COMMENTATIONES BIOLOGICAE
Societas Scientiarum Fennica

On the salinity conditions off the south coast of Finland since 1950, with comments on some remarkable hydrographical and biological phenomena in the Baltic area during this period

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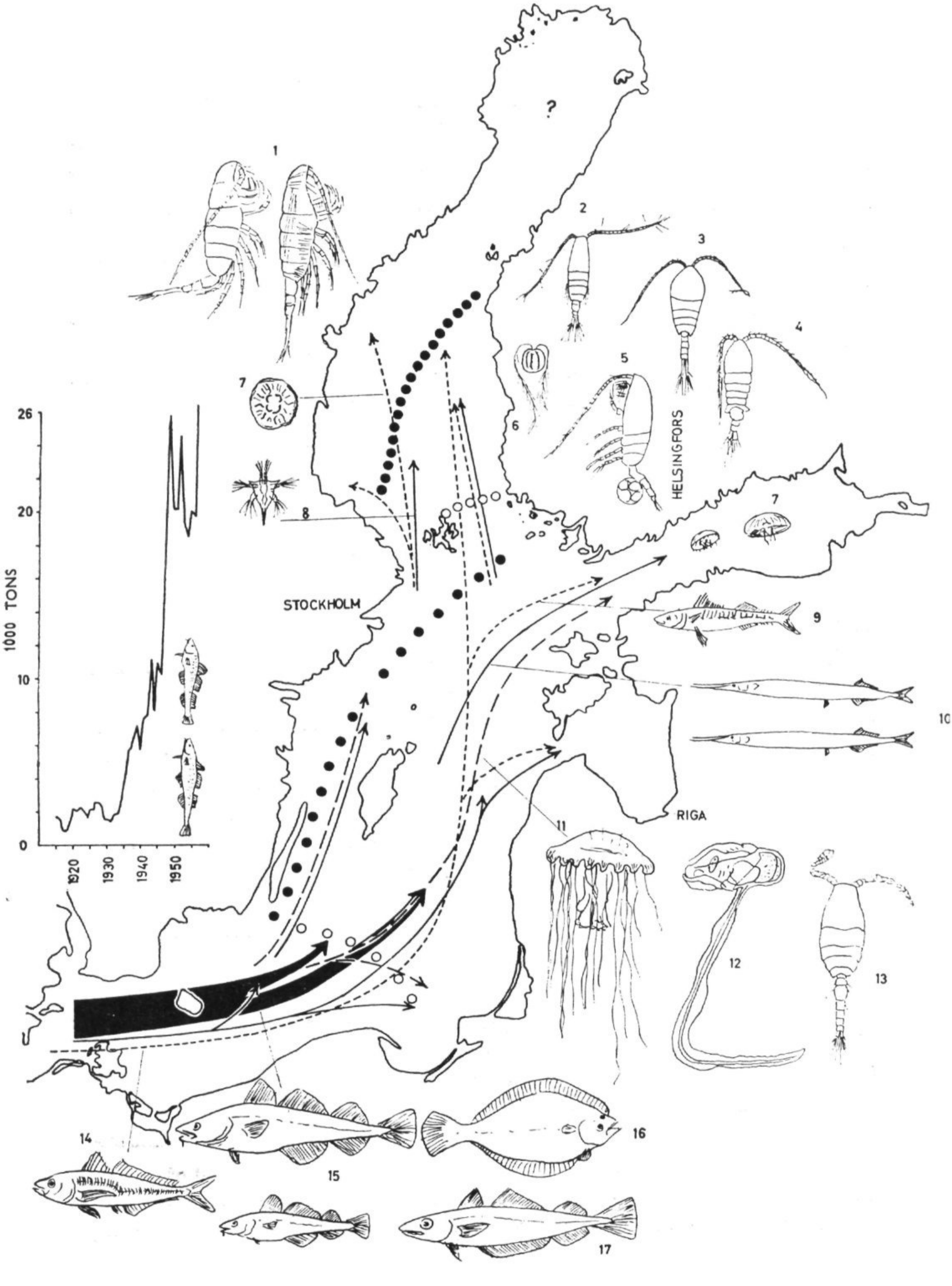
1. Introduction

When the ice-cap covering Northern Europe during the last glaciation began to melt away some 15,000—20,000 years ago, a series of grand-scale ecological »experiments» were started by Nature in the Baltic basin in connection with the fluctuations in its salinity regime which occurred in late- and postglacial times (Baltic Ice-Lake: fresh water, Yoldia Sea: brackish water, Ancylus Lake: fresh water, Littorina Sea: brackish water). The mixture of lacustrine and marine organisms characteristic of the Baltic of our days clearly mirrors the influence of the last two stages, the Ancylus Lake and the Littorina Sea.

Since the end of the comparatively salty Littorina phase, the salinity of the Baltic has remained roughly stable. As in other brackish areas, oscillations have without doubt occurred, but it was not until the beginning of this century that regular hydrographical observations elucidating the phenomenon were commenced, under the auspices of the International Council for the Exploration of the Sea. The work carried out since then has shown that fairly marked salinity oscillations are to be reckoned with. Special attention is merited by the change observed in the last few decades. After a period of comparatively strong dilution in the 20's, the salinity of the Baltic basin began to rise in the early 30's, and in the 40's and early 50's reached a level unprecedented since the start of regular recordings.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HELSINGFORS
STOCKHOLM
RIGA
26
20
10
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1000 TONS
1920
1930
1940
1950

Since then the area has, on the whole, been more saline than in the early decades of the present century.

The interest which this phenomenon has aroused among the hydrographers working in the Baltic area has found expression in the numerous publications on the subject; see, for instance, LISITZIN (1948), GRANQVIST (1949, 1952), WYRTKI (1954), SOSKIN (1956), BARANOV & SPAICHER (1956), NIKOLAEV (1956), MAŃKOWSKI (1958), AHLNÄS (1962), ALEKSANDROVSKAYA & KALEI (1962), FONSELIUS (1962), and GLOWINSKA (1963).

However, the recent change in the hydrographical conditions of the Baltic waters has been of interest not only to hydrographers. The biologists have likewise been faced with remarkable phenomena which have accompanied the salinity increase: the invasion of stenohaline marine organisms, the extension of the range and breeding areas of others, etc. Of direct practical significance has been the improved conditions for several marine fish species of commercial importance. The most remarkable example is

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Fig. 1. Map of the Baltic, with examples of marine animals which have extended their range as a consequence of the salinity rise in recent decades (and a case of the contrasting phenomenon of recession of stenohaline brackishwater species). After LINDQUIST 1960.

The arrows indicate direction of spread. Continuous lines: widening of range with reproduction. Broken lines with long strokes: widening of range, without reproduction. Broken lines with short strokes: occasional invasion (»guests»).

1. The copepod *Limnocalanus grimaldii*. Open circles indicate limit of range prior to the salinity increase. Black dots: present distribution (very roughly; the species is also abundant in the Gulf of Riga and off the Finnish coast). Being a brackishwater form with low salinity tolerance, *Limnocalanus* has suffered from the rise of salinity.

2, 3, 4, and 5. Other copepods (*Acartia longiremus, Temora longicornis, Centropages hamatus, Pseudocalanus elongatus*) which have become more common in the Gulf of Bothnia and the Gulf of Finland (invasion from the northern part of the central Baltic).

6. The ctenophore *Pleurobrachia pileus*. Same feature.

7. The jellyfish *Aurelia aurita* has penetrated farther into the Gulf of Finland and on isolated occasions has also been observed in the Gulf of Bothnia.

8. The barnacle *Balanus improvisus* (nauplius larva depicted) has become more common in the Gulf of Bothnia (observed up to Ulvöarna).

9. The mackerel, *Scombrus scombrus*, has been met with occasionally in the Gulf of Finland and the Gulf of Bothnia.

10. The garfish, *Belone belone*, has penetrated farther into the Baltic (occasional spawning observed even off the Finnish south coast).

