THE DETECTION AND DISTRIBUTION OF
LARVAL ARCTO-NORWEGIAN COD, *GADUS MORHUA*,
FOOD ORGANISMS BY AN IN SITU PARTICLE COUNTER

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ABSTRACT

An in situ particle counter system was developed to count measure food particles in numbers per liter within the size range 150-600 μm, the sizes of copepod nauplii captured by first feeding cod larvae. Patches of particles/nauplii of 50-100 per liter were found in the spawning and larval first feeding area. Different sizes of copepod nauplii showed diel vertical migration, and this influenced the formation of patches. Mixing of the water column by wind forces created a homogeneous vertical distribution of particles. Gut content analysis of cod larvae during these hydrographical conditions indicated reduced accessibility of food organisms to larvae.

During the last few years fisheries scientists have done a great deal of laboratory work on the behavior of fish larvae and their energy requirements for growth and survival (Hunter 1972; Laurence 1974; Lasker and Zweifel 1978; Houde 1978; Werner and Blaxter 1980). A review of these data (Hunter 1981) shows that differences exist between the required density of prey particles for first feeding larvae to survive and the densities found in the sea. Since pelagic fish larvae are successful in their environment, it is recognized that there must be patches of suitable concentrations of food organisms for first feeding larvae (Lasker and Zweifel 1978). This has been demonstrated for the northern anchovy, *Engraulis mordax*, in laboratory experiments by Hunter and Thomas (1974) and in a series of field investigations by Lasker (1978). Houde and Schekter (1978) have shown increased survival of larval bay anchovy, *Anchoa mitchilli*, and sea bream, *Archosargus rhomboidalis*, when exposed to simulated food patches in a laboratory experiment.

This work has been stimulated by Hjort's (1914) hypothesis which simply stated that larval mortality rates may be due to variable feeding conditions at a critical stage, which in turn causes variations in year-class strength. It has been difficult to test this simple hypothesis in field surveys because of the inadequacy of the sampling gear used (May 1974). To obtain a better understanding of the relationship between estimates of food densities required by fish larvae in the laboratory and densities found in the open sea, samples should be taken which are relevant to larval searching behavior. This would require an enormous number of plankton samples. It would be time-consuming to obtain these samples with conventional plankton gear. Furthermore, water movement and dispersion would make it difficult to obtain time and space relationships for studying the formation and dynamics of plankton patches (Steele 1978). One way of studying these relationships is by using in situ instruments (Boyd 1973; Pugh 1978; Tungate and Reynolds 1980).

In this study an instrument designed to count and measure particles in situ in the size range of food organisms most frequently captured by cod larvae was used. Investigations were made on the spawning and first feeding grounds of the Arcto-Norwegian cod, *Gadus morhua* Linnaeus, during two successive years (1980-81). During the first survey, investigations were made in a sheltered fjord where cod larvae are known to appear in high numbers (Ellertsen et al. 1977) and where the current system has been described (Furnes and Sundby 1981). The objective was to find and study the formation of microzooplankton patches and to study larval cod feeding under different environmental conditions with regard to food density, water turbulence, etc. In the following year, the main first feeding area, an open ocean bay, was surveyed in order to find and study the vertical and horizontal distribution of microzooplankton patches in this exposed area.

The present study is part of a project, started in 1975, dealing with growth, mortality, and drift of cod larvae in the Lofoten area (Ellertsen et al. 1976).

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MATERIALS AND METHODS

The Particle Counter

The in situ particle counter system was built and described by Mohus (1981), Eriksen (1981), and Eriksen and Mohus (1981). It is presented schematically in Figure 1. The system is based on a Hiac PC-320 Particle Counter[2] which works on the principle of light blockage. The sensor (E-2500, dynamic range 80-2500 μm) is installed in a pressure-proof box together with a depth detector. A pump is connected to the sensor, and the sensor and pump are mounted to a rig which is lowered into the sea by winch. Seawater is pumped through a 60 cm long by 2.5 cm diameter hose through the sensor orifice (3 mm), at a flow rate of 6.15 1/min. Particles are counted by the Hiac PC-320 Particle Counter and depth is monitored by the depth detector unit. The "Micro-count" datalogger unit contains an

[2]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

input-output interface to accomodate incoming data, a large internal data storage area, operator communication via a small CRT display, a keyboard, and a microprocessor with program to control the system. The microcomputer samples data from the Hiac PC-320 Particle Counter and the data sample time can be selected from 1 to 99 s. Finally, a Silent 733 terminal is connected to the microcomputer. This terminal contains a full text keyboard and a page printer used for initial operator communication and printout of data tables. Two cassette tape stations are included in the terminal.

The system operates from the surface to 50 m depth, and the registration of particles is presented on the TV monitor as the sensors are lowered into the sea. The vertical distribution of particles can be presented on the monitor at 1, 2, or 5 m depth, depending on the selected depth intervals. Data are, however, printed out in 1 m depth intervals from the surface to 50 m depth as concentration of particles per liter in six different size groups (150-600 μm) on the Silent 733 terminal immediately after the samples have been made. An in situ particle profile is
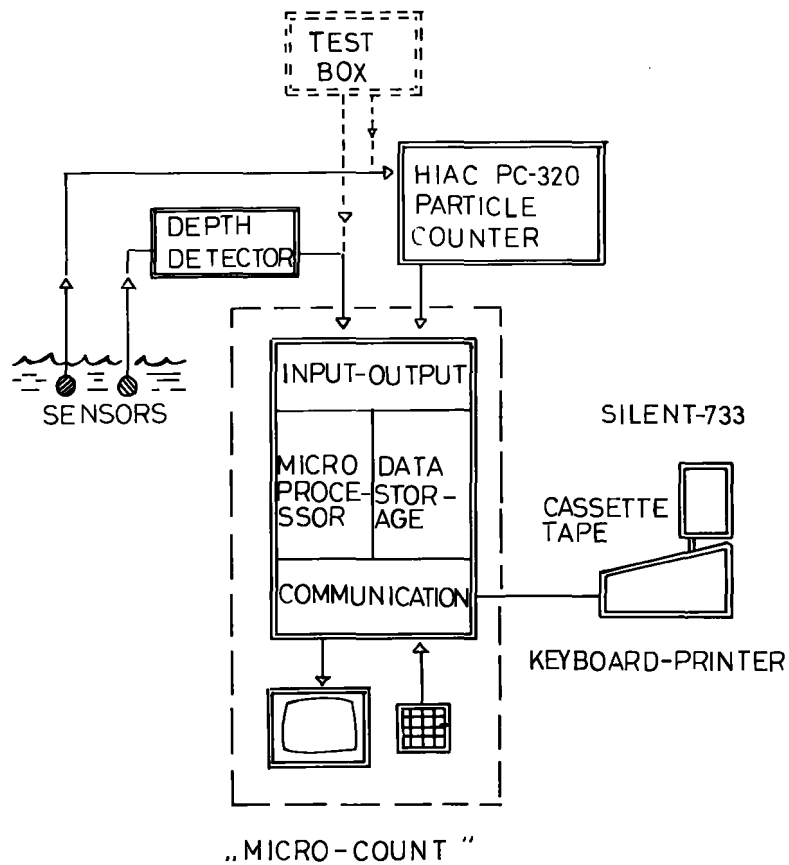

FIGURE 1.—The particle counter system.

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defined in the present paper as the concentration of particles within the size range of 150-600 μm from the surface to 50 m depth in 1 m depth intervals.

