Appendix C

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Modelling the ocean circulation on the West Greenland shelf with special emphasis on northern shrimp recruitment

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Abstract

The ocean circulation on the West Greenland shelf are modelled using a 3D finite element circulation model forced by wind data from the Danish Meteorological Institute-High-Resolution Limited Area Model operational atmospheric model for the Greenland area and tides at the open boundary. Residual anticyclonic eddies are generated around the shelf banks north of 64°N and areas of permanent upwelling are located west of the shelf banks. The potential distances of shrimp larvae transport from larval release to settling at the bottom were studied, using a particle-tracking model. Particles released (hatched shrimp larvae) south of 62 °N had a probability of about 2% of being lost to the Canadian Shelf, whereas for particles released north of 64 °N almost none were lost from the West Greenland Shelf. The particles tended to have long retention times at the shelf banks caused by the residual anticyclonic eddies. The retention times increased slightly for particles tracked at depths from 80 to 30 m with minor implications for potential transport distances of larval shrimp and plankton.

Keywords: West Greenland; Oceanography; Modelling; Residual circulation; Upwelling; Residence times; Shrimps

1. Introduction

The surface circulation off West Greenland is dominated by the north going West Greenland Current. It is a mixture of cold low-saline Polar Water of the Arctic region and the temperate saline Irminger Water of the Atlantic Ocean. At intermediate depths Labrador Sea Water is found,

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and at the bottom overflow water from the Nordic Seas are found.

Currents in the ocean are often dominated by fluctuating motions, and they are often caused by barotropic tidal oscillations on the continental shelves. Understanding the residual flows is crucial for the understanding transport of, e.g. heat, salt, nutrients, plankton and fish larvae. Until now no detailed description exists on the ocean circulation on the West Greenland Shelf. Only few direct current measurements have been performed, most recently a few lowered ADCP measurements were done on a few cruises (e.g., Pickart et al., 2002). Surface drifters have been used to construct mean current circulation in the area (Cuny et al., 2002; Jakobsen et al., 2003; Reverdin et al., 2003) and floats were used to construct a mean current field at intermediate depths (Lavender et al., 2000). However, the limited number of drifters, floats, and hydrographical observations are not sufficient to allow detailed descriptions of the circulation patterns on the Greenland shelf as they are sparse in both time and space (e.g., Houghton and Visbeck, 2002).

Historically, Atlantic cod (*Gadus morhua*) has been the most important resource for commercial fisheries in Greenland waters (Pedersen and Rice, 2002). However, after 1970 Atlantic cod productivity dropped due to a colder and more variable ocean climate leading to the present very low cod abundance in West Greenland waters (Anon, 2003; Buch et al., 2003, 2004). During the last 30 years northern shrimps (*Pandalus borealis*) have become the commercially most important fishery resource for the Greenland society. Inter-annual variations in distribution, abundance and population structure (age, length, sex composition) of shrimp are assessed based on an annual shrimp trawl survey performed in July–August (Kanneworff and Wieland, 2003). These surveys indicate large variability in year-class strength, e.g. the 1999 year-class being much larger than the 2000 year-class (Pedersen et al., 2002; Kanneworff and Wieland, 2003; Wieland, 2003).

Differences in year-class strength of shrimps are to a large extent established during the pelagic larval life mainly driven by environmental changes (Anderson, 2000; Pedersen et al., 2002). However, the hydrographic and biological processes behind the observed variability in recruitment of shrimp in West Greenland and in other areas are not well understood (Pedersen et al., 2002). Many controlling factors influence larval shrimp survival, year-class variability and spatial distributions of shrimps. The strength of each factor probably varies between areas of distribution and in time. The pelagic larval transport by ocean currents is one of the key controlling factors for species distribution and regional variability in marine resources (e.g. Ådlandsvik and Sundby, 1994; Proctor et al., 1998; Incze and Naimie, 2000; Sætre et al., 2002). Ocean currents influence recruitment directly by advection and indirectly through temperature, food availability and predator/prey interactions (e.g. Pedersen et al., 2002). Knowledge of larval drift paths and hence links between subpopulations are important to develop management strategies for fisheries, which take spatial variation of the recruitment process into account.

The objectives of this study are (1) to give a detailed description of the ocean circulation on the West Greenland shelf, (2) to evaluate the calculated current fields using models for particle tracking and ocean drifter data, (3) to examine the spatial and temporal scales of potential larval shrimp drift predicted by models for the duration of pelagic larval development and particle transport, and (4) to examine if differences in the barotropic conditions forced by differences in the wind condition can explain the marked differences in year class strength of shrimps as indicated by age-1 abundance (see Pedersen et al., 2002).

