

INFLUENCE OF SEA TEMPERATURE ON HERRING DISTRIBUTION AND MIGRATION IN THE NORWEGIAN SEA IN APRIL 1997

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After spawning at the west coast of Norway, the Norwegian spring spawning herring migrates northwestwards into the Norwegian Sea to feed in early April. The herring enters areas with distinct oceanographic features both horizontally and vertically in the frontal zone between the warm Atlantic water and the cold Arctic water. The Atlantic water enters the central Norwegian Sea by means of the outer branch of the Norwegian Atlantic Current which runs northeastwards and further north- and northwestwards from the Faroe Islands as an unstable frontal jet.

To investigate the influence of sea temperature on the distribution and migration of herring, we performed two synoptic transects with the research vessels R/V "G.O. Sars" and R/V "Håkon Mosby" in April 1997. The R/V "G.O. Sars" recorded the herring distribution by echo integration, tracked selected schools by sonar and took samples by pelagic trawl, while R/V "Håkon Mosby" carried out continuous sea temperature and salinity recordings of the transects by operating a SeaSoar vehicle, undulating from sea surface to 300 m depth.

The relations between sea temperature, herring distribution and migrations horizontally and vertically are studied by combining the synoptic recordings from the two research vessels.

Keywords: echo integration, herring, Norwegian Sea, sea temperature.

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Introduction

The polar front between warm Atlantic water and cold Arctic water is characterised by a sharp decline in temperature together with high concentrations of zooplankton (Blindheim 1989).

We presume the front offers profitable foraging on zooplankton for actively feeding herring that are highly motivated by hunger proceeding the non-feeding periods of overwintering and spawning (Nøttestad et al. 1996, Fernö et al. 1998, Slotte 1999). The relationship between herring distribution and temperature is likely to be indirect, possibly through effects on biological production. There is generally higher concentrations of phyto- and zooplankton in frontal areas (Wiborg 1955; Mann and Lazier 1991), and this will attract pelagic fish to such productive areas (Skjoldal et al., 1993; Melle et al., 1994).

The migration of the mature herring after the spawning season are generally downstream in the direction of the current, and the stock appears to be contained within the Norwegian Sea gyral (Harden Jones, 1968). Runnström (1936) and Fredriksson (1944) suggested that the herring keep within the cyclonic current system of the Norwegian Sea, thus limiting the horizontal temperature range herring will experience during the feeding migration. Herring in the Norwegian Sea are also known to perform substantial seasonal variations in vertical distribution (Devold 1963; Nøttestad 1999), influencing the herring's vertical temperature range (Misund et al. 1997a).

After spawning at the banks of the Norwegian coast in February- March, most of the spent herring in recent years migrate out in the Norwegian Sea through a corridor between 67°N and 68°N (Misund et al., 1998). Adult herring follow the plankton bloom northwestwards in order to feed on the spawning concentrations of zooplankton (Pavshtiks, 1959; Østvedt, 1965; Melle et al., 1994). In April, herring swim westwards into the polar front areas between the warm Atlantic water and the cold Arctic water (Misund et al., 1997a). Smaller fish do not move so far to the north and west during the feeding season as compared to larger fish (Marty and Wilson 1960, Nøttestad et al., in press). Recent investigations on herring distribution in relation to temperature have suggested that herring do not move into colder water than approximately 2°C (Misund et al., 1997a; 1998), and herring has not been observed to cross the polar front during the feeding migration after the stock collapse in the late 1960's (Røttingen 1989; 1992; Dragesund et al., 1997; Misund et al., 1997b; Vilhjálmsón et al., 1997). In the sixties, on the other hand, herring were found feeding along the cold front east of Iceland, but passed through the front containing sea temperatures below 2°C and entered the feeding areas north of Iceland in early June (Østvedt 1965). The present cruise was part of the ICES coordinated survey activity on Norwegian spring spawning herring and the environment in the Norwegian Sea that have been established between EU, the Faroes, Iceland, Norway and Russia (Anon 1997b).

The spring movements of the herring may be governed by the seasonal changes in the production and distribution of their food (Fernö et al., 1998). Biological spring spreads north and north-west across the Norwegian Sea along the line of the branches of the Atlantic current. Pavshtiks (1959) suggested that the larger herring move from region to region feeding heavily on the pre-spawning concentrations of *Calanus finmarchicus* to reach the polar front at the time of biological spring when *Calanus hyperboreus* is abundant in the cold water.

