NAFO Sci. Coun. Studies, 18: 35–42

Fluctuations in Abundance of the Baltic Cod (*Gadus morhua*) Stock in Relation to Changes in the Environment and the Fishery

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Abstract

Fluctuations in abundance and yield of the Baltic cod (*Gadus morhua*) stock was observed to vary with fishing effort and strengths of year-classes. The success of reproduction, and hence year-class strength, was closely related to the salinity and oxygen contents at depths where the cod eggs are deposited. A combination of salinity not less than 11‰ and oxygen content not less than about 2.3 ml/l was found important for fertilization success and egg development. Such conditions were dependent on inflows from the North Sea. The explosive development of the stock and yield in the late-1970s and early-1980s could not be explained by inflow and fishing effort exclusively, but possibly included an increased level of nutrients.

Key words: Abundance, Baltic cod, depth, *Gadus morhua*, eggs, North Sea, oxygen/salinity, reproduction

Introduction

A peak in abundance of cod (*Gadus morhua*) in the Baltic and the maximum yield in the recent history of the fishery have been registered in the late-1970s to mid-1980s followed by a drastic decline (Anon., MS 1990). The yield has been observed to fluctuate due to varying fishing effort and to varying strengths of year-classes (Anon., MS 1980, MS 1991; Thurow, 1974). The success of reproduction and hence the year-class strength is closely related to the salinity and the oxygen conditions in the depth strata where cod eggs are able to float (Wieland and Zuzarte, 1991). In this paper the fluctuations in abundance of the Baltic cod stock are discussed in the light of fishing effort, inflow of saline water and eutrophication.

The Baltic Area

The Baltic Sea is the largest brackish waterbody in the world covering an area of 375 000 km^2 with a volume of 22 000 km^3. The mean depth is 34 m and the maximum depth 459 m (Landsort Deep). The drainage basin covers an area of 1 750 000 km^2 yielding about 470 km^3 freshwater per year.

The Danish Straits and the Kattegat form a transition area to the North Sea (Fig. 1). Precipitation and evaporation is of the same order of magnitude, which means that the net outflow from the Baltic Sea is equal to the run-off from the drainage basin. The water exchange through the Danish Straits is, however, 6–10 times larger and dependent on differences between the surface level in the Kattegat and the western and central parts of the Baltic caused by the barometric situation. This means that inflow of saline water is mainly caused by persistent westerly winds, but also by a deep water current generated by the horizontal salinity gradient between the North Sea and the Baltic Sea.

Salinity

The Kattegat, the Danish Straits and the westernmost part of the Baltic are meeting points for the high saline water masses from the North Sea (35‰), and the brackish water masses from the Baltic (8–10‰ at the surface). Due to the difference in the specific gravity of the two water masses, a stratification occurs with the brackish Baltic water on the surface and the more saline North Sea water along the bottom.

In the transition areas there are two sills, one in the southern Sound at Drogden (depth 6 m) and another at Dars (depth 18 m) (Fig. 1), over which 20% and 80%, respectively, of the inflows have to pass. These prevent inflow of high saline water under average weather conditions and also cause a mixing of bottom and surface water reducing the salinity of the inflowing water very much. Only under extreme weather conditions is high saline water forced over the sills. With respect to salinity the result is that three strata are found in the Baltic; a more saline bottom layer, an intermediate layer with lower salinity and a brackish surface layer. Big inflows of high saline water occur very irregularly,