2. Methods

2.1. The hydrodynamic model

Both diagnostic and prognostic simulations were calculated on a finite element mesh covering Baffin Bay, Davis Strait and part of the Labrador Sea with a large open southern boundary from Cape Farewell to the southern part of Labrador (Fig. 1). In the horizontal plane the model

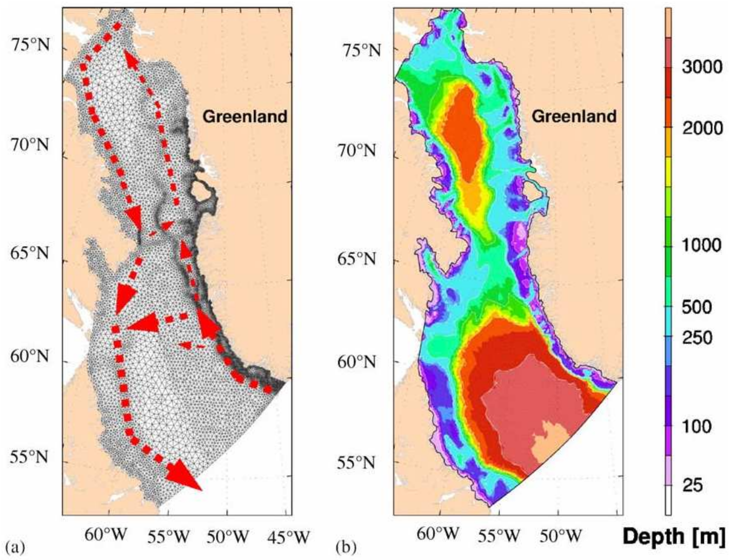

Fig. 1. Model mesh (a) and model bathymetry (b). The mesh consists of 10796 nodes and the resolution varies between 1.4 and 47.3 km. The large-scale circulation is shown in (a).

resolution varies from 1.4 to 47.3 km with fine resolution over the shelf, and coarser resolution over deep waters. The model uses 13 terrain-following coordinates for the vertical. In order to reduce errors from calculations of horizontal gradients, a hybrid mesh was implemented, with horizontal levels for the upper 500 m, where the vertical stratification is strongest.

The calculations of current fields were performed in two model steps: (1) a diagnostic baroclinic model using the temperature and salinity fields described below, and (2) a barotropic prognostic model forced by tides and three hourly data for wind taken from the operational weather forecasting model Danish Meteorological Institute-High-Resolution Limited Area Model (DMI-HIRLAM) (Sass et al., 1999). Eight different constituents were included in the modelling of tides and added as a change in surface elevation at the southern boundary.

The diagnostic baroclinic simulations were performed using a 3D linear harmonic model named Fundy (Lynch and Werner, 1987; Lynch et al., 1992; Greenberg et al., 1998). The model solves for the dynamical variables, elevation and current, forced by density gradients and boundary conditions.

The prognostic simulations were performed using a 3D ocean circulation model named Quoddy (Lynch and Werner, 1991; Lynch et al., 1996). This model is non-linear, hydrostatic, and includes a free surface and the level 2.5 turbulence closure scheme of Mellor and Yamada (1982) for the vertical mixing and Smagorinsky formulation for the horizontal mixing (Smagorinsky, 1963).

Simulations of hydrography and current were performed from April to November. Two different years, 1999 and 2000, were simulated in order to compare wind effects on calculated particle transport (larval shrimp transport) from each of the selected particle (larval) release areas (Fig. 2). These years were chosen because an intensive field program was set up in both 1999 and 2000 showing large difference in year-class strength of shrimps measured at age-1. The 1999 year-class was found being several times larger than the 2000 year-class (Pedersen et al., 2002). The 1999 year-class is the largest year-class ever in the

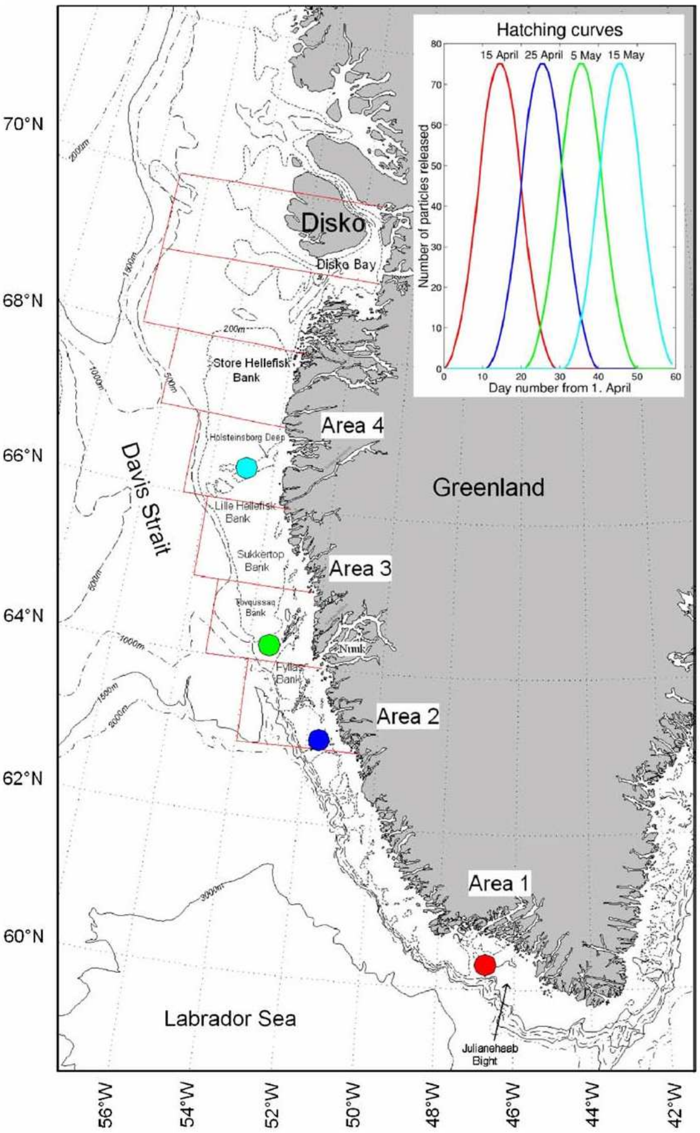

Fig. 2. Bathymetric chart of the West Greenland Shelf study area, with indication of selected hatching areas (1 = red, 2 = blue, 3 = green, 4 = turkis), which are the start positions for the particle-tracking model in 1999 and 2000. Duration of larval release and date of peak hatching by area as input to the model is also shown (Hatching curves). Each Hatching curve sums up to 1000 particles. The red boxes are used in the calculation of percentage settled on the shelf (see Tables 1–4).

annual West Greenland shrimp assessment survey (Wieland, 2003).

