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The role of interannual environmental variations in the geographic range of spawning and feeding concentrations of redfish *Sebastes mentella* in the Irminger Sea

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The Irminger Sea is occupied by the most abundant population of the redfish, *Sebastes mentella*, in the North Atlantic. Results of Russian and international surveys of redfish in the Irminger Sea between 1982 and 2003 are summarized here. Interannual variations in redfish spatial distribution and oceanographic conditions are also analysed. Distribution patterns of spawning and feeding concentrations of redfish are established, and the role of oceanographic factors in the formation of concentrations and in the migrations of redfish are shown. The habitat of the mature redfish population in pelagic waters is confined within the Sub-polar cyclonic Gyre. Redfish spawning grounds extend along the western slope of the Reykjanes Ridge in the areas of intensive rise of intermediate waters. Seasonal variation in water temperature above the ridge slopes is one of the factors causing feeding redfish to migrate westwards, to the central area of the Sub-polar Gyre. Atlantic Water advection, intensified by the Irminger Sea, and water temperature increase in the upper 200-m layer in the second half of the 1990s produced a considerable shift of commercial concentrations of feeding redfish from their usual grounds westwards, to the NAFO Regulatory area.

Keywords: environmental variations, Irminger Sea, North Atlantic Ocean, redfish *Sebastes mentella*.

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Introduction

The oceanographic regime of the Irminger Sea and adjacent waters, which is formed by various North Atlantic current systems (North Atlantic, Irminger, East and West Greenland, Labrador), is called the Sub-polar Gyre (Dickson *et al.*, 1988), and is bound to the basins involved, that is, the Irminger and Labrador Seas. Results were obtained during the International Geophysical Year (Dietrich, 1957) and the Northwestland survey (Lee, 1968), and provide a basis for modern scientific research in this region of the world ocean. Thermohaline changes in the Irminger Sea are associated with interannual changes in the northern North Atlantic (Bersch *et al.*, 1999; Mortensen and Valdimarsson, 1999; Pedchenko, 2001).

The oceanic redfish species *Sebastes mentella* (Travin, 1951) is the most abundant target species in the North Atlantic commercial fishery, and forms an important component of the catch. It belongs to the demersal-pelagic group of fish, and lives in deeper water than other redfish species. Redfish *S. mentella* concentrations are observed over a wide area, from the shores of Nova Scotia in the west to the Barents Sea in the east (Pavlov, 1992). In 1962 and 1963, attempts were made to catch redfish with a pelagic trawl, but with very poor results (Zakharov, 1964). It is important to note here that the redfish stock in the Irminger Sea was discovered by Russian research as late as 1981.

It has been observed that the area occupied by the mature part of *Sebastes mentella* population in the Irminger Sea is situated within the bounds of the Sub-polar cyclonic Gyre (Figure 1), which is formed by the current system described above. Spawning redfish in April–May are distributed along the Reykjanes Ridge (Magnússon, 1983). Dense *S. mentella* concentrations are found between 59°30′ and 62°N from 28° to 32°W at a depth range of 400–850 m (Shibanov *et al.*, 1995). In June–December, redfish are

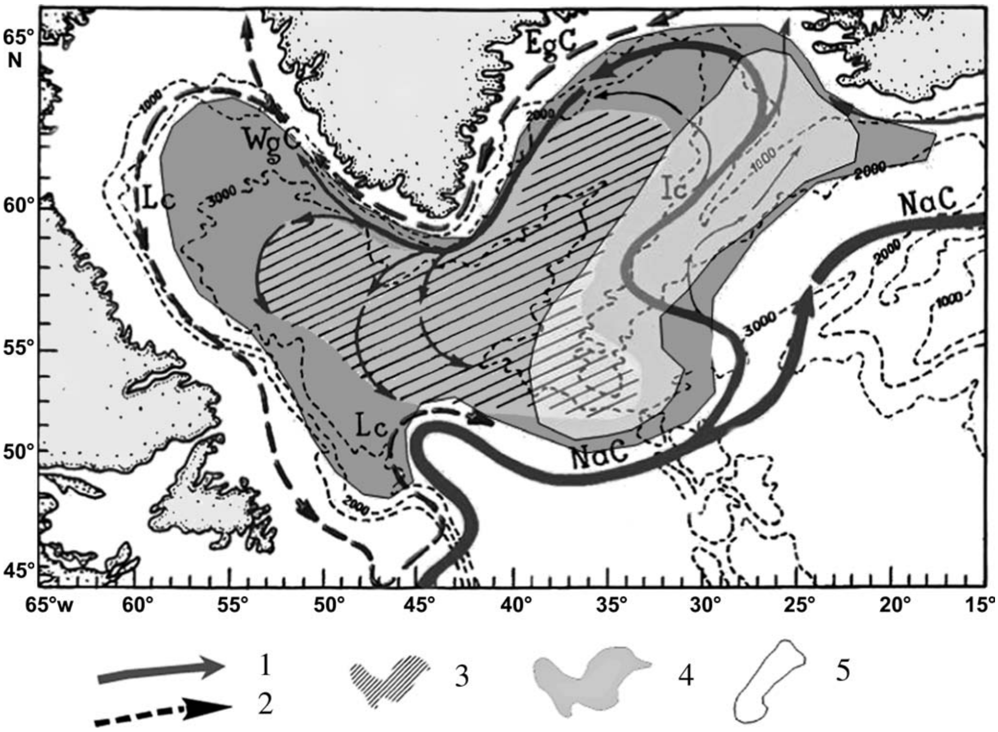

Figure 1. Scheme of the Sub-polar Gyre of the North Atlantic and distribution of redfish. Warm currents (1): NaC, North Atlantic; IC, Irminger. Cold currents (2): EgC, East Greenland; WgC, West Greenland; LC, Labrador. Central part of Sub-polar cyclonic Gyre (3); general distributional area of redfish (4); and reproduction region (5).

found west of the Reykjanes Ridge above the abyssal part of the Irminger Sea and the eastern part of the Labrador Sea. Active feeding of redfish leads to increasing densities of fish in summer. According to data collected between 1982 and 1995, the main redfish feeding concentrations have been observed in the area 53°−64°N and 30−44°W at depths of 70−550 m (Pedchenko *et al.*, 1996).