An object found in the Hiac sensor was measured so that the largest projected area was converted to a circle of the same area. By calibration, the object was given a length similar to the diameter of this circle.

The contours of *Artemia* nauplii were drawn by using a microscope drawing tube. Their areas were estimated by planimeter and converted to areas of circles and their diameters calculated. Their size distribution was then divided into four 50 μm length groups of 200 to 400 μm. Four of the Hiac Particle Counter channels were set according to the sensor calibration diagram to the corresponding size groups.

The instrument system was tested and calibrated in the laboratory by comparing microscope and Hiac measurements of the size-frequency distribution of a sample of laboratory hatched *Artemia* nauplii. Tests were also made at sea when the research vessel was anchored. The in situ instrument data were compared with plankton pump samples taken simultaneously. These samples were taken by a submersible electric pump (Flygt 2051, 250 l/min) which pumped samples on deck through a 50 m long by 5 cm diameter hose. Samples were taken at 0, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, and 40 m depths. This is defined as a zooplankton pump profile. Seawater was collected in calibrated tanks (23.7 l), and zooplankton were filtered through 90 μm mesh plankton nets. Zooplankton were identified and counted by microscope, the whole sample (23.7 l) was counted. Results of the samples from these 11 depths were statistically compared with the in situ counts from corresponding depths by paired t-tests.

Field Investigations

The main objectives of field investigations were to use the in situ instrument system to find particle patches and to identify larval cod food organisms and study their vertical distribution. Observations were made in the Lofoten area (Fig. 2). The effect of wind driven turbulence on the distribution of particles and the consequences on larval cod feeding incidence were studied in the Austnesfjord (Fig. 3), which is in the main spawning area of the Arcto-Norwegian cod. Stations and sections in the Austnesfjord are shown in Figure 3. A section is a transect with a series of stations. Austnesfjord was chosen because cod larvae are known to appear in high numbers (Ellertsen et al. 1977), and the dynamics of the current system

are known (Furnes and Sundby 1981). During the 1980 cruise, a Wolfe wind recorder was placed on land in the fjord to continuously measure wind velocity and direction.

In 1981, observations were also made in the main first feeding area, an open ocean bay (Fig. 2), for cod larvae. The objectives were to find these food particle patches for cod larvae and to investigate the extent and densities of these patches in this exposed area.

Distribution of cod larvae in the first feeding areas was studied from the Juday net (80 cm, 375 μm mesh) samples taken in vertical hauls from 30 to 0 m. In the Austnesfjord, three stations were taken on eight sections (Fig. 3). The vertical distribution of cod larvae in the Austnesfjord was investigated only when the ship was anchored. A total of 42 samples were taken by a submersible electric pump (Flygt B2125, 3.4 m³/min) at 5, 10, 15, 20, 25, 30, and 35 m depths every 3 h from 1600 h 13 May to 1000 h 14 May 1980. Fifteen cubic meters of seawater was sampled at each depth. Seawater was pumped through a 40 m long by 15 cm diameter hose and filtered through a Juday net (40 cm, 180 μm mesh) into a large tank on deck. Cod larvae were preserved in 4% Formalin in 10‰ seawater solution. Gut contents of
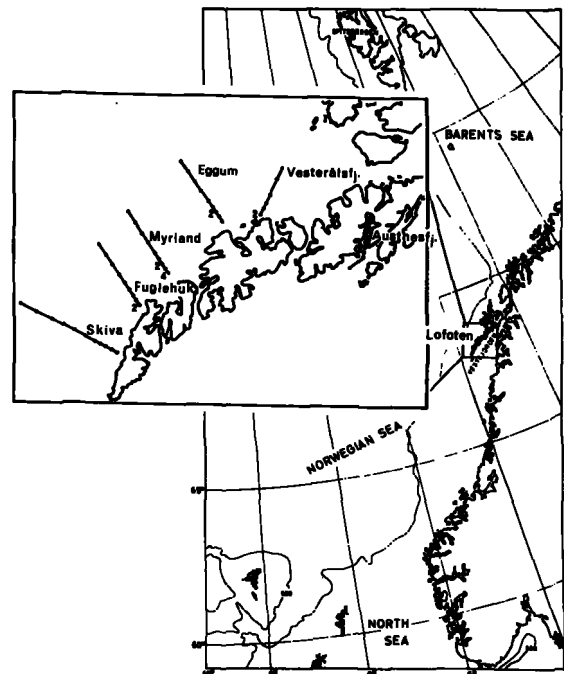

FIGURE 2.—Map of the Lofoten area with stations and sections 21 April-8 May 1981. The figures on the stations refer to number of cod larvae/m² surface.
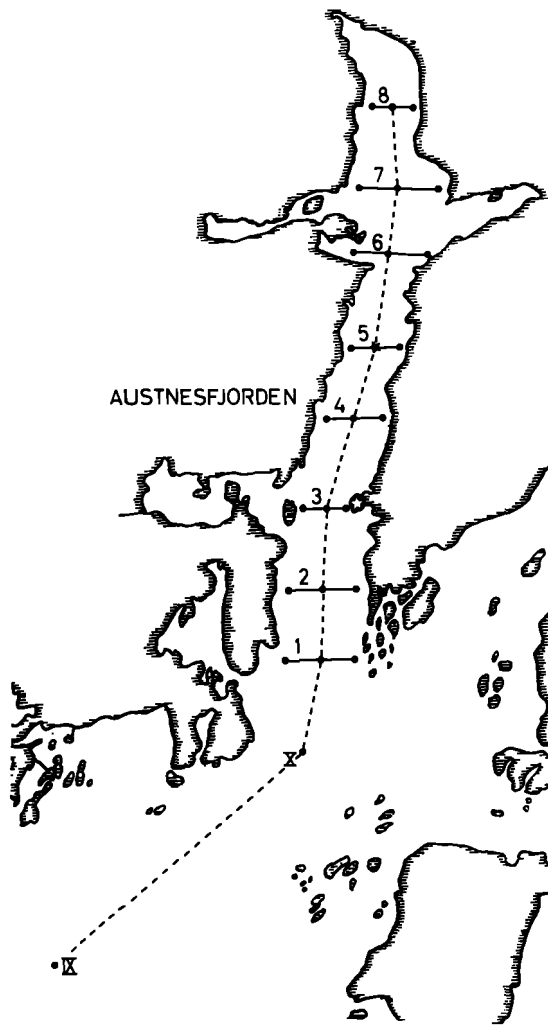
FIGURE 3.—Map of the Austnesfjord with stations. ● Juday net and particle/zooplankton stations, position of the 24 h station ★, and the Wolfe wind recorder ☆.

Size (μm)	No. of *Artemia* nauplii counted by	
	Particle counter	Microscope
200-249	101	5
250-299	416	14
300-349	848	23
350-399	177	3

1. A chi-square test for independence in the 4 × 2 table (3 df) showed no significant difference ($P < 0.05$) between the two methods of measuring *Artemia* nauplii.

Paired tests between microscope and in situ particle counts were done on data from two different 24-h stations in the Austnesfjord (Figs. 4, 5). Plankton pump samples were taken from 11 different depths on each profile, and the mean counts from these depths were tested against the mean in situ counts from the same depths. A comparison was also made between the mean of all plankton pump counts from each profile, and the mean of all in situ counts from the corresponding profile.