2.1.1. Temperature and salinity fields

Temperature and salinity fields used by the diagnostic model were constructed from observations, obtained from two different sources. For the local area of interest, i.e. for the shelf area off West Greenland south of 70 °N hydrographic measurements obtained at three different cruises in 2000 were used (Buch and Nielsen, 2001). Six standard sections up to 68 °N were taken in early July, more data from the Fylla Bank and Sukkertop Bank were collected in May and medio July and finally data from the Disko Bay and further north was taken in early August. For the rest of the model domain, i.e. main part of the Labrador Sea and Baffin Bay, the World Ocean Database 1998 (Conkright et al., 1999) were used. Only observations taken in the period May–August were selected. The observations were objective interpolated to a rectangular grid of resolution of about 5–20 km in both directions on 25 horizontal levels at depths 5, 10, 20, 30, 50, 75, 100, 125, 150, 175, 200, 250, 300, 400, 500, 600, 750, 1000, 1250, 1500, 1750, 2000, 2500, 3000, 3500 m. The interpolation was performed using Ocean Data View software (Schlitzer, 2003). The interpolation routine "variable resolution, rectangular grid" (VG-gridding) analyses the distribution of the data points and constructs a rectangular grid with variable resolution, where the grid-spacing varies according to data density in the two directions. Finally, the data were interpolated both vertical and horizontal to the desired computational mesh.

2.2. Particle tracking

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 the current field. An understanding of the strengths and weaknesses of the calculated current field is a prerequisite for a proper interpretation of the particle transport.

The particle tracking model, developed at DMI, use the same finite element data structure as in the Fundy and Quoddy models. It calculates the lagrangian advection and add diffusion in order to simulate the small-scale turbulence not resolved in the ocean models.

The model used a time step of 1 h to resolve the tidal motion. Horizontal diffusion corresponding to 60 m^2/s was added by a random walk procedure (see, e.g. Hunter et al., 1992; Visser, 1997; Spagnol et al., 2002 for random walk theory in advection–-diffusion models). Particles were released at 30, 50 and 80 m depths and kept at these levels until settling (100 days later). No vertical migration was included, but particle tracking in different depths was performed to estimate the sensitivity of the transport to the depth.

2.2.1. Location of larval shrimp release and development

Four commercially important fishing areas along West Greenland were chosen for larval shrimp release (egg hatching) (Fig. 2). According to Horsted (1978) egg hatching occurs in south-west Greenland in April–May. The duration of the berried (ovigerous) period is longer at lower temperatures (Bergström, 2000). Therefore, the hatching period was set to be 1 month later in the northern release area compared to the southern due to the lower temperatures on the northern shrimp grounds (Wieland, 2003).

Durations of pelagic larval development were estimated using the Bĕlehrádek function and in situ temperature measurements (Storm and Pedersen, 2003). The average duration of pelagic transport (from hatching to settling to the bottom) was set to 100 days, which is within estimated durations of between 80 and 120 days for larvae in West Greenland waters (Storm and Pedersen, 2003).

Particles were released at four areas where concentrations of egg-bearing northern shrimp females have been observed. In each of the areas, the particles were released at three locations with 1000 particles each. The release was distributed in time using a Gaussian distribution over a 30 days period for each of the locations. The peeks of the release curves were from south to north at 15 April, 25 April, 5 May, and 15 May, (Fig. 2).

The West Greenland shelf was subdivided in boxes by latitude and close to the 1000 m depth contour to the west (Fig. 2). Particles positioned west of these boxes after 100 days (shrimp larvae at settling) were considered lost from the West Greenland population. In the modelled particle tracking, the particles (larvae) that hit land were skipped. It is not obvious if a particle should stay if it hits land or slip along the coast and thereby gain a net reduced velocity until it is transported away from the coast again. In either case the solution is unphysical.

3. Results

3.1. Circulation on the South West Greenland shelf

Mean surface (50 m) currents on the shelf off South West Greenland calculated from the hydrodynamic models are of the order of 20 cm/s northward (Fig. 3). It is split up into an outer part located on the shelf break and one close to the coast. At about 64 °N the outer part split into two parts, one going offshore following the cyclonic circulation in the Labrador Sea and the other flowing further north at about 5–10 cm/s.

The mean flow is calculated both for 1999 (not shown) and 2000 at 50 m depth (Fig. 3). It reveals a complicated circulation pattern on the shelf with clockwise circulation around the banks. Similar mean flow is seen at 30 m depth (not shown).