The fishing season for redfish is confined to the spawning and feeding periods. During the period 1982−1992, the Irminger Sea fishery was carried out mainly from April to August at depths shallower than 500 m. Since 1992−1993, the fishing season has been prolonged considerably and has taken place from April to October (until December in 1995). Vessels have operated at a depth range of 200−950 m, but mainly deeper than 600 m in the first and second quarters, and at depths above 500 m in the third and fourth quarters. During the fishing season, the fishery moves from the northern part of Irminger Sea to areas south of 60°N and west of about 32°W, where the fishery continues until October. ICES data show a historical minimum catch of 28 000 t in 1991, and the highest level (180 000 t) in 1996. Between 1999 and 2003, total catches of redfish have been between 110 000 and 127 000 t (ICES, 2002).

Several Russian (1982−1993, 1995, and 1997) and International Joint (1994 and 1996) trawl-acoustic surveys have been conducted on the oceanic redfish in the Irminger Sea and adjacent waters. Reports presented by ICES between 1982 and 1991 estimated stock sizes of about 0.4−1.2 million t, and in the years 1992−1996 of about 1.6−2.6 million t (Ermolchev *et al.*, 1984; Pavlov *et al.*, 1989; Magnússon *et al.*, 1992, 1994, 1996; Shibanov *et al.*, 1994, 1996). Later International Joint surveys (1999, 2001, and 2003) showed stock decreases and movement of redfish concentrations southwestwards into the Labrador Sea (Sigurdsson *et al.*, 1999, 2001, 2003).

Detailed Russian scientific studies, carried out in the Irminger Sea since the discovery of the redfish stock in 1981, have revealed that oceanographic factors play an important role in the spatial distribution of fish in the period of reproduction and feeding.

Analysis of these data by the author revealed some regularity in the distribution of spawning and feeding fish concentrations, and in the conditions of the habitat in the Irminger Sea and adjacent waters. This paper attempts to explain the influence of interannual environmental variations on the distribution of spawning and feeding concentrations of redfish *S. mentella* in the Irminger Sea.

Material and methods

Investigations were carried out on the basis of data from Russian surveys and observations performed in the

Irminger Sea and adjacent waters in the spring/summer of 1980–1997. Most oceanographic data in the Irminger Sea (Figure 2a) was collected during Russian scientific research cruises of PINRO and AtlantNIRO between 1980 and 1990, ichthyoplankton surveys (1984–1995), and trawl-acoustic surveys (1982–1997). The periods of ichthyoplankton and trawl-acoustic surveys, size of the area surveyed, and the number of oceanographic stations are given in Tables 1 and 2. In addition to these data, analysis of redfish habitat conditions and reasons for changes in spatial distribution in the feeding period made use of material from the International Joint trawl-acoustic surveys performed in June–July 1996, 1999, 2001, and 2003, in which Russia took an active part (Table 3). During all of these surveys, spatial and temporal environmental variabilities were monitored. A total of about 9500 oceanographic stations was visited during these years (see Figure 2b).

Oceanographic observations were conducted down to 1000-m depth using Nansen bottle series and CTD sounds along the tracks of the ichthyoplankton (April–May) and trawl-acoustic (June–July) surveys, on the oceanographic sections and on the stations in the areas of commercial concentrations of redfish during spring and summer (Figure 3).

The distribution of redfish in spring coincides with a depth at which zooplankton form abundant aggregations, constituting a dense, deep scattering layer. This did not allow the use of hydroacoustic equipment to estimate population size with sufficient precision. For this reason, the distribution of just-extruded redfish larvae (determined with a Bongo plankton net) has been assumed in this paper to be precise enough, and to reflect objectively the distribution of adult redfish (especially spawning females); the plots of larval distribution with pronounced gradations of density are satisfactorily correlated with those of adult redfish (Shibanov *et al.*, 1995). Information about the depths at which redfish are caught in each month was taken from the PINRO bio-fisheries database.

Adult feeding redfish distribution in the area of Russian and International trawl-acoustic surveys was determined using data from the acoustic measurements in nautical mile 0–500- and 500–900-m layers (Shibanov *et al.*, 1996; Melnikov *et al.*, 1998; Sigurdsson *et al.*, 1999, 2001, 2003). The areas of densest fish concentrations in these layers were selected according to the maximum values of the backscattering strength of redfish over previous years. The location of mean values of area backscattering strength of redfish found at more than 10 m^2 nautical $mile^{-2}$, at depths above 500 m, and at 4°C isotherm at 200 m in the Irminger Sea in summer was obtained from the reports on Joint International surveys on redfish stock in 1994, 1996, 1999, 2001, and 2003 (Magnússon *et al.*, 1994, 1996; Sigurdsson *et al.*, 1999, 2001, 2003).