During the first 24-h station, 19 vertical profiles were made. No significant differences ($P < 0.05$) was found when the mean counts ($n = 19$) from each of 11 different depths were compared, nor when the mean counts from the different profiles were compared. The same statistical test was made on data from 14 vertical profiles on the second 24-h station. There had been an increase in the variability of microzooplankton both horizontally and vertically during this 24-h station (Fig. 5A, B). No significant differences ($P < 0.05$) was found between the mean in situ counts and the mean plankton pump counts when the different profiles were tested. We found, however, a significant difference ($P < 0.05$) when the mean counts from corresponding depths were tested. This difference was found between in situ and plankton pump counts both from 30 and 40 m depths. No significant difference ($P < 0.05$) was found between counts from 0, 0.5, 7.5, 10, 12.5, 15, 20, and 25 m depths. This difference may have resulted from samples having been taken at different depths. The in situ instrument was equipped with a depth detector, but the depth of the submersible pump was controlled only by the meter wheel on the winch.

Distribution of Particle/Nauplii in the Fjord

The vertical distribution of particles/nauplii for a 24-h station made during 22-24 April 1981 in the

about 20 larvae from each depth were examined by dissecting the larval gut under the microscope.

During 24-h stations in situ particle profiles, CTD profiles, and zooplankton pump profiles were made simultaneously every 2 h. On sections, zooplankton pump profiles were made on every second station.

RESULTS

In Situ Instrument Tests

Results of the comparison between microscope and particle counter measurements is presented in Table
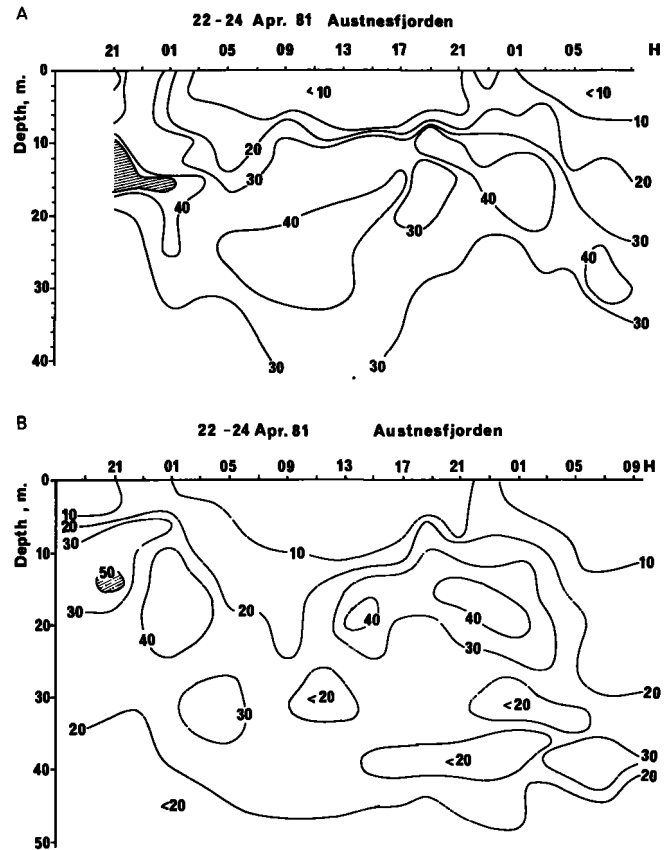
FIGURE 4.—Isopleth diagrams of the particle concentrations (per liter) (A), and nauplii (per liter) (B), center station, section 5 in Austnesfjord, 22-24 April 1981.

Austnesfjord is presented in Figure 4A and B. The maximum observed particle concentration was a small patch of 50 particles/l at about 15 m (Fig. 4A). A patch of 40 nauplii/l at the same depth was identified from pump samples (Fig. 4B). The particle/nauplii isolines in the upper 20 m show a tendency of ascending towards the surface at midnight, indicating their diel vertical migration. This observation was repeated on another 24-h station made 6 d later at the same position (Fig. 5A, B). Particle concentration had increased markedly during this period; more than 50 particles/l were found at 25-35 m depth on every profile. A very dense surface patch was found at midnight with more than 500 particles/l. Figure 5B shows a similar distribution of nauplii during the same 24-h station. Since there was no wind in the fjord and consequently little or no vertical turbulence, the hydrographic conditions during this 24-h station were perfect for this type of observation. This is shown in Figure 6 where the hydrographic conditions is presented by the temperature distribution in the upper 60 m.

Figure 7A and B presents the particle (150-600 μm) distribution from 0 to 40 m depth through a section of the Austnesfjord made at night on 27-28 April 1981 from 2130 to 0420 h. There was little or no wind in the fjord when the section was made. Patches of more than 100 particles/l were found in the surface water of the outer parts of the fjord. A particle minimum layer (<10/l) was observed at 10 m in the middle of the fjord. In the bottom of the fjord three patches of more than 50 particles/l were found at different depths. Figure 7B shows the naupliar distribution on the same section. Highest concentrations (>100/l) were observed in the bottom of the fjord, at intermediate depths and in the surface water of the outer parts of the fjord.

The same section made through the fjord the next day from 0950 to 1610 h (Fig. 8A, B) showed that the particle/nauplii distribution in the fjord had changed completely. A particle/nauplii minimum layer (<10/l) was found from the surface down to about 20 m through most of the fjord length. The surface patches in the outer parts of the fjord had disappeared. Only
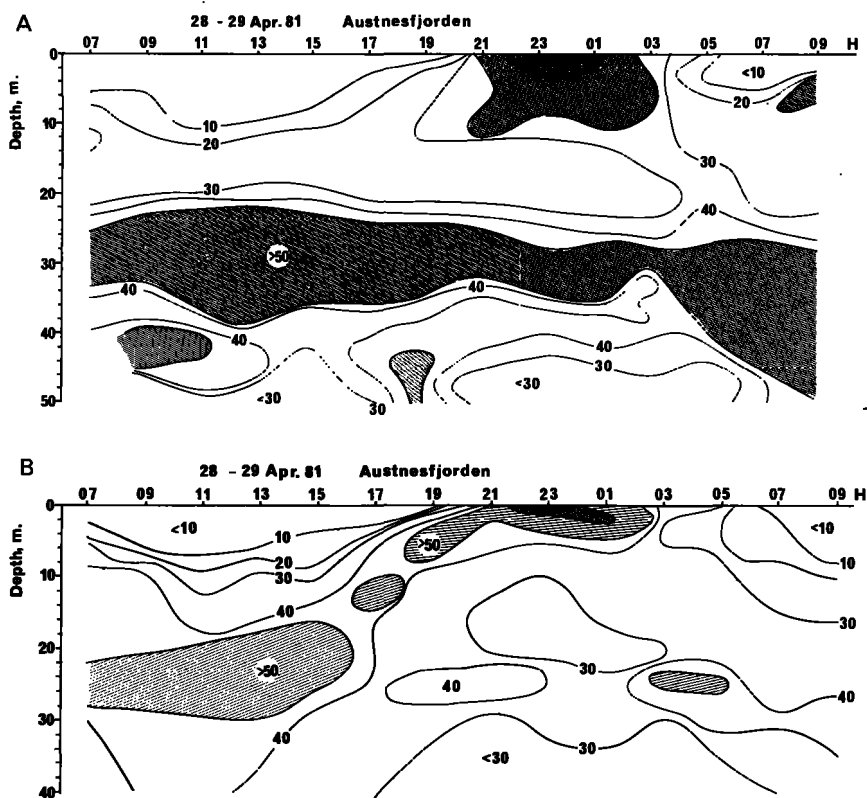
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FIGURE 5.—Isopleth diagrams of the particle concentrations (per liter) (A), and nauplii (per liter) (B), center station, section 5 in Austnesfjord, 28-29 April 1981.
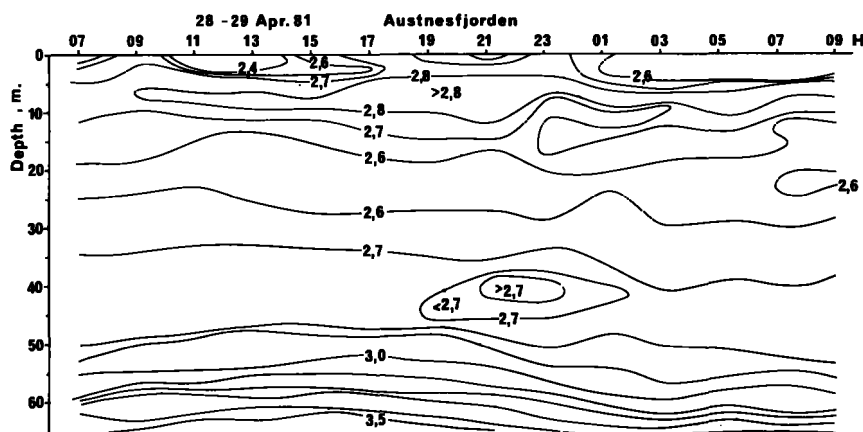