11. The jellyfish *Cyanea capillata* has been met with farther to the north.

12. The tunicate *Oikopleura dioica* and 13, the copepod *Oithona similis* have become much commoner in the southern Baltic and in parts of the central Baltic proper.

14. The horse mackerel, *Caranx trachurus*, has appeared as a »guest» in the southern Baltic.

15, the cod, *Gadus morrhua*, 16, the long rough dab, *Drepanopsetta platessoides*, and 17, the whiting, *Gadus merlangus*, have increased in abundance in the southern Baltic, the cod also in more inward areas, including the Gulf of Bothnia. The annual landings of cod in Sweden in recent decades are shown in the diagram inserted to the left.

the enormously increased abundance of the cod since the late 30's, which has caused a rise in the catch of this fish without precedent in the history of Baltic fishery (cf. Figs. 1 and 6; as will be pointed out in a later connection, this feature seems, in part, to have been due to other effects of the inflow than high salinity as such). Among the many papers in which the biological role of the salinity increase since the 30's is discussed the following may be especially mentioned: HELA (1947, 1951), KÄNDLER (1949, 1954), NIKOLAEV (1950, 1957), MAŃKOWSKI (1951, 1962), SEGERSTRÅLE (1951, 1953), PURASJOKI (1953), DEMEL (1957), LINDQUIST (1958, 1959, 1960). Cf. Fig. 1.

In this connection it should be noted that, parallel with the salinity, the temperature of the Baltic waters has also risen in recent decades (cf., for instance, BARANOV & SPAICHER 1956, SHURIN 1960, FONSELIUS 1962 [see Fig. 4 in the present paper]) and that this change seems likewise to have had biological consequences. An example is the abundant occurrence of the fish *Belone belone* in the eastern Baltic in the late 30's, which was ascribed by DEMEL to the warming of the water, a view shared by L. S. BERG (NIKOLAEV, discussing the matter in 1950, reckoned with the combined effect of the salinity and temperature increases).

As is readily understandable, there has been vigorous discussion of the reasons for the recent change in the salinity conditions of the Baltic (LISITZIN 1948, KÄNDLER 1949, NIKOLAEV 1950, WYRTKI 1954, BARANOV & SPAICHER 1956, SOSKIN 1956, 1959, AHLNÄS 1962, FONSELIUS 1962; etc.). Cf. also HELA (1947). The conclusions arrived at may be summed up as follows:

After 1930, the frequency of deep cyclones over western Europe increased. The westerly gales became more frequent and caused strong influxes of saline water into the Baltic. The effect of this phenomenon was accentuated by the simultaneous decrease in the discharge of the rivers emptying into the basin, which led to a lowering of the mean level of the Baltic and in consequence an increase in the intensity of the deep compensation current bringing in water of oceanic origin. Like the increased frequency of saline influxes, the diminished river discharge is also attributed to changed meteorological conditions, viz. strengthening of the anticyclonal activity over the eastern part of continental Europe. Finally, both phenomena are considered to have a common background, viz. the general climatic change (increase in the atmospheric circulation) which, since about 1930, has led to increased transport of air and water over the northern hemisphere from the west. Another result of this change has been a marked rise in the temperature of the air and the ocean, well known for its remarkable consequences: melting of glaciers at high latitudes, northward extension of the range of commercially important fish, e.g. cod; etc. The recent rise in the salinity of the Baltic waters is thus only one of many expressions of a large-scale meteorological change.

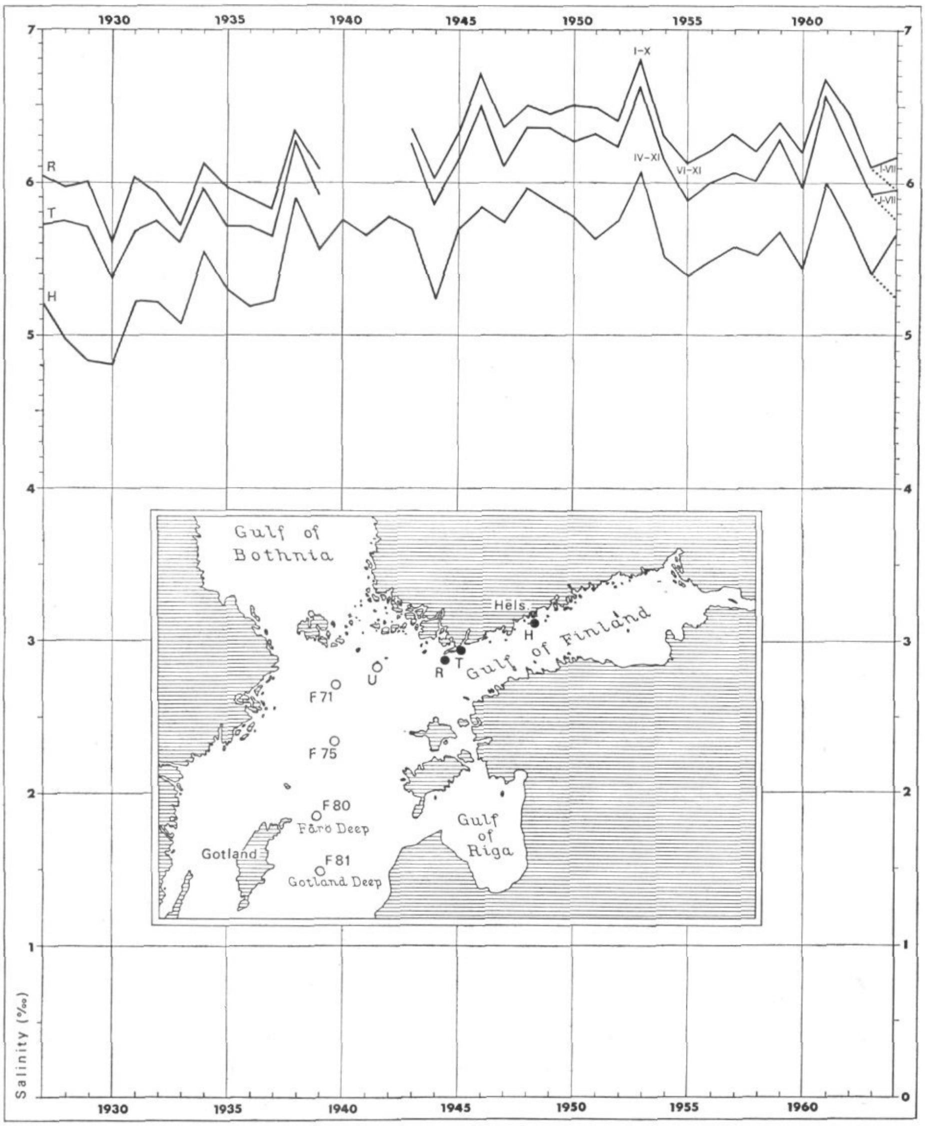

Fig. 2. Salinity ($^0/_{00}$) at 5 m depth at the hydrographical stations of Russarö (R), Tvärminne (T), and Harmaja/Gråhara (H) during the period 1927—first half of 1964 (for comparison, the value for the first half of 1963 is indicated by a dotted line). The breaks in the observations at Russarö and Tvärminne around 1940 are due to war conditions. After SEGERSTRÅLE 1951, 1953, and 1957, with the addition of the period since 1956. The inserted map shows the location of the just-named stations and the following, mentioned in the text: Utö (U, depth c. 90 m), F 71 (163 m), F 75 (165 m), F 80 (Fårö Deep, 205 m), F 81 (Gotland Deep, 249 m).

An earlier event in this reaction chain has recently been suggested, namely solar activity, which influences the atmospheric circulation and has undergone intensification since the beginning of the 30's (AHLNÄS 1962 and paper by SOSKIN, presented at the annual meeting of the ICES in Copenhagen in 1958; quoted by AHLNÄS).