The analysis of environmental conditions associated with the main fish distributions was carried out by associating acoustic data (down to 900 m) for 5 nautical mile before and after each CTD station that was visited during ichthyoplankton and trawl-acoustic surveys. Both the real values for temperature and salinity over the layers and their average values for the densest fish concentrations in the layer, calculated for each station, were used. The total ranges of these characteristics were also calculated for three different densities of redfish expressed as integrated values of <10, 10–30, and >30. Using these data, temperature and salinity variations in the layer of redfish distribution in the survey area in 1982–2003 were determined, both overall and in the areas of the densest concentrations. On the basis of a synthesis of the available information, conditions suitable for spawning and feeding aggregations of redfish were established.

Summaries of water mass distributions and frontal zone positions, water dynamics, and spatial–temporal variations in temperature and salinity in the Irminger Sea were based on the author's calculations, using Russian data and material contained in Pedchenko (2001).

Results and discussion

The mature part of the *Sebastes mentella* population in the Irminger Sea is distributed within the bounds of the Sub-

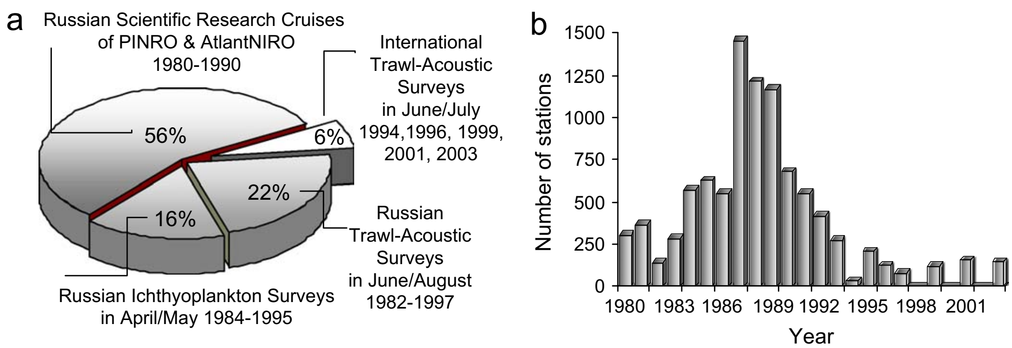

Figure 2. Number of oceanographic stations visited in the Irminger Sea during 1980–2003. Percentage of data collected during different Russian researches and international surveys for redfish (a), and the number of stations in each year (b).

Table 1. Russian ichthyoplankton surveys in the Irminger Sea 1984–1995.

No.	Date	Area surveyed (nautical mile^2)	Number of oceanographic stations
1	20 April–10 June 1984	96 000	111
2.	10 April–16 May 1985	100 000	89
3.	22 April–15 June 1986	170 000	156
4.	29 March–04 June 1987	114 000	90
5.	14 April–19 May 1988	277 000	117
6.	16 April–31 May 1989	190 000	125
7.	20 April–21 May 1990	120 000	115
8.	14 April–16 May 1991	115 000	75
9.	20 April–29 May 1993	126 000	107
10.	18 April–17 May 1995	136 000	90

polar cyclonic Gyre (Shibanov *et al.*, 1996). The environmental condition affecting this area depends on the temperature and flow rate of the Irminger Current above the slope of the Reykjanes Ridge. The interaction of currents with large-scale topographic features determines the water mass distribution and the locations of frontal zones. These separate Atlantic water currents form the Subarctic Water of the cyclonic Gyre.

Our investigations showed that the *Sebastes mentella* reproduction area is located close to the east periphery of the Sub-polar Gyre (see Figure 1). In the spawning period (April–May) fish are distributed at depths from 150 to 1050 m in the frontal zone. The latitude at which spawning concentrations of redfish are found has varied in different years, depending on the temperature conditions and the

Table 2. Russian trawl-acoustic surveys in the Irminger Sea 1982–1997.

No.	Date	Area surveyed (nautical mile^2)	Number of oceanographic stations
1	10 July–19 July 1982	40 000	15
2.	17 June–31 June 1983	50 000	35
3.	03 August–10 August 1984	55 000	40
4.	15 July–15 August 1985	71 000	90
5.	02 July–06 August 1986	117 000	80
6.	04 June–06 August 1987	215 000	54
7.	24 June–30 July 1988	163 000	124
8.	28 June–29 July 1989	149 000	59
9.	09 June–06 July 1990	73 000	78
10.	13 June–13 July 1991	105 000	115
11.	26 May–11 July 1992	190 000	162
12.	06 June–07 July 1993	120 000	100
13.	24 June–30 July 1995	167 000	119
14.	21 June–21 July 1997	159 000	81

Table 3. International Joint trawl-acoustic surveys with Russian participation in the Irminger Sea.

No.	Date	Country participants	Area surveyed (nautical mile^2)	Total number of oceanographic stations
1.	19 June–15 July 1996	Iceland, Germany	256 000	116
2.	18 June–11 July 1999	Iceland, Germany	265 000	124
3.	17 June–12 July 2001	Iceland, Germany, Norway	420 000	155
4.	28 May–30 June 2003	Iceland, Germany	400 000	146

water dynamics above the Reykjanes Ridge. However, in general, their orientation along the western slope of the ridge remained unchanged during the period 1982–1995 (Shibanov *et al.*, 1995). Details of the distributions of spawning redfish aggregations over the Reykjanes Ridge above and below 500 m are shown in Figure 4.