FIGURE 6.—Isopleth diagram of the temperature distribution, middle station, section 5 in Austnesfjord, 28-29 April 1981.
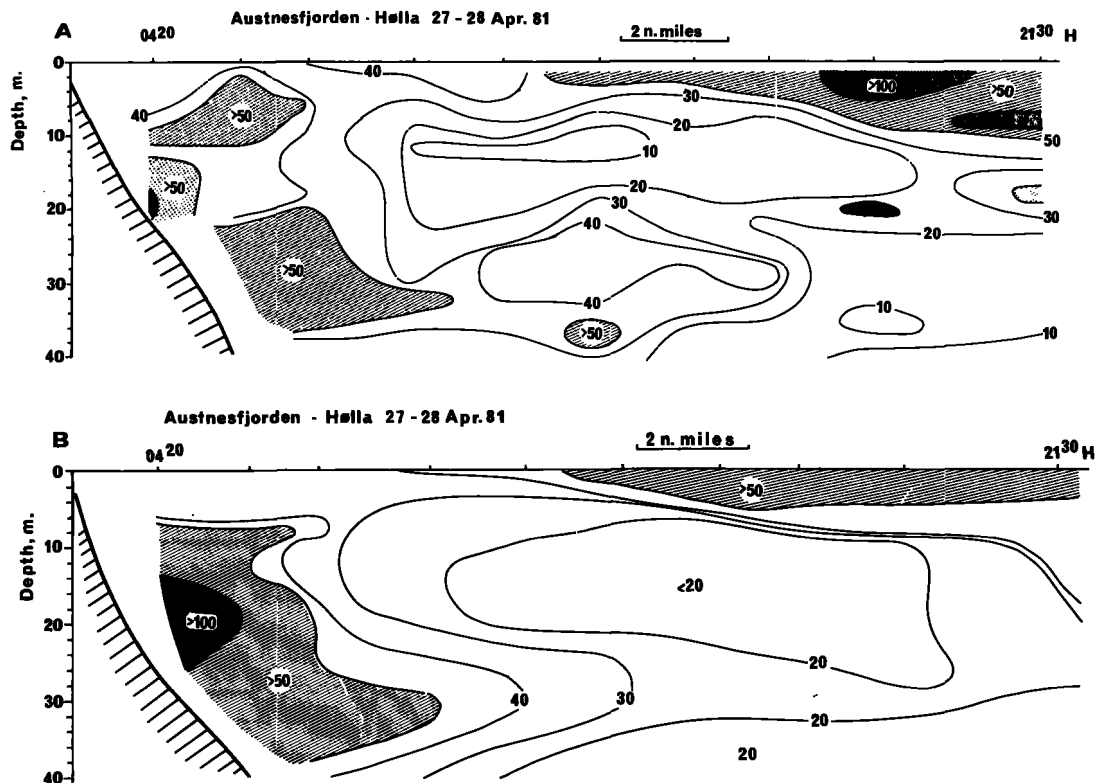
FIGURE 7.—Particle (A) and nauplii (B) distributions (per liter) in the upper 40 m of Austnesfjord, 27-28 April 1981, at 2130 to 0420 h. (Particle size range 150-600 μm, nauplii all sizes.)

one patch with >50 particles/nauplii per l was observed between 20 and 40 m at the bottom of the fjord.

Effect of wind driven turbulence on vertically migrating particles is presented in Figure 9A, B, and C. The figure presents data collected continuously from 9 to 15 May 1980, on wind velocity and direction, temperature, and particle distribution in the water column. Due to technical problems, only particles within the size range 300-500 μm were measured by the particle counter in 1980. From 9 to 12 May the wind was blowing downfjord with varying velocity. On 12 May the wind changed direction 180° and blew upfjord with a velocity of 5-10 m/s (Fig. 9A). Unfortunately, observations of temperature and particle distribution were not made from 10 to 11 May. However, one 24-h station was made on 9 May during the period when the wind was blowing downfjord. At this time, the upper 10 m of the water column showed tendencies of mixing, and colder intermediate water