*

As far as the waters off Finland are concerned, the biological consequences of the recent rise in salinity have been discussed in papers by ERKAMO (1942), HELA (1947, 1951), the author (1951, 1953), PURASJOKI (1953), and LINDQUIST (1958, 1959, 1960). As a continuation of the surveys reported in the two just-mentioned papers by the author on the development of the salinity conditions off the south coast of Finland, a report on the salinity of the area in the period 1952—1956 was given in 1957 (SEGERSTRÅLE 1957; all the three papers concerned are based on data collected by the Institute of Marine Research of Finland). In the present account the surveys are extended to comprise the period up to the middle of 1964. The need for such a continuation has been felt especially by the biologists working at the centre of Finnish marine-biological activity, the Zoological Station at Tvärminne, which is situated at the entrance to the Gulf of Finland.

The hydrographical stations dealt with in the present paper are Russarö, Tvärminne and Harmaja/Gråhara belonging to the observation network of the Institute of Marine Research (for location, see Fig. 2; in the publications of 1951, 1953 and 1957, a fourth station, Tammio/Stamö, was included). As earlier, the survey refers to the 5-m level (the surface values do not give a true picture of the milieu of littoral organisms, because, under the ice cover in winter, the uppermost layer may be greatly diluted, owing to river outflow and subsequent stratification of the water). The data presented have been compiled from the routine recordings at the stations concerned (normally three times a month). The values up to and including 1961 were available in the publications of the Institute of Marine Research, those referring to the following years, which have not been published so far, were placed at the author's disposal by the said Institute.

In Fig. 2 a survey of the new data, as well as those included in the papers of 1951, 1953, and 1957, is given in the form of curves, which thus cover the period 1927—1964 (the hydrographical observations at the Tvärminne Station were started in 1927).

In the course of the work on the present continued survey, however, it proved advisable to include in the discussion the salinity conditions off the Finnish south coast not only in recent years, but during a longer period, viz. since about 1950 and, further, to comment upon some hydrographical and biological features in other parts of the Baltic basin in the years concerned. As will be demonstrated below, in several respects this period is of exceptional interest to workers in the Baltic area. For utilized unpublished data from regions outside Finnish coastal waters, see below.

Acknowledgements. The author's sincere thanks are due to Dr. FOLKE KOROLEFF of the Institute of Marine Research, Helsinki/Helsingfors, who placed at his disposal unpublished hydrographical data collected at the three Finnish hydrographical stations with which the present paper is especially concerned and in connection with the cruises of R/V »Aranda» in the northern part of the Baltic proper and in the Gulf of Finland in 1961–1964. The author is also indebted to the Director of the Institute, Professor ILMO HELA, and to Dr. KOROLEFF, who have, as hydrographers, read the manuscript critically.

2. The salinity conditions off the south coast of Finland since 1950 and their background

As may be expected, the three stations dealt with in Fig. 2 indicate a gradual decrease of the salinity towards the east. On the other hand, the curves exhibit, *inter se*, a high degree of parallellism. As a gross average, a salinity rise of half a per mille since the 30's is observable.

As regards the development of the salinity conditions at the stations concerned since the survey of 1957, in which the last year treated was 1956, the curves show that the values obtained for the four subsequent years, 1957 to 1960, do not deviate much from those for the three preceding years, 1954–1956. Furthermore, we observe that this period of altogether seven years is characterized by a lower salinity than most of the years since 1945. On the other hand, at all stations the comparatively strong dilution in 1954–1960 is preceded by a very marked salinity peak in 1953 and followed by a new, less conspicuous rise in 1961.

The peak of 1953 and the subsequent dilution period deserve to be commented upon in some detail. As a matter of fact, the salinity values reached in the peak year are the highest ever recorded at the stations concerned, being as follows: Russarö 6.82, Tvärminne 6.64, Harmaja/Gråhara 6.07. The contrast between the record salinity in 1953 and the following marked dilution is also exceptional. As we shall find, both features mirror general phenomena within the Baltic basin.

On discussing the background of the record salinity of 1953, it may be recalled that irregular peaks in salinity have often been observed in the Baltic area (cf. Fig. 2) and that they have proved to be caused by special meteorological and hydrographical situations, leading to extraordinarily strong influxes of oceanic water through the Danish Sounds. In such cases the incoming water may totally occupy these inlets to the Baltic basin. In recent decades, when the salinity of this basin has been increasing, particularly strong inflows have been observed, for instance, in the years

1933—35, 1937—38, 1947—48, 1951 and 1963; see, for instance, HELA (1947), SOSKIN (1956), WYRTKI (1954), and GLOWINSKA (1964). The strikingly high salinity observed in 1953 off the south coast of Finland was due, as will soon be demonstrated, to a »piston stroke» in 1951, exceptional in the annals of Baltic hydrographical research. This inflow has been discussed in the just-mentioned paper by WYRTKI (cf. also MAŃKOWSKI 1958, AHLNÄS 1962, FONSELIUS 1962; a remarkable case of saline inflow into the Baltic in 1930 was analysed by HELA [1944], who subjected the feature of such saltwater pulsations through the Danish Sounds to a thorough theoretical discussion). The following details are mainly borrowed from WYRTKI's publication.

In the middle of November 1951, the prevailing winds above northern Europe suddenly changed direction from SE and E to W. For about one month heavy westerly gales forced water from the North Sea into the Baltic. The effect of this process was greatly strengthened by a striking difference in water level between the Baltic and the Kattegat, a feature which, in its turn, was conditioned, on the one hand, by the foregoing period of easterly winds and, on the other, by the rise of the Kattegat level caused by the damming-up effect of the westerly gales (on November 25, a sea level difference of not less than 140 cm was observed between Korsör at the Great Belt and Gedser at the entrance to the Baltic between the Danish Isles and the continent). As a result, the water flowing into the Baltic acquired a considerably greater speed than the winds alone could have accounted for (at times more than 200 cm per second was measured). According to WYRTKI's calculations, between November 23 and December 16, 1951, a water volume of not less than 200 km^3 passed into the Baltic (the annual inflow through the Danish Sounds into the Baltic proper is estimated at 472 km^3; cf. BROGMUS 1952). The effect of this influx was greatly enhanced by the high salinity of the incoming water, averaging c. 22 $^0/_{00}$. This exceptionally high value was ultimately conditioned by a strong transport of oceanic water into the North Sea and the Kattegat in previous years (cf. AURICH 1953). In retrospect, the enormous amount of salt added to the water body of the Baltic by the end of 1951 was due to a rather exceptional sequence and combination of meteorological and hydrographical features.

The effect of the inflow of saline water through the Danish Sounds is, of course, especially clearly observable in the westernmost part of the Baltic proper. Very strong influxes such as that of 1951, however, are followed by a marked rise in salinity even as far east as Finnish waters (for other examples, see AHLNÄS 1962).

According to AHLNÄS (l.c.), the consequences of the inflow in November —December 1951 were noted at the hydrographic station of Utö, situated at the southern fringe of the southwestern archipelago of Finland (see Fig. 2) as early as June 1952, i.e., seven months later. (According to FONSELIUS, 1962, p. 40, the Landsort Deep was affected somewhat earlier.) By that time, however, the rise in salinity there was confined to deeper layers (maximum depth of the station, c. 90 m). The period of strikingly high salinity in these strata, with an anomaly of more than 2.00 ‰, lasted for five months, being the most persistent strongly saline period ever observed at Utö.

In some other cases, too, it has been found that the front of inflowing water may reach Utö in as little as 7 months, but instances are also known when this process has been much slower, taking up to about 20 months; as an average, 11 months is given (LISITZIN 1948, AHLNÄS 1962; cf also HELA 1947, who gives a range of 11 – 19 months).

As regards the progression of the highly saline influx of 1951 towards the inner parts of the Baltic, the following details may be given (MAŃKOWSKI 1958, 1959, FONSELIUS 1962). *In January 1952, the inflow had already reached the Bornholm Basin*, where a salinity of more than 21 ‰ was noted, a record there since sampling started (cf. Fig. 3 in the present paper). In the Gdańsk Basin the arrival of the salty front was not noted until April, and the Gotland Basin was reached at about the same time. In these two areas also, salinity values higher than ever before were measured.

