

**THE IMPACT OF EGGS VERTICAL ASCENT SPEED AND WATER DYNAMICS ON
ABUNDANCE AND SURVIVAL OF THE NORTH-EAST ARCTIC COD (*GADUS
MORHUA MORHUA* L.) IN THE BARENTS SEA AT EARLY LIFE STAGES**

by

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ABSTRACT

Water dynamics plays an important role in the life of fish at early stages, when passive way of movement prevails over active. Impact of dynamic processes on eggs begins right after they have been spawned. To study this impact a model of eggs ascent based on water density stratification and a hydrodynamic model have been developed. To study the distribution and to derive the abundance indices for cod eggs and larvae data from ichthyoplankton surveys at the Lofoten grounds in 1987-1989 have been used.

An estimated depth of the lower boundary of thermocline, where the spawning of cod takes place, was 97 m in warm years, 119 m in normal years and 147 m in cold years. However, in cold years it takes the eggs 27 hours to move up to the surface through the upper 100 m layer and 35 hours in warm years. The difference in the speed of ascent is due to varying density of seawater.

A model of transport of passive particles has shown that in cold years the drift of markers simulating eggs and larvae was slower and they had a westerly distribution. Conversely, in warm years with intensive water circulation, the majority of markers (up to 80%) were transported to the southern Barents Sea.

A comparison of abundance indices for eggs and larvae and coefficients of their survival with some oceanographic parameters has shown a relationship between them. In warm years, when most eggs and larvae of cod are brought into the southern part of the Barents Sea, their survival is higher than in cold years.

INTRODUCTION

Although peculiarities of spawning of many commercial species are different, the incubation of their eggs, in most cases, takes place in the sea surface layer. Due to their buoyancy, the eggs ascend passively from the depth, where they have been spawned, to the surface. The ascent occurs due to the difference in the density of eggs and seawater (Coombs, 1981). As the eggs move up to the surface they experience the impact of physical, hydrochemical and other factors, which may influence their further development and survival, and survival rate at early stages of development is a decisive factor in formation of year class abundance (Houde, 1987; Anderson, 1988; Koutsikopoulos, Fortier and Cagne, 1991; van der Lingen, Huggett, 2002; Mukhina, Marshall, Yaragina, 2002).

Of great importance for the speed and time of ascent is an overall water circulation pattern at spawning grounds, which is responsible for the pattern of subsequent drift of eggs and larvae (Okubo, 1962; Fortier, Leggett, 1983; Checkley et al., 1988; Bartsch et al., 1989; Neilson, Perry, 1990).

An early life history of the North-East Arctic cod (*Gadus morhua morhua* L.) has been studied for one century now. This research has shown that the most important spawning areas of cod are located on the Lofoten grounds in the zone of the Norwegian coastal current. The greatest number of cod (50% of mature fish) spawn in a confined coastal area near Røst and Vesteraalen banks, where as much as 60-70% of eggs are spawned, with the most massive spawning noted in Vestfjord in the south of the Lofoten Islands (Spawning and Life History ..., 1994; Ozhigin et al., 1999). The spawning season starting with the first days of March progresses to its peak in the first week of April and finishes in the end of May (Pedersen, 1984; Ellertsen et al., 1987). Eggs and larvae of cod are distributed in the 30 m surface layer (Solemdal, Sundby, 1981; Serebryakov, Aldonov, 1984; Bjørke, Sundby, 1984; Ozhigin et al., 1999). Drift of eggs and larvae from spawning areas is governed by dynamic processes in the surface water, which have their annual differences and peculiarities (Ellertsen et al., 1981; Dvinina, Mukhina, 1984; Mukhina, Mukhin, Dvinina, 1987).

From the 1980s studies of the processes of transport of juvenile cod in the first months of their life have been afforded higher priority. B.Aadlandsvik (1989), by using a uniform numerical model of circulation, taking account of the wind impact only, calculated the volume of water transported across the section Fugløy bank – Bear Island and compared the variability of flow across this section and the distribution pattern of the 0-group Arcto-Norwegian cod over the period from 1970 to 1986. A.S.Averkiev and V.Yu.Chantsev (1995) simulated the distribution of markers, imitating the eggs of cod, at the border between the Norwegian and Barents Sea in a field of currents, which were an arithmetic sum of only two components: geostrophic current computed by a dynamic method, and a drift current. Worth mentioning are also studies to simulate the transport of herring larvae (Svendsen et al., 1995) and halibut eggs and larvae (Aadlandsvik et al., 1999).

To date our knowledge of this topic is still incomplete. In the present state of the art it is feasible by using modern hardware, advanced software and a rather extensive database of oceanographic information to enhance the current knowledge of the impact of dynamic processes on the strength of cod year classes. To this end a computation of the cod eggs ascent speed and a simulation of ichthyoplankton transport have been done in this paper.

MATERIAL AND METHODS

Computation of the eggs ascent speed

The paper addresses a speed of ascent of eggs of the North-East Arctic cod on the Lofoten spawning grounds. Data from oceanographic observations at station Skrova (68°07'N, 14°39'E) for the period from 1936 to 1992 have been used to describe environmental conditions. Oceanographic data were available through the courtesy of the Institute of Marine Research, Bergen, Norway. The model used to compute eggs ascent speed is based on generally known laws of physics (Javorsky, Detlaf, 1971; Kukhling, 1985). In general terms the force acting on a body can be expressed as follows:

$$F = mg, \quad (1)$$

where m – body mass; g - acceleration of gravity.

The ascent of an egg is impacted by a number of major acting forces: F_1 – force of buoyancy; F_2 – force of gravity; F_3 – resisting force (Fig. 1). A resulting force (F_Σ) acting on an egg will be expressed as:

$$F_\Sigma = F_1 - F_2 - F_3. \quad (2)$$

An egg would float up, if $F_\Sigma > 0$, sink, if $F_\Sigma < 0$ and be at rest, if $F_\Sigma = 0$.

The ascent takes place due to the difference between the egg and seawater density. The larger the difference is the faster the speed of ascent. As an egg ascends, it passes through various water layers with uniform densities, and in doing so changes its acceleration, therefore a resulting force will look as:

$$F_\Sigma = m_1 a_1, \quad (3)$$

where: m_1 – mass of an egg; a_1 – acceleration of egg ascent.

The weight of an egg can be expressed using its density (ρ_1) and volume (V_1):

$$m_1 = \rho_1 V_1. \quad (4)$$

Assuming that an egg has a spherical form, its volume can easily be calculated through its radius (R):

$$V_1 = \frac{4}{3} \pi R^3. \quad (5)$$

Let us look at the forces acting on an egg. Force of buoyancy is directly proportional to the density of seawater (ρ_2) and the higher the density of water is, the stronger the force of buoyancy:

$$F_1 = \rho_2 V_1 g. \quad (6)$$

Force of gravity hinders the egg from floating up. The higher the density of an egg is, the slower its ascent is:

$$F_2 = \rho_1 V_1 g. \quad (7)$$

Another force hindering the eggs from ascent is the force of resistance, which depends on dynamic viscosity of water (η), egg size and ascent speed (v):

$$F_3 = 6\pi\eta R v. \quad (8)$$

Speed of a body in accelerated movement is described by the following expression:

$$v^2 - v_0^2 = 2aS, \quad (9)$$

where v_0 - initial speed; S – distance covered.

Let us assume that at the initial point of time (point of extrusion of eggs) the speed of eggs is 0 ($v_0 = 0$), the equation then will look as follows:

$$v^2 = 2aS. \quad (10)$$

Let us express acceleration from (10):

$$a = \frac{v^2}{2S}. \quad (11)$$

Let us rearrange (2) using (3), (6) – (8), then:

$$\rho_1 V_1 a = \rho_2 V_1 g - \rho_1 V_1 g - 6\pi\eta R v \quad (12)$$

Considering (11), expression (12) will read as follows:

$$\rho_1 V_1 \frac{v^2}{2S} = \rho_2 V_1 g - \rho_1 V_1 g - 6\pi\eta R v \quad (13)$$

To calculate the speed of eggs ascent let us undertake a number rearrangements:

$$v^2 \frac{\rho_1 V_1}{2S} + 6\pi\eta R v = gV_1(\rho_2 - \rho_1) = 0, \quad (14)$$

$$\frac{v^2}{2S} + v \frac{6\pi\eta R}{\rho_1 \frac{4}{3}\pi R^3} + g(1 - \frac{\rho_2}{\rho_1}) = 0, \quad (15)$$

$$v^2 + v \frac{9\eta S}{\rho_1 R^2} + 2gS(1 - \frac{\rho_2}{\rho_1}) = 0. \quad (16)$$

The calculation of the eggs ascent speed reduces to the solution of square equation (16), which roots are as follows:

$$v = - \frac{9\eta S}{2\rho_1 R^2} \pm \sqrt{\frac{81\eta^2 S^2}{4\rho_1^2 R^4} - 2gS(1 - \frac{\rho_2}{\rho_1})}. \quad (17)$$

Two roots will be a solution to equation (16). In calculations only positive values of speed are used as the eggs have positive buoyancy.