Analysis of oceanographic data collected during spring of 1982–1995 revealed that the frontal zone above the Reykjanes Ridge was distinctly apparent in the temperature and salinity distributions at depths from 200 to 800 m. Its boundaries, shape, and the position of local eddies inside the frontal zone changed from year to year (Pedchenko, 1995). Variation in the speed of water flow and topography affected the current direction, flux volume, and location of upwelling intermediate water (Tciganov and Lebedev, 1981). In this case, the transport of the Irminger Current and Labrador Waters over the western slope of the Reykjanes Ridge was an important factor.

Atmospheric circulation in the North Atlantic sector has far-reaching effects on Atlantic hydrography and on the marine ecosystem (Burkov, 1980; Drinkwater, 1994; Dickson and Meincke, 1999). Analyses of long-term changes in water transport through the 3K section in the northern part of the Reykjanes Ridge in April in the years 1982–1995 and variation in the North Atlantic Oscillation (NAO) winter index confirmed this. The volume of Atlantic Water transported in the Irminger Current in spring showed a pattern opposite to the changes in the NAO index (Figure 5). Our investigation showed that, with increased advection of Atlantic Water, the main spawning *S. mentella* aggregations moved to the north and, under decreased advection, they were distributed in the central and southern parts of the reproductive area.

Redfish were very sensitive to environmental changes, and the thermohaline preferences of redfish were determined as part of this study. During spawning, commercial concentrations of fish were found predominantly in the Subarctic Water mass at temperatures between 3.7 and 6.2 °C and salinities between 34.84 and 35.08

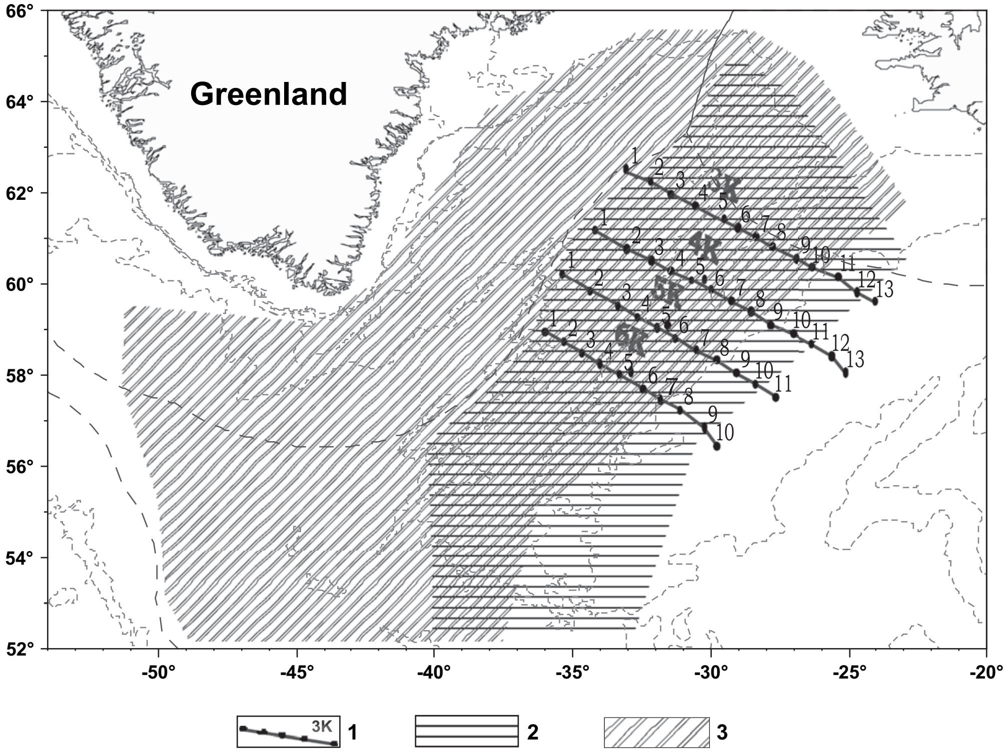

Figure 3. The investigation areas. 1, Positions of oceanographic sections; 2, area of ichthyoplankton survey of redfish in April–May 1984–1993, 1995; and 3, area of summer trawl-acoustic survey of redfish in 1982–2003.

(Pedchenko, 1992, 2001). Strong transfer and wide spatial distribution of the Labrador Waters into the Irminger Sea in the 1980s allowed the formation of fish spawning concentrations at depths <500 m (Figure 6). In the middle 1990s, gradual weakening of the western transfer of air masses over the North Atlantic caused intensification of advection of Atlantic Waters by the Irminger Current, an increase in temperature in the upper 500-m layer and, correspondingly, a change in the structure of water masses. In my opinion, deepening of the boundary of

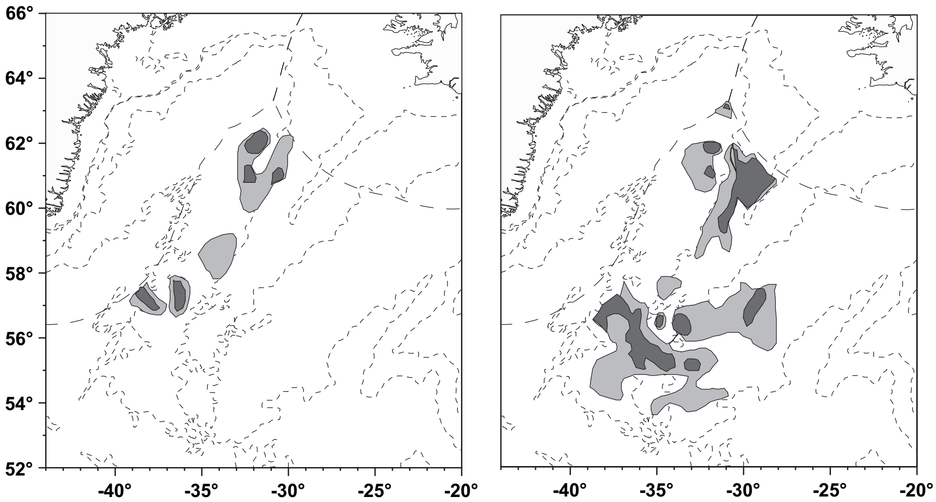

Figure 4. Distribution of most dense spawning redfish aggregations above (left) and below (right) 500-m depth shown by the area ichthyoplankton survey in April–May 1995.