In view of the salinity rise at Utö as early as June 1952, it may appear strange that the corresponding peak is not observable in the curves for Russarö, Tvärminne, and Harmaja until 1953 (distance between Utö and Russarö not more than about 90 km). However, the depth factor must be taken into account in this connection. At the Utö station, with a maximum depth of about 90 m, the increase in salinity in 1951 was, as we have found, confined to the depth, whereas the curves concerned refer to the 5-m level. The transfer of salt from the deeper layers to the surface, caused by the *turnover in autumn, upwelling, storms, etc.*, is *obviously a slow* process in Finnish coastal waters. For Utö it has been concluded that it takes two years or more (LISITZIN 1948, BARANOV & SPAICHER 1956). In the case of the three stations treated in the present paper, where the depth sampled is less than at Utö (Russarö c. 30 m, Tvärminne c. 30 m, Harmaja c. 30 m) it has to be pointed out that the salty bottom current entering the Gulf of Finland makes its way along the central, comparatively deep parts; hence, even at the stations mentioned the ascent of salt to the upper layers may be expected to be considerably delayed.

As regards the situation off the Finnish south coast after the peak in 1953, the salinity curves in Fig. 2 show, as was pointed out previously, that in the year following this record value there was already an abrupt change to a fairly low value and, further, that this year inaugurated a longer period of comparatively strong dilution which lasted up to and including 1960, i.e. in total seven years. During this period the salinity was roughly 0. 5‰ lower than in 1953; on the other hand, even at this level the salinity exceeds that before the start of the rise in the 30's.

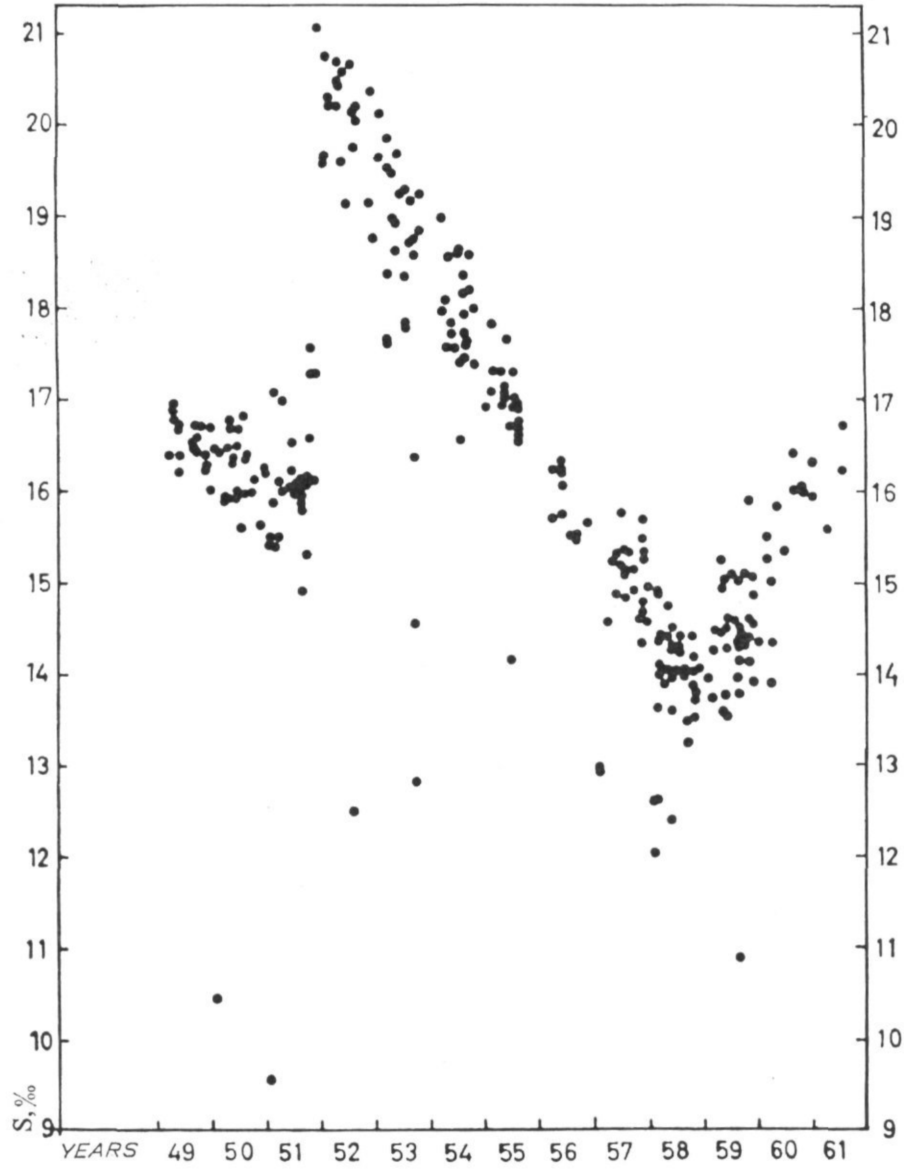

Fig. 3. Salinity (‰) in the years 1949–1961 in the Bornholm Basin, at 80 m depth. The sudden rise in 1952, when values were reached which were unprecedented since observations started in the Basin at the beginning of this century, as well as the subsequent rapid decrease in salinity, ending in 1959, is clearly seen. The diagram is part of one given by Fonselius (1962).

The just-mentioned period of dilution off the south coast of Finland corresponds to a marked decrease in salinity in the western Baltic (Fig. 3). As far as concerns the year 1955, which exhibits the lowest value, it may also be noted that, according to the results of Russian hydrographers (summarized by NIKOLAEV, 1957, p. 43), in the year in question, the waters of the open Baltic were subject to strong dilution on account of an unusually strong discharge of the continental rivers in 1954 and the first half of 1955.

As emerges from the curves, the long period of low salinity at the three stations dealt with came to an end in 1961, a year which exhibits a new salinity peak not much lower than that of 1953. The following data elucidating the background of this rise may be given (FONSELIUS 1962, AHLNÄS 1962). In 1959, observations in the Bornholm Basin indicated the arrival there of a new inflow of strongly saline water through the Danish Sounds. The Landsort Deep was reached in the middle of 1960 and the deep layers at Utö at almost the same time. The peak of 1961 at the 5-m level off the Finnish south coast and the comparatively high salinity values also observed there in 1962 (see Fig. 2) were apparently caused by this inflow.

As will be seen from Fig. 2, the salinity peak of 1961 was, in its turn, followed by a very marked decline, so that two years later values were reached which were about as low as those of 1955, which represent the minimum during the long dilution period after 1953. From 1964 data are available from the first half of the year only; however, comparison with the corresponding values obtained in 1963 (see Fig. 2) indicates a new rise of the salinity curves. This peak would seem to be due to the inflow of saline water observed in the central Baltic in 1961 (ALEKSANDROVSKAYA & KALEI 1962). According to GLOWINSKA (1964), an influx of oceanic waters into the Baltic also took place in 1963, but its effect on the salinity conditions of the upper layers off the coast of Finland cannot, after all, have been observable as early as the first half of 1964 (the influx did not reach the south-western part of the Gotland Basin until December 1963). On the other hand, the strength of the 1963 inflow (cf. below, p. 18) renders it likely that it will in due time, conceivably in 1965, cause a marked rise in salinity in the upper layers off the Finnish coast.

3. The influence of the 1951 inflow on the marine element of the Baltic fauna

As is well known, animals of marine origin which do not belong to the normal Baltic fauna are constantly transported into the basin with incoming salty water. This feature, which, for natural reasons, is especially marked in connection with »piston strokes» of the type described earlier in this paper, has been discussed by several authors, for instance, KÜNNE (1937), NIKOLAEV (1950), DEMEL (1957), MAŃKOWSKI (1951, 1959, 1962), and LINDQUIST (1959, 1960). A case in point, well known on account of its economic importance, refers to the haddock (*Gadus aeglefinus*), a large population of which appeared in the westernmost Baltic in 1925—1926 as a consequence of a prior influx of oceanic water containing large amounts of larvae of the fish. In his paper of 1962, MAŃKOWSKI lists 15 species of macroplankton in the Baltic observed in the course of this century which are similarly to be regarded as »guests».