So, we have derived an estimate of speed at which an egg starts its ascent. The time of passage through the first layer can be calculated from:

$$v = v_0 + at, \quad (18)$$

where t –time of passage.

With the initial speed $v_0 = 0$, we have:

$$t = \frac{v}{a}, \quad (19)$$

and taking into account (11)

$$t = \frac{2S}{v}. \quad (20)$$

As an egg moves through from one layer to another its acceleration changes and hence so does the speed. Initial speed of an egg in every new layer will be different from 0 and equal to the speed at which it has left the previous layer. Therefore, equation for the movement of an egg in upper layers will be equivalent to (9).

Having done similar rearrangements (12) – (17) and knowing that initial speed is not equal to 0, we can derive an equation for calculating the speed of eggs ascent due to buoyancy force:

$$v = - \left(\frac{9\eta}{2\rho_1 R^2} \pm \sqrt{\frac{81\eta^2}{4\rho_1^2 R^4} - \frac{18}{S} \left(g \left(1 - \frac{\rho_2}{\rho_1} \right) - \frac{v_0^2}{2S} \right)} \right) S. \quad (21)$$

Using (9) to express time, we will have:

$$t = \frac{2S}{v + v_0}. \quad (22)$$

The density of seawater was calculated by using the Knudsen equation (Oceanographic Tables, 1975). Coefficients of dynamic viscosity were borrowed from Oceanographic Tables (1975). Estimates of physical parameters of eggs of the North-East Arctic cod were borrowed from the paper by T.S.Rass (1949):

- egg density (1.0235-1.0260) g/cm³;
- egg weight (0.926-2.200) mg;
- egg diameter (1.13-1.65) mm.

In calculating the time and speed of ascent the same egg characteristics have been used for all years under consideration. The average density of an egg was taken as equal to 1025 kg/m³.

The distribution of major elements of vertical structure in temperature, salinity and density profiles is fairly the same. Lines of transition from one element of the vertical structure to

another are located virtually at the same depth for different water parameters. Therefore, for the sake of convenience we used water temperature distribution in the analysis of water vertical structure, as similar studies are available for the Barents Sea.

The spawning of the North-East Arctic cod takes place in a thermocline (Ellertsen et al., 1981), therefore for the lower boundary of a transition layer a depth, where the eggs are spawned, has been taken. In view of this, for estimating the speed of eggs ascent, it was, in the first place necessary, to define the boundaries of water temperature transition layer.

To define the boundaries of stratification elements, zones with significant and insignificant temperature variations were identified in the water vertical structure (Belkin, 1981, 1991; Ivshin, 1999). To conclude if the gradient variation is significant or not, it is usually compared to a certain critical value. This critical value could have a wide range of variation and is decided on the basis of overall task, conditions in the area under study, time and space scale, errors in data. Numerical values for this criterion with references to the literature can be found in the paper by I.M.Belkin (1981). To reflect major peculiarities of the profile, on the one hand, and to avoid insignificant heterogeneities, on the other, a critical value of the gradient was taken as equal to $0.02^{\circ}\text{C}/\text{m}$

The value for the gradient of water temperature (GradT) was calculated as:

$$\text{GradT} = \frac{(T_{i+1} - T_i)}{(Z_{i+1} - Z_i)}, \quad (23)$$

where $i = 1, 2 \dots n$ – depth layer number, starting from the surface; T_i – water temperature ($^{\circ}\text{C}$) at depth i ; Z_i – depth i (m). The water temperature was assumed be varying significantly, if a module of temperature gradient was more than $0.02^{\circ}\text{C}/\text{m}$ ($\text{Abs}(\text{GradT}) \geq 0.02^{\circ}\text{C}/\text{m}$) and insignificantly, if it was less than $0.02^{\circ}\text{C}/\text{m}$ ($\text{Abs}(\text{GradT}) < 0.02^{\circ}\text{C}/\text{m}$). The depth of change of water vertical distribution type from a uniform to gradient and vice versa was taken as a boundary of transition from one element of stratification to another. It was assumed that water temperature varied linearly between depth layers.

A structure of any vertical profile of water temperature can be shown as a number of alternating gradient and uniform zones (Fig. 2). For instance, a profile zone ($T_1, Z_1; T_2, Z_2$) (Fig.2) is a top quasi-homogeneous layer with a small water temperature gradient. An area of maximal gradients is located at ($T_2, Z_2; T_3, Z_3$), which is a thermocline or transition layer. Right underneath the transition layer there is another quasi-homogeneous layer ($T_3, Z_3; T_4, Z_4$).

A peak of cod spawning is in early April (Ellertsen et al., 1987), therefore for each year from 1936 to 1992 oceanographic conditions at Lofoten spawning grounds in the period from 15 March to 15 April were assessed on the basis of data from Skrova station. Estimates of time and speed of eggs ascent were related to water temperature. For doing this all temperature data were split into three groups (Tereschenko, 1999; Tereschenko, Dvinina, Borovaya, 1985). Sea temperature conditions were assessed on the basis of root-mean-square deviation of water temperature (σ_T) in the 200 m layer in the following manner:

- cold year, $\Delta T, ^{\circ}\text{C} < - 0.5 \sigma_T$;
- normal year, $- 0.5 \sigma_T \leq \Delta T, ^{\circ}\text{C} \leq 0.5 \sigma_T$;
- warm year, $\Delta T, ^{\circ}\text{C} > 0.5 \sigma_T$,

where ΔT – water temperature anomaly in the 0-200 m layer.

Simulation of transport of eggs, larvae and 0-group cod

A calculation of current fields and simulation of transport of passive particles, imitating eggs, larvae and 0-group cod, were in this paper done by using three-dimensional numerical hydrodynamic model (Trofimov, 2000). A model area, which was a trapeze with the bottom left-hand and top right-hand angles at 05° E, 67° N and 60°E, 80°N, respectively, was approximated by a grid with an interval of 01°00' longitudinally, 00°20' latitudinally and with alternating interval at z allowing to cover the depth 0, 10, 20, 30, 50, 100, 150, 200, 300, 400 m. Coefficients of vertical turbulent viscosity in the air, ocean and horizontal turbulent viscosity in the ocean were taken equal to 0.15 m²/s, 0.015 m²/s, 500 m²/s, respectively (Trofimov, 2000).

For analysis, a period of three years (1987-1989) was reviewed notable for showing three gradations of the water temperature conditions in the Barents Sea, namely, 1987 – a cold year, 1988 – a normal year and 1989 – a warm year (Terschenko, 1999, 2000).

In calculating the currents, in whose field a transport of markers took place, mean monthly fields of air pressure for the period from March to September 1987-1989 borrowed from the Climate Diagnostics Center (NOAA, <http://ingrid.ldgo.columbia.edu>) via Internet, mean monthly fields of seawater density calculated by the Knudsen equation (Oceanographic Tables, 1975) using temperature and salinity data from oceanographic database available at PINRO and current velocity at boundaries of the model area, calculated by flows across relevant sections and sounds (Kudlo, 1961; Orlov, Poroshin, 1988; Midttun, 1985; Slagstad, 1987; Loeng, Ozhigin, Adlandsvik, 1997).

In simulating the transport of eggs and larvae of cod sources of markers (eggs) were represented by three rectangular areas (Fig. 4) within the following coordinates: 67°10'N, 11°00'E and 67°40'N, 12°00'E; 68°00'N, 09°00'E and 68°40'N, 13°00'E; 69°50'N, 16°00'E and 70°10'N, 18°00'E, and were operating for 45 days from 10 March to 25 April with intensity reflecting the intensity of cod spawning. Overall, 6 000 markers were released in the 0-30 m layer in the simulated spawning season, 2 000 markers by each source.

The spawning of cod was simulated in the following manner: in the first day of the spawning season 0.1% of the total amount of markers were randomly released in each of the three areas, in the second day – 0.3%, in the third - 0.5% etc. and so on until the peak of spawning, when each source released 4.5% of the total number of markers, i.e. 90 markers. Then the process reversed and in the last day of spawning, as at the beginning, 0.1% of the total amount of markers was released in each area.