3.1.1. Residual eddies

Eddies are found on the shelf off West Greenland, especially north of 64 °N to the Disko Bay at 68 °N, where the tides are strongest. On the southern part of Tovqussaq Bank (64.5 °N, see Fig. 2 for location) a strong permanent anticyclonic eddy was found (Fig. 3). It had a diameter of about 30 km and mean speed of 5–10 cm/s. Further north at the Store Hellefiske Bank just north of Holsteinsborg Deep, another permanent anticyclonic eddy was found with a mean speed of 4–7 cm/s and a diameter of the order of 20 km. Around the northern part of Store Hellefiske Bank another anticyclonic eddy is found with mean speed of less than 10 cm/s except for the north-eastern side, where large mean speed exceeding 20 cm/s are found. Close to the coast the flow divides with one branch returning south around the Bank and another turning north entering the Disko Bay.

As the mean wind stress for the period is almost zero over the area shown in Fig. 3, the modelled barotropic circulation is basically a result of the interaction between the tidal flow and the bottom

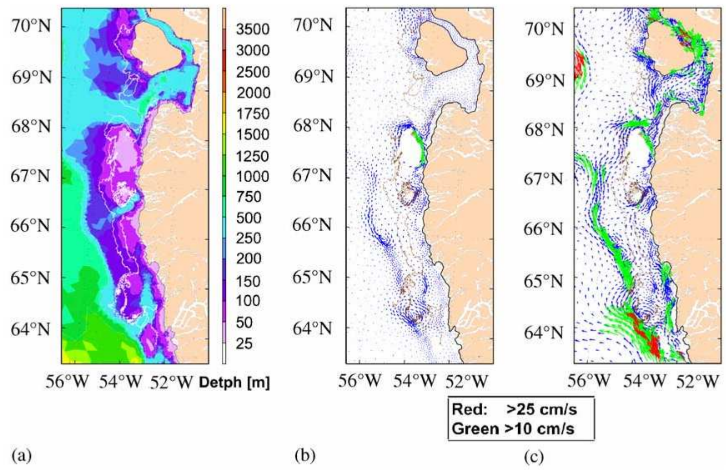

Fig. 3. Model bathymetry (a), modelled mean currents (April–November) at West Greenland in 2000 for the prognostic (barotropic) run (b) and the sum of the prognostic and diagnostic (baroclinic) runs (c) all at 50 m depth. Overlayed on the panels are trajectories of 2 WOCE-SVP drifters drogued at 30 m.

friction. This statement is confirmed by an identical simulation using the same model setup just without windstress forcing resulting in the same eddies (not shown).

We found good agreement between the current simulations and drifter tracks of two drifters deployed in May 2000 with a drogue in 30 m (Fig. 3). The drifter tracks showed several eddies as well as tidal-induced anticyclonic loops. The most prominent eddy was the clockwise circulation around the southern part of Store Hellefiske Bank, where one drifter was trapped for 7 weeks. Also noticeable are the clockwise circulation around the southern part of Tovqussaq Bank and the circulation closely following the northern part of Store Hellefiske Bank. To a large extend the meanders of the drifter trajectories fit well with the simulated mean current field for April to November 2000.

3.2. Particle tracking and larval shrimp transport

Particle transport simulations from the four release areas showed that after 100 days about 99.5% of the particles were located (assumed settled) on the West Greenland shelf and only about 0.5% settled on the Canadian Labrador shelf and in the Davis Strait west of the shelf (Fig. 4, Tables 1 and 2). Along the West Greenland shelf particles from release area 1–2 mainly settled between 64 °N and 67 °N at depths between 50 and 600 m, while particles from release area 3 to 4 settled further north between 64 °N and 68 °N for area 3 and 66 °N and 70 °N for area 4. Particles settled along the Canadian Labrador shelf mainly between 500 and 1000 m originated from the southern release area 1. Hence particles from the southern release areas were transported the longest distances, while particles from release area 3 and 4 were transported relatively short distances.

As the particles reached Tovqussaq Bank, Lille Hellefiske Bank and Store Hellefiske Bank, they tended to stay there for a while following the mean anticyclonic flow around the banks. Thereby particles had longer retention times and were concentrated at the banks between 64.5 °N and 68.5 °N. About half the particles from area 1 to 2 and one third from area 3 settled at Tovqussaq Bank (64.5 °N).

Trajectories of particles by release areas for two years, 1999 and 2000, were almost identical despite differences in wind fields between years (Tables 1 and 2, for 50 m). Tracking of several particles released in different depths (30, 50 and 80 m) for 2000 showed minor differences in transport patterns indicating only minor effects of adding vertical behaviour to the particles (Tables 1, 3 and 4). Tracking particles 100 days at 30 m instead of 50 m showed slightly enhanced retention time and concentration of particles (probability of larval shrimp settling) on the Hellefiske Banks between 65 °N and 68 °N (Table 3). On the other hand, tracking particles 100 days at 80 m depth instead of 50 m resulted in a slightly lower retention time and concentration on the Hellefiske Banks (Table 4).

4. Discussion

4.1. Residual currents on the West Greenland shelf

We compared the diagnostic simulations to the surface drifter climatology for the 1990s by Jakobsen et al. (2003) in order to validate the ocean model. Similar values for the mean northward flow driven by the baroclinic forcing were found and the large scale circulation seems alike. The drifter climatology looks much smoother than the model as it was interpolated to 1 times 2 degrees, which is a much coarser resolution than in the model, especially on the shelf. Therefore the permanent eddies are smoothen out in the drifter climatology.

