 28°W.
- Southwest of Iceland south of 66°N and east of 28°W.

The few particles taking the route southeast of Iceland are included in the “Southwest of Iceland” part.

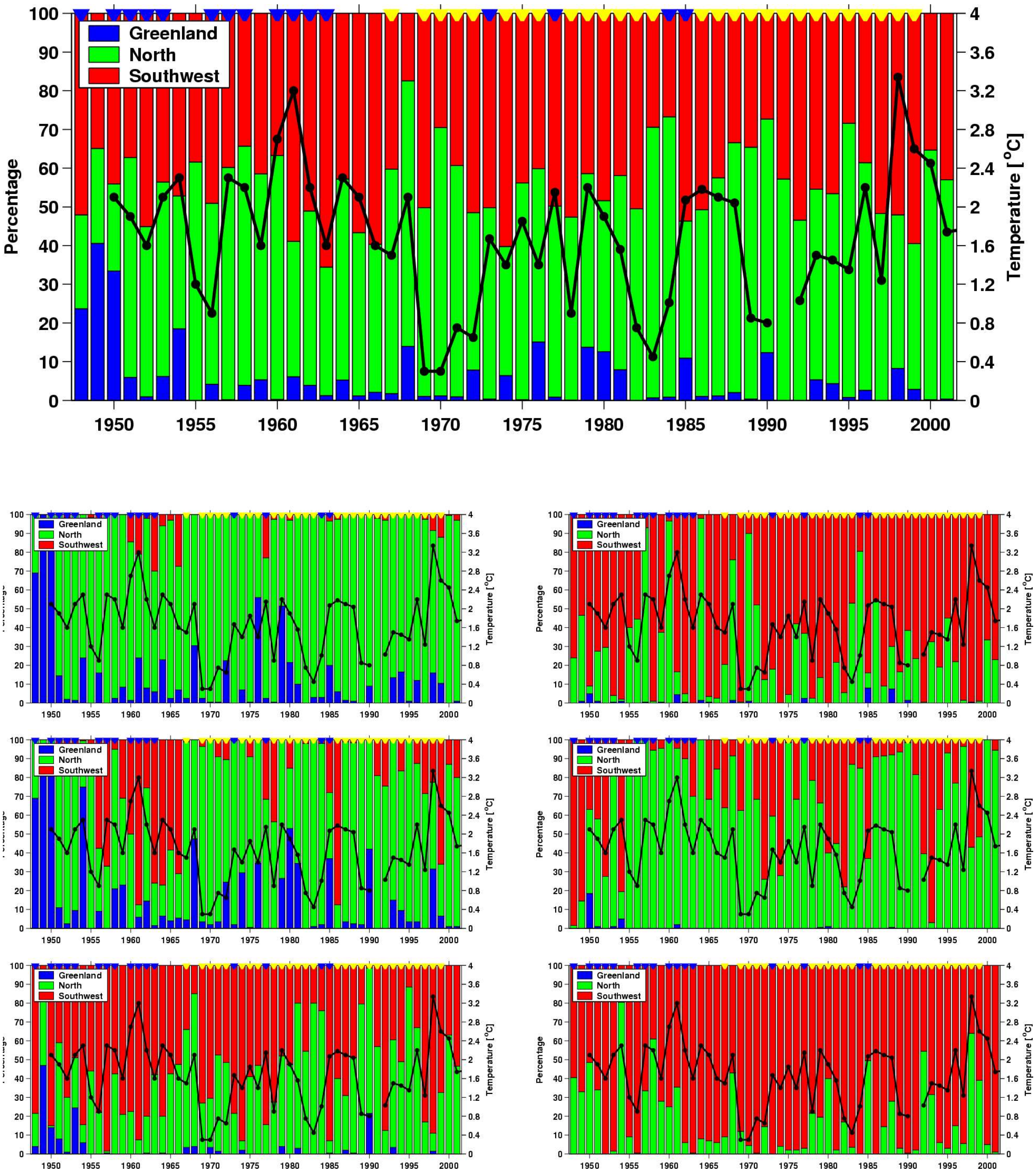

Figure 11. Modelled relative abundance indices of 0-group cod in three sub-areas after 180 days: Greenland area (blue), southwest of Iceland (red) and north of Iceland (green). Black line is the temperature on top (0–40 m) of Fylla Bank st. 2. Blue triangles on top indicate years where the observed year class strength of cod at age-3 at West Greenland exceeding 100 tonnes and yellow triangle years below 50 tonnes. The top figure shows the distribution mean for the six spawning locations used in the model, and the six small figures below shows the results for each individual spawning ground. Left (right) is the statistics from the three western (eastern) spawning positions shown Figure 7 by circles and labelled 1–3 (4–6).