For analysis of markers distribution the model area was divided into four zones (Fig. 4): south-western (Norwegian Sea), north-western (Greenland Sea), south-eastern (southern Barents Sea) and north-eastern (northern Barents Sea). This is a conventional division and it does not correspond to the geographic division of the area under study. Markers, that hit the land, remain there and are not included in calculation of percentage.

In simulating the markers transport their position was determined as follows:

$$\lambda_2 = \lambda_1 + \Delta t (V_\lambda + \eta_\lambda) 180 / (\pi R \cos \varphi_1), \quad (24)$$

$$\varphi_2 = \varphi_1 + \Delta t (V_\varphi + \eta_\varphi) 180 / (\pi R), \quad (25)$$

where $\lambda_1, \varphi_1, \lambda_2, \varphi_2$ - initial longitude, latitude for marker position and ultimate latitude and longitude after time Δt ;

V_λ, V_φ - constituents of current velocity at point (φ_1, λ_1)

π - a constant equal to 3.1416...;

R - Earth radius equal to 6371 km;

$\eta_\lambda = \eta \sin \gamma$;

$\eta_\varphi = \eta \cos \gamma$;

γ - random direction (from 0 to 360°);

η - value equal to the average current velocity in the model area.

The approach used is based on a method of random wandering (Bowden, 1988; Averkiev, Chatsev, 1995). The value η allows assign each particle (marker) a random shift in addition to the main one in each time interval. This has been done in order to take into account the impact of periodic currents, in particular, tidal, on the process of passive particle distribution. As is known, their velocities are commensurable to velocities of non-periodic currents or could even be higher, and besides, tidal currents have a reversing nature, i.e. they are not responsible for resulting transport of particles, but contribute to additional diffusion of the cloud of markers. Value η is taken such that the diffusion of random movement corresponds to the coefficient of turbulent diffusion equal to 500 m²/s (Bowden, 1988; Aadlandsvik et al., 1999).

Indices of eggs abundance and assessment of their distribution have been borrowed from materials provided by the Russian ichthyoplankton surveys conducted by PINRO in the north-eastern part of the Norwegian Sea and south-western part of the Barents Sea in April-July 1987-1989 (Mukhina, 1992). Assessment of distribution of the 0-group cod has been borrowed from materials provided by the 0-group surveys in the Barents Sea (Anon., 1987, 1988, 1989).

RESULTS

Fig. 5 shows the vertical distribution of water temperature at Skrova station in early April in years with different temperature conditions. In early April water temperature at the surface is minimal (2.5°C for cold years; 2.8°C for warm years). An upper quasi-homogeneous layer is found in the layer from the surface down to 10 m in warm years and to 50 m in cold years. So, thermocline boundaries are located at shallower depth in warm years, than in cold years. Temperature gradient in the transition layer is also higher in warm years (0.044°C/m), than in cold years (0.035°C/m). In calculating and analyzing the speed of eggs ascent it has been assumed that the spawning of cod near Skrova station takes place at the lower boundary of the thermocline. Estimated depth of the lower boundary changes considerably in relation to water temperature conditions. For instance, it is 97 m in warm years, 119 m in normal years and 147 m in cold years.

Vertical distribution of viscosity of seawater for years with different temperature conditions is shown in Fig.6. A vertical run of the viscosity curves is converse to the run of water temperature curves. Viscosity declines with depth, maximal gradient is found in the transition layer at depth 50-150m. In warm years boundaries of the transition layer are located closer to the surface, than in cold years.

Density of seawater has a considerable impact on the speed and time of eggs ascent. Largest differences in the water density stratification for years with different temperature conditions are noted for the upper 75 m layer (Fig.7). The largest density in upper layers is typical of cold years, when lower water temperatures and higher salinities are observed. In warm years water density in upper layers is much lower than in cold years. Maximal gradients of conditional

density ($0.004\text{-}0.006\text{ m}^{-1}$) in the pycnocline are found in 50-150 m layer. Fig. 8 shows long-term mean seasonal variation of density stratification at Skrova station. Maximal water densities are noted in March-April at the time of peak in cod spawning (Fig.8, dash line). At this time conditions develop, when the difference between eggs and seawater density is maximal, which results in the fastest speed of eggs ascent. From mid-June to mid-September the density of water in the surface layer may be less than 1025 kg/m^3 (Fig. 8, solid line) therefore, the difference between the water and egg density becomes negative and the ascent of eggs becomes unfeasible.

Maximal speed of eggs ascent is observed, when they move through the deepest layers (Fig.9) and varies from 1.27 mm/s in cold years to 1.15 mm/s in warm years. As the eggs ascend to the surface their speed declines gradually and remains virtually unchanged in the upper 50 m layer. It is for this layer that maximal differences in the ascent speed are noted in the years with different temperature conditions. In cold years the eggs pass through the upper layer at a speed of 0.96-0.98 mm/s, while in warm years the speed of ascent is much less 0.78-0.82 mm/s. The time of eggs ascent from the site where they have been spawned to the surface may vary in the range of 1.5 to 2 days depending on the temperature conditions of the year (Fig.10).

Figs. 11-13 show results from observations of distribution of cod eggs and larvae as well as results from simulating the distribution of markers for May 1987-1989. A good agreement between simulated and observed distribution has been noted. In cold 1987 a portion of markers was distributed farther north, up to $74^{\circ}30'N$, than in normal 1988 and warm 1989. In 1988 markers were concentrated near the coast of Norway, while in 1989 an intensive transport of passive particles (markers) into the Barents Sea was noted, although their distribution was different from the observed distribution of cod eggs and larvae.

Figs. 14-16 show the factual distribution of 0-group cod and simulated distribution of markers in September 1987-1989. Our data clearly indicate that in 1987 and 1988 the distribution area of 0-group cod was virtually the same except, that the densities in cold 1987 were higher near the border between the Norwegian and Barents Sea, while in normal 1988 dense aggregations moved along the Norwegian coast into the Barents Sea. This was reflected in the results of simulation. In addition, in 1987 an intensive transport of markers to Spitsbergen was noted, while in 1988 the majority of markers moved into the Barents Sea, however, no further, than $41^{\circ}00'E$. In 1989 an overwhelming part of markers was transported into the Barents Sea, and were distributed as far east as Novaya Zemlya (Fig. 16).

Table 1 presents the information on the number of markers (as percentage of the total number) found at different stages of calculations in the four zones of the model area defined relative to the Bear Island (Fig. 4). It is evident from the table, how in years with different temperature conditions the distribution of markers in the model area changed according to the variation of current intensity.

Table 1. Percentage of markers remained within the model area in simulations of the distribution of eggs, larvae and 0-group cod in 1987-1989

Month	Zones relative to the Bear Island			
	Southwest	Northwest	Southeast	Northeast
1987				
March	97.0	0.0	3.0	0.0
April	83.9	0.0	16.1	0.0
May	67.0	0.0	33.0	0.0
June	60.2	0.2	39.6	0.0
July	51.9	0.6	47.4	0.0
August	42.3	1.3	56.3	0.0
September	35.1	2.6	62.2	0.0
1988				
March	97.8	0.0	2.2	0.0
April	86.3	0.0	13.7	0.0
May	65.6	0.0	34.4	0.0
June	48.8	0.0	51.2	0.0
July	36.2	0.1	63.6	0.0
August	23.5	0.4	76.0	0.0
September	15.1	1.1	83.6	0.2
1989				
March	97.3	0.0	2.7	0.0
April	74.6	0.0	25.4	0.0
May	51.4	0.0	48.6	0.0
June	35.8	0.1	64.2	0.0
July	26.4	0.2	73.4	0.0
August	20.4	0.4	79.2	0.0
September	11.3	2.3	86.2	0.3

To summarize the above said, it could be noted that in cold 1987, when the circulation system was weak, a spread of markers imitating eggs, larvae and 0-group cod was slower and a westerly distribution prevailed, and by September almost a half of the total amount of markers still remained in the Norwegian Sea. In that year logarithm (lg) of index of eggs and larvae abundance was 1.0 and 0.1, respectively, and survival rate was 0.1. Conversely, in warm 1989 due to higher intensity of warm currents the majority of markers (up to 80%) was found transported into the southern Barents Sea, and the abundance of eggs and larvae was higher than in 1987 (logarithm of the abundance index was 1.9 and 1.2, respectively), survival rate accordingly was much higher (0.63). Normal 1988 characterized by medium circulation intensity was intermediate in terms of markers distribution between cold 1987 and warm 1989. Worth mentioning is that in April, May and June of that year a pattern of changes in the distribution of markers between the four zones was closer to 1987, while in other months (July, August and September) to 1989. Accordingly, survival rate in 1988 was only slightly higher than in 1987 – 0.13.