Thus, temperature preferences connected to food concentration and distribution are believed to give useful information and knowledge on herring distribution (see also Maravelias and Reed 1995). The problem is although complex and a simple interpretation does not seem applicable, because the nature of the migratory mechanism is not fully understood (Harden Jones 1968; Fernö et al., 1998).

The purpose of this cruise was primarily to study the relationship between the physical and biological environment and the migration behaviour of herring schools in the Norwegian Sea. This field work aimed to give a synoptic view of herring distribution and migration in relation to temperature distribution using a SeaSoar undulating sensor. Two research vessels were used, R/V "G.O.Sars" and R/V "Håkon Mosby", and the spatio-temporal temperature profiles were linked to 3-D recordings of herring schools based on echosounder and sonar observations. This is one of the first studies attempting to link herring distribution to temperature profiles on the same spatio-temporal scale (micro- to meso-scale) (Levin, 1992; Mackinson et al., (in press)).

Material and Methods

In order to investigate the influence of sea temperature on the distribution and migration of herring, we performed two synoptic transects (Figure 1) with the research vessels R/V "G.O. Sars" and R/V "Håkon Mosby" in April 1997 (Figure 2). Continuous acoustic recordings of fish and plankton were made onboard R/V "G.O.Sars" from 6-22 April 1997 by a calibrated echo integration unit consisting of a 38 kHz Simrad EK500 working at a range of 0-500 m. The integration unit was connected to a Bergen Echo Integrator (BEI) for postprocessing of the recordings and allocation of area backscattering strengths (s_A) to species. The s_A –

recordings per nautical mile were averaged over five nautical miles. The echo sounder was operated with the following settings: max. power: 4000 W, time varied gain: 20 logR, pulse length: 1 ms, bandwidth: wide, angle sensitivity: 21.9, 2-way beam angle: -21.0 dB, Sv transducer gain: 25.0 dB, TS transducer gain: 24.9 dB, 3 dB beamwidth: 7.0 dB (Anon 1997a).

A 95 kHz Simrad SA950 sonar was used to record schools near surface at a range of 50-300 m to the side of the vessel, and to track selected schools in the survey area for a period of up to one hour each. The sonar was operated with the following settings; TX power: max, range: 300 m, pulse: FM auto, gain: 9, display gain: 9, TVG: 30 log R, AGC: weak, Normalization: weak, Ping-to ping filter: weak. The sonar is connected to a HP 9000 work station with software for detection and measurements of schools. This school detection system was operated with the following settings; minimum range; 50 m, maximum range: 300 m, colour detection threshold. 15, detection radius: 30 m, minimum gap: 5 m, minimum width: 5 m, minimum interval: 5 m, minimum detection pings: 4 (Anon 1997a).

The aim of school tracking was to obtain information about the dynamic behaviour of herring during their feeding migration in the Norwegian Sea. A differential geographical positioning system (dGPS) was applied for precise positioning of the tracked schools. In addition to depth, direction and speed of migration and the search path of schools in different areas, the school dynamics was studied by recording intra- and interschool events observed on the sonar screen on sheets and video-tapes for later analyses (Pitcher et al., 1996; Mackinson et al., (in press)). The school detection program calculated number, area and relative density of schools. Trawl stations by use of the Åkra-trawl with a vertical opening of about 30 m were taken to identify the species. At each trawl station CTD and MOCNESS stations were also taken to enable us to relate herring behaviour to the local physical and biological environment.

SeaSoar survey

R/V "Håkon Mosby" conducted continuous environmental recordings applying a SeaSoar CTD / ADCP vehicle. ADCP was running continuously with 5 min average interval and some varying cruising speed (4-5 knots). SeaSoar was used between the surface down to 300 m depth with 500 m cable. Transects were performed at 66°30' N between 1°32'58 E and 4°00'30 W and at 67°00' N between 2°04'35 E and 3°59'71 W (Figure 1). These transects took place from 14 April 1997, 13:40 GMT until 16 April 1997, 07:56 GMT.