In mean 6 % are found at Greenland, 50 % north of Iceland and 44 % southwest of Iceland for the period 1948–2001 (Table 2). The ratio between particles drifting to Greenland and north of Iceland is about 1/9. Based on 0-group abundance indices for the period 1970–1992, Astthorsson et al. (1994) found a ratio of 1/8, which is almost the same. The ratio based on drifters from the 1990s are much higher (1/2) but if we only consider the drifters ending up in the relative warm Irminger Water branch of the

EGC, then the ratio is reduced to about 1/5. Despite having comparing different years, this suggests that the survival of the 0-group larvae are considerable lower at East Greenland than north of Iceland.

Table 2. Modelled abundance indices of 0-group cod after 180 days and data from 1970–1992 based on 0-group abundance indices (from Astthorsson et al., 1994).

	Greenland	North	Southwest
1948–2001, all	5.6 %	50.1 %	44.3 %
YC > 100 tonnes	6.4 %	46.8 %	46.8 %
YC < 50 tonnes	3.9 %	52.3 %	43.8 %
Astthorsson et al.	8 %	64 %	28 %

A direct validation of the yearly cod larvae drift simulations is not straight forward, as observations are sparse both in time and space. The YC is the most complete and an obvious data series for testing the drift model. However, we do not find any clear relationship between the YC and the modelled drift of cod larvae towards Greenland (compare blue triangles with blue bars in Figure 11), which surprised us.

There can be several reasons why a relationship between strong YC and larval drift towards Greenland did not show up in our experiments:

- The quality of the ocean model: Ribergaard and Sandø (2004, in prep.) found that the baroclinic currents in the Denmark Strait area and at East Greenland are modified mainly caused by too small amount of multi-year ice in the model. Moreover, the surface currents are underestimated as the vertical mean of the mixed layer, which can be quite deep. How much this affects the drift simulations are unclear, but the large variations in the drift simulations indicate, that the model is able to simulate at least small differences in drift between years. But the Great Salinity Anomaly in the late 1960s is not seen in the model, so it is unclear if the model is able to simulate large fresh water pulses from the Fram Strait. The lack of sea-ice at East Greenland has the consequence, that the water masses gradually become too warm and saline as they is approach West Greenland. This affects the baroclinic currents.
- The spawning grounds could have changed position from year to year, depending on local conditions around Iceland such as food and temperature. The spawning location largely affects the final position of the particle drift as seen in the next chapter.
- Strong YC are measured at West Greenland at age-3 but the data do not tell, if cod larvae stays at East Greenland and arrive e.g. one or two years later as young cod when the conditions are favourable for them. The food supply at Greenland could have been better during warm periods as speculated by Stein (2004) which will favour the conditions for cod. Moreover favoured environmental conditions at Greenland could enhance migration, but these considerations are highly speculative and by no means confirmed by observations.
- The cod larvae abundance is likely subject to major variability and will highly affect the amount of cod larvae ending up at Greenland. Even a year with a strong transport towards Greenland can result in small amount of cod larvae at Greenland if the larvae abundance is small. If this is the case one could expect, that the amount of cod larvae north of Iceland would be low as well. But this is not necessary true, as large numbers of the surviving juvenile population may originate

from small inshore spawning grounds within fjords west, north and east of Iceland (Begg and Marteinsdottir, 2000b).

- Changes in the feeding conditions in the nursery area as suggested by Malmberg and Blindheim (1994). The timing of the spawning of Calanus finmarchicus is dependent on temperature and can vary about 6 weeks between cold and warm years at Iceland. Moreover Brander et al. (2001) suggest that the local wind conditions also influences the timing of the primary production by changing the stratification, and Sundby et al. (1994) found that the turbulence generated by winds largely affects the encounter rate between cod larvae and their prey. Therefore, changes in temperature and wind conditions at the exact time of spawning may be of special importance.
- The coarse NCAR/NCEP winds may not be of sufficient quality in the Denmark Strait area, where the cross-frontal transport is taking place. This of course affects the quality of the ocean currents and thereby the drift experiments.
- Weekly currents are too coarse for simulating the changing wind conditions within the Denmark Strait, which is largely caused by the passage of low-pressure systems. This affects the modelled cross-frontal transport within the Denmark Strait.