As may be expected, the record inflow through the Danish Sounds which occurred by the end of 1951 resulted in an extensive introduction into the Baltic of animals belonging to the category concerned.

In his papers of 1959 and 1962, on the macroplankton of the southern Baltic, MAŃKOWSKI gives interesting data in this subject. He states that the macroplankton caught in 1952—1954 in the area from the Arkona Basin to the Gdańsk and Gotland Basins contained numerous »guest» species. Of those treated, three may be mentioned here which are among the most characteristic biological indicators of saline influxes, viz. the copepod *Calanus finmarchicus*, the chaetognath *Sagitta setosa*, and the medusa *Melicerta octocostatum*. *Calanus* and *Sagitta* were captured in striking quantities. As regards *Melicerta octocostatum*, MAŃKOVSKI considers the species an especially significant biological indicator of saline inflows, as it requires a salinity of at least 16 ‰. According to him (1962), the medusa concerned appeared in the Baltic as long ago as 1949, as a consequence of an influx of salt water and, thanks to that of 1951, it remained a member of the Baltic fauna up to 1955.

The biological consequences of the 1951 inflow were also clearly indicated by the fish fauna. As was mentioned previously, the cod population of the Baltic began to increase strongly in the late 30's, in connection with the rise in salinity and unprecedented catches of the fish were afterwards landed in the Baltic area (cf. Fig. 1, inserted diagram, and Fig. 6). It has been suggested that this feature was mainly due to the combined effect of factors favouring breeding: (1) higher salinity and better oxygen supply in the deeps of the central and southern Baltic proper (the area between the Danish Isles and the entrances to the Gulf of Bothnia and the Gulf of Finland), where breeding mainly takes place, (2) better possibility for the pelagic eggs of the fish to keep afloat in water of higher density (salinity), (3) higher production of plankton organisms, constituting the food of the larvae, on account of ascent of deeper layers rich in accumulated nutrient salts; a consequence of intruding heavier (saltier) water along the bottom (KÄNDLER 1949, MEYER & KALLE 1950, NIKOLAEV 1950, 1957, MAŃKOWSKI 1951, SOSKIN 1956; etc., cf. below, p. 22.) According to NIKOLAEV (1957), in 1953 a strikingly strong year-class of cod was produced and he ascribes this to the increased salinity of the Baltic, also stressing the abundance of plankton in the year concerned.

The mackerel also deserves mention in this connection. The fish is another of those members of the ichthyofauna of the Baltic that have clearly been favoured by the recent salinity increase; since the onset of this process it has become much more common and widespread in the area than before (NIKOLAEV 1950, 1957, MAŃKOWSKI 1951; etc.). As in the case of the cod, the consequences of the inflow in 1951 are clearly observable (KÄNDLER 1954). Whereas spawning was earlier restricted even in the comparatively saline Belt Sea, reproductive activity in this area, manifested by the abundance of eggs in the plankton, proved very extensive in 1953, and KÄNDLER assumes this feature to be a result of the rise in salinity in 1952. The strength of the 1953 year-class led, some years later, to the frequent occurrence of the mackerel as far eastwards as the Gulf of Riga (NIKOLAEV 1957). The abundant stock of mackerel which invaded the Belt Sea in connection with the influx of 1951 and was responsible for the exceptionally extensive breeding in 1953, gave rise to a fishery of unexpected dimensions; in 1952 the catch of mackerel exceeded the earlier maximum by threefold (KÄNDLER 1954).

In this connection some data may also be given on the biological consequences of a later marked influx of saline water into the Baltic, viz. that observed in 1963 (cf. above).

According to TIEWS (1964), German observations made in the Arkona Basin in the spring of 1964 established that young specimens of the long rough dab (*Drepanopsetta platessoides*), a fish not met with there in 1962, were abundant by that time and that the stock of whiting (*Gadus merlangus*) had increased considerably in this basin and in the Bornholm Basin as well. Furthermore, east of Gotland cod was caught in great quantities as deep as 145 – 150 m, whereas it had proved absent in the Gotland Basin in 1962 below the level of 80 m, apparently on account of unfavourable oxygen conditions (cf. below, p. 18).

4. Hydrographical and biological consequences of the stagnation period following the 1951 inflow

The influx into the Baltic of exceptionally large amounts of strongly saline and, therefore, heavy, water that occurred by the end of 1951, in combination with the contrasting phenomenon of unusually weak oceanic intrusions in subsequent years and certain other hydrographical features, resulted in a strikingly long period during which the heavy layers in the depressions of the Baltic proper more or less stagnated. Here, too, we are faced with a phenomenon unprecedented in the annals of Baltic hydrographical research (cf. GLOWINSKA 1963). As will be shown below, its biological consequences have proved correspondingly remarkable.

The comments made will mainly be concerned with the Gotland Basin and the adjacent, more northern part of the Baltic (see map, Fig. 2). This basin, which on account of its width and depth (249 m) holds a special position among the depressions of the Baltic proper, is isolated from the Fårö Basin by a sill 140 m deep. The Fårö Basin has a maximum depth of 205 m and is limited in the north by a 115 m sill from an extensive deep area which continues directly into the shallower Gulf of Finland. The hydrography of the Gotland Basin and its adjacent waters during the period under discussion has been treated by MAŃKOWSKI, FONSELIUS, SHURIN, ALEKSANDROVSKAYA & KALEI, and others. Moreover, as mentioned in the introduction, the present author has had access to unpublished Finnish data elucidating the hydrographical situation in recent years in the region concerned.

A. The influence of the stagnation on the oxygen conditions and the ensuing consequences for the benthic fauna

As is well known, it is the water moving along the bottom from the North Sea that carries the oxygen to the deeper layers of the Baltic, for these, on account of their comparatively high density, cannot be aerated from the surface through convectional processes. In water stagnating in depressions of the bottom, the oxygen content gradually decreases as a consequence of the respiratory activity of the benthic organisms as well as the decomposition of dead organic matter, and finally anoxic (= anaërobic, cf. FONSELIUS 1962) conditions may follow and hydrogen sulphide may even appear in the deepest layers. The further inwards a depression is situated, the smaller are the chances of satisfactory oxygen conditions, as on its way inwards the bottom current is progressively deprived of oxygen. For this reason, the Gotland Basin holds an especially unfavourable position, which is still further accentuated by its great depth.

According to FONSELIUS (1962, cf. Fig. 4 in the present paper), the oxygen supply at 200 m in the Gotland Deep dropped from about 2 ml/l in 1955 to near zero during the following year and from 1957 to the beginning of 1961 no oxygen at all was observed. In 1957 the anoxic layers extended at times to 150 m above the bottom. In 1958 the smell of hydrogen sulphide could even be detected in the samples and this situation lasted till July 1961, when the O_2 value suddenly rose to 2 ml/l. FONSELIUS suggests that this increase was due to the inflow of saline water in 1959 (cf. above, p. 13) which is assumed to have affected the deep layers of the Gotland Basin comparatively late. His data are supplemented by those given by ALEKSANDROVSKAYA & KALEI (1962), who noted a temporary amelioration of