This relationship was also reflected in the strength of cod year classes of 1987-1989 as assessed by the ICES Arctic Fisheries Working Group (Anon, 2003). For instance, the abundance of 1987 year class of cod as 3-yr-olds was estimated at 242749×10^3 fish, 1989 year class 720690×10^3 fish, while the year class of 1988, which according to specific features of water circulation was close to 1987, at 411783×10^3 fish.

DISCUSSION

Speed and time of eggs ascent from spawning sites to the surface are largely dependent on the vertical structure of water physical parameters. In years with weak circulation, the rate of cooling of surface water is higher, which contributes to increased thickness of the upper uniform layer and deeper thermocline depth. As is known, the spawning of cod takes place in the thermocline, and, vertically, the position of its boundaries can vary considerably between years (Ozhigin, Tretyak, Yaragina, Ivshin, 1999). For instance, according to the long-term data a difference in the depth of thermocline boundaries could be as much as 50 m (Fig.5). For individual years this could even be more. In view of the different depth of spawning, the distance to be covered by eggs before reaching the surface is nearly 1.5 times shorter in warm years, than in cold years. Since the boundaries of thermocline are located deeper in cold years, the total distance to be covered by eggs is longer. Seasonal variability of the depth of isopycnic surfaces at Skrova station (Fig.8) has indicated that in summer season an influx of radiation heat and fresh water from flood lead to reduced density of seawater in the surface layer. Then the situation develops, when isopycnic surface of 1025 kg/m^3 acts as a “lid” for eggs in the period from mid-June to mid-September. Low water densities in the upper layers at that time prevent the eggs from ascending to the surface. Presuming, that the spawning of cod would have taken place at that time of the year, only eggs with the smallest density had been able to ascend to the surface, which is usually noted for young fish.

A difference in the speed of ascent (Fig. 9) is, primarily, due to different water densities: cold years are characterized by lower heat content and higher salinity of surface water, which leads to increased water density. Although seawater viscosity is lower in warm years, than in cold, it does not impact significantly on the time of eggs ascent. The time of ascent is, in the first place, related to the distance to be covered by eggs to reach the surface.

Although the speed of ascent in cold years is higher than in other years, ascent time will be longer. However, when equal distances are considered, the picture will be different (Fig. 10, upper 100 m layer). In cold years it takes the eggs 27 hours to go through this layer, while they spend 35 hours on this ascent in warm years. So, in moving from warm to colder water the adaptation time of eggs is longer in warm years. In years with low heat content temperature “pressure” on eggs is higher, which in turn could adversely affect the process of embryo development and survival in general.

It would be appropriate to indicate the reasons, which were likely to bias the results and to cause more differences between simulated distribution of passive particles and observed distribution of eggs, larvae and 0-group cod:

- the number of spawning grounds is larger in reality, than that used in the model, and it varies between years;
- the location of spawning grounds also differs from year to year, and it is not fixed like it has been assumed in simulations;
- the intensity of spawning differs between areas, while in this paper all sources of markers are equivalent;
- the assessment of actual distribution of eggs, larvae and 0-group cod has been based on the findings from ichthyoplankton surveys and 0-group surveys, which lasted one to three months, whereas simulation results refer to a definite point in time.

Some of the above listed reasons could have been avoided; however, this was not the case, since the purpose was to assess the impact of water circulation on transport of eggs, larvae and 0-group

cod in years differing in water temperature conditions. And this relationship in its true form could only be studied only if identical spawning situations are considered for different years.

CONCLUSIONS

This paper has reviewed reasons for possible differences in time and speed of ascent of the North-East Arctic cod at spawning grounds at the Lofoten Islands and specific features of the vertical distribution of major oceanographic parameters (temperature, salinity, density, viscosity of seawater) in relation to temperature conditions of the year.

Regarding the vertical structure of water temperature it has been established, that the depth of transition layer can vary considerably between years (the difference up to 50 m according to long-term data), which in turn influence the depth of cod spawning.

Water viscosity declines with increasing water temperature. Therefore, in cold years this parameter is more powerful in preventing the eggs from ascending, than in the period with higher water temperatures.

Speed of eggs ascent is higher in cold years, than in warm years. Largest differences in the speed of ascent are noted for the upper 50 m layer.

Time needed by eggs to reach the surface is related to the depth of spawning. Since in cold years the spawning takes place deeper, than in warm years, the time spent by eggs to ascend is longer. Nevertheless, in cold years it takes the eggs 8 hours less to go through the upper 100 m layer, than in warm years. The eggs are exposed to a stronger thermal impact during rapid ascent, because of abrupt change of water temperature, than in gradual ascent. This could adversely affect the development and survival of eggs.

A good agreement has been noted between the actual distribution of eggs, larvae and 0-group cod and results from simulations of passive particles simulating them.

In cold 1987, when the system of warm currents in the model area was weak, the transport of markers, imitating eggs, larvae and 0-group cod, was slow. They had a westerly distribution. In September nearly a half of markers still stayed in the Norwegian Sea.

Conversely, in warm 1989 characterized by intensive water circulation, the majority of 0-group cod (up to 80% of markers) was transported into the Barents Sea.

In warm years, when most of the cod eggs and larvae are brought into the southern Barents Sea, survival rate is higher than in cold years.

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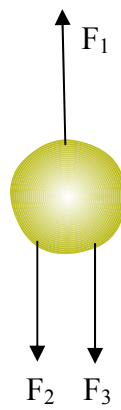