masses were observed from 15 to 55 m above the transition layer. Within the cold intermediate water masses a particle maximum layer was found (Fig. 9C). It is believed that the wind was blowing the surface water downfjord and this was compensated for by intermediate water masses moving in the opposite direction. On 9 May we observed a patch of particle-rich intermediate water moving in from the outer part of the fjord. The particle isolines in the upper 10 m followed the isotherms (Fig. 9B, C). When the wind direction reversed and increased in velocity on 12 May (Fig. 9A), the fjord became more exposed to the wind force and the wave action from the open ocean outside the fjord. Under this condition the current system will reverse (Furnes and Sundby 1981). The surface water became completely mixed within about 24 h (Fig 9B), and no particle diel vertical migration was observed during this condition (Fig. 9C). The particle concentration decreased and became almost homogeneous from the surface to 40 m.
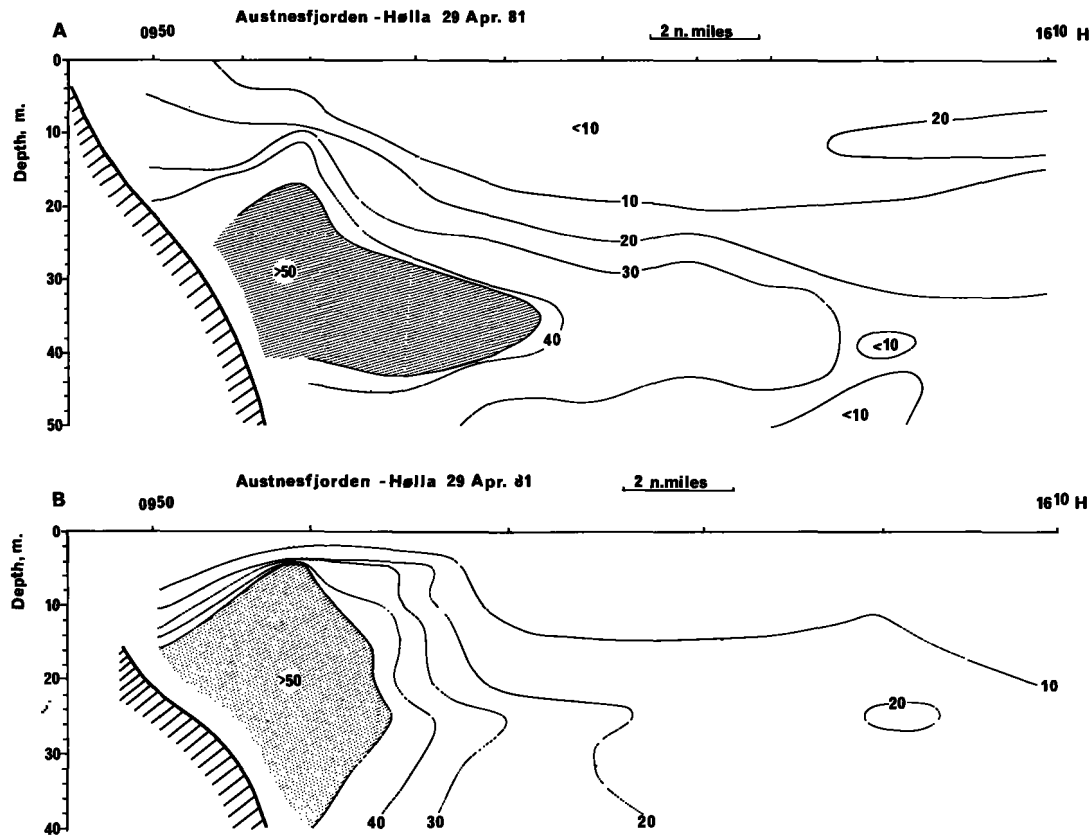
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FIGURE 8.—Particle (A) and nauplii (B) distributions (per liter) in the upper 40 m of Austnesfjord, 29 April 1981, at 0950 to 1610 h.

Distribution of Cod Larvae

The highest concentration of cod larvae (140-290 larvae/m²) was observed in the middle of May at the bottom of the Austnesfjord both in 1980 and 1981 (Fig. 10). This has also been observed on previous cruises (Ellertsen et al. 1977). The research vessel was therefore anchored at the middle station on section 5, where 24-h stations were made.

In 1981, the study of the distribution of cod larvae in the exposed open ocean bay of Vesterålsfjorden showed that larvae were only found on the innermost stations with a maximum of 4 larvae/m² (Fig. 2), e.g., only two cod larvae in vertical Juday net hauls from 30 m depth.

Gut contents of 738 cod larvae were examined from 39 pump samples. Fewer than 10 larvae were found in pump samples from 30 and 35 m depths from the 01-02 h pump profile and from 35 m depth from the

04-05 h pump profile. These larvae have not been included in the analysis (Fig. 11B). A total of 1,204 prey organisms were found, out of which 96.5% were identified as copepod nauplii. Only 1.7% of the prey organisms could not be identified. About 0.5% of the larval cod gut content was bivalve veliger larvae, copepod eggs, and phytoplankton (*Peridinium* sp.), and 1.3% was identified as copepod fecal pellets. The size distribution of the main prey organisms (e.g., copepod nauplii) ranged from 140 to 520 μm with a mean size of 224 μm (all measurements as carapace length).

Gut content analysis of cod larvae is presented in Figure 11B as feeding incidence (percent larvae with gut content) and larval feeding ratio (number of prey organisms per larval gut). The feeding incidence varied between 73 and 100% in samples from the three pump profiles taken before midnight. In 61% of these samples the feeding incidence was as high as
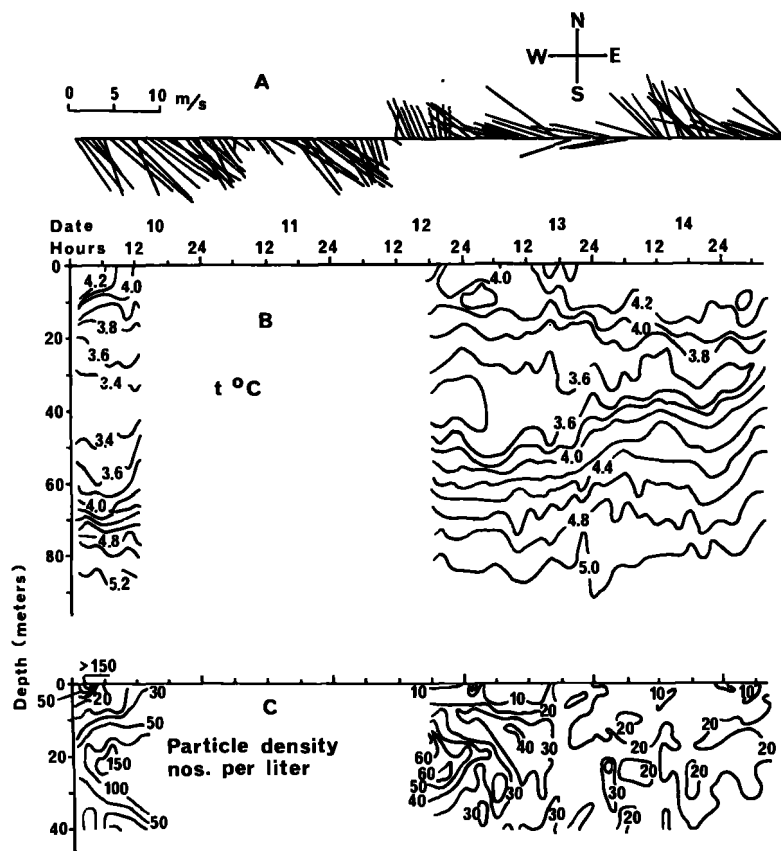
FIGURE 9.—Wind velocity (length of vector, see m/s scale) and direction from the abcissa (A), isopleth diagrams of temperature (B), and particle concentration (300-500 μm) distribution (C), at the middle station on section 5 in Austnesfjord, 9-15 May 1980.

90-100%. The larval feeding ratio was ≥1 prey/larval gut in all samples taken before midnight. In 71% of these samples the feeding ratio was ≥2 prey/larval gut and in 14% of the samples ≥3 prey/larval gut. In samples taken after midnight, however, the feeding incidence varied between 4 and 92%. The lowest level was found in pump samples from 25 m depth from the 01-02 h profile. In 38% of the samples taken after midnight the feeding incidence was <50%. Only in the last pump profile made at 09-10 h the larval feeding incidence was more than 50% in all samples. The feeding ratio was <1 prey/larval gut in all samples from 01-02 h profile, and ≤1 prey/larval gut in 61% of all samples taken after midnight. A feeding ratio level <1 prey/larval gut was not observed in samples taken before midnight. The highest feeding ratio observed in samples taken after midnight was

1.65 prey/larval gut from the 25 m depth samples taken from the 09-10 h pump profile.