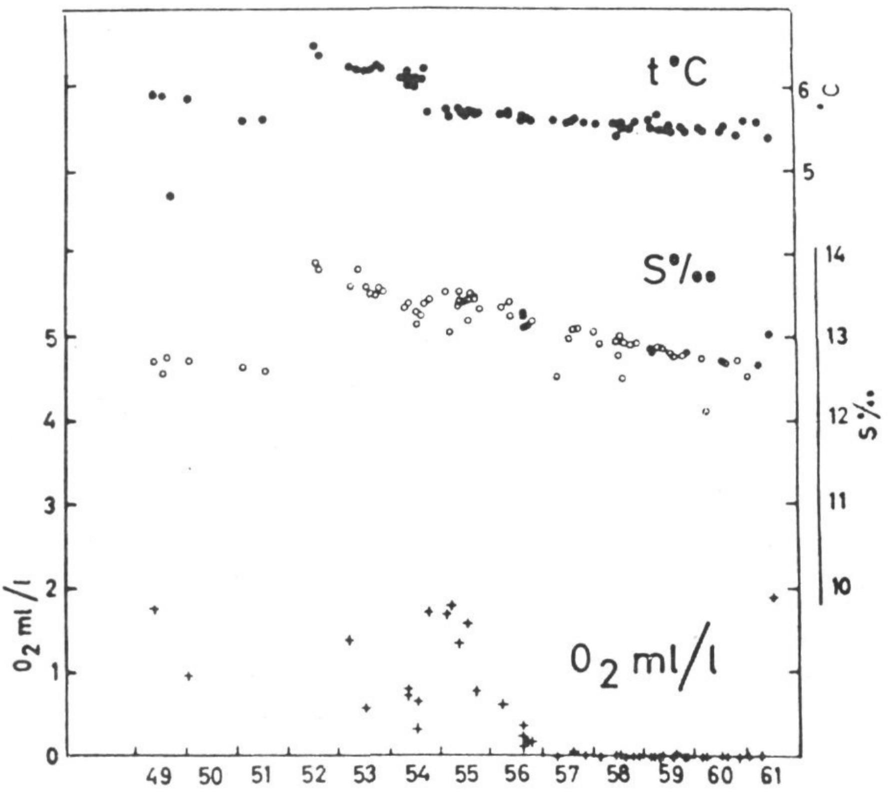

Fig. 4. Dissolved oxygen, salinity, and temperature in the Gotland Basin from 1949 to 1961, at 200 m depth. Note especially the rise in salinity in 1952 and the period of deoxygenation in 1957—1960. The diagram is part of one given by FONSELIUS (1962).

the oxygen conditions in the Gotland Deep in August, 1961, (165 μg-atom/l; 21% of saturation).

Data on the deoxygenation of the deeper layers of the Gotland Basin in 1958—1961 have also been given in several papers by SHURIN (1960, 1961, 1962, 1964). According to her, in 1958 and 1959, there was no oxygen at all or only quite negligible quantities in the Gotland Deep below the level of 90 m, and from this depth down to the bottom the water contained hydrogen sulphide. However, the increase in salinity in the southern Baltic in 1960 was accompanied by an amelioration of the oxygen conditions in the southern part of the Gotland Deep. Referring to data supplied by ALEKSANDROVSKAYA and KALEI (l.c.), SHURIN states that in May 1961 hydrogen sulphide was still present in the Deep from 180 m downwards, but by August it had disappeared from the water (cf. FONSELIUS 1962, p. 34); however, H_2S remained in the bottom substrate over the whole area concerned. As regards 1962, the author mentions that the deeper layers of the Gotland Basin contained very little O_2 (less than half a ml/l). It should be added that German observations in May, 1962, even established the presence of hydrogen sulphide below 75 m (MEYER-WAARDEN 1963).

Total or practical deoxygenation of the Gotland Deep was observed in 1961 (late July) and 1962 (same time) on the cruises of the Finnish R/V Aranda (cf. p. 9). At the same time strikingly low oxygen values were further found in the deeper layers at the hydrographic station F 75 and even as far north as F 71 (for location and depth, see Fig. 2).

The hydrographical work carried out on board Aranda in June and July 1963 showed that the oxygen situation had still further deteriorated by this year, anoxic conditions being observed not only in the deeper layers of the Gotland Basin (F 81) but also in the Fårö Deep (F 80) and at F 71. Values below 1 ml/l were found up to approximately the following levels above the bottom: F 81: 125 m, F 80: 105 m, F 71: 30 m. The totally or virtually deoxygenated bottom area must thus have been very large. From 1964, comparable data are not available, but the cruise of Aranda to the region off the entrance to the Gulf of Finland in that year clearly points to a continuation there of the previous very unfavourable oxygen situation (see below).

By contrast, in the Gdańsk Deep, and also in the south-westernmost part of the Gotland Deep, the oxygen conditions underwent an amelioration in 1963. According to GLOWIŃSKA (1964), the saline inflow into the Baltic in that year (cf. above, p. 13) reached these areas by the late autumn of 1963, causing an increase in the oxygen values to more than 3 ml/l. Supplementary data on the effect of this influx on the ventilation of the regions concerned are found in an article by TIEWS (1964), in which the preliminary results of the cruise of the German R/V »Anton Dohrn» to the central Baltic proper in 1964 are given. On this cruise, which took place during the period April 17—May 11 that year, water rich in oxygen was found in the Gdańsk Deep and the inflow had also reached parts of the Gotland Deep. According to GLOWIŃSKA (l.c.), the volume of the 1963 influx into the Baltic must have been comparatively large in view of the fact that water of unusually high salinity (above 20 ‰) was found at the bottom of the Arkona Deep during the whole period from June to November. Afterwards the salinity there decreased to a minimum of 18.25 in February 1964, but then a new increase took place and in May a salinity of 19.85 was measured.

As emerges from the above survey, anoxic conditions or very low oxygen values have characterized the Gotland Basin from 1957 to late 1963, i.e. in not less than 7 successive years — a case unprecedented since hydrographical observations were started in this region (see Fig. 5 in FONSELIUS' paper of 1962). We have, further, concluded that a similar situation has prevailed even longer in the deeper waters north of the Gotland Basin.

Some data may be given on the oxygen conditions off the entrance to the Gulf of Finland and in the Gulf itself.

The cruises of Aranda in 1962—1964 showed that off the Gulf, below a level of about 100 m, only negligible amounts of oxygen (less than 1 ml/l) were present. As far as the Gulf itself is concerned, SHURIN (1962) states that in 1960 the deoxygenated area of the Gotland Deep was not confined to the Deep alone, but extended into the outer part of the Gulf of Finland, up to the region off Tallinn, a feature that was obviously due to the pushing effect of the influx of water into the Gotland Basin in the same year (cf. above p. 17). In 1963 and 1964, the hydrographers on board Aranda sampled a series of stations along the central part of the Gulf. In the former year, more than 10 stations, with a maximum depth of 85 m, were visited between the regions off Hamina (Fredrikshamn) and Hangö (Hanko). At most stations the O_2 values found in the near-bottom layers were not remarkably low, the only exception being the deepest one, situated off Porkala, where 1.53 ml/l was measured at 75 m. By contrast, the cruise in 1964 clearly proved that the oxygen situation in the Gulf had deteriorated. The 5 stations of the former series, where sampling was repeated in that year — the area covered by them extended from off Helsinki westwards to the mouth of the Gulf — exhibited throughout, at the greatest depth sampled, 65—70 m, oxygen concentrations of less than 2 ml/l. It is thus obvious that, since the cruise in 1963, water very poor in oxygen had penetrated into the Gulf from the area outside. As a background to this phenomenon, it may be noted that, according to the observations made on board Aranda in 1963 and 1964, the hydrographical situation off the Gulf of Finland was, in the latter year, characterized by a rise of the layers with very low oxygen values (at most about 1 ml/l), up to c. 70—75 m, a process that must have favoured the intrusion of practically anoxic water into the Gulf in this year. It is a well-known fact that a compensation current is constantly flowing eastward along the bottom of it and that the irregular hydrographical conditions outside, especially in the Gotland Basin, render the oxygen conditions in the deeper layers of the Gulf highly unstable (cf., for instance, BUCH, 1945).

We shall now turn to the biological consequences of the long period of stagnation since the early 50's.