Fig. 1 Forces acting on an egg

F_1 – force of buoyancy; F_2 –force of gravity; F_3 – resisting force

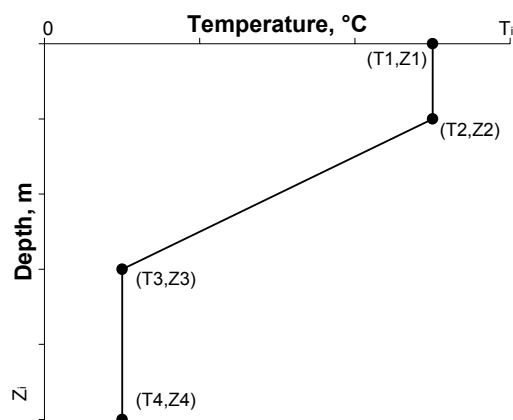


Fig.2 Symbolic water temperature vertical profile

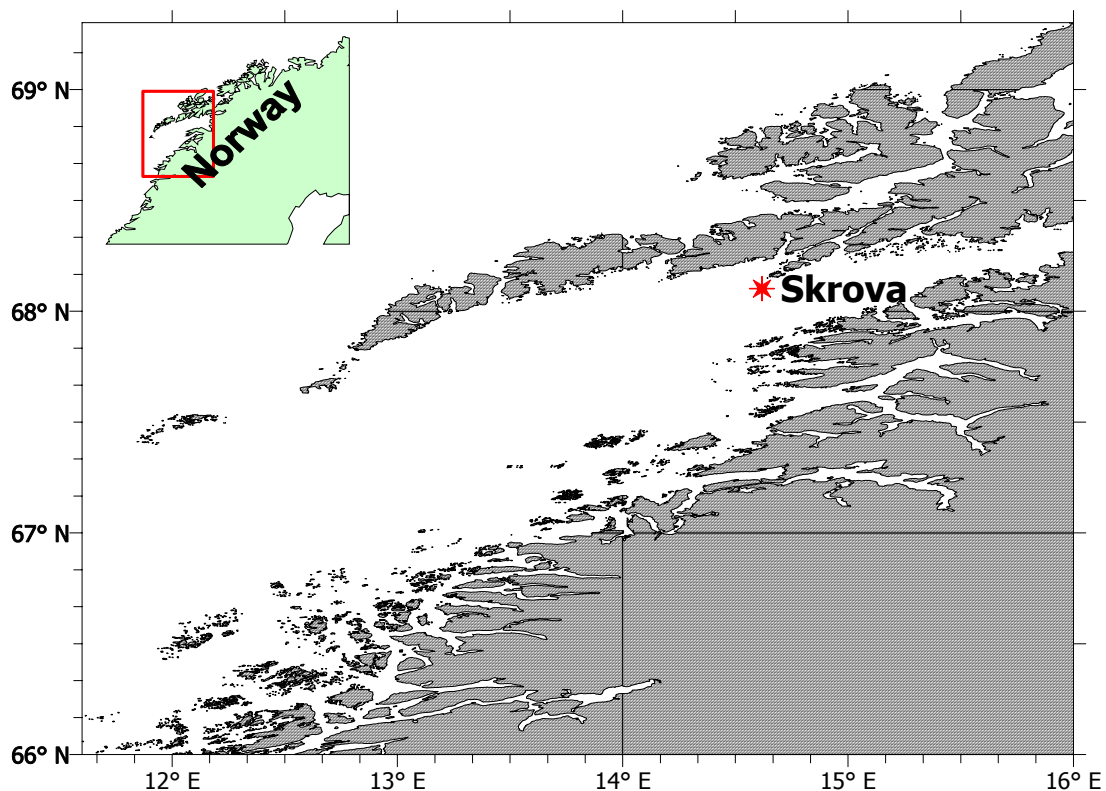


Fig.3 Lofoten Islands and Skrova observation station

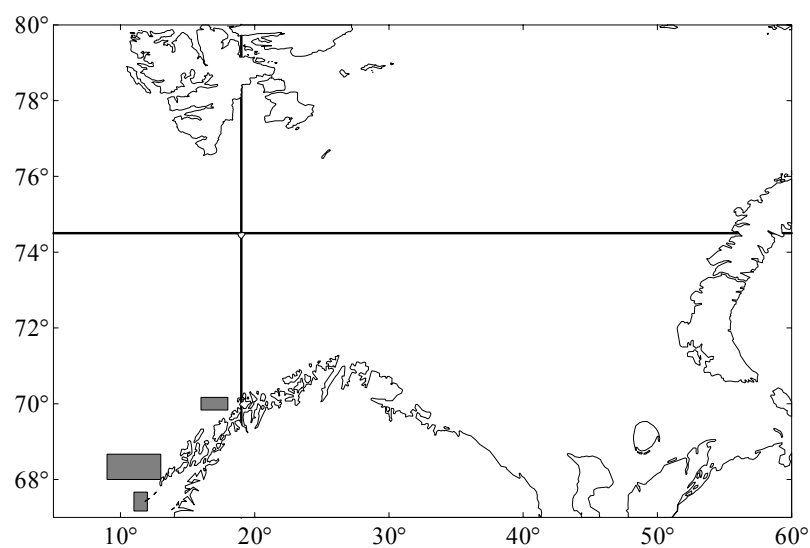


Fig. 4 Location of sources of markers in simulations of the transport of eggs, larvae and 0-group cod and division of the model area into four zones relative to the Bear Island

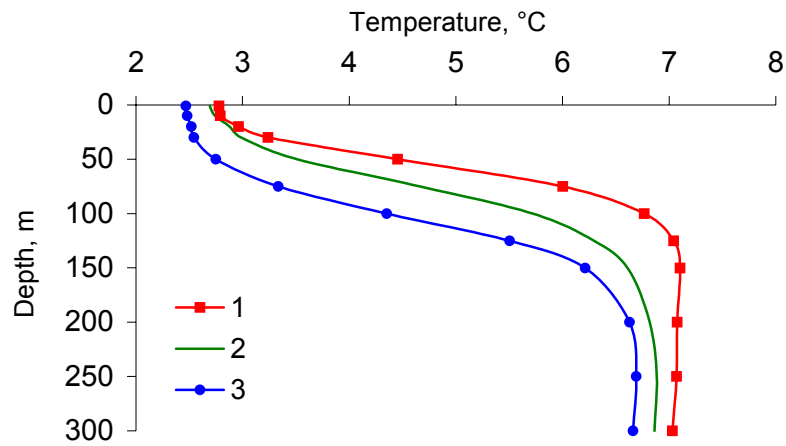


Fig. 5 Vertical water temperature profiles at Skrova station as of April 1 in years with different thermal conditions: 1 – warm; 2 – normal; 3 – cold

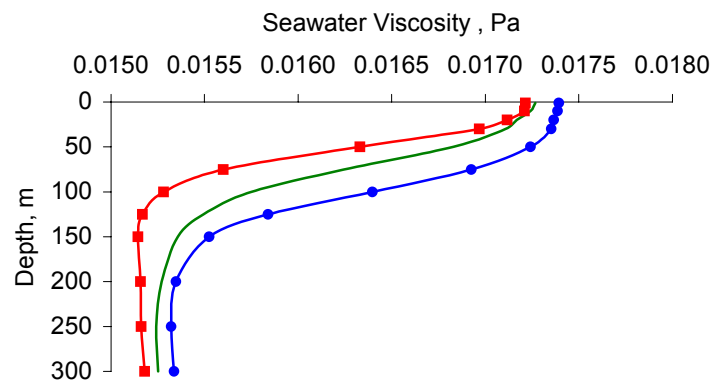


Fig. 6 Vertical profiles of seawater viscosity at station Skrova as of April 1 in years with different thermal conditions. For symbols see Fig. 5

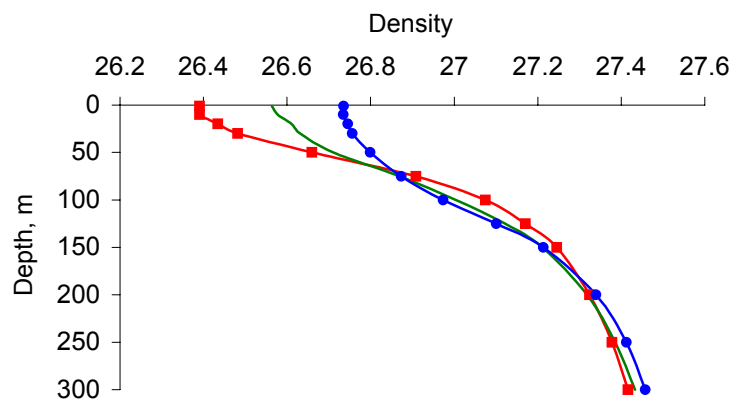


Fig. 7 Vertical profiles of density at station Skrova as of April 1 in years with different thermal conditions. For symbols see Fig. 5.

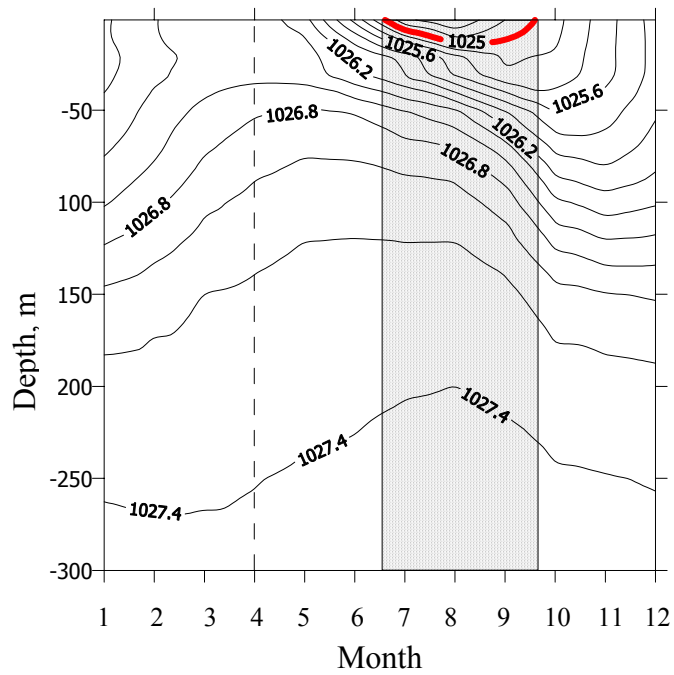


Fig. 8 Yearly variation of water density structure at Skrova station. Dash line shows the peak of spawning, solid line shows the depth of isopycnic 1025 kg/m^3 , shaded area - its lifetime.

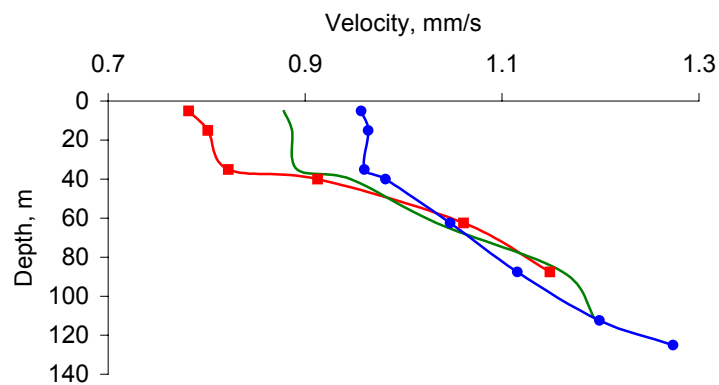


Fig. 9 Vertical profiles of eggs ascent speed as of April 1 at Skrova station in years with different thermal conditions. For symbols see Fig. 5.