Distribution of Particles/Nauplii in Open Ocean Waters

The main first feeding area of the Arcto-Norwegian cod is thought to be the waters outside the Lofoten islands and in the open ocean bay of the Vesteråls-fjord (unpubl. data). Figure 12A and B shows the particle and nauplii distributions in the northeast section in the Vesterålsfjord. Plankton pump samples were only taken at every second station on the section. The figure shows a similar distribution pattern. However, due to the more frequent samples taken by the particle counter, a more accurate distribution picture of the particles on the section was achieved.
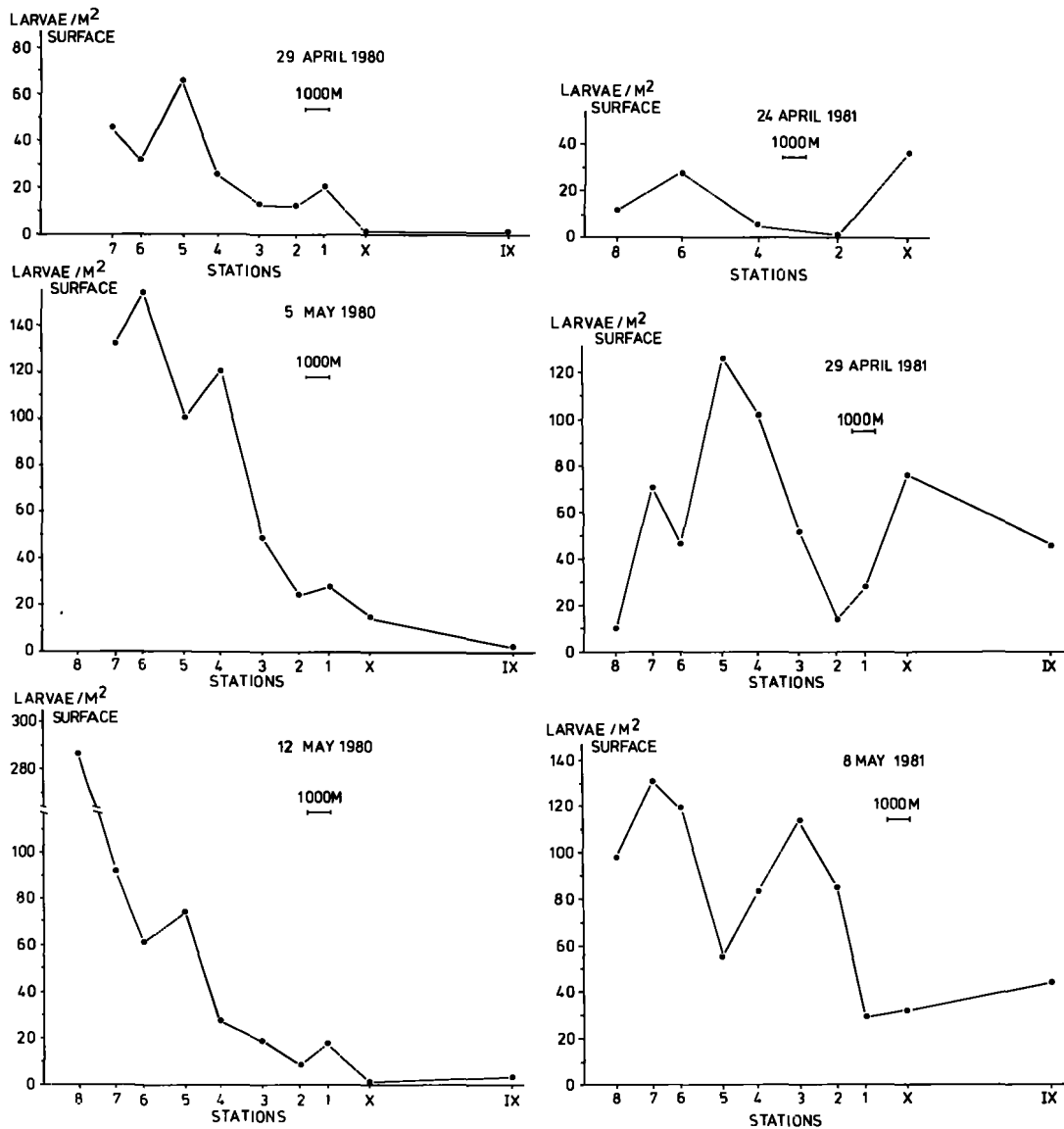
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FIGURE 10.—The average number of cod larvae/m² surface on sections 1-8 and stations X and IX in the Austnesfjord, April-May 1980 and 1981.

Sections were also made at four locations in the open water off the Lofoten islands. On three of these sections (Eggum, Myrland, and Fuglehuk), patches with high particle concentrations (≥50/1) were observed about 11 km (8 n mi) off shore. All sections had low particle concentrations (10-30/1) in the surrounding water masses (Figs. 13-15). The similarity of the positions of these three patches suggests that they are components of the same water mass with higher

particle concentrations than the surrounding water masses. On the Skiva section (Fig. 16A-D) the particle distribution patterns were more complicated. The section was surveyed during daytime and two patches were observed, one at about 5-10 m (>100 particles/l) and another 20-25 m (>50 particles/l). Particle concentration decreased further offshore. The same section was surveyed at night (Fig. 16C), and two surface patches were found.
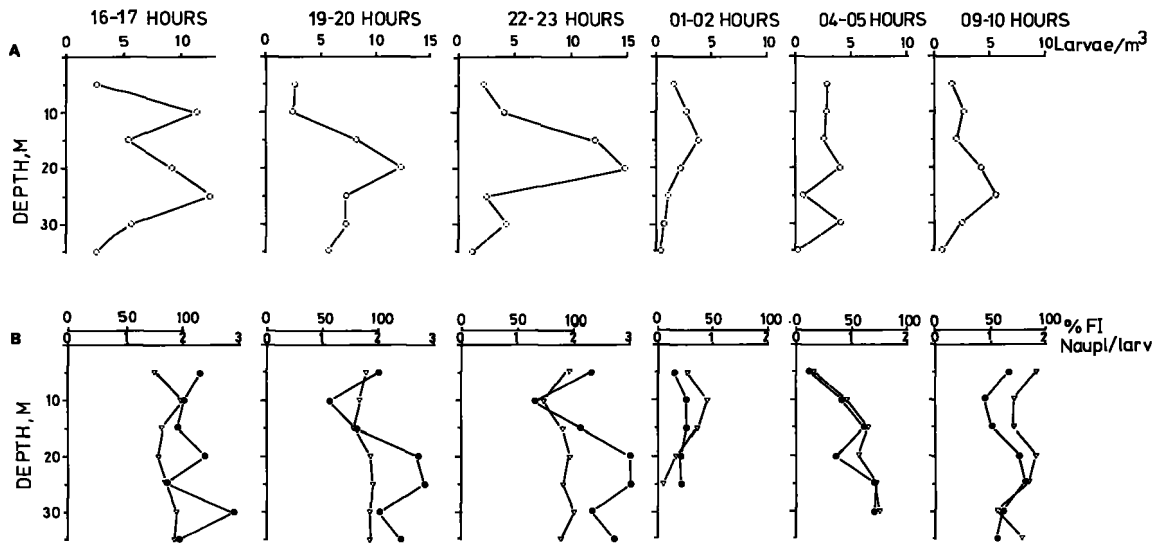
FIGURE 11.—Distribution of first feeding cod larvae (per m³) (A), and the larval feeding incidence (% larvae with gut content) ▽ and larval feeding ratio (nauplii/larval gut) ○ (B), during the 24 h sampling station, 13-14 May 1980, at middle station, section 5 in Austnesfjord.
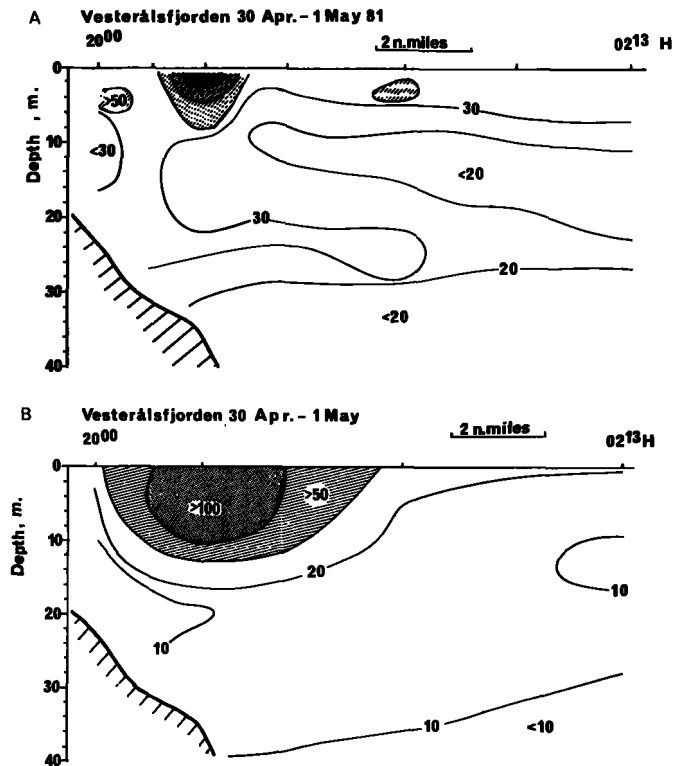