We found that most of the meandering of the two drifters could be explained by the mean current field (Fig. 3). The good correspondence of the simulated current fields with the drifter tracks is most profound around the banks. As no direct current measurements have been taken in the area, it is hard to validate the current fields, but the similarities between the two surface drifters suggest that the model results are reliable.

Several studies have described the theory of residual currents around banks (e.g. Ou, 1999; Robinson, 1981; Loder, 1980) and numerical

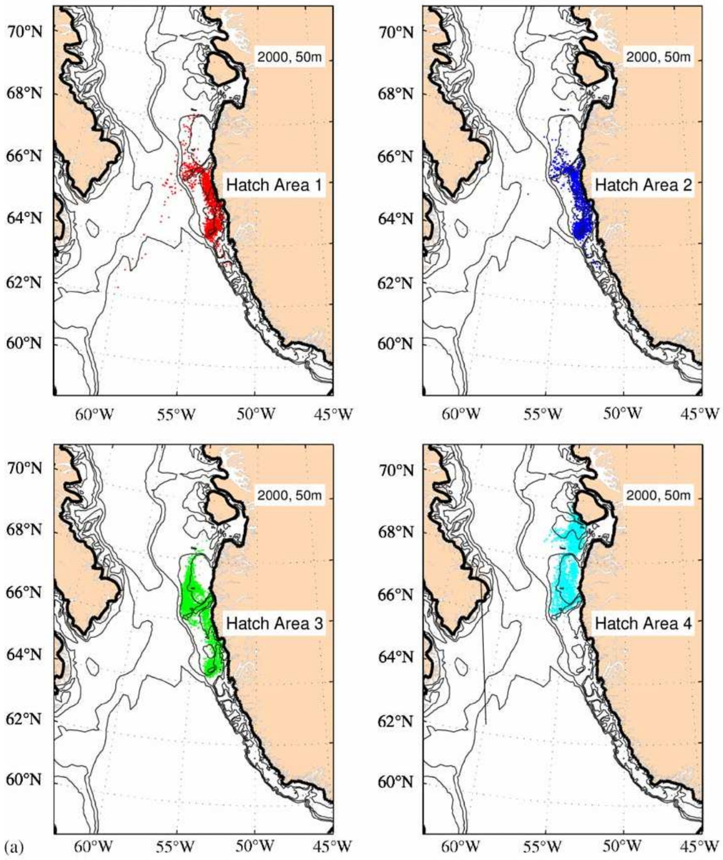

Fig. 4. (a) Settling positions of particles after 100 days by release area (Hatch area). Colours represent the release area as given in Fig. 2. Model depth contours shown: 100, 200, 500 and 1000 m. (b) Particle positions after 20, 40, 60, and 80 days by release area (Hatch area 1–4). Colours represent the release area as given in Fig. 2. Model depth contours shown: 100, 200, 500 and 1000 m. (c) Snapshot of particle positions 20 April, 30 May, 9 July, and 18 August by release area (Hatch area 1–4). Colours represent the release area as given in Fig. 2. Model depth contours shown: 100, 200, 500 and 1000 m.

modelling has been used to simulate flow over Georges Bank (Lynch and Naimie, 1993). Here the formation of the permanent eddies is a result of the interaction between the complicated topography and the high tidal currents in the area giving rise to a residual current around the banks. This can be explained by the concept of topographic steered flow. As a consequence of conservation of potential vorticity, the flow tends to follow isobaths with shallower depths to right (on the northern hemisphere). When the tidal flow is northward the current thus strengthen on the western side of a bank. Vice versa when the tide changes and flow is southward, the current strengthen on the east side of the same bank, and the mean flow is thus clockwise around the bank. The same argumentation gives counter-clockwise eddies around trenches.

The tides in the area are primarily semidiurnal with large difference between neap and spring tides

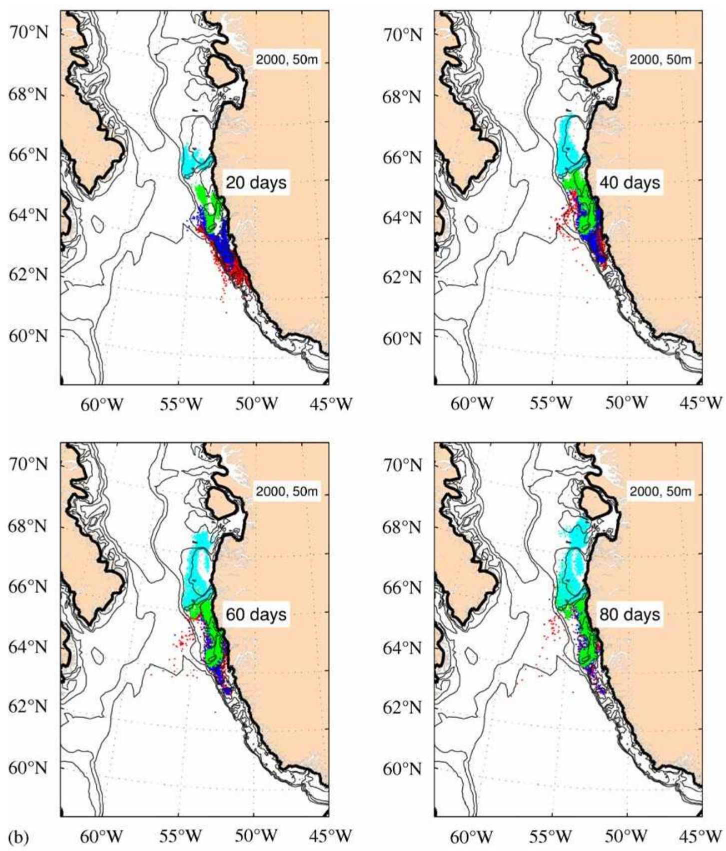

Fig. 4. (*continued*)

(1.5 versus 4.6 m at Nuuk, Buch, 2002). Therefore the intensity of the anticlockwise circulation around the banks on the shelf will vary with a period of about fourteen days (not shown), as the strength of the barotropic tidal current and the tidal elevation is directly related.