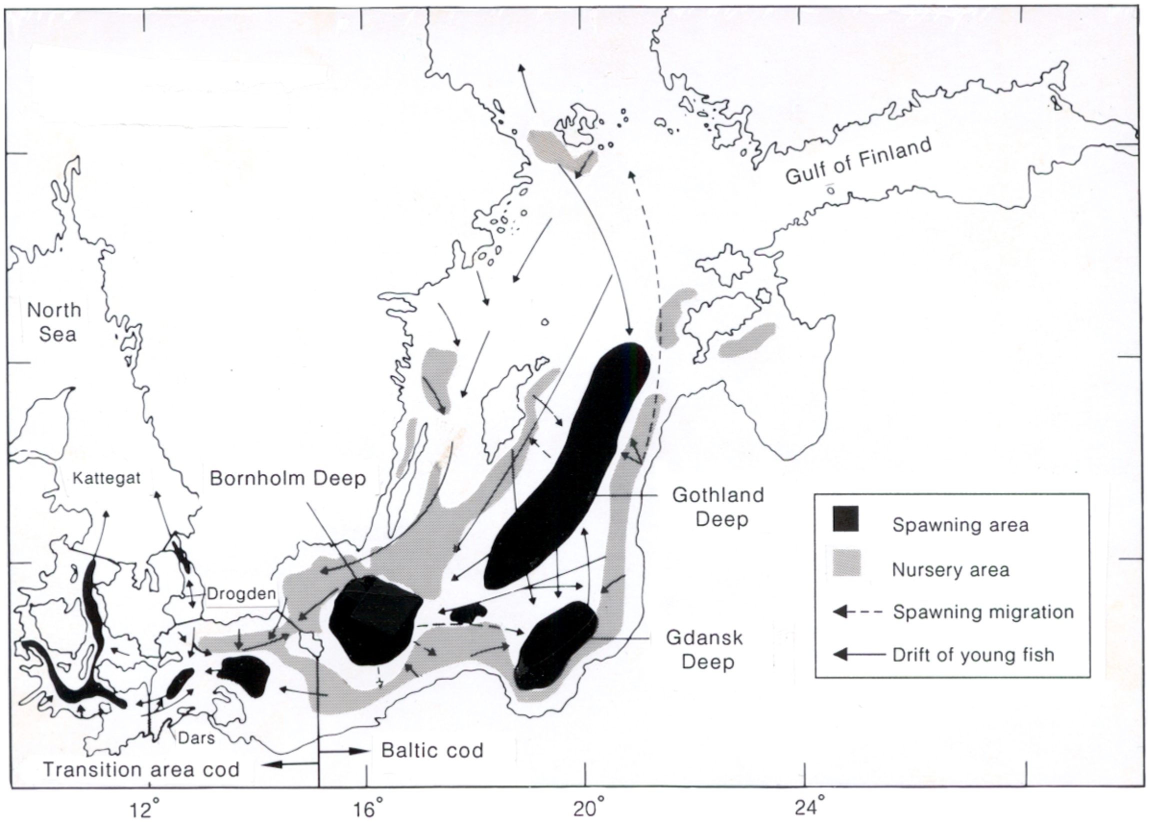

Fig. 1. Spawning and nursery areas in the Baltic. (Anon., MS 1978, appendix, with some additions).

and several years may pass in between. The average salinity in the bottom layer in the Bornholm Deep, in the Gdansk Deep and the Gothland Deep may be 18, 14 and 11‰, respectively, but these will decrease in periods with no inflow. The surface layer, which is almost isohaline vertically, is separated from the deep water by the primary halocline. The transition layer is about 10–20 m thick. The depth of the halocline increases from 50 to 60 m in the Bornholm Deep to 80 m in the Gothland Deep. The salinity in the surface layer is about 7‰ in the Gothland Deep and 8‰ in the Bornholm Deep.

Oxygen

The surface layer above the halocline is supplied with oxygen by thermal convection but the halocline forms an effective barrier to convection, which means that the main oxygen supply below the halocline is dependent on inflow through the Danish Straits. Due to sedimentation of organic matter there is a persistent oxygen consumption and, if not made up for by inflow, results in an extended but varying oxygen deficiency in the deeps depending on the frequencies of inflows. Since 1977, no major inflow has occurred (Fonselius *et al.*, 1984; Fonselius, pers. comm.) and the situation has been that of a decreasing salinity, a decreasing oxygen content and the development of hydrogen sulfide in the eastern deeps (Matthäus, 1991; Juhlin, 1990).