ASCII-files with acoustic data from the echosounder (BEI) was imported to SAS system for Windows, Release 6.12 for further analyses. Graphical output on acoustic herring registrations was given as contour plot in AutoCAD LT 98, AutoCAD Release 14. Temperature data from the SeaSoar sensor was also imported to SAS and analysed in comparison to the acoustic data. Geographical maps were designed in MapInfo Professional, Version 5.0.1.

Herring survey

For mapping distribution, recording abundance and tracking selected herring schools, an area between 66° – 67° 30' N and 2° E – 4° W was surveyed by a regular grid with 30 nautical mile spacing north-south (Figure 1). In nine cases a proper herring sample was caught by the pelagic trawl. The herring in the area averaged 31.3 cm and 0.203 kg. The herring catches contained more than 50% females. The weather conditions were rather bad during the surveys, and we had wind stronger than 25 ms⁻¹ (Baufort force 6) for 12 of the 15 days at sea. In three occasions when the wind was about 45 ms⁻¹ (storm) we had to turn the vessel up against the waves and reduce the speed.

Results

Temperature distribution

In April 1997 there were considerable horizontal and vertical gradients in the sea temperature within the study area, while herring were mainly distributed between 1-5°C (Figures 3 & 4).

The herring made diurnal vertical migrations from between 300-400 m depth during the day to above 50-100 m during the night. The temperature range between the surface area and 400 m depth was up to 4°C in some areas. Distribution of herring along the horizontal (east-west) transects at 66°30' N and 67°00' N showed that herring did not cross the 2°C isotherm.

However, tracked herring schools were sometimes observed in deep water masses below 2°C for shorter periods (Figure 5). The temperature in the area surveyed was characterized by a distinct front from east to west which had its direction north – south at about 0°. At 50 m depth the temperature was about 4° C at about 0°, decreasing westwards and increasing eastwards. At 300 m depth the temperature was about 2° C at about 0°, and similarly decreasing westwards and increasing eastwards.

Herring distribution and migration

A total of 32 herring schools between 8-18 April 1997 were tracked from about 20 to 65 min in different positions within the study area (Figure 6). The schools were distributed all over the survey area, and occurred at depths from about 20 m to about 350 m. Generally, the schools were swimming at depths from 150-350 m during daytime (08:00-18:00), ascended to the surface during the evening, and descended during the night. Number of schools recorded on the echosounder within a distance of 5 nm varied between 0 and 13 distinct schools along the predetermined transects. After dawn the schools generally spread out close to surface to form loose shoals with low relative density, while reorganized into tight schools in the

morning. Schools recorded west of 0° occurred at greatest depths (Figure 5). The horizontal migration speed varied from $0,07$ to $1,75 \text{ m s}^{-1}$. Schools swam faster the higher the prevailing sea temperature in the range $1,43^\circ\text{C}$ - $6,24^\circ\text{C}$ ($r = 0,54$, $p < 0,05$). Herring schools swam faster in warmer and shallower water masses than deeper down in the water column, whereas no significant differences were found between school area and temperature. Smaller schools swam faster than larger schools, although no significant differences were found ($r = 0,34$, $p > 0,05$). Most schools headed in a southwestern direction, especially those schools swimming in shallow water (Figure 5). The average migration direction for the schools tracked was 195° and the average migration speed in that direction was $0,33 \text{ m s}^{-1}$. The analysis revealed that the swimming speed was significantly faster (Wilcoxon 2-sample test, $p < 0,05$) for the schools tracked during the night (average speed = $0,60 \text{ m s}^{-1}$, $\text{SD} = 0,46 \text{ m s}^{-1}$, $n = 21$) compared with the schools tracked during the day (average speed = $0,33 \text{ m s}^{-1}$, $\text{SD} = 0,09 \text{ m s}^{-1}$, $n = 11$) (Figure 7). There was no significant difference (Wilcoxon 2-sample test, $p > 0,05$) in swimming direction for schools tracked during the day or at night. Thus, the heading of the schools was independent of time of day. Herring school size measured as s_A -value showed significant positive correlation with depth along 67°N ($r = 0,60$, $p < 0,05$), while s_A -value showed a non-significant negative correlation with depth along $66^\circ 30' \text{N}$ ($r = -0,45$, $p > 0,05$).