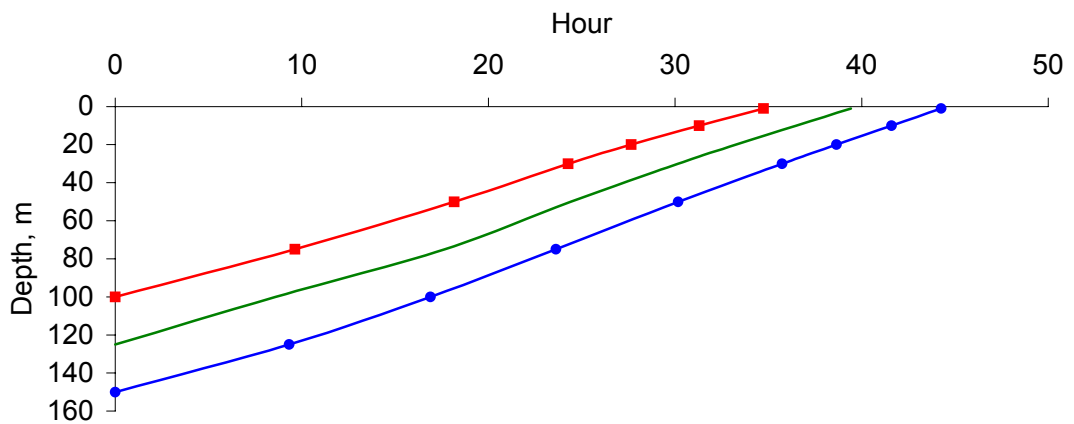


Fig. 10 Time of eggs ascent (hour) as of April 1 at Skrova station in years with different thermal conditions. For symbols see Fig. 5.

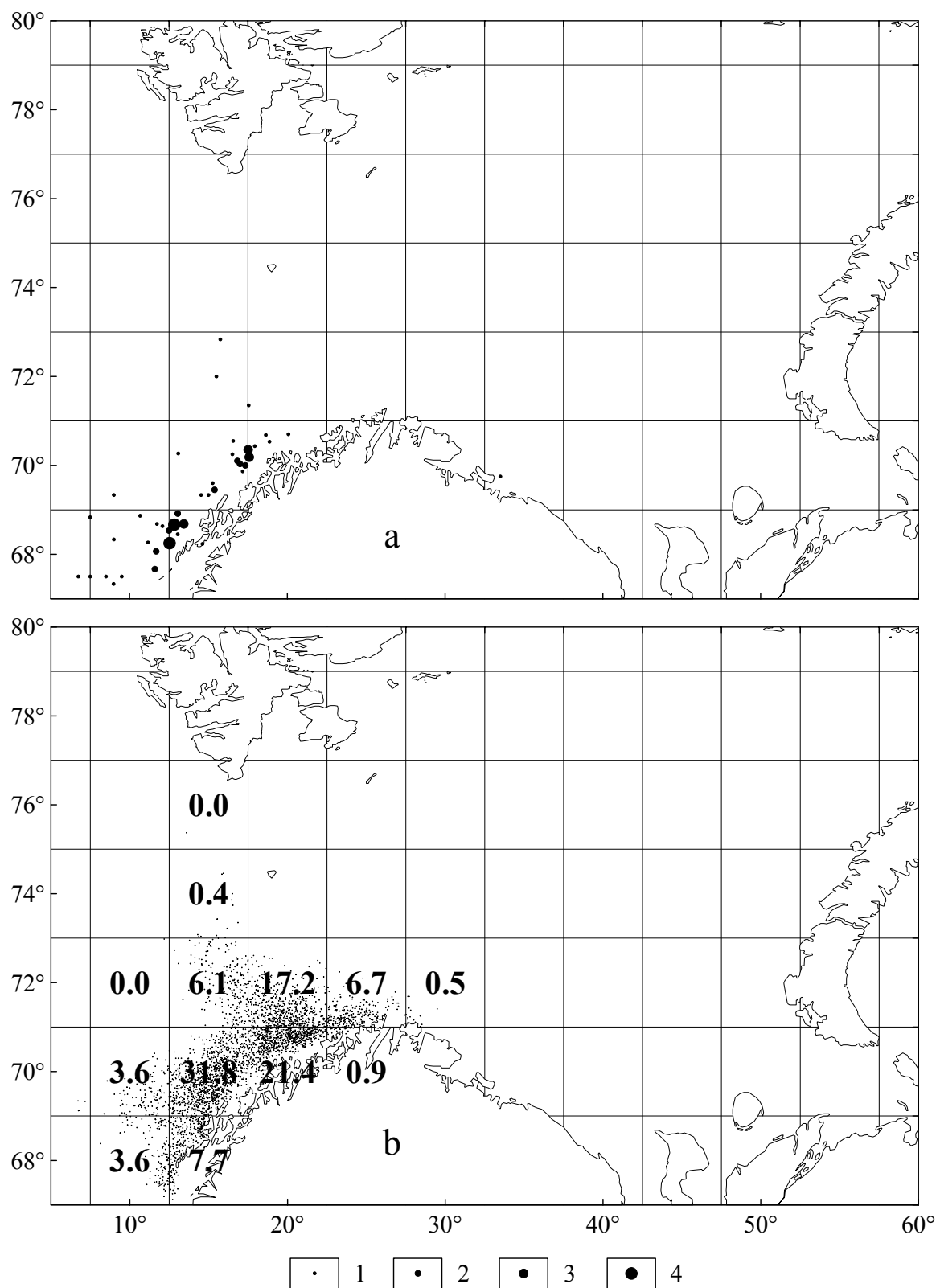


Fig. 11 Actual (a) and estimated (b) distribution of eggs and larvae of cod in May 1987: 1 – 1-9 individuals per haul, 2 – 10-49, 3 – 50-99, 4 – 100 and more.
Here and in Figs. 12-16 figures indicate the number of markers (percentage of the total amount) in each respective rectangle