The permanent eddies must not be mixed up with baroclinic eddies which are found to be formed close to the shelf off West Greenland (e.g. Cuny et al., 2002; Jakobsen et al., 2003). These eddies are formed on the shelf break and in the front between the cold and low-saline Polar Water and the warm and salt water of Atlantic origin (Modified Irminger Water) by baroclinic instability.

4.2. Larval shrimp settling and age-1 shrimp abundance

Only 1.9% of the particles from the southern release areas were lost from the West Greenland shrimp population in 2000 (1.5% in 1999). These were caught in the general fast floating cyclonic circulation towards Labrador. The transport time from the Julianehaab Bight (release area 1) to Fylla Bank was about one month. On the other hand almost all the particles (larvae) released from the release areas further north (release area 2–4) settled on the West Greenland shelf.

About 10% of the particles hit land, most from the two southern areas, and were excluded from

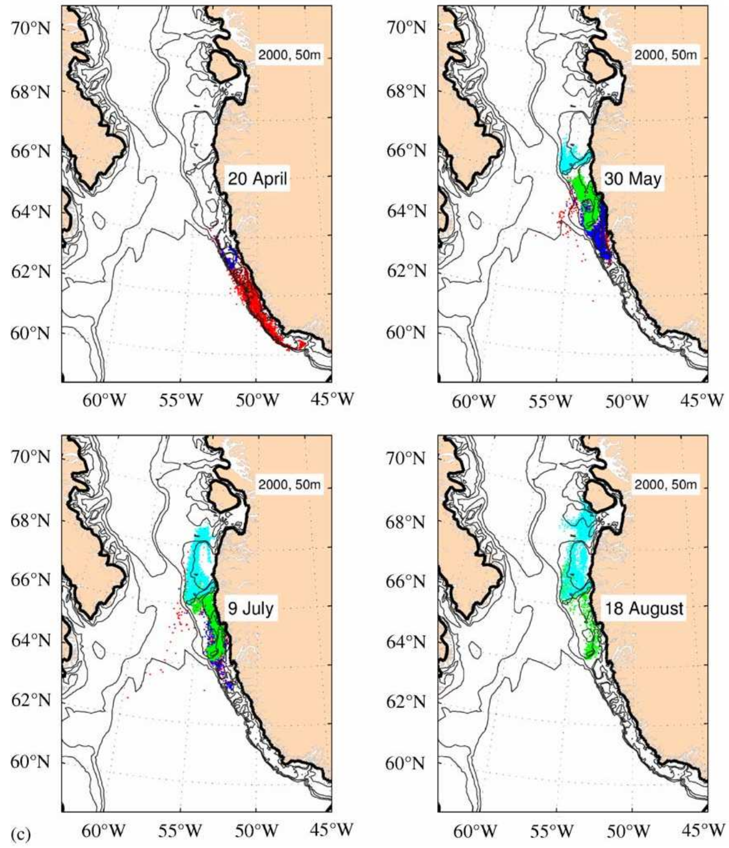

Fig. 4. (*continued*)

Table 1
Percentage settled after 100 days by latitude and release area (Hatch1–4) as given in Fig. 2

Latitude	Hatch1	Hatch2	Hatch3	Hatch4	Hatch1–4
69–70	0.0	0.0	0.0	20.1	5.0
68–69	0.5	0.0	1.3	37.6	9.9
67–68	1.1	0.6	18.9	24.7	11.3
66–67	18.7	20.9	37.5	17.6	23.7
65–66	29.9	16.1	11.8	0.0	14.5
64–65	47.0	61.6	30.4	0.0	34.8
63–64	0.8	0.7	0.0	0.0	0.4
Lost	1.9	0.1	0.0	0.0	0.5

Particles was kept at 50 m depth in 2000.

the statistics. As most of these skipped particles hit land in the Hellefiske Bank area some at the southern part of the Disko Island, we believe that the skipped particles have minor effect on our results. However, the percentage of particles lost to the Canadian Shelf was probably underestimated. According to, e.g. Jakobsen et al. (2003), the area between 62 °N and 64 °N is characterized by high eddy activity off the West Greenland shelf. As a part of the West Greenland Current turn west at about 64 °N, as a part of the main cyclonic circulation in the Labrador Sea, the percentage of particles leaving the West Greenland shelf towards the Labrador side is most likely underestimated in

Table 2
Difference between 1999 and 2000 of percentage settled at 50 m after 100 days by latitude and release area (Hatch1–4) as given in Fig. 2

Latitude	Hatch1	Hatch2	Hatch3	Hatch4	Hatch1–4
69–70	0.0	0.0	0.0	2.6	0.7
68–69	−0.3	0.3	1.0	2.0	0.8
67–68	0.1	1.8	6.3	−2.5	1.4
66–67	1.6	0.6	−7.1	−2.1	−1.7
65–66	−2.7	1.8	−0.7	0.0	−0.4
64–65	1.8	−4.6	0.5	0.0	−0.6
63–64	−0.1	0.1	0.0	0.0	0.0
Lost	−0.4	0.0	0.0	0.0	−0.1

Positive values meaning higher percentage settled in 1999 than in 2000.