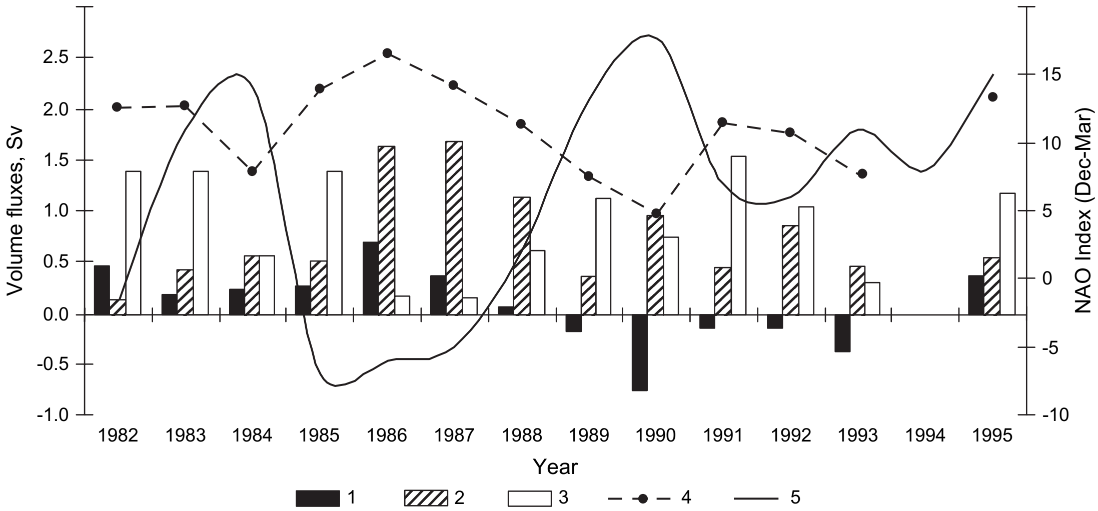

Figure 5. Variation of water transport in the 200–500-m layer on the 3K section in April and the winter (December–March) index of the NAO (data from Dickson and Meincke, 1999) from 1982 to 1995. 1, Subarctic Waters (Stns 1–3); 2, water of Frontal zone (Stns 3–6); 3, Irminger Current Waters (Stns 6–9); 4, total transport; 5, winter index of the NAO based on the difference of sea level pressure between Horta, Azores, and Reykjavik, Iceland.

Labrador Waters was one of the reasons for the redistribution of fish to greater depths and changed conditions in areas of intensive spawning. During April–May 1995, the spawning area was located at depths between 350 and 850 m. In general, fish concentrated from 550 to 700 m under the deep scattering layer, where the temperature and salinity were 3.2–6.2°C and 34.86–35.08, respectively. Therefore, the deeper redfish distribution caused movement into waters of optimal temperature and salinity, and brought the fish into new habitat conditions at spawning.

The non-homogeneous distribution of *S. mentella* in the spawning period indicated that an additional factor (or several factors) could be affecting the process of fish aggregation. Analysis of vertical profiles of temperature and salinity from CTD data showed inversions into water layers from 300- to 800-m depth in some parts of the survey area. Most often, these peculiarities of vertical distribution of hydrographic parameters were observed in places of redfish concentration. CTD profiles, obtained in areas of redfish aggregation in the northern and southern parts of the spawning area are presented in Figure 7.

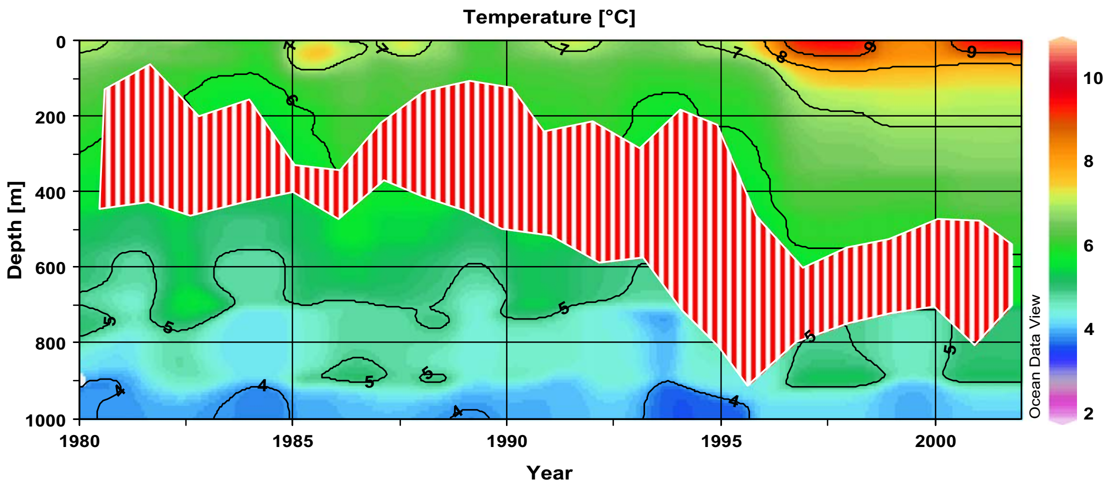

Figure 6. Changes in the temperature of the water column in the Irminger Sea in the redfish spawning area in the northern part of the Reykjanes Ridge in 1980–2003. The shaded area represents the depths of the redfish fishery in spring.