2.3. Modelled drift from the Icelandic spawning grounds

Results from the model setup do not confirm the hypothesis, that strong YC at West Greenland are a result of recruitment from Iceland, we look into the mean drift instead. We group the years into high and low YC and NAO years and make a monthly mean for each group (see data chapter), which we used as forcing to our drift model.

2.3.1. Mean conditions

Figure 12 shows the observed mean (1970–1998) spatial distribution of pelagic juvenile cod together with the modelled spatial distribution after 180 days of simulation (September, 23), i.e. particles 120–180 days old.

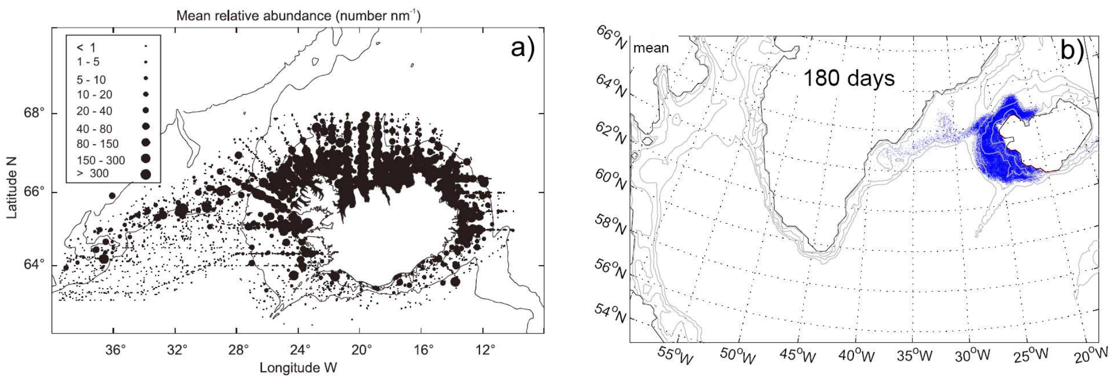

Figure 12. a) Mean (1970–1998) relative abundance of pelagic juvenile cod from Begg and Marteinsdottir, 2000a. b) Modelled mean distribution after 180 days (particles 120–180 days underway) using monthly mean currents for the period 1948–2001. Depth contours are 500 m (left) and 100, 200, 500 and 1000 m (right).

The distribution shows some striking similarities. Most of the particles continue north of Iceland, whereas only few turn west towards Greenland following the 500 m depth contour. The separation is taking place close to the Denmark Strait sill at about 66°N. These findings are also seen in the drifter data set presented in the previous chapter.

However, there are also some differences between the observations and the model output. In the model simulations the particles do not continue as far clockwise around Iceland as observed for 0-group cod. The reason is most likely that, whereas spawning is taking place both west, north and east of Iceland in fjords, spawning in the model only takes place southwest and west of Iceland. In the model, the particles are spread all over Southwest Iceland, whereas pelagic juvenile cod are found mainly closer to the coast. The reason could be, that in the model the spawning is uniformly distributed southwest of Iceland, whereas observations show that the spawning are scattered in the area. Moreover, the monthly smoothing in the current fields removes fast changing currents and thereby decreases the spreading of particles in the weak currents southwest of Iceland.

For each modelled spawning site, the percentages of particles that drifted to Greenland after 180 days are shown in Figure 13. The final positions of the particles are very sensitive to the initial position. Most of the particles ending up at Greenland are initiated at the continental shelf break west of Iceland, whereas the particles initiated on the shelf mainly drift slowly northward. This leaves the question, if spawning occasionally takes place far offshore in the Irminger Water? If the answer is yes, one could speculate if the spawning sites are dependent on the hydrographic environment related to the strength of the Irminger Water.