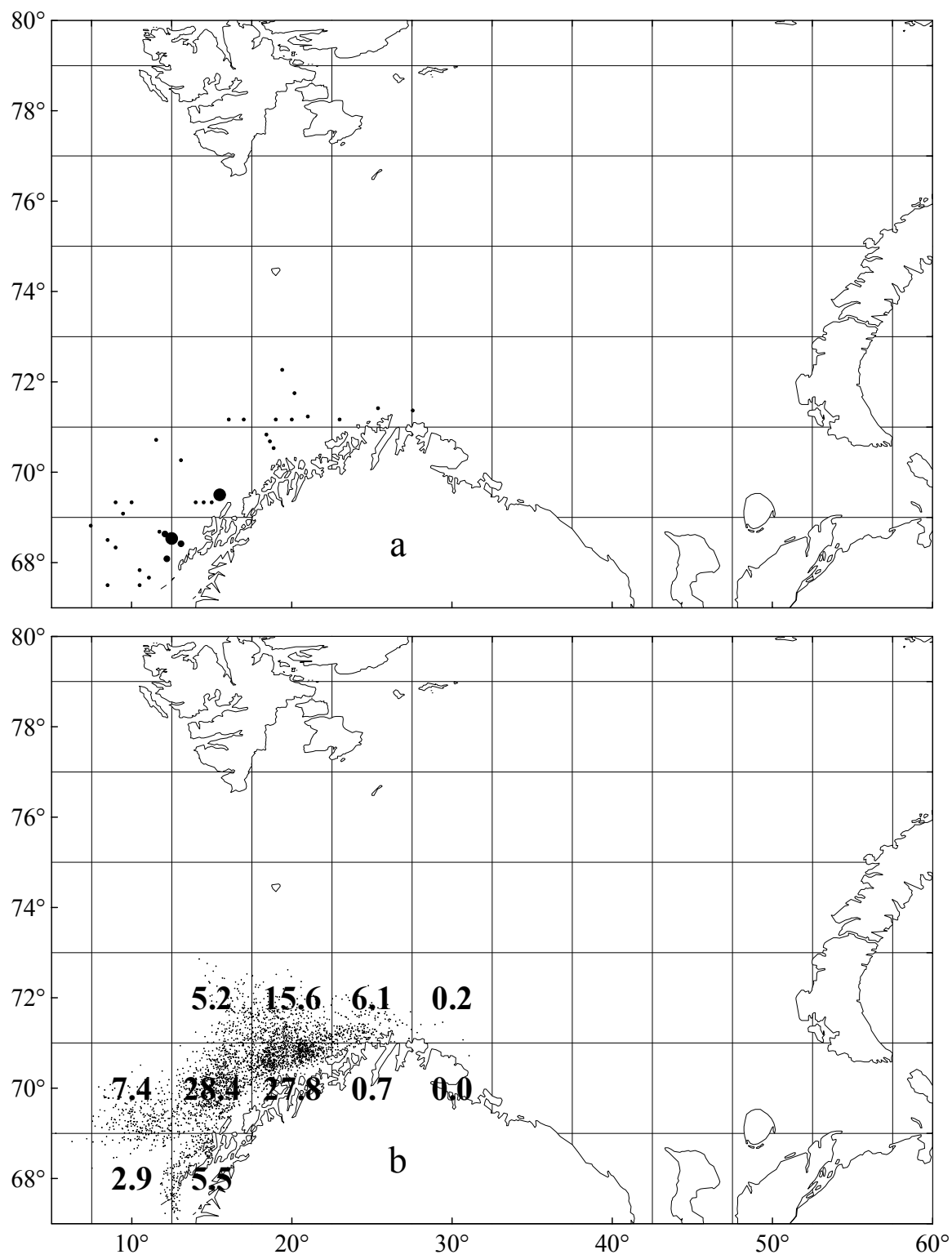


Fig. 12 Actual (a) and estimated (b) distribution of eggs and larvae of cod in May 1988. For symbols see Fig. 11

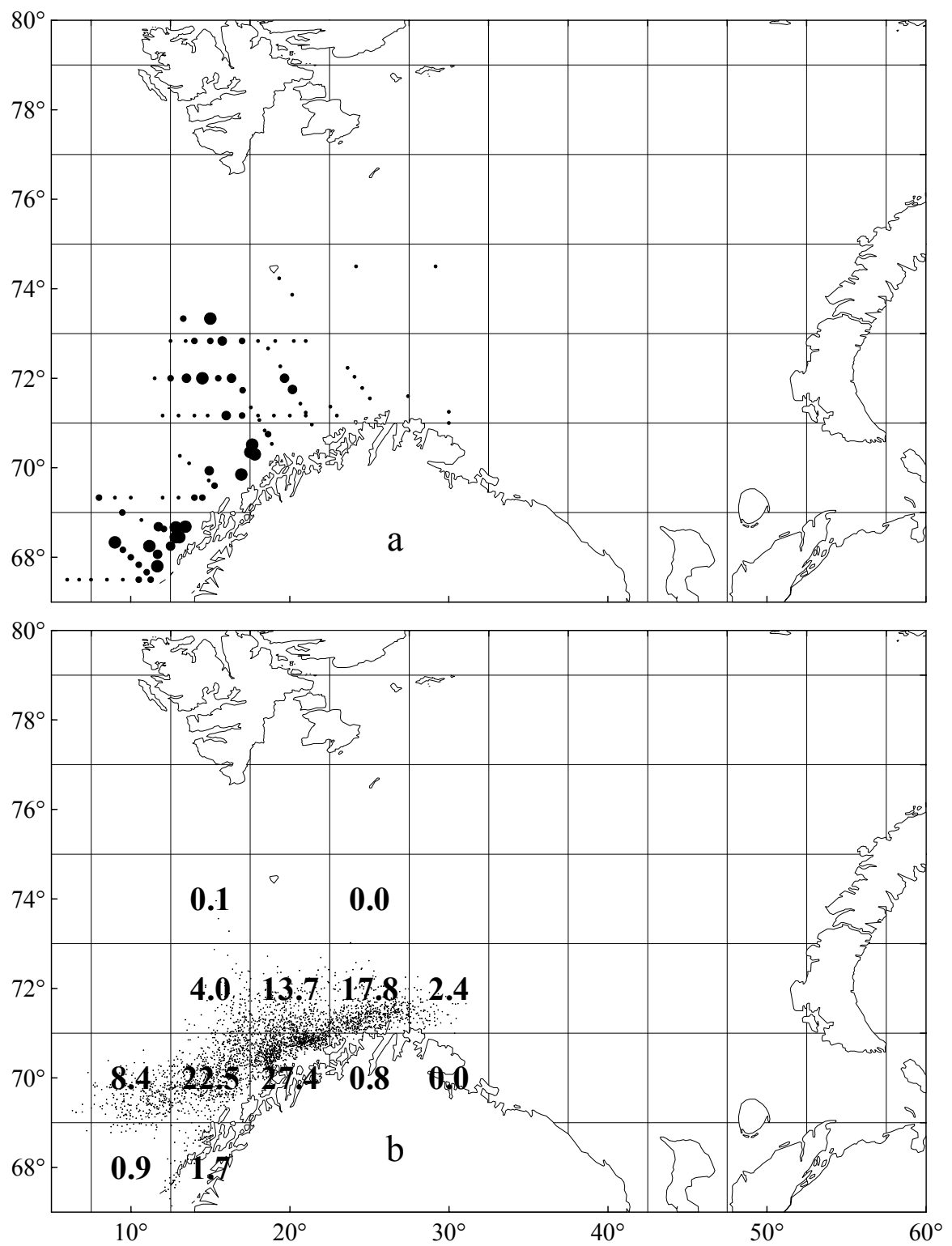


Fig. 13 Actual (a) and estimated (b) distribution of eggs and larvae of cod in May 1989. For symbols see Fig. 11

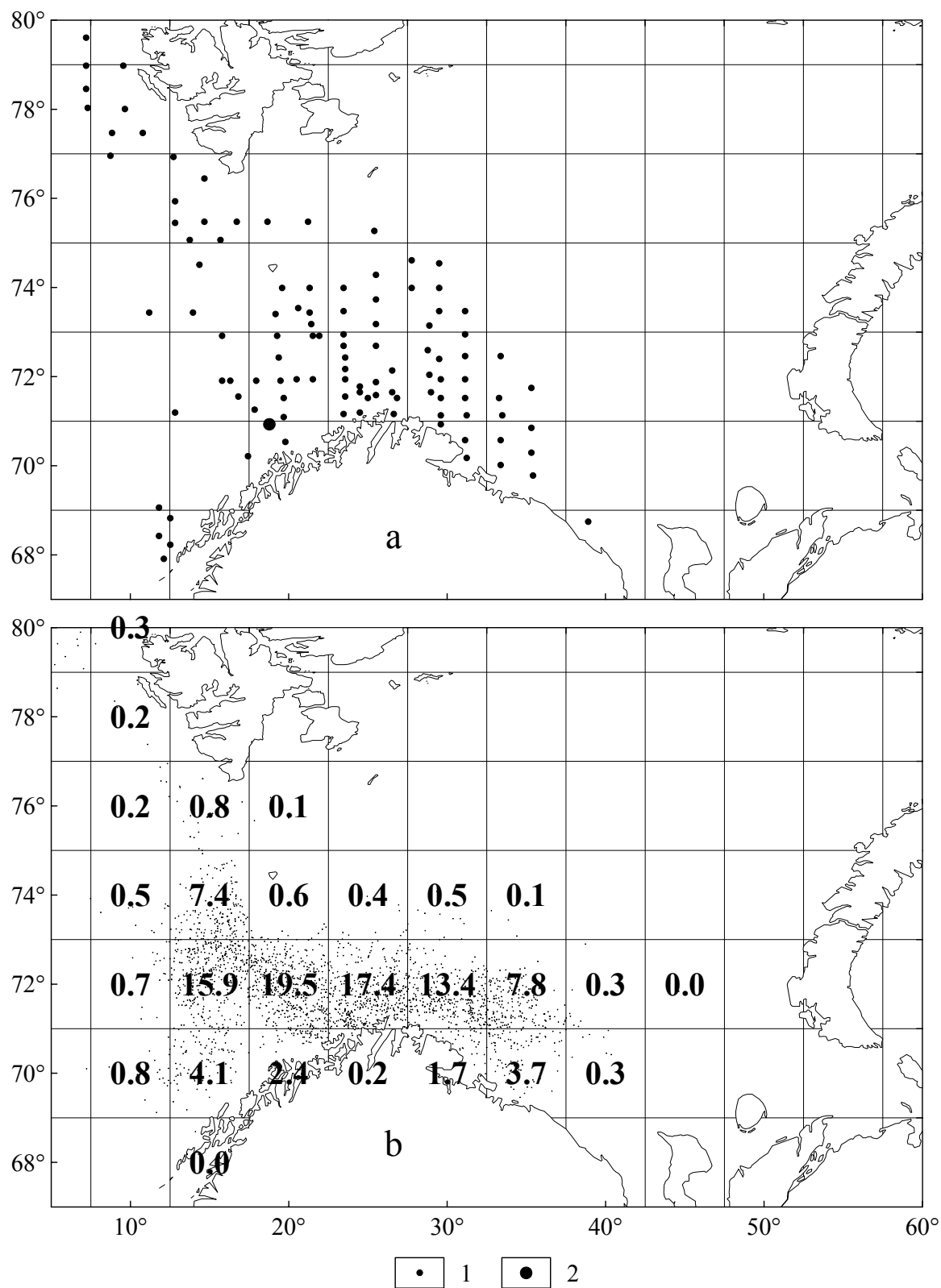


Fig. 14 Actual (a) and estimated (b) distribution of 0-group cod in September 1987: 1 – 1-85 fish per nautical mile; 2 – 85 and more.