The schools were relatively stable and the event rate was low ($\bar{e}_{\text{average}} = 1,89 \text{ events} * \text{h}^{-1}$). However, both joining ($j_{\text{average}} = 0,50 \text{ joins} * \text{h}^{-1}$) and splitting ($s_{\text{average}} = 0,66 \text{ splits} * \text{h}^{-1}$) of schools were repeatedly observed, indicating adaptive adjustments of school size to the prevailing conditions. Intraschool events such as clumping ($c_{\text{average}} = 0,12 \text{ clumpings} * \text{h}^{-1}$) and reorganization ($r_{\text{average}} = 0,15 \text{ reorganizations} * \text{h}^{-1}$) were also observed, as well as ring formation ($r^*_{\text{average}} = 0,09 \text{ ring formations} * \text{h}^{-1}$). Number of neighbouring schools observed during tracking varied substantially (0 to >10 , $n_{\text{average}} = 1,63$). There were some indications of

antipredator behaviour patterns. However, no mammal predators were observed visually in the distribution area of the herring schools, nor were any fish predators caught during the rather intensive trawling. Herring schools were observed to migrate vertically during the tracking period. When passing over the school after tracking to estimate school size and vertical extent, some but not all schools dived rapidly downwards up to 100 m. The diving reaction reflects antipredator behaviour, and the response variation may be caused by differences in the state of the schools.

Inspections of stomach content showed *C. finmarchicus*, *Euphausiids* and *Chaetognaths* to be important food items. At one station apparent feeding on larger food items, *Chaetognaths* and *C. hyperboreus* at almost 400 m depth during day time was observed.

Discussion

Herring migrations have been investigated over many years (Harden Jones 1968; Jacobsson & Østvedt 1996). Most studies are, however, descriptive and little is published about the factors that govern spatial distribution (see Fernö et al., 1998). Our cruises attempted to combine synoptically an acoustic exploration survey of herring and an environment exploitation and monitoring survey.

Atlantic herring tolerate a wide range of temperatures and salinities (Blaxter, 1985), and our results support this finding. The temperature tolerance of the herring probably changes with the season and other internal and external factors (Misund & al. 1997a). Marchall and Elliott (1998) showed that herring distribution was correlated to temperature, and that temperature proved to be the best predictor of total abundance. Herring are sensitive to temperature change

(Murawski 1993), and most pelagic species are able to detect temperature variations as small as 0.1°C (Sund et al., 1981) or less (Murray, 1971; Hoar and Randall, 1979), which allows them to orientate toward areas where the prey are usually more abundant (Fernö et al., 1998). Cushing (1968) stated that there is no simple relation between herring and temperature because the fish are found in dense patches at all temperatures from 2°C to 9°C. Yet, the distribution of sonar traces of herring in the Norwegian Sea bears some relation to the current structure and frontal areas (Tåning et al., 1955). Another boundary at which herring gather has been described by Steele (1961) in the eastern North Sea in spring. Former studies suggest that herring during feeding migration avoid very low temperatures by swimming fast out of such areas (Jakobsson 1969; Jakobsson and Østvedt 1996). Results from Maravelias (1997) indicated that areas with higher probability of finding herring present were located in well-mixed waters and transition zones between frontal and stratified waters. The largest herring aggregations were consistently observed in the same areas. Herring appeared to avoid the cold bottom waters of the North Sea during the summer, probably due to the relatively poor food resources there (Maravelias 1997).

Mocness-samples of zooplankton from studies in the cold front in the Norwegian Sea in April 1995 and 1996 showed that the prey organisms most important to herring peaked in abundance at 200-400 m depth (Dalpadado & al. 1996). By swimming at great depth, the herring thereby also increase the probability of encountering prey patches (Misund & al 1997a). The schools were relatively stable and the event rate was low compared to what has been observed in other situations (Pitcher et al., 1996; Mackinson et al., (in press)). Low temperatures measured in frontal areas with tracked schools may have reduced the swimming activity level of herring. The migration behaviour of the herring schools seemed to be influenced by the temperature distribution in the front.