The fauna

The biomass of the fish has been dominated by a small number of species, of which the most important with respect to biomass could be listed in order of magnitude as herring, cod, sprat and flounder. The total biomass of these in 1990 was about 6.5 million tons. Other species are salmon and sea trout with a biomass about 5 000 tons in 1990, 4-bearded rockling and 3-spined stickleback which are not landed, turbot with a biomass about 1 000 tons in 1990. In the western part of the Baltic, there is an increased species diversity due to a higher salinity and a shorter distance to the Kattegat.

The Baltic Cod

The stocks

There are two stocks of cod in the Baltic Sea which are quite well separated by a border along longitude 14°30'E immediately west of Bornholm (Fig. 1). On the eastern side, the true Baltic cod stock is found to extend up to about 63°N latitude. On the western side, the transition area cod stock is found up to the southernmost Kattegat. The separation of stocks is shown by meristic characters

(Schmidt, 1930), by electrophoresis (Sick, 1965; Jamieson and Otterlind, 1971) and by numerous tagging experiments (Aro, 1989). A review of stock identification in the Baltic is given by Bagge and Steffensen (1989). The total stock size of the western and eastern stock in 1989 was 40 000 tons and 350 000 tons, respectively (Anon., MS 1991). In the following only the true Baltic cod stock on the eastern side will be considered.

Landings

The landings of cod from ICES Subarea III d as reported in the ICES Report of the Working Group on Assessment of Demersal stocks in the Baltic, and the Bulletin Statistique (Bull. Stat., 1990 and Anon., 1990), are shown from 1911 to 1990 in Table 1. This Subarea is identical to the ICES Subdiv. 24–32. Thus it should be noted that as Subdiv. 24 is included, part of the western stock is included as well, but only amounting to 3–5% of the total. It appears that until 1938 the total landings were below 30 000 tons. During the Second World War, landings increased to about 80 000 tons. Following a drop just after the War, they increased to vary in the range of 112 000–197 000 tons during the period 1948–74. Since 1979, the landings increased substantially to a maximum of 413 000 tons in 1984 and then declined in 1990 to the level of 165 000 tons. The reasons for the increasing yield may be attributed to either an increase in fishing effort or stock size or a combination of both.

Abundance as indicated for catch and effort

Up to the second half of the 1930s the fishing effort on cod was low. The main fishery was on flounder and in the western part it also included plaice (Jensen, 1954). Due to the outbreak of the Second World War, it was not possible for the German fleet to work in the North Sea, and 85 steam-trawlers were transferred to the Baltic. From Table 1 it appears that the increase of landings 1939–44 were almost exclusively caused by this effort. Thurow (1974) gives an evaluation of the early development of effort and abundance based on data given by several authors (Alander, 1948, 1949; Dementjeva, 1959; Jensen, 1954; Kändler, 1944, Sahlin, 1959). The increases in effort is suggested to be:

Germany between 1931–35 and 1937–38	2.6 times
Denmark between 1931–35 and 1936–39	2.5 times
Denmark between 1936–39 and 1950–53	2.7 times
Denmark between 1931–35 and 1950–53	7.0 times
USSR between 1948 and 1951	4.0 times
Sweden between 1933 and 1957	3.6 times

During the same period the catch-per-unit-effort seemed to have increased slightly, but as the data were scattered, partly obtained by research vessels in different areas and not comparable, they were probably not reliable. However, some exceptions are available in published literature. Data are given by Dementjeva (1959) based on commercial vessels as yearly mean catch/hour during 1948–56, which show a decrease from 1948 to 1953 followed by an increase to the same level as in 1948. Otterlind (1974) presented the catch of cod per fisherman in the trawl fishery 1932–70 off the Swedish South Coast. This showed a small increase from 1932 to 1940, a sharp increase from 1940 to 1948, a decrease from 1948 to 1953, followed by increases to the beginning of the 1960s. This coincides very well with the catch-per-unit-effort in the period given by Dementjeva, but it should be stressed that part of the transition area stock is included in the Swedish data.