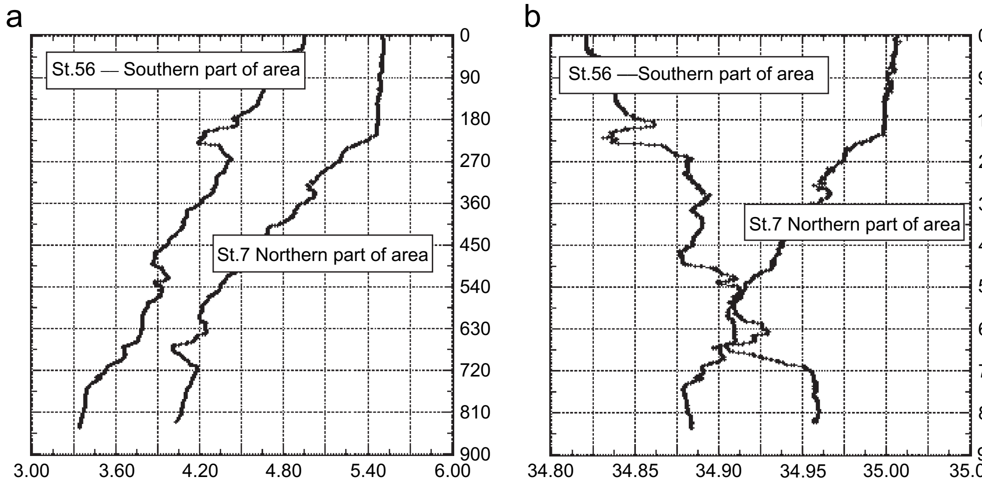

Figure 7. Temperature (°C) (a) and salinity (b) profiles in the areas of redfish concentrations in the northern (Stn. 7) and southern (Stn. 56) parts of redfish spawning area in 1990.

I share the opinion of others (Fedorov, 1976; Turner, 1985) that the formation of thermohaline irregularities is related to the processes of local vertical mixing and lateral advection. Investigations of the dynamic process in open parts of the North Atlantic confirm that the range of the vertical deviation varies according to the intensity of intermediate water upwelling (Turjakov and Kuznetsova, 1977). Supporting this idea are many observations of vertical deviations in the water column at about 100−250 m made during the spring survey on the western slope of the Reykjanes Ridge close to areas of fish aggregations. Concentrations of *S. mentella* formed over a "cap" or on the periphery of intermediate water upwelling, which is easy to determine by a local decrease in the depth of the 3.5 or 4.0°C isotherms and the position of the oxygen minimum, as well as by the availability of inversions along temperature and salinity profiles.

It is possible that the process of upwelling of water to the surface of an intermediate structure is one of the requirements for successful redfish propagation. The biological necessity of this phenomenon could relate to the fact that favourable feeding conditions for the survival of *S. mentella* larvae at early stages of development are formed and maintained as a result of the transport of biogenic elements into the photic layer as a result of upwelling (Pedchenko, 2001).

After extrusion of larvae, redfish normally migrate westwards, to the central part of the sub-polar circulation for feeding and coupling. It was shown that, in addition to biological prerequisites, the feeding migration of redfish is caused by the seasonal increase of water temperature in the area used for reproduction (Pedchenko *et al.*, 1996). The Russian investigations in 1995, 1997, and 1999 showed that a part of the spawned fish stay above the Reykjanes Ridge at depths of more than 500 m, where seasonal changes of temperature are less significant (Figure 8) (Shibanov *et al.*, 1996; Melnikov *et al.*, 1998; Pedchenko, 2001).

In the large feeding area, redfish concentrations are found close to areas rich in meso- and macroplankton at different depths from 150 to 850 m. Feeding concentrations of fish were found over a wide temperature range from 2.1 to 6.4°C and at salinities from 34.72 to 35.08. The depth of redfish concentrations increased from the central part to the periphery of the Sub-polar Gyre in association with vertical

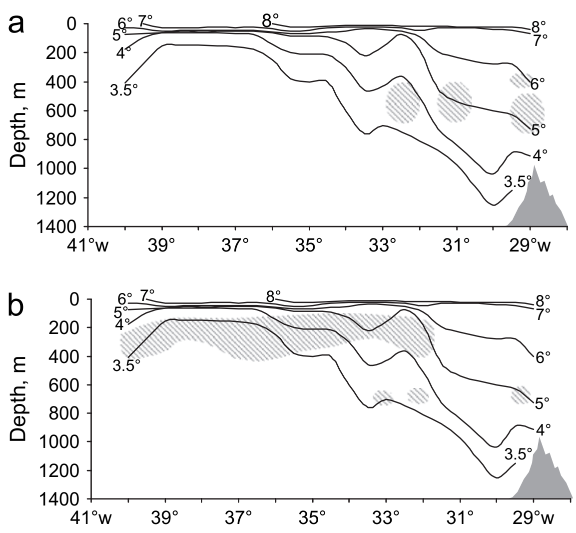

Figure 8. Vertical distribution of temperature and locations of redfish concentrations (shading) in the spawning (a) and feeding (b) periods along section 60°30′N in the Irminger Sea in 1995.

and spatial changes in the location of Subarctic intermediate waters (Pedchenko, 2001). The isothermal surface of 4°C reliably reflects the vertical location of redfish concentrations and can be used for analysis of their year-to-year variations (Shibanov *et al.*, 1997). The maximum depth of fish distribution is found in the Reykjanes Ridge area. However, redfish did not form large concentrations at depths below 500 m, and their density was less than in the 0–500-m layer.