Table 3
Difference between 30 and 50 m of percentage settled after 100 days by latitude and release area (Hatch1–4) for 2000 as given in Fig. 2

Latitude	Hatch1	Hatch2	Hatch3	Hatch4	Hatch1–4
69–70	0.0	0.0	0.0	0.4	0.1
68–69	0.0	0.1	0.1	−10.4	−2.5
67–68	1.4	0.0	0.2	11.5	3.2
66–67	−2.0	0.7	3.7	−1.6	0.2
65–66	−4.3	6.3	1.9	0.0	1.0
64–65	3.7	−6.3	−5.9	0.0	−2.1
63–64	−0.8	−0.7	0.0	0.0	−0.4
Lost	2.0	−0.1	0.0	0.0	0.5

Positive values meaning higher percentage settled at 30 m than at 50 m depth.

the particle tracking model, where constant diffusion was used.

The simulated larval shrimp transport and zoeal stage development from the four release areas showed agreements with the composition of stages in field sampled shrimp larvae during transect studies in 1999 and 2000, taking into account mortality and that larval release occur to a varying degree along the whole coast of West Greenland (Pedersen et al., 2002; Storm and Pedersen, 2003). The concentrations of modelled particles at the time of potential larvae settlement on the West Greenland shelf in the areas 64–65 °N and 68–69 °N showed overlaps with high abundance

Table 4
Difference between 80 and 50 m of percentage settled after 100 days by latitude and release area (Hatch1–4) for 2000 as given in Fig. 2

Latitude	Hatch1	Hatch2	Hatch3	Hatch4	Hatch1–4
69–70	0.0	0.0	0.0	−10.6	−2.6
68–69	−0.3	0.3	0.2	7.4	1.9
67–68	−0.1	2.0	−2.9	−2.3	−0.8
66–67	3.1	5.3	−13.6	5.4	0.1
65–66	−16.8	−5.6	2.6	0.0	−4.9
64–65	12.3	−2.8	13.7	0.0	5.8
63–64	0.5	0.6	0.0	0.0	0.3
Lost	1.3	0.1	0.0	0.0	0.3

Positive values meaning higher percentage settled at 80 m than at 50 m depth.

indices of juvenile age-1 shrimp from the annual shrimp survey (compare Fig. 4, this paper and Fig. 9 in Pedersen et al., 2002). However, in areas of model simulated high settling concentrations between 65 °N and 68 °N the annual shrimp survey generally showed relatively low abundance of age-1 shrimp. There are several possible explanations for the missing overlap between the modelled settling concentrations and abundance indices of juvenile shrimp: (1) the annual shrimp survey have very few samples at depths <200 m, therefore age-1 shrimp may be present at depths <200 m, (2) in the first year after settling the juveniles may migrate to concentrate in local areas with favourable growth and survival conditions, (3) there may be strong predation on the juveniles in the first year after settling from fish and adult shrimps, (4) the survival of age-0 shrimp differs between settling areas due to differences in hydrographical features, food production, and food availability, (5) in the model the particles are assumed to settled immediately after 100 days however real shrimps are expected to have large flexibility to adjust the settling time or swim in cross-shelf directions, e.g. using tidal currents to find suitable settling locations.

According to Simard et al. (1990) age-0 shrimp occur primarily at shallow (<100 m) depths. However Lilly et al. (1998) found a wide dispersal of age-0 shrimps, and that new settled shrimps occurred primarily in cod stomachs caught in deep water (>300 m). They state that if the absence of age-0 shrimp from stomachs of cod caught in shallow water in their study accurately reflects the distribution of that age group, then larval shrimp settle at greater depths than previously assumed and move to shallower water during their first year. The West Greenland shelf between 65 °N and 68 °N are an important nursery area for a number of fish species, e.g. Greenland halibut, redfish and long rough dab and age-0 shrimps have been found in stomachs from fish caught in the deeper areas, confirming settling and predation mortality here (Pedersen and Riget, 1993; Pedersen, 1994, 1995). Whether age-0 shrimp settle at all depths 50–1000 m as indicated by the particle tracking in this study and differentiate into locally distributed concentration of age-1 shrimp during the first year due to mortality and/or migration to local areas with favourable growth and survival conditions are at present unknown.

In the transport simulations the particles were stopped and considered settled after 100 days, without taking into account differences in hydrography conditions, depths, local settling conditions at the bottom or physiological feeding history conditions of larval shrimp cohorts. Models of larval shrimp behaviour during the pelagic phase to settling are needed, e.g. vertical migrations, larval preferences/avoidance for physical and biological conditions. Inclusion of such models might give a more realistic picture of larval transport and settling on the West Greenland shelf.