FIGURE 12.—Particle (A) and nauplii (B) distributions (per liter) in the upper 4 m on the section in Vesterålsfjord, 30 April-1 May 1981.
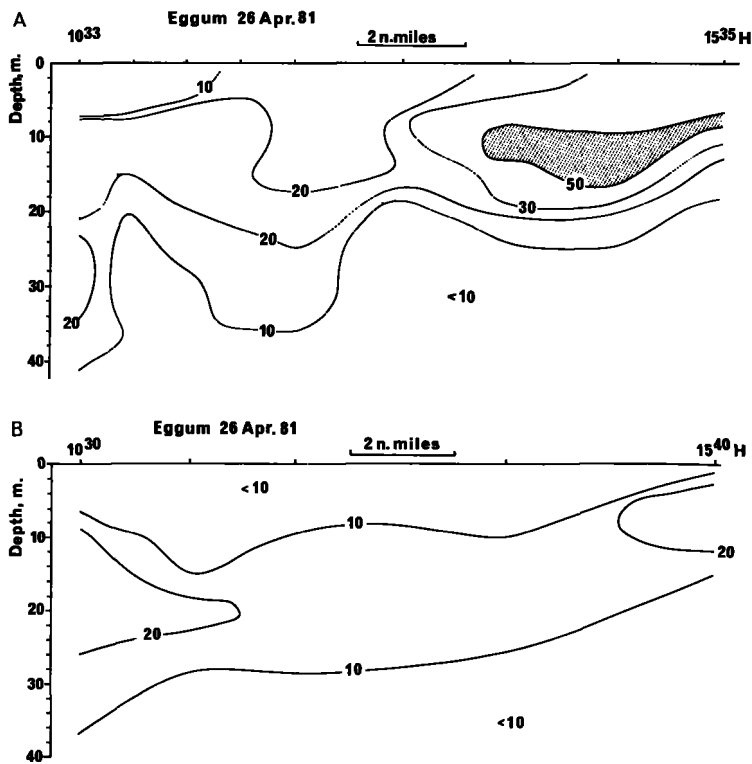
FIGURE 13.—Particle (A) and nauplii (B) distributions (per liter) in the upper 40 m on the
Eggum section, 26 April 1981.

DISCUSSION

Food particles found in the alimentary tract of larval cod consist, with few exceptions, of copepod nauplii in the size range of 140-520 μm. This observation did not differ significantly from that of Ellertsen et al. (1977), who found the size variation to be within 140-600 μm. The in situ instrument was set to detect particles in this size range. Investigations have shown that in May copepod nauplii outnumber all other particles in this size range in the Lofoten area (Ellertsen et al. 1977; Wiborg 1948a, b). The main objective when designing this instrument was to obtain a quick, reliable impression of naupliar distributions without laborious, time-consuming countings by microscope. The tests performed to compare the in situ instrument system and the plankton pump samples showed good agreement between the two methods. The critical food concentrations for first feeding cod larvae are not precisely known. They are thought to be on the order of 40-200 nauplii/l based on studies of swimming activity, larval search volume, and oxygen requirements of first feeding cod larvae

(Solberg and Tilseth 1984). Patches of particles/nauplii with the required densities for first feeding cod larvae to survive were found in the spawning and first feeding area by these methods.

The results presented in this paper show some of the dynamics in the formation and distribution in time and space of microzooplankton patches. The vertical distribution and density of nauplii changes due to the diel vertical migration of these organisms (Figs. 5, 6).

The concentration of particles/nauplii in a patch was dependent on the hydrographic situation and on the distribution and concentration of microzooplankton in the water column (Figs. 5, 6). Consequently the vertical distribution of particles and nauplii will be dependent on factors such as hydrographic conditions and time of day when the observations are made.

Increased wind force caused mixing of the surface layers and led to a homogeneous vertical particle distribution. No surface patch was observed at night during windy conditions, and the mean particle concentration in the water column dropped steadily dur-
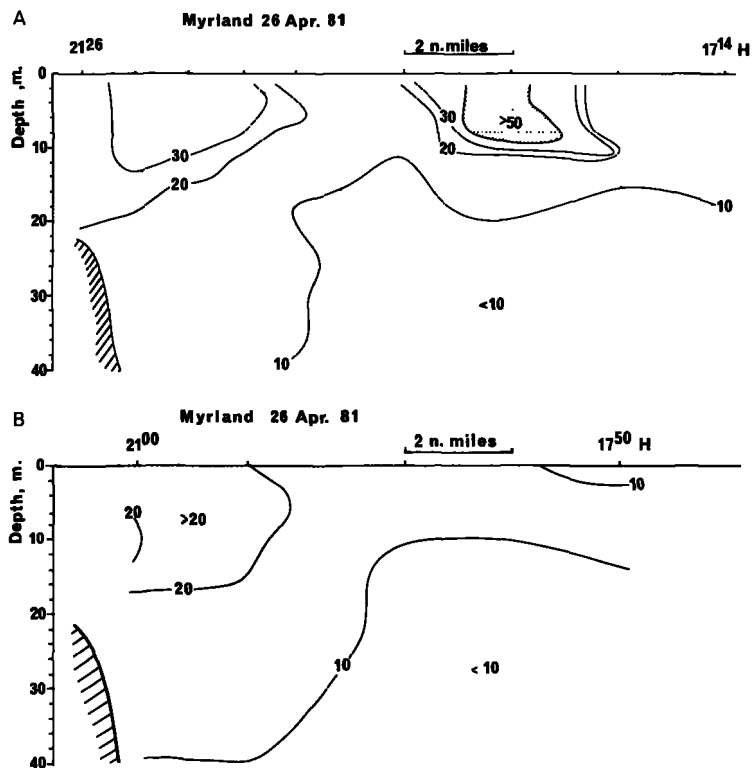
FIGURE 14.—Particle (A) and nauplii (B) distributions (per liter) in the upper 40 m on the Myrland section, 25 April 1981.
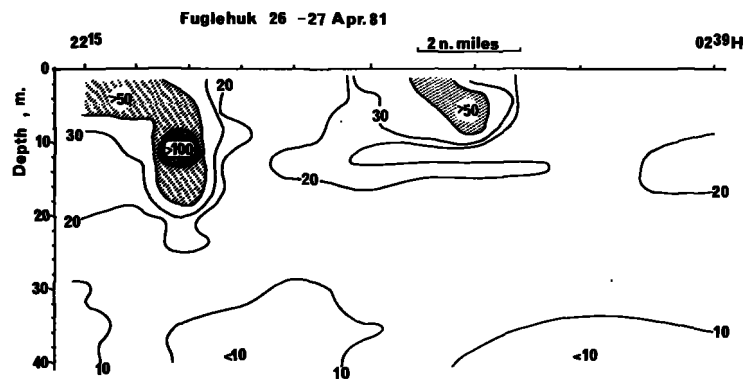