Russian investigations from 1982 to 1993 showed that redfish are evenly distributed within the feeding area forming, in some parts, tight concentrations in the shape of "spots" in the 150–500-m layer. These areas were observed both at the periphery of the Sub-polar Gyre and in the central part of the circulation. High values of horizontal gradients of temperature and salinity were recorded there.

Depending on the intensity of upwelling, the size of concentrations varied from 2 to 20 nautical mile^2, and fish density (a value of area backscattering strength) significantly exceeded 500 m^2 nautical mile^{-2} in some cases. Such a measure of fish concentration was registered during the Russian trawl-acoustic survey in June/July 1993, and is presented in Figure 9. In the region of 10–15 nautical mile^2, the density of concentrations increased from the periphery to the centre, from 10–25 to 1000+ nautical mile^{-2} (Shibanov *et al.*, 1994).

The location and areas of densest fish concentrations and the value of maximum density itself varied from year to year. Year-to-year dynamics of these indices agree with the variations in temperature and salinity described above, and were caused by Atlantic Waters being advected through the Irminger Current.

Year-to-year changes in the distribution and density of redfish concentrations over the feeding area were one of the reasons for large variations of redfish stock assessments during trawl-acoustic surveys. Significant changes in the distribution of feeding fish concentrations in the area of the Irminger Sea in the 0–500-m layer and the shift of the summer redfish fishery to the west in the area of the Labrador Sea were revealed during 1996–1998 (Magnússon *et al.*, 1996; Melnikov *et al.*, 1998). In my opinion, they were caused by increasing transport of Atlantic Waters by the Irminger Current and an increase of water temperature in the Irminger Sea, initiated in the mid-1990s. This tendency was first noted in the Irminger Sea at the beginning of the current decade (Figure 10), and has continued.

From the trawl-acoustic survey data collected from 1994 to 1997, enhanced advection of the Atlantic Waters and an increase in the heat content of water in the feeding area resulted in a considerable redistribution of fish aggregations in space and in depth. Results of the 1999 trawl-acoustic survey showed that densities of redfish aggregations were higher in the southwest (Sigurdsson *et al.*, 1999). Having surveyed the area up to 54°N 48°30′W, zero boundaries of redfish distribution were not found. The responses of fish to the changing conditions in the Irminger Sea are provided by an overlay of maps of temperature distribution at the 200-m layer and mean values of area backscattering strength greater than 10 m^2 nautical mile^{-2} in the 0–500 m layer in 1994–2003 (Figure 11). Material from the international survey of redfish stocks in 1999, 2001, and 2003 showed that the relative density of redfish concentrations were much lower than in 1996 and 1997. Maximal densities of redfish in units of Sa in the 0–500-m layer did not exceed 50 m^2 nautical mile^{-2}. During the surveys, fish concentrated in depths down to 500 m (Sigurdsson *et al.*, 2001, 2003). The reduction in redfish catches from the depths below 500 m has been observed since 1997. In 1999–2001, the redfish fishery was carried out at depths of >500 m, and fishing concentrations continued to shift westwards to 48°30′W. Similar situations in the area were observed in 1990, 1992, and 1993. However, the redfish fishery in the Labrador Sea was not carried out at significant depths west of 42°W.

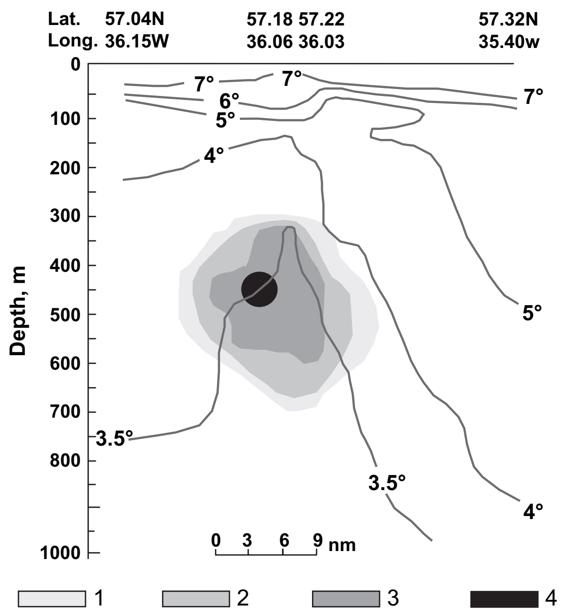

Figure 9. Temperature (°C) and densities of redfish concentrations on a vertical section in the area of local upwelling in June 1993. Densities (t nm^{-2}): 1, 50–100; 2, 100–200; 3, 200–500; and 4, more than 500.

Conclusions

The investigations have shown that the spatial distribution of *S. mentella* is, in many respects, determined by oceanographic conditions in the Irminger Sea and adjacent waters. Seasonal migrations of mature fish are determined by the main stages in the annual cycle. However, the duration and particular details of each are modified, depending on the oceanographic situation of a certain year.