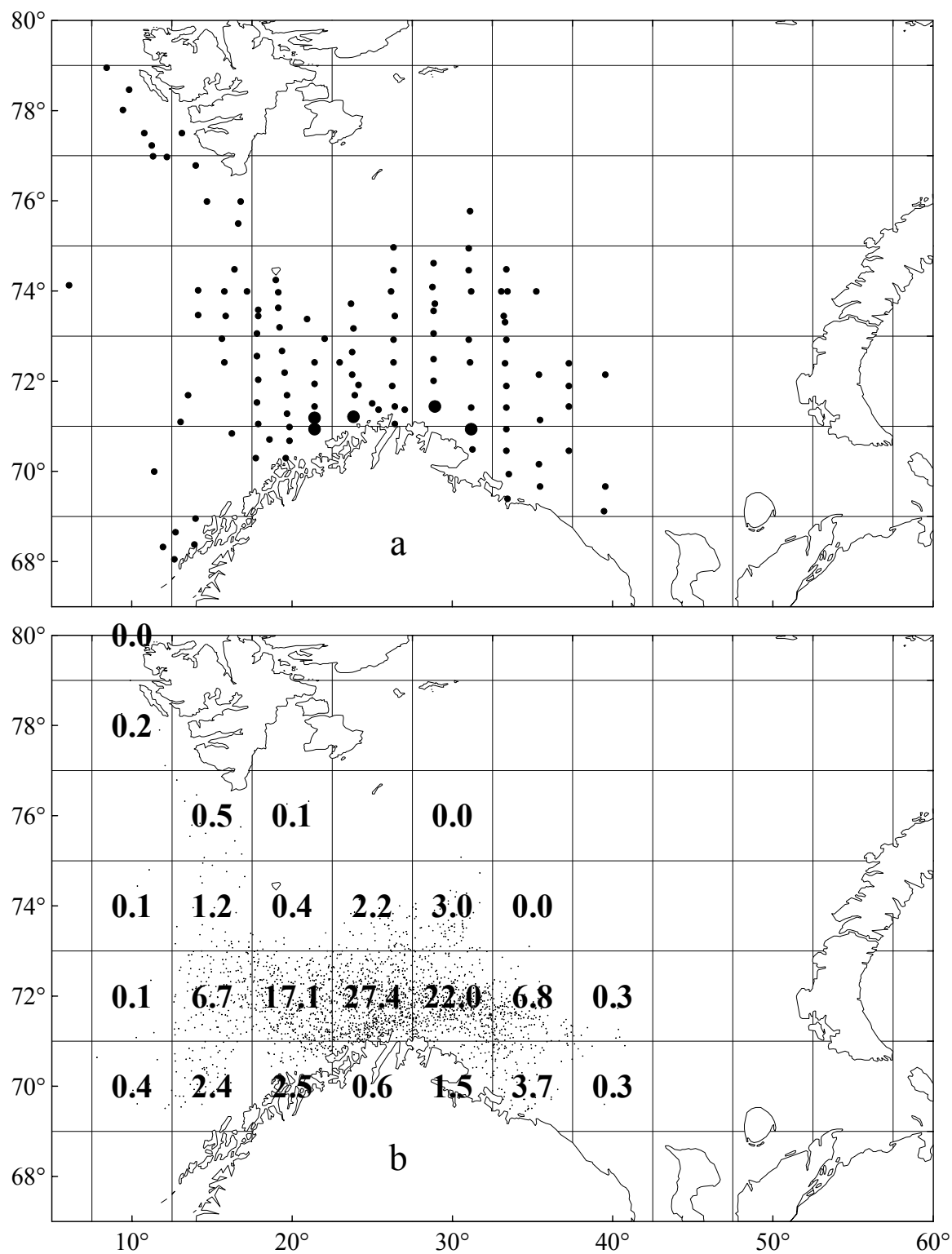


Fig. 15 Actual (a) and estimated (b) distribution of 0-group cod in September 1988. For symbols see Fig. 14

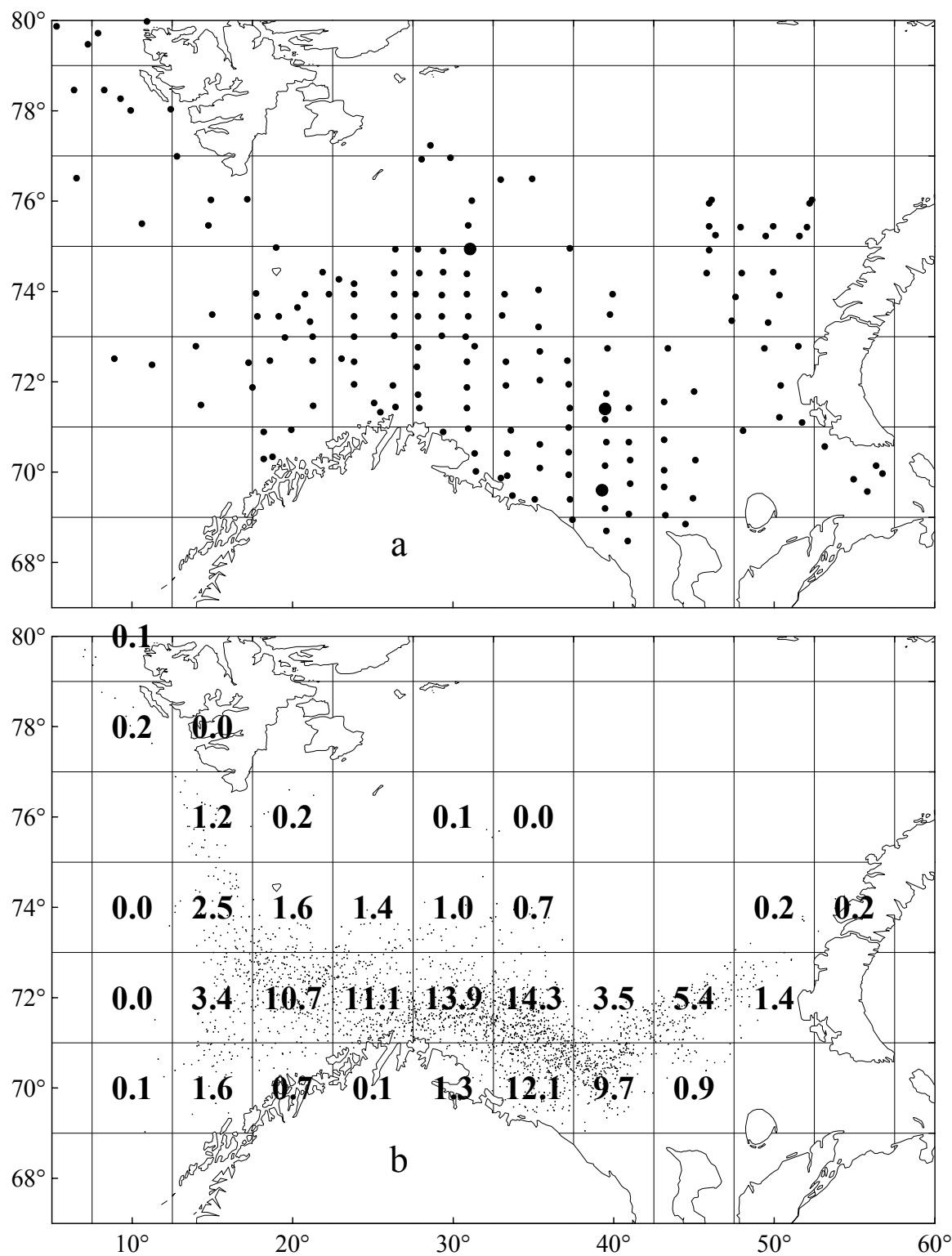


Fig. 16 Actual (a) and estimated (b) distribution of 0-group cod in September 1989. For symbols see Fig. 14