In her afore-mentioned papers (1960, 1961, 1962, 1964), SHURIN has also presented the results of investigations into the bottom fauna of the Gotland Basin and adjacent areas of the Baltic, carried out in 1949—1962. As may be expected, this work has shown that the deterioration of the

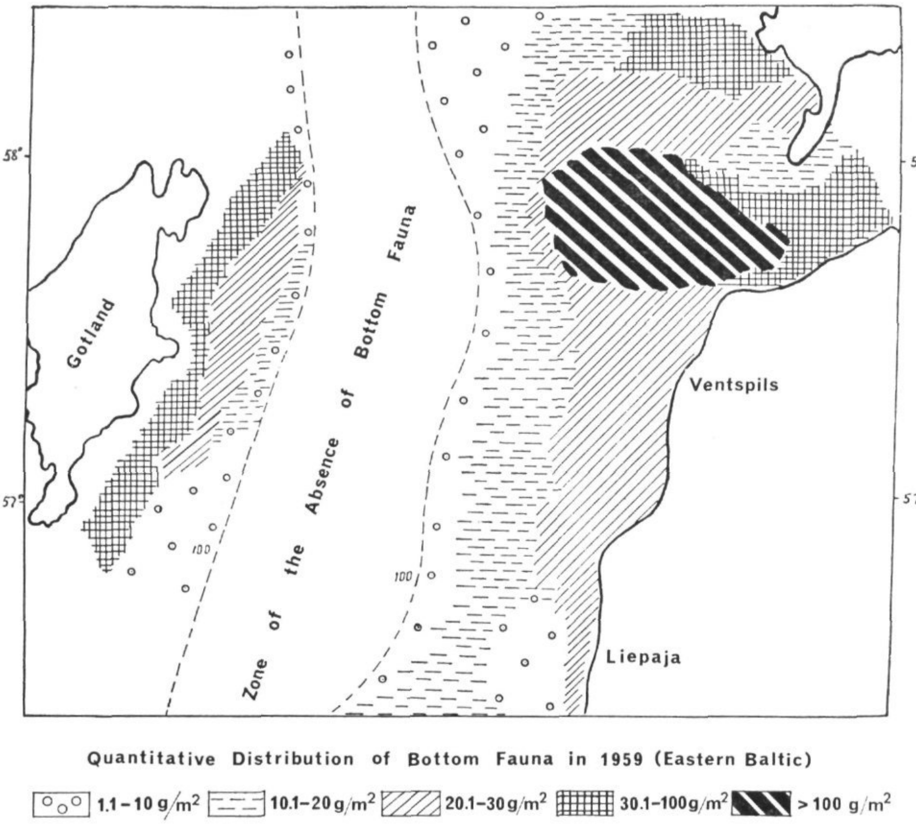

Fig. 5. The dead zone in the Gotland area and adjacent waters in 1959. After SHURIN (1961).

respiratory conditions near the bottom, which was the consequence of the stagnation and which have been discussed above, led to a catastrophe for the benthic animals inhabiting the area concerned. Whereas sampling in 1949—1950 revealed that the increase in salinity had resulted in a marked abundance of several marine benthic species (*Priapulus caudatus*, *Scoloplos armiger*, *Terebellides strömi*, *Diastylis rathkei*, and others) in the northern and eastern regions of the open Baltic, and bottom animals were encountered down to 150 m in the Gotland Deep, it turned out, when the work was continued in 1956—1959, that this favourable situation had been followed by a marked decline. By 1958 and 1959, the deeper parts of the Gotland and Gdańsk Basins were found to be practically lifeless deserts, and this also applied to the Bornholm Basin. The total area concerned was estimated at not less than 12,000 sq. miles (Fig. 5). The feeding conditions of fish were accordingly affected. As regards *Macoma baltica*, SHURIN observed in 1958 that the population of the bivalve had died below the level of 90 m and she suggested that it perished between 1956 and 1958. The work carried out in 1959 showed that most stations exhibiting animal life were confined to the zone above about 80 m. Owing to improved oxygen conditions in the southern part of the Gotland Deep in 1960 (see above, p. 17), the zone concerned was found to extend downwards to about 110 m this year in the region mentioned, and between 80 and 90 m eight benthic species were captured, against only three in 1959 (these especially hardy species were *Harmothoë sarsi*, *Scoloplos armiger*, and *Diastylis rathkei*). However, the survey of 1962 indicated a further decline of the biomass of the bottom fauna of the Gotland area, mainly because of the decrease in the numbers of *Macoma*. It thus seems apparent that the slight amelioration of the respiratory conditions in the latter half of 1961 (cf. above, p. 17) had not produced any change in the catastrophic situation.

Since SHURIN's work was carried out, data on the benthic fauna of the Gotland area seem not to have been published. However, the observations on the oxygen conditions on board Aranda in the years 1963 and 1964 clearly suggest that the catastrophic situation in the area has continued, and further, that the region practically devoid of bottom animals has in these years also comprised more northern deep waters belonging to the Baltic proper. For this area, the same conclusion may be drawn from the Finnish hydrographical observations made in 1961 and 1962 (see above, p. 18).

Some notes on the Gulf of Finland may be added.

Observations on the occurrence of two common bottom animals in the Gulf, made in 1954—1959, suggest unfavourable oxygen conditions at greater depths (SEGERSTRÅLE 1962, p. 11): *Macoma* was caught in all localities above 38 m, but in only two out of 11 localities with depths ranging from 54 to 74 m; and the abundance of *Pontoporeia* proved much lower than that found at a corresponding depth in the Gulf of Bothnia, which is constantly well aerated down to the bottom. A special observation deserves mention in this connection. When sampling on board Aranda off Tvärminne in August, 1954, SJÖBLOM found (cf. GRANQVIST 1954, p. 55), at the deepest station visited there (No. 17), with a depth of 65 m, an unusually large number (41) of empty shells of *Macoma*, but no live bivalves. On inspection of the sample concerned, the present author observed that a large proportion of the shells did not exhibit the signs of heavy corrosion typical of empty *Macoma* shells occurring on the bottom of the Gulf, but had a rather fresh appearance. This fact suggests that the animals concerned had perished not long before and it seems likely that they had been suffocated by an inflow of deoxygenated water. As a matter of fact, the amount of oxygen measured near the bottom on the same occasion was not more than 3.20 ml/l, and at the depth in question strong fluctuations are to be reckoned with (cf. above, p. 19). It is also to be noted that during the same cruise such a low oxygen value as 1.18 ml/l was observed at the hydrographical station F 56 a, situated at 68 m depth east of Tvärminne, off Porkala.

The stagnation period discussed above, which led to the extinction, for many years, of the benthic fauna living in the deeper parts of the open Baltic, emphasizes the significance of a sufficient inflow of oceanic water into the Baltic. At the same time, the fact that such a long-lasting stagnation is an exceptional feature underlines the relatively favourable biological status of this area as compared with another large brackishwater basin, viz. the Black Sea, where the layers below about 200 m are constantly anoxic and, hence, totally deprived of higher life.

B. The stagnation period as related to the nutritive conditions of the Baltic

It is notorious that, with respect to its biological productivity, the Baltic is a much less favourable area than the North Sea and other comparable oceanic waters. According to DEMEL (1960), the average biomass of the benthic fauna of the North Sea amounts to 240—300 g/m^2, whereas in the Baltic it is not more than 30 g/m^2, and he also reckons with great differences with regard to plankton production. Against this background, the divergences in fish yield are also understandable: DEMEL gives 30 kg/ha for the North Sea in 1957 against only 10 for the Baltic; and he stresses that in that year the latter figure was about twice as high as in pre-war times.

Among the reasons for the low productivity of Baltic waters is the comparatively poor nutritive condition of the basin. This is due, on the one hand, to the restricted inflow of oceanic water and, on the other, to the exclusion of the deeper layers of the Baltic, which are rich in biogenic salts derived from organic matter, from the convectional processes and thus from fertilizing the upper strata to which primary production is confined (cf. above, p. 14). As regards the former factor, it is to be remembered that the shallowness of the inlets to the Baltic prevents the deeper oceanic layers, comparatively enriched with nutrient salts, from entering the area; therefore, immediately after an inflow of the superficial water the deeps of the southern and central Baltic are especially poor in nutrients and it is only with time that new resources accumulate (cf., for instance, BUCH 1932, PIATEK 1962). As far as the latter factor is concerned, hydrographical work has shown that it is only under special circumstances that these fertilizing resources of the Baltic depressions are brought up to the surface, the ascent being mainly restricted to upwelling in coastal regions and uplifting of bottom layers by heavier inflowing water (cf. above, p. 14).