The two years, 1999 and 2000, showed marked differences in year-class strength as indicated by ages 1–3 abundances in the annual shrimp survey (Kanneworff and Wieland, 2003; Wieland, 2003). Trajectories of particles by release areas for the 2 years were almost identical. The setup of the physical model systems used in this study may underestimate the interannual variability, especially below the Ekman layer, where the strength of the currents most likely are dependent on the time of the year, as the strength of both the Irminger Water and the Polar Water inflow has an annual oscillation and also interannual variations as is the case between 1999 and 2000 (discussion on hydrographic conditions below). This may explain the high similarity between the particle trajectories in 1999 and 2000, as the model use the same diagnostic climatology both years. The difference in recruitment cannot be attributed to physical transport alone for example variable food availability and predation are important factors. For shrimp recruitment results by Pedersen and Storm (2002) suggest that year-class strength variability of northern shrimp mainly is determined during the pelagic larval phase by food availability (bottom-up processes).

The conditions favourable to larval development and survival (in the field), and the timing of migration toward the bottom are key elements in the understanding of the recruitment process. For shrimps in Gulf of St. Lawrence, eastern Canada, it seems that a positive link exist between the intensity of primary production in the spring (i.e. conditions for the larval stages survival) and shrimp recruitment (age-1 abundance) (P. Ouellet, Institut Maurice-Lamontagne, Mont-Joli, Canada, by correspondence).

4.3. Hydrographic conditions

Hydrographical observations off West Greenland made the first week of July showed that both 1999 and 2000 were characterised by similar mild conditions above normal, but there are some differences (Buch, 2000; Buch and Nielsen, 2001). The sea surface temperature was generally higher in 1999 compared to 2000 and the mean salinity on top of the Fylla Bank slightly higher. In the depth interval 50–400 m, a decrease in both salinity and temperature indicates a relative high inflow of Polar Water west of the Fylla Bank in 2000. In 1999 the depth of the front between the Polar Water and the (modified) Irminger Water was between 50 and 100 m closer to the surface compared to 2000 on the sections from Fylla Bank to Store Hellefiske Bank.

The wind conditions at the time of spawning in April and May were different in 1999 and 2000. In most of April 2000 the wind was coming from south whereas in May 2000 it was more from a northerly direction. In April and May 1999 the wind was primarily blowing from north.

Combining the differences in hydrographic and wind conditions in 1999 and 2000, upwelling of nutrient rich water seems more favourable in 1999 as the front separating the Polar Water from the Irminger Water was closer to the surface. Thereby, in 1999 less wind energy was needed to lift a water parcel to the surface layer. Northerly winds will force upwelling on the western flank on the shelf as a response on the Ekman transport towards west. This most likely occurs both in April and May 1999 but only in May 2000. This might explain a major part of the large difference in year class strength of shrimp in 1999 and 2000 as the conditions in 1999 were favoured by more upwelling of Atlantic origin water than was the case in 2000.

4.4. Model improvements and future studies

Effort should be put on improvement and validation of both ocean circulation modelling, biological modelling, and the coupling between these.

Future improvements of biological modelling will come from studies of: (1) Locations and timing of larval release sites in relation to varying sea temperatures during the berried (ovigerous) period (information from commercial fisheries on the distribution of egg-carrying females in early spring); (2) Fine-scale vertical distribution of larvae by stage in relation to environmental variables, e.g. temperature, salinity/density, and light, (field studies on selected locations); (3) Horizontal distribution of larvae in relation to their physical and biological environment (field studies along the entire coast of West Greenland); (4) Location and characterisation of settling areas (extension of the annual West Greenland bottom trawl survey with more stations in selected areas, especially in shallow (100–150 m) waters).

It is relevant to use coupled models to investigate possible links between shrimp populations in different regions. For example to what extent are shrimp populations in East and West Greenland connected? And to what extent are West Greenland shrimp populations connected to shrimp populations in East Canada?

Northern shrimp has become a dominant species for the commercial fisheries in the Northwest Atlantic (West Greenland and East Canada) but there is no good explanation for the recent increase in abundance. Scenarios of impacts of climate change point to a modification of the hydrographic regime in the Northwest Atlantic. These changes in the hydrography imply also an impact on the biological properties of the water masses including conditions that likely affect shrimp larvae growth and survival. Future studies should investigate and document the fine-scale vertical distribution of shrimp larvae stages (all stages) in order to define the habitat and conditions (temperature and trophic relationships) for shrimp larval growth and development in different regions. That knowledge should help to foresee the potential impacts of environmental change on the shrimp populations.

5. Conclusions

- Topographically trapped anti-cyclonic eddies are found on the shelf off West Greenland as a result of the interaction between the complex topography and the large tides. The most active area of permanent eddies are found between the Fylla Bank (64°N) and Store Hellefiske Bank (68°N) where the tides are largest.
- Large 14 days difference in the intensity of the permanent eddies as a result of the large difference between neap and spring tide.
- Long residence times are found on the Lille- and Store Hellefiske Bank between 65°N and 68°N and at Tovqussaq Bank (64.5°N).
- Shrimp larvae released south of about 64°N have a higher probability of being lost from the area by the general cyclonic circulation in the Labrador Sea compared to larvae produced by the more northern populations.
- Differences in wind condition between 1999 and 2000 alone cannot explain the large difference in year class strength of 1-year-old shrimps. Differences in hydrographic conditions may play a major role as the front between the Polar Water and the Irminger water was shallower in 1999. Thereby less wind energy was needed for

upwelling of nutrient-rich water to increase and fuel primary production and larval shrimp food availability. However, this remains to be confirmed by field observations and, e.g. by numerical ocean simulations.

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