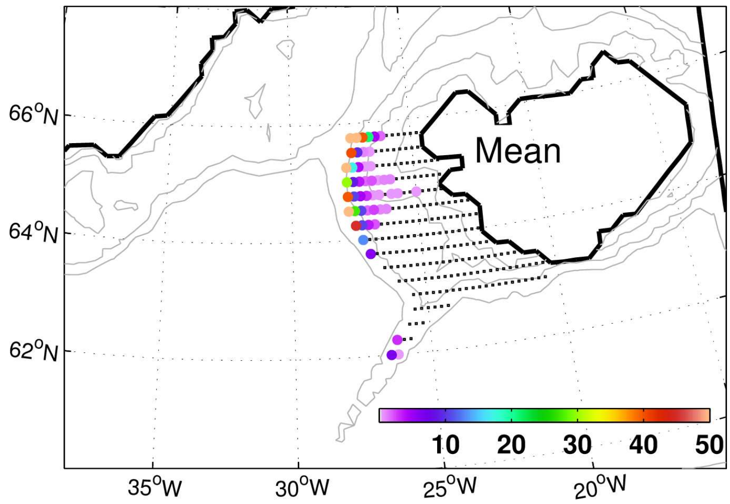

Figure 13. Percentage of particles drifting towards Greenland based on drift simulations using monthly mean currents for the period 1948–2001. Black dots are areas from where no particles drifted to Greenland after 180 days. Depth contours: 100, 200, 500 and 1000 m.

2.3.2. Drift using standard high and low YC years

Monthly mean currents are calculated from MICOM and used as input to the drift model for standard high and low YC years (see data chapter). The drift simulations are shown in Figure 14 a–b and the percentage ending up at Greenland for each spawning site (Figure 15 a–b). Four striking differences are seen:

1) More particles drifts to Greenland for high YC compared to low YC (Figure 15).
2) The number of spawning sites containing particles drifting to Greenland is highest for high YC and the spawning sites are extended towards east (Figure 15).
3) The particles are concentrated closer to the Iceland coast for high YC (Figure 14).
4) More particles drifting towards southeast of Iceland for high YC (Figure 14).

The drift simulations support the hypothesis that the drift from Iceland to Greenland was higher in years of high YC. More spawning sites deliver particles to Greenland indicating a strengthening of the Irminger Current system. However the link is much weaker than expected. One explanation could be that the migration of cod towards Greenland in some years did not take place as cod larvae, but one or two years later probably caused by favourable living conditions. This is indirectly supported by Wieland and Hovgård (2002) who reported a higher importance of Southeast and East Greenland as both potential spawning and settling areas for recruitments of West Greenland cod than shown in earlier studies.

2.3.3. Drift using standard High and low NAO years

Similarly, monthly mean currents are calculated from MICOM and used as input to the drift model for standard high and low NAO years (see data chapter). The drift simulations are shown in Figure 14 c–d and the percentage ending up at Greenland for each spawning site (Figure 15 c–d). The following are seen:

1) Slightly more particles drift to Greenland for low NAO index than for high NAO index (Figure 15).
2) The number of sites delivering particles to Greenland is highest for low NAO (Figure 15).
3) Spawning sites closer to the coast of Iceland deliver particles to Greenland for low NAO index compared to high NAO (Figure 15).
4) Almost no particles drift southeast of Iceland for both high and low NAO index (Figure 14).

It is surprising that no significant differences are found in the number of particles drifting to Greenland in the low NAO years compared to high NAO years. According to Blindheim et al. (2001) and Buch et al. (2004) the strength of the Irminger Current was increased for low NAO, which we expected to result in an increased drift of particles towards Greenland.

Malmberg and Valdimarsson (2003) suggested, that it is not only the strength of the NAO that determinate the strength of the drift towards Greenland, but also the position of the Icelandic low which would affect the Ekman drift locally in the Denmark Strait. They argued that different tracks of the Icelandic Low have affected the hydrographic conditions around Iceland during the second half of the 20th century in combination with the strength of the NAO, which was reflected in three different hydrographic regimes.