A well-known example of upwelling is offered by the inner part of the Gulf of Finland, where the inflowing bottom current is forced to the surface, with a strikingly high production of plankton as a consequence (cf., for instance, BUCH l.c.; the fertilizing effect of the river Neva is also to be considered in this connection); another example is the Bay of Puck on the Polish coast (GLOWIŃSKA 1963).

Besides the poor nutritive conditions, the low salinity of the Baltic must also be taken into consideration as partly responsible for its low productivity, because this factor excludes quite a number of large marine animals from the basin concerned. This is especially true of the benthic fauna of Baltic waters, which includes, for instance, only a few lamellibranchs and no echinoderms (apart from the outermost part of the area).

The feature of stagnation and subsequent ascent of layers enriched with nutrient salts and the fertilizing effect of this process has been hinted at repeatedly in the present paper. However, the long period of stagnation in the open Baltic since the early 50's prompts a discussion of its own. As a background, an earlier remarkable case of stagnation and subsequent uplifting in this area may be briefly reviewed (KALLE 1943, MEYER & KALLE 1950; cf. also DIETRICH 1963).

Hydrographical investigations in the Gotland Basin in 1931 showed clear signs of stagnation of deeper layers, the oxygen content being low and the amount of phosphates derived from organic matter produced in upper layers great (part of the phosphates found in the Basin may originate from more western depressions; cf. GLOWIŃSKA 1963). Two years later the situation had altered as a consequence of the inflow along the bottom of heavy water of oceanic origin — as will be remembered, it was by that time that the increase in the salinity of the Baltic area began. This »new» water was rich in oxygen but contained little phosphates and, because of its greater density, it forced its way below the stagnating layers, lifting them, together with their phosphate resources, towards the surface. It was estimated that the weight of the phosphate-phosphorus which ascended in this way from the Gotland Basin and was incorporated in the primary production of the surface layers of the central Baltic amounted to not less than 30,000 tons. In view of the rate of loss known from fertilization experiments in lakes, an additional annual production of 150,000 tons of fish was estimated for the eastern Baltic during the first years of the turnover. In fact, the catches of cod increased enormously during this period (Fig. 6). The remarkable strong representation of the year-class of cod in 1953 should also be recalled and its suggested connection with the fertilizing effect of uplifted deeper layers (p. 14 above).

Turning now to the stagnation period discussed in the present paper, its exceptionally long duration must have led to the accumulation, in the deeper layers of the Baltic proper, of enormous amounts of biogenic salts.

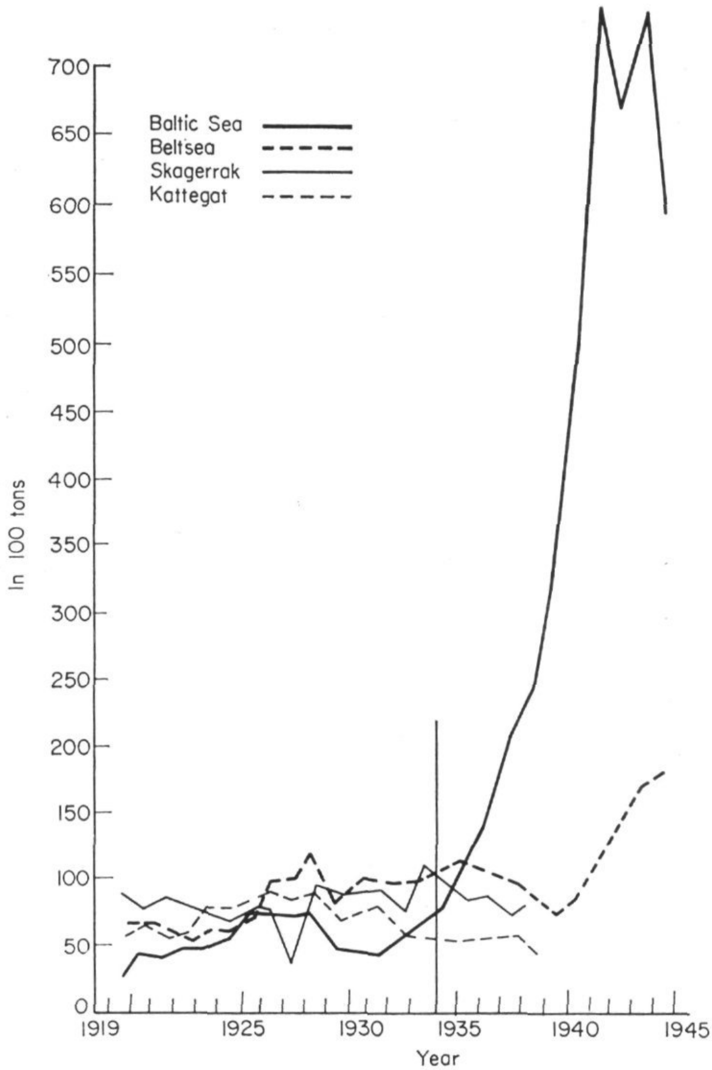

Fig. 6. Catches of codfish by the fishing industries of Germany, Denmark, Norway, Sweden and Poland in the Baltic proper, the Belt Sea, Skagerrak, and Kattegat, 1919—1944. After MEYER & KALLE (1950).

FONSELIUS (1962) has calculated that in October 1959, a minimum of 37,000 tons of phosphate-phosphorus was present in the Gotland Basin under the 140 m level; together with the Fårö Basin, 40,000 tons are reckoned with. To be sure, the influx into the Gotland Basin noted by him in July, 1961, lifted the bottom layers, but this process has apparently not been very efficient in view of the fact that the Aranda observations in the basin concerned on July 22 of the same year gave, at 208 m, an oxygen content of only 0.25 ml/l; further, the cruise in the following year indicated a total absence of oxygen at 220 m.

Some fertilizing effect of the ascent in 1961 may, however, perhaps be reckoned with. NIKOLAEV *et al.* (1964) report that in 1962, in the northern part of the central Baltic (region between Klaipeda [Memel] and the Gulf of Finland), there was a density and biomass of zooplankton (mainly copepods) which exceeded all earlier experience, and he suggests that the animals concerned were favoured by, on the one hand, the moderate warming of the upper layers in that year and, on the other, the manuring effect the large outflow of river water, especially along West Dvina (Daugava), in 1961. The latter effect was possibly accentuated by the uplifting process mentioned above.

As regards the strong saline inflow into the Baltic in 1963 which, on its way northwards, had reached the Gotland Basin by the spring of 1964 (cf. above, p. 18), there can be little doubt that it led, and is still leading, to a considerable ascent of the deeper layers in the Baltic proper. In view of the long duration of the stagnation period and the ensuing accumulation of enormous quantities of biogenic salts in these layers, the prerequisites for a correspondingly efficient fertilizing of the upper layers, i.e. for a high primary production, were, at any rate, available in 1964.

Summary

As a continuation of earlier reports, the author presents annual averages of the salinity observed at 5 m depth at three hydrographical stations off the south coast of Finland from 1957 up to and including the first half of 1964. In this connection the salinity conditions at these stations since 1950, as well as certain remarkable hydrographical and biological features in other parts of the Baltic proper during this period, are discussed. The following phenomena may be pointed out:

(1) The record salinity observed off the Finnish coast in 1953 was due to the influx into the Baltic of highly saline water, on a scale hitherto unknown, by the end of 1951. This inflow allowed a number of stenohaline marine animals to enter the basin and favoured the marine element of its fauna (extension of range, increase in abundance, etc.).

(2) The long duration of the stagnation of deeper layers in the Baltic proper which followed the influx in 1951 and the catastrophic consequences for the benthic animals, due to the unfavourable oxygen conditions involved, were also phenomena unprecedented in the annals of Baltic research. The correspondingly marked accumulation of nutrient salts during the stagnation period and its biological significance are discussed.

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