Tiews (1974) compared the catch-per-hour of cod made by the German steam trawlers (1934–44) with the catch-per-hour made by the research vessel "*Anton Dohrn*" 1962–70 in the Bornholm Deep, the Gdansk Bay and the southern Gothland Deep. The catch rates in the Bornholm Deep in 1966, 1969 and 1970 were similar to those from 1939–44, but in the Gdansk Deep and the Gothland Deep the catch rate in 1969 and 1970 were much higher. Due to varying oxygen conditions near the bottom in the Baltic, catch-per-unit-effort data from research vessels with bottom trawl were possibly not reliable. These vessels worked in short periods, and consequently the choice of period may have been the main influence on the catch. Data obtained from commercial vessels working the whole year are better.

Data from commercial USSR 150 hp vessels (1974–88) have been submitted to the ICES Working Group on Demersal Species in the Baltic. The data are shown in Table 2, together with those reported by Dementjeva (1959), which refer to the same area (Eastern Gothland Deep) and the same type of vessels (Latvian trawlers). The stock in the period 1948–56 was at a lower level than in the period 1974–86. After 1986 the stock declined to the level of the former period. The maximum catch/day were observed in 1979 and 1980.

Abundance estimated from VPA

The first VPA on the Baltic stocks based on national age readings of landings was run in 1975 (Anon., MS 1975). An attempt based on Polish age readings only was made in 1972 (Anon., MS 1973). Since 1975 the VPA has been updated yearly by the Working Group on Assessment of Demersal Stocks in the Baltic.

Until 1987, the natural mortality was set to be 0.3 but from 1988 onwards it was reduced to 0.2. The

TABLE 1. Landings of cod ('000 tons) from the Baltic (Subarea III d) Subdivisions 24–32.