FIGURE 15.—The particle distribution (per liter) in the upper 40 m on the Fuglehuk section 26-27 April 1981.

ing the observation period (Fig. 10). This indicates that wind forces have caused increased water turbulence, and that these forces have exceeded the naupliar swimming rate. Mixing of surface layers and reduction in particle concentration occurred a few hours before midnight 13-14 May, and the water column became completely mixed down to a depth of 16 m (see Figure 10). Cod larvae were sampled both before and after this condition occurred (see Figure 11). Larval gut content analysis from these samples showed a reduction both in feeding incidence and feeding ratio in samples taken the first few hours
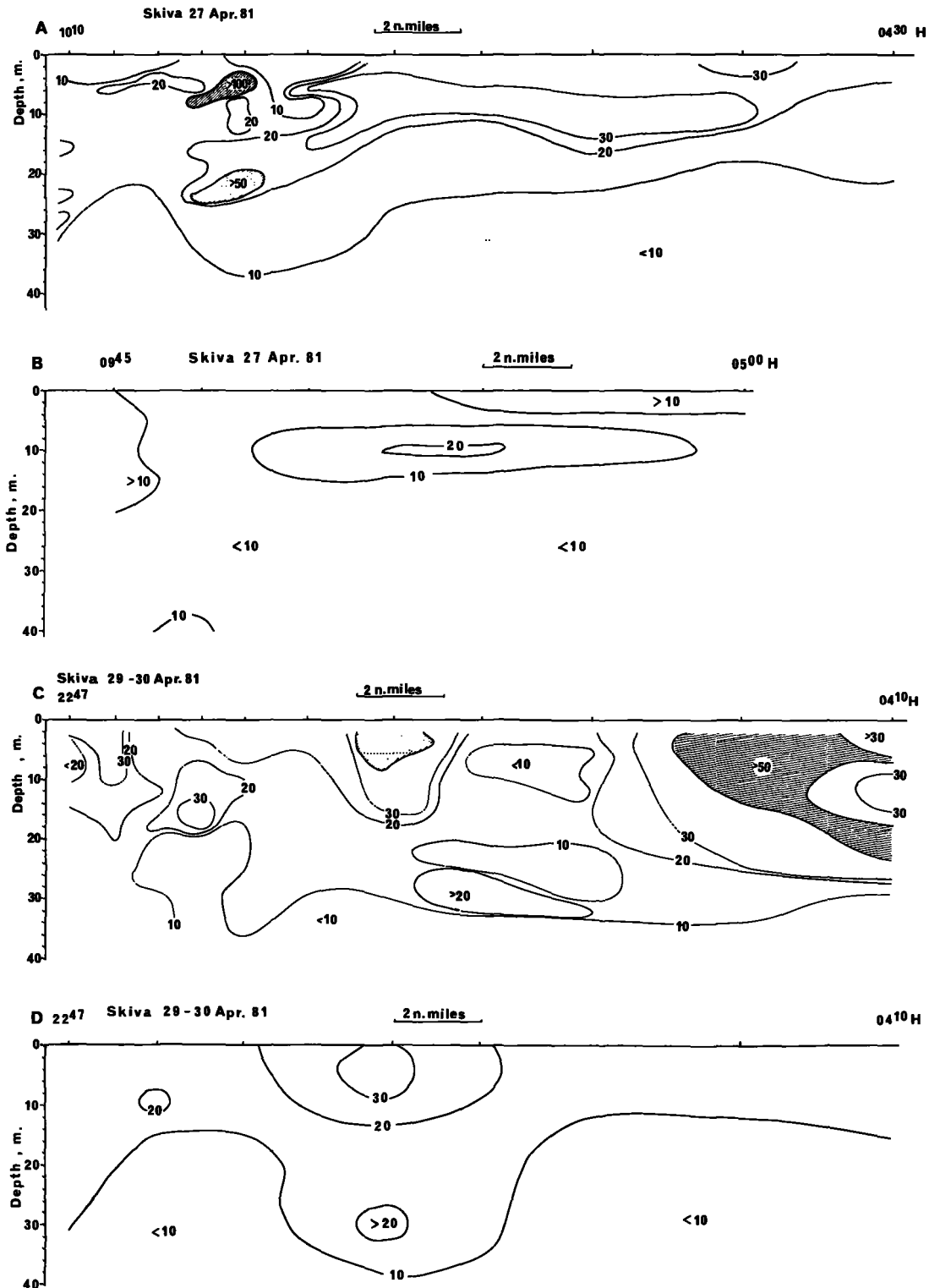
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FIGURE 16.—The particle and nauplii distribution (per liter) in the upper 40 m on the Skiva section 27 April 1981 (A, B) and the particle and nauplii distribution 29-30 April 1981 (C, D).

after this hydrographic condition had occurred. During the following hours the larval feeding incidence increased again, most rapidly in larvae sampled at 15-30 m, indicating that food particle concentration did not become critical. (Note that the particle concentration in Figure 10C only represents particles within 300-500 μm size range.) However, the feeding ratio did not increase significantly, indicating a more difficult accessibility of food particles to the larvae. Similar observations were made by Lasker (1975, 1978), where stability of the water column in the upper 30 m was necessary for food organisms to aggregate in concentrations high enough to exceed the threshold for feeding stimulus of first feeding northern anchovy larvae. This observed reduced feeding in cod larvae cannot be explained by a diel feeding rhythm. Cod larvae are visual feeders; the light intensity threshold for feeding is 0.1 lx (Ellertsen et al. 1980). The light intensity in the upper 40 m does not drop below this level in Lofoten in May, and cod larvae are found with newly captured nauplii in the gut at all hours (Gjøsaeter and Tilseth 1981).

The number of cod larvae found in the main first feeding area was too small to do a comparison on larval feeding conditions. However, patches with particle/nauplii concentrations of more than 50/l were observed on every section made in this area. Sizes of these patches were, on the other hand, small compared with the volume of water surveyed. The life span of these patches is probably very short because of the influence of biological and physical factors, especially when the upper 50 m of the water column is unstable. This is the normal situation in the Lofoten area in May (Furnes and Sundby 1981). Therefore, prey organism patches with concentrations above the critical level for first feeding cod larvae would probably be broken down, due to increased water turbulence when the wind forces increase. A series of storms during the larval cod first feeding period could thereby have serious effects on larval feeding conditions and consequently on survival and recruitment.

ACKNOWLEDGMENTS

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