Temperature may have both direct and indirect impact and implications for herring distribution and migration. Direct influence could appear in very cold water masses, where temperature drop below 1-2 °C. In our study, the migration or swimming speed was significantly lower in cold and deep water compared to the warmer water higher up in the water column. Low temperatures may put limitations on swimming capacity and speed (He 1993; Videler and Wardle 1991; Videler 1993), general metabolism (Videler 1993), as well as reduce the energy absorption capacity and physiological processes (Zachariassen, 1992). Woodhead (1959) have found that cod taken from water colder than 2 °C have more chloride in their blood than those taken from water warmer than 2 °C. In the colder water, then, the chloride-secreting cells in the gills were not functioning properly, in spite of the fact that these cells proliferate in fish in cold water (Cushing, 1968). With decreasing temperature enzymatic processes slow down and thereby also the chloride-secretion over the gills for marine fish, and if the bodyfluids ionic concentrations becomes altered, it may be lethal to the fish (Zachariassen, 1992). Since investigations on herring distribution in relation to temperature indicate that herring do not move into colder water than approximately 2° C over longer periods (Misund et al., 1997a; 1998), the effect that temperature has on membrane transport may therefore be a limiting factor for the outer distribution of these marine fish species. Additionally, various temperature regimes may indirectly influence the concentration and distribution of prey species in mixed water masses in cold front areas.

Waters with specific temperature properties are attractive to herring due to the process of frontal mixing which enhances primary and secondary production. Results indicate that herring appear to prefer the well-mixed waters and transition zones and avoid the stratified and frontal areas (Maravelias and Reid, 1997). The older year-classes of herring showed a

westerly movement along the transect from April to June, and were found farthest to the west (Misund et al., 1997b). The herring did not cross the cold front although feeding conditions, judged from zooplankton biomass distributions, seemed far better than in Atlantic water (Melle et al., 1994). Similarly, Misund et al., (1997a) found in another experiment that herring did not seem to cross the polar front when reaching the cold-water front, at about 0 degrees, and the herring turned southward along the front. Herring seem to concentrate at, or near such boundary areas, which are associated with high productivity (Maravelias and Reid, 1995). Since there is a preference towards these areas one might suggest that herring, to forage optimally, stay in the warmer waters because of the benefits from higher swimming capabilities with higher water temperatures. Swimming and foraging in areas with too low temperature may cost more than its benefits, even though food concentration may be highest in the coldest area (see Melle et al., 1994). Clearly, extreme temperatures may have a direct effect on herring behaviour, distribution and migration.

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Figure legends:

Figure 1. Map over the geographical positions of the two investigated east-west directed transects along 66°30' (- . -) and 67°00' N (- -) during the synoptic surveys 14-16 April 1997 onboard R/V "G.O.Sars" and R/V "Håkon Mosby" in the Norwegian Sea.

Figure 2. A synoptic survey design which illustrates R/V "G.O.Sars" performing acoustic mapping with sonar and echosounder as well as pelagic trawling, MOCNESS and CTD stations along predefined transects, while R/V "Håkon Mosby" applied the undulating SeaSoar CTD sensor to continuously monitor the temperature profile from the surface down to 300 m depth along the same transects.

Figure 3. Horizontal and vertical distribution and concentration (s_A -values) of herring in relation to temperature profiles down to 300 m along 66°30' N (002° E to 004° W). Note day/night marking and density differences in acoustic observations, and results from stationary CTD stations included down to 500 m along the transect. A total distance of 165 nm were analysed.

Figure 4. Horizontal and vertical distribution and concentration (s_A -values) of herring in relation to temperature profiles down to 300 m along 67°00' N (002° E to 004° W). Note day/night marking and density differences in acoustic observations, and results from stationary CTD stations included down to 500 m along the transect. A total distance of 165 nm were analysed.

Figure 5. Migration speed, direction and depth for 32 tracked herring schools in relation to sea temperature and geographical position along an east-west axis (3°00' W - 2°00' E).

Increasing length of the arrows indicate increasing migrations speed, while a colour scale is included to distinguish the sea temperature related to each school.

Figure 6. Map including migration speed and direction of 32 tracked herring schools in relation to geographical location of the schools and sea temperature in those specific areas.

Figure 7. Relation between herring migration speed (ms^{-1}) and temperature ($^{\circ}\text{C}$) at recorded migration depth for 32 tracked herring schools.