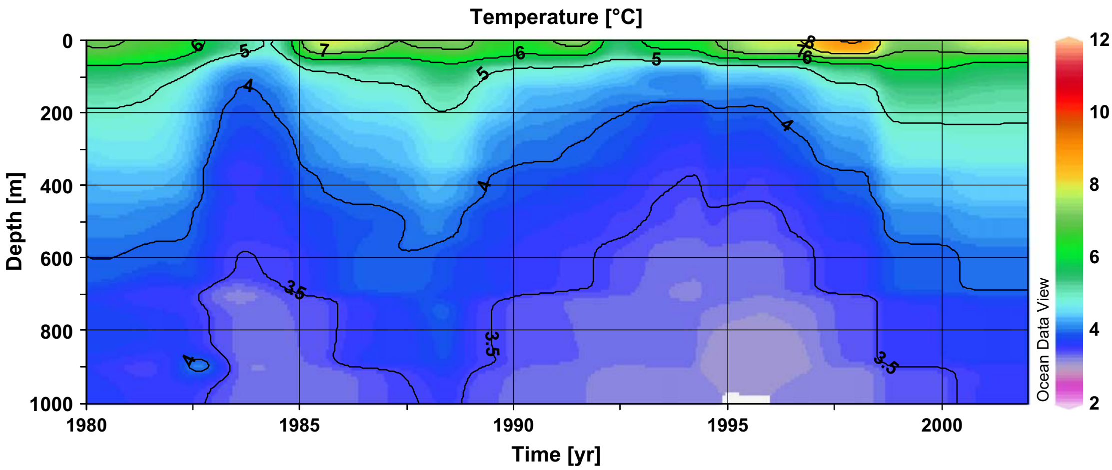

Figure 10. Changes in the temperature of the water column in the Irminger Sea in the redfish feeding area in the central part of the Subpolar Gyre in 1980–2003.

The dependence of the dynamics over the Reykjanes Ridge on the atmospheric circulation in the North Atlantic was confirmed. Interannual changes of water transfer by the Irminger Current influence the temperature and salinity distributions in the Irminger Sea, as well as the distribution and habitat of adult redfish in both the spawning and feeding periods. Large decreases in the redfish stock assessment, revealed during international trawl-acoustic surveys from 1999 to 2003, were caused by the intensification of Atlantic Water advection into the Irminger Sea and increases of water temperature in the depths occupied by fish. This resulted in increases in the feeding area and the vertical distribution of redfish, and in the formation of small, dense local concentrations of fish in the Labrador Sea.

Accumulated knowledge of special oceanographic features and long-term monitoring of the oceanographic situation in the area will permit the rational planning of surveys, and allow modification of assessment methods for redfish stocks. The observed relationships between habitat conditions and fish behaviour can also be used for the development of models of rational exploitation of *S. mentella* stocks in the Irminger Sea.

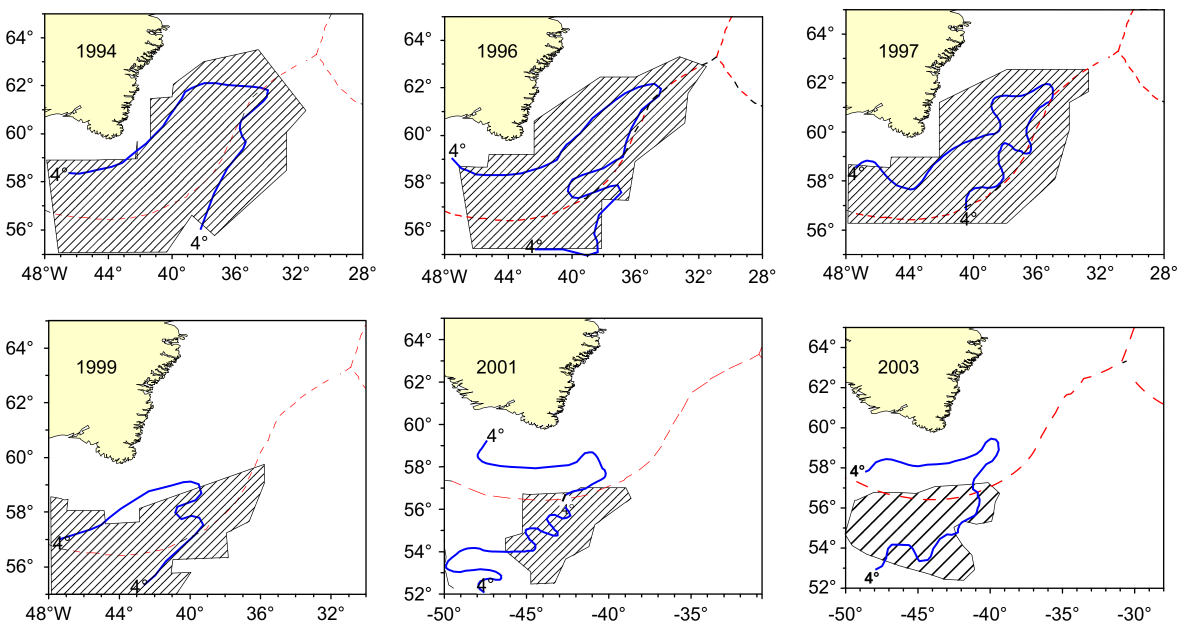

Figure 11. Locations of mean values of area backscattering strength of redfish more than 10 m^2 nautical mile^{-2} at depths above 500 m (shading) and the 4°C isotherm at 200 m in the Irminger Sea in June/July 1994–2003.

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