		Faroe		Germany					Total	Grand
Year	Denmark	Islands	Finland	FRG	DDR	Poland	Sweden	USSR	Bull. Stat.	total
1911	0.4	–	–	0.4		–	0.7	–	1.6	–
1912	0.5	–	–	0.6		–	0.6	–	1.7	–
1913	0.5	–	–	0.8		–	0.7	–	1.9	–
1914	0.7	–	–	0.9		–	1.2	–	2.8	–
1915	1.4	–	–	1.2		–	1.8	–	4.3	–
1916	1.0	–	–	2.3		–	1.6	–	4.8	–
1917	0.5	–	–	0.7		–	0.9	–	2.2	–
1918	0.6	–	–	0.6		–	0.9	–	2.1	–
1919	0.9	–	–	0.5		–	1.4	–	2.8	–
1920	1.3	–	–	0.9		–	2.3	–	4.5	–
1921	1.1	–	–	1.0		–	2.2	(1)	4.3	5.3
1922	0.9	–	–	1.5		0.1	2.2	(1)	4.8	5.8
1923	0.9	–	–	1.9		0.2	1.9	(1)	4.9	5.9
1924	1.0	–	–	1.3		0.1	1.6	1.3	5.3	5.3
1925	1.1	–	–	1.7		0.1	2.4	2.5	7.7	7.7
1926	1.3	–	–	1.8		0.1	2.7	1.5	7.4	7.4
1927	1.2	–	–	1.8		0.1	2.7	1.1	6.9	6.9
1928	1.2	–	–	2.0		0.2	2.6	1.2	7.2	7.2
1929	0.8	–	–	1.5		0.2	1.6	0.7	4.8	4.8
1930	0.9	–	–	1.5		0.1	1.6	0.5	4.6	4.6
1931	0.8	–	–	1.1		0.2	1.5	0.6	4.1	4.1
1932	0.7	–	–	1.7		0.4	1.9	0.9	5.6	5.6
1933	1.0	–	–	2.0		0.3	1.9	1.6	6.8	6.8
1934	1.4	–	–	2.3		0.5	2.7	0.8	7.7	7.7
1935	1.7	–	–	3.0		0.5	5.0	1.0	11.2	11.2
1936	1.9	–	–	4.5		0.9	5.9	3.0	16.2	16.2
1937	1.9	–	–	7.7		1.7	6.2	3.3	20.9	20.9
1938	3.5	–	–	8.6		1.1	6.9	3.4	23.4	23.4
1939	3.7	–	–	14.0		2.7	7.6	3.4	31.5	31.5
1940	6.3	–	–	34.2		–	6.1	12.9	46.6	59.5
1941	14.3	–	–	52.9		–	8.1	(5)	75.3	80.3
1942	13.3	–	–	44.6		–	8.2	(5)	65.9	70.9
1943	9.9	–	–	53.1		–	11.9	6.1	74.8	80.9
1944	9.6	–	–	42.6		–	8.6	(5)	60.7	65.7
1945	2.8	–	–	5.0	–	1.5	11.6	(5)	14.4	25.9
1946	8.5	–	–	3.4	–	19.2	11.2	5.8	20.6	48.1
1947	8.1	–	–	18.8	(1)	29.4	14.8	10.9	22.9	83.0
1948	10.6	–	–	28.7	(2)	32.6	21.1	17.8	31.6	112.8
1949	14.4	–	–	24.4	(3)	37.7	25.8	25.6	64.6	125.9
1950	6.6	–	–	13.2	6.0	48.0	20.3	41.9	40.0	136.0
1951	11.7	–	–	3.2	8.0	51.2	20.5	46.9	35.6	141.5
1952	13.0	–	–	3.7	7.0	61.2	24.6	49.0	41.4	158.5
1953	12.4	–	0.1	3.6	12.0	46.6	19.5	28.2	35.5	122.4
1954	11.4	–	0.1	3.7	12.0	48.7	18.6	40.6	33.8	135.1
1955	12.9	–	0.1	4.2	12.0	39.0	20.6	37.6	114.3	126.4
1956	11.8	–	0.1	4.3	14.0	50.0	19.8	61.4	147.3	161.4
1957	16.0	–	–	10.7	23.0	56.2	26.4	64.6	173.8	196.9
1958	17.6	–	0.1	8.7	21.0	36.5	20.8	46.1	129.8	150.8
1959	19.0	–	–	7.4	18.0	35.0	22.6	40.5	124.5	142.5
1960	19.8	–	–	10.1	10.0	49.4	27.3	44.4	151.0	161.0
1961	25.3	–	–	8.2	7.0	37.9	28.4	(30)	99.7	136.7
1962	22.1	–	–	5.4	7.0	40.9	25.1	31.3	129.9	136.9
1963	23.6	–	–	3.2	7.0	47.5	22.8	30.6	127.7	134.7
1964[a]	23.3	–	–	4.3	5.0	39.7	16.2	24.5	105.1	110.1
1965	21.5	–	–	5.2	7.2	41.5	21.4	22.4	105.2	119.2
1966	22.7	–	–	3.3	6.7	56.0	22.5	38.3	135.7	149.5
1967	25.8	–	–	2.5	16.8	56.0	23.4	43.0	144.6	167.6
1968	28.3	–	0.1	4.8	19.4	63.2	24.0	43.6	157.3	183.4
1969	29.4	–	0.1	7.2	21.8	60.1	22.3	46.6	154.2	182.5
1970	28.0	–	0.1	7.0	13.6	68.4	17.8	32.3	–	167.2

TABLE 1. (Continued).