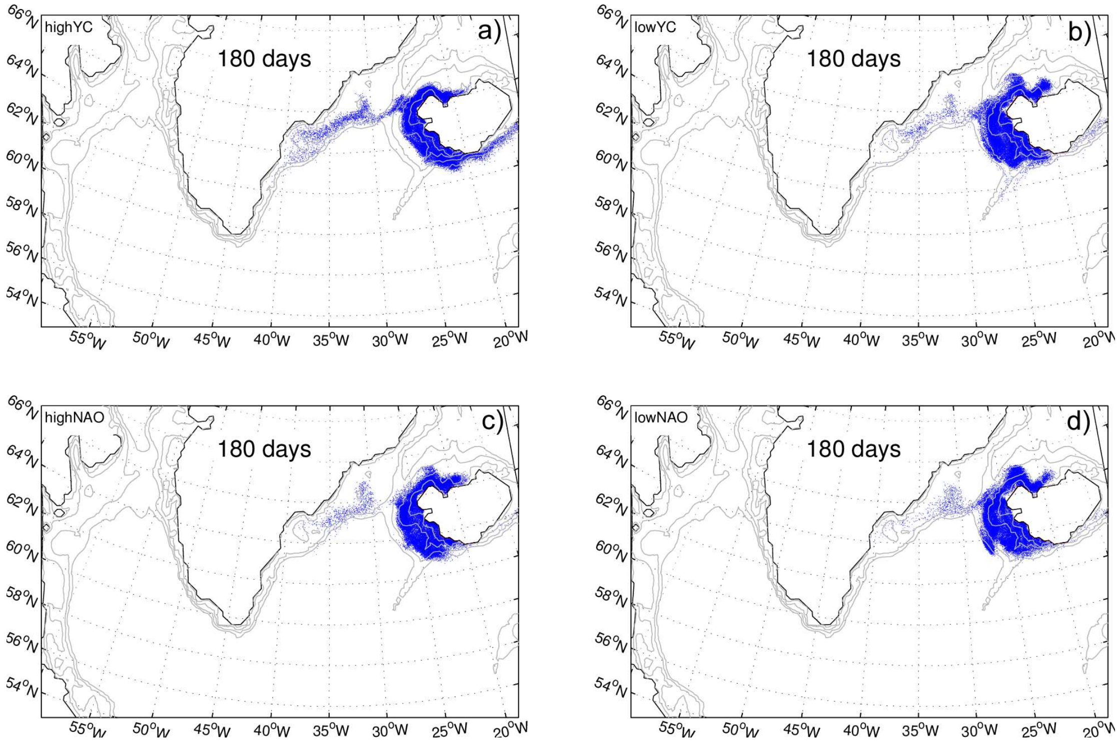

Figure 14. Modelled mean distribution after 180 days (particles 120–180 days underway) using monthly mean currents for years of high and low year class size at age-3 West Greenland cod (a and b) and for years of high and low NAO index (c and d). Depth contours: 100, 200, 500 and 1000 m.