Year	Denmark	Faroe Islands	Finland	Germany FRG	Germany DDR	Poland	Sweden	USSR	Total Bull. Stat.	Grand total
1971	30.0	–	0.1	4.6	7.4	54.2	15.7	20.9	–	132.9
1972	42.0	–	0.1	5.0	9.2	57.1	16.5	30.7	–	160.6
1973	44.7	–	0.1	15.9	10.4	49.8	18.4	20.1	–	159.4
1974	39.5	–	0.2	12.2	7.9	48.7	16.4	38.1	–	163.0
1975	46.5	–	0.3	12.5	11.3	69.3	18.0	49.3	–	207.2
1976	57.1	–	0.3	14.3	7.3	70.5	20.1	49.0	–	218.6
1977	54.6	–	0.3	18.9	10.0	47.7	17.6	29.7	–	178.8
1978	36.8	–	1.4	5.2	7.7	64.1	16.2	37.1	–	168.6
1979	41.6	3.9	2.9	10.5	8.0	79.8	22.4	75.0	–	244.1
1980	57.1	1.3	6.0	12.4	6.5	123.5	31.9	124.4	–	363.1
1981	75.7	2.7	5.7	9.2	11.2	120.9	43.4	87.7	–	356.5
1982	78.6	4.3	8.1	14.5	9.5	92.5	46.4	86.9	–	341.8
1983	92.3	6.1	8.9	16.2	9.1	76.5	53.6	92.2	–	354.9
1984	98.1	6.4	9.4	30.7	8.0	93.4	65.7	100.8	–	412.5
1985	91.1	5.9	7.2	26.8	5.1	63.3	54.5	78.2	–	332.1
1986	88.8	4.6	5.6	20.2	2.4	43.2	49.3	52.1	–	266.2
1987	74.3	5.6	3.0	15.3	4.6	32.7	47.3	39.2	–	222.0
1988	67.9	6.9	2.9	14.6	4.3	33.4	54.8	28.9	–	212.9
1989	61.9	4.5	2.3	13.2	1.9	36.9	55.7	14.7	–	191.1
1990	54.1	2.9	1.7	5.7	1.5	32.0	53.2	13.5	–	164.6

[a]1911–1964 after Thurow (1974) but without footnotes.

TABLE 2. Mean daily catch by USSR trawlers in the Eastern Gothland Deep. (1948–56 Dementjeva 1959. 120 hp trawlers, 1974–88 Unpublished USSR data, 150 hp tawlers).

Year	Catch (tons)	Year	Catch (tons)
1948	1.82	1976	3.06
1949	1.45	1977	2.10
1950	1.36	1978	3.18
1951	1.29	1979	4.29
1952	1.39	1980	5.00
1953	1.14	1981	3.56
1954	1.24	1982	2.73
1955	1.27	1983	2.62
1956	1.66	1984	2.66
		1985	2.18
		1986	1.98
1974	2.50	1987	1.75
1975	2.60	1988	1.24

effect of this measure was that the biomass at the beginning of the year was reduced by about 30%. At the same time the maturity ogive was changed. Therefore, the 1991 VPA was used with a correction for the years before 1970. The recruitment, spawning stock size, the fishing mortality and the yield for the period 1966–90 are shown in Fig. 2 (Anon., MS 1991). The recruitment at age 2 increased from a level of 300 million in the 1960s to more than 450 million in 1972, 1975, 1976, 1977, 1979, 1980 and 1981, with the largest year-class ever in 1976 (770 million). Since 1981, the recruitment has continually decreased (except in 1985). The level of recruitment of the year-classes 1989 and 1990 were below 1 million. The yield increased to a maximum of about 400 000 tons in 1984 and then declined to about 156 000 tons in 1990. The fishing mortality had an increasing trend since 1979 reflecting a heavy increase of effort due to the transfer of fishing vessels from the North Sea, a change to larger vessels, and the introduction of pelagic trawling for cod.

The development of pelagic single boat trawling, which was introduced by German vessels, made it possible to fish continually on a diurnal basis in contrast to bottom trawling. The bottom trawling can only be performed in areas with sufficient oxygen near the bottom and only from sun-up to sundown, because the cod leave the bottom when it gets dark. Consequently, the effort increased at least by a factor 3 for vessels which switched over to the pelagic method.

From Fig. 2, it appears that the fishing mortality in the 1960s was almost as high as in 1990. This is very surprising and is most likely an artifact caused by applying unrealistically high fishing mortalities in the earlier VPAs.

The Reproduction of Baltic Cod

Spawning area

There are three main spawning areas for Baltic cod; the Bornholm Deep, the Gdansk Deep and the Gothland Deep (Fig. 1). Spawning usually begins in March, reaches maximum in May–June and finishes in September.

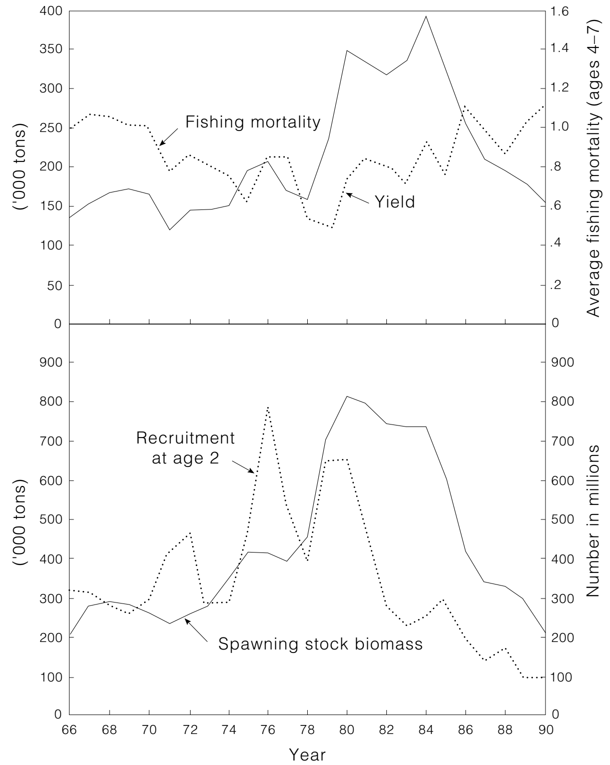

Fig. 2. Recruitment, spawning stock size, fishing mortality and yield in ICES Subdiv. 25-32, at 1 January in 1966–90 (Anon., 1991).

Salinity and oxygen

In the spawning areas, salinity of not less than 10‰ is necessary to keep the eggs afloat (Grauman, 1973). At a lesser salinity the eggs are deposited on the bottom and do not develop, but even if the salinity allows the eggs to float, the oxygen content is a determining factor for the development. Fertilization of the eggs is possible at lower salinities than 10‰, but with a rapidly decreasing percentage of fertilization and with a ceasing of further development (Westin and Nissling, 1991).

The cod eggs are found below the halocline in the Bornholm Deep between 60 and 75 m at salinities of 11–13‰ (Müller and Pomerantz, 1984), and in the Gothland Deep they are at depths of 80–100 m or where the salinity allow them to float (not less than 10‰). The oxygen content in the strata where the eggs are concentrated may vary from 0.5 to 6.0 ml/l, varying between months and years depending on inflow of saline and oxygenated water from the North Sea. The lower limit for oxygen content at which development of cod eggs is possible is 1 ml/l, at which level the egg mortality is very high (Grauman, 1973). Experimental investigations on cod eggs from the Bornholm Deep indicate that below 2.3 ml/l the development of the eggs does not proceed beyond stage III (Wieland and Zuzarte, MS 1991). Hence a combination of salinity not less than 11‰ and oxygen content not less than about 2.3 ml/l is very important for survival of the cod eggs. As salinity and oxygen content below the halocline is dependent on inflow from the North Sea, stagnant periods which reduce the salinity and the oxygen content have a negative effect on the year-class strengths in the Baltic.