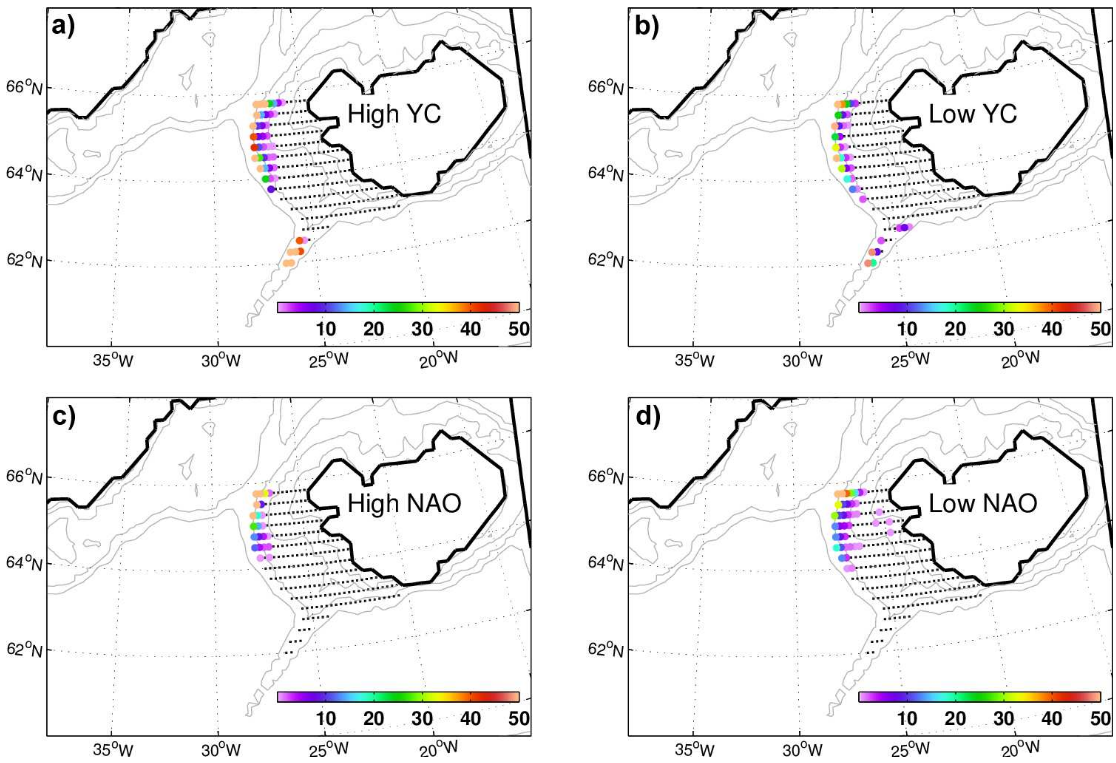

Figure 15. Percentage of particles drifting towards Greenland after 180 days based on drift simulations using monthly mean currents for years of high and low year class size at age-3 West Greenland cod (a and b) and for years of high and low NAO index (c and d). Depth contours: 100, 200, 500 and 1000 m.

We tested if the position of the Icelandic low was related to the YC of West Greenland cod. We speculated that if the Icelandic low is situated south of Iceland the drift towards Greenland is increased whereas a position north of Iceland results in decreased drift to Greenland and an increasing strength of the East Greenland Current. We used monthly mean sea level pressure from the NCAR/NCEP re-analysis (from http://www.cdc.noaa.gov) to determine the position of the Icelandic low by searching for the minimum pressure in the box (70°W–0°W , 55°N–80°N), which is the same method as used by Portis et al (2001). We used both summer (May–September) and winter (December–March) months as well as other combinations, but no good agreement was found between the high YC in Figure 2 and the position of the Icelandic Low for low NAO years (not shown). Also there was no relation between the position of the Icelandic low and the strength of the NAO.

Therefore, alternative explanations must be investigated:

- The surface currents in MICOM are not of sufficient quality for the drift simulations as discussed in the previous chapter.
- Local wind conditions over the Denmark Strait can largely influence the crossing of particles from the northward IC and the southward EGC.
- Spawning locations have changed in time.
- Larval abundance changed in time.

The third and forth points are hard to test, as the observations back in time are sparse or not existing. To test the second point we first need a better wind climatology than NCAR/NCEP with higher spatial resolution, and secondly, to run the ocean model with a higher spatial resolution. Finally the drift experiments should use hourly ocean currents instead of using weekly means. This is highly recommended for a future study.

3. Final remarks

The hypothesis by Hansen and Buch (1986) that extremely strong year-classes of Atlantic cod at West Greenland is a result of recruitment from Iceland could not be confirmed by our drift simulations. However, the drift simulations do not either reject the drift hypothesis as the model setup has some limitations as shown by Ribergaard and Sandø (2004, in prep.).

The hypothesis by Buch et al. (2004) that changes in recruitment at West Greenland is related to climate changes reflected in the NAO index could not be confirmed by the drift simulations. They argue that the variations in recruitment are related to drift from Iceland and to local water temperatures. The first statement is equivalent to the hypothesis by Hansen and Buch (1986) which could not be confirmed nor rejected. The second statement relates to the local Atlantic cod stock at West Greenland which is somehow out of the scope in this study, but local temperature alone can only explain part of the past variations in recruitment.

Keeping the limitations of the model in mind the results from the drift model reveals, that the final position is extremely dependent on the initial position even though diffusion is added to the particles. It is suggested, that the spawning sites at Iceland could have changed position in the past or alternative another site had delivered cod larvae in years where strong year class strength at West Greenland is observed. This has to be investigated further using observations.

For a future drift study we recommend higher spatial and temporal resolution of both the atmospheric forcing and the ocean model. This is special important in the Denmark Strait area, where the crossing takes place. Additionally, the diffusion should be taken from the ocean model and the temporal resolution of the ocean currents should be in the order of hours.

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Appendix E

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