Inflows and stagnant periods

Long-term trends of salinity below the halocline in the Gothland Deep (Fonselius *et al.*, 1984; Matthäus, 1991) are shown in Fig. 3. Periods with continuously decreasing salinity values were observed from 1922 to 1933 and from 1952 to 1962. Both periods began with very high salinities, possibly caused by heavy inflows. A big inflow into the Gothland Deep also began in 1935 but, due to the World War, there was no further information between 1940 and 1947. After the 1952 inflow, four smaller ones occurred with stagnant periods in between. The last major inflow occurred in 1979 (Matthäus, 1991). Figure 4 shows the salinity and

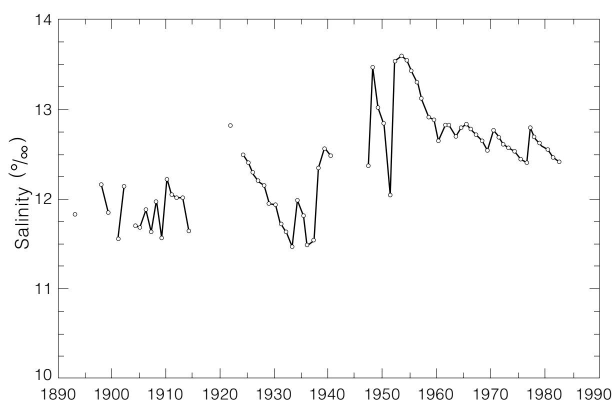

Fig. 3. Annual mean values of all salinity data (200-m depth) at the Gothland Deep station from 1890 to 1982 (Fonselius *et al.*, 1984).

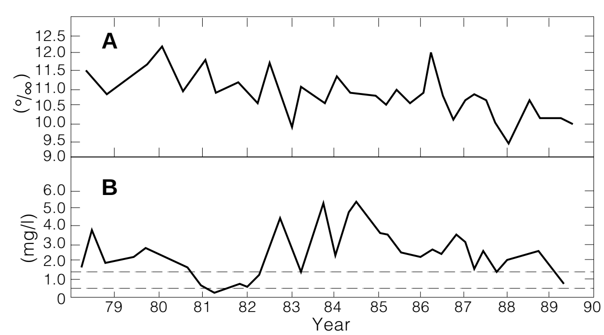

Fig. 4. (**A**) Salinity and (**B**) oxygen content at Station BY9 in 1979–90 (Olenin, 1991).

oxygen contents in the southeastern Gothland Deep from 1979 to 1990 (Olenin, 1991). An improvement of oxygen content occurred late in the year in both 1983 and 1984, which was after the spawning season for cod. In 1985 a similar improvement in oxygen content occurred but it was at a time within the spawning season, and the last average year-class was also produced in that year. Information on the most recent oxygen and salinity conditions from the same area indicates unfavourable conditions for spawning also in 1991.

Discussion

Some authors have demonstrated a positive correlation between inflows and year-class strengths of cod (Bay, 1984; Kosior and Netzel, 1989).

Besides increasing salinity and oxygen content, however, inflows also force nutrients from the bottom to the photic zone stimulating primary production. This effect may also be very important for successful development of cod larvae. Around 1920 the dominance of winds from west-southwest increased by about 25% (Jensen, 1954), which may have supported the inflows to the Baltic and the subsequent increase of the stock size. In 1957 an increase of effort in combination with improved fishing methods resulted in a fishing yield maximum of 196 000 tons. The explosive development of the stock in the late-1970s and early-1980s, however, cannot be explained by inflow and effort exclusively, therefore it possibly included an increased level of nutrient input from other sources (freshwater outlets and the atmosphere, e.g. nitrogen). The high nutrient contents together with a proper salinity and oxygen regimes is believed to have produced the rich year-classes of 1972, 1975, 1976, 1977, 1979, 1980, 1981 and 1985. The stagnant period since 1979, during which the oxygen consumption increased due to an increased sedimentation of organic matter, appears to have caused the production of a series of small year-classes, especially in the Gothland and Gdansk Deep (Uzars *et al.*, MS 1991). The reproduction of cod in the Baltic seems at present to be exclusively dependent on the spawning success in the Bornholm Deep.

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