On the stagnation and recent turnover of the water in the Baltic

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ABSTRACT

A short description of the hydrography and water balance of the Baltic is given. The different pycnoclines in the Baltic proper are described. The inflow of salt water through the Danish sounds and the development of stagnant conditions in the deep basins are described. The renewal of the stagnant deep water and the "fertilization" of the surface water with nutrients are discussed. The oxygen utilization and the accumulation of nutrients through decay of organic matter in the deep water are described. The formation of ammonia, nitrogen and hydrogen sulphide in the stagnant water is briefly explained.

The oxygen decrease in the Baltic deep water during the present century and possible reasons to this phenomenon are discussed. The recent stagnation and deep water renewal during 1969 are described by help of figures. The "Baltic Year" programme is described and some results are discussed. The accumulation of phosphate during the stagnation and the spreading of phosphate in the deep water and the "fertilization" of the surface water during the water renewal in 1969 are shown by help of figures.

An increased primary production in the surface water is predicted and a prognosis for the future development of the oxygen conditions in the Baltic is given. It is concluded that Man has increased the oxygen utilization in the deep water by the enormously increased discharge of untreated waste water from industries and communities and that the Baltic therefore has been "overstrained". Finally it is suggested that measures against future waste discharge have to be taken in order to give the Baltic a chance to recover.

1. General characteristics of the deep waters of the Baltic

The Baltic is one of the smallest intracontinental mediterranean seas. The annual supply of fresh water exceeds the evaporation during the year. Thus its water balance is positive. It so happens that the annual precipitation is almost exactly as large as the evaporation. The annual net outflow of fresh water therefore is equal to the river discharge. The Baltic is the largest brackish water area of the world. Since the water is brackish, there must be an inflow of salt water from the ocean. Fresh water has a lower density than salt water. Therefore two different water layers are formed, a light surface layer with a very low salinity and a heavier deep layer with a higher salinity. These layers are separated by a pycnocline or halocline, where the salinity suddenly changes. The annual excess of fresh water, mixed with some salt water, flows as a surface current out from the Baltic forming the "Baltic Current" in Kattegatt and Skagerack. Heavy salt water flows in the opposite direction as a bottom current below the outflowing surface water along the bottom of the Danish sounds. The water balance has been computed by Brogmus (1952). He finds the annual discharge of rivers to be 471 km^3. The inflow of salt water is also given to be 471 km^3. The sum of these, 942 km^3, flows out through the Belts and Öresund as the "Baltic Current".

The water exchange between the surface layer and the deep layer may be calculated, if the water balance and the mean salinities of the surface water, the deep water and the inflowing salt water are known. The mean salinity of the surface water may roughly be estimated to be 7‰, the mean salinity of the deep water 11‰ and the mean salinity of the inflowing water 17.5‰. Then the transfer of water from the bottom to the top layer becomes about 1 250 km^3 and the transfer downward roughly 750 km^3 (Fonselius, 1969).

It has to be pointed out that the salinities are only rough averages. Therefore only the order of magnitude of the water exchange is

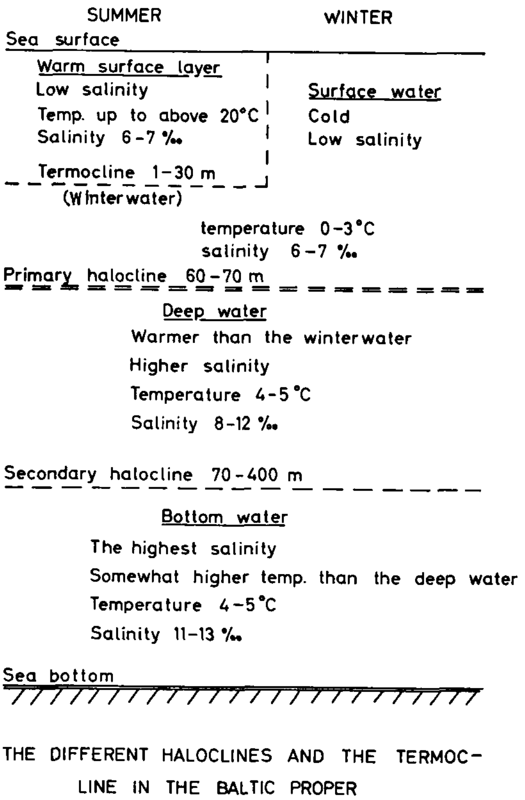

Fig. 1. The different water layers and pycnoclines in the Baltic proper.

obtained. One of the main tasks of the hydrographic work in the Baltic is to get better estimates of these exchange rates. It would then be possible to calculate the transport of nutrients through the halocline and to get a better knowledge of the processes which regulate the oxygen conditions in the Baltic deep water.

The halocline is an impediment to the mixing or exchange of surface water and deep water. Therefore it is also an impediment to the exchange of oxygen between the water layers. The surface water is generally saturated with oxygen. It is in constant contact with the atmosphere and the gas exchange through the surface is fast enough to keep the water close to the saturation limit.

When the surface water during the winter is cooled from above, its density increases. It sinks downwards and is replaced by water from below. The new water is continuously cooled and a vertical convection is started. This convection transports oxygen-saturated water down below the surface. The upwards moving water brings nutrients from below to the surface water which generally has a very low nutrient content. This vertical convection cannot penetrate through the halocline. The density of the deep water is too high and therefore it only extends down to the upper boundary of the halocline. The water below the halocline is thus not influenced by the "winter convection". This halocline is a permanent feature in the Baltic and is called the "primary halocline".

During the spring the surface water is heated by the sun. Its density decreases and a thin light and warm surface layer is formed. Its thickness increases during the spring when the warming continues. It is separated from cold water below by a thermocline which may move down to more than 30 m depth in the late summer. Between this thermocline and the primary halocline the remains of the cold winter surface water are found. This cold layer is recognized as a temperature minimum in bathythermograms. The water below the primary halocline has a temperature of about 4–6°C during the whole year.

It may sometimes happen that water with an unusually high salinity is forced in over the sill to the Baltic. Such water has a high density and may therefore sink to the bottom of the deepest basins and remain there for longer or shorter time. Then a secondary halocline may be developed between the bottom water and the deep water in the basin. The different waterlayers, haloclines and the thermocline are illustrated in Fig. 1.

The deep water in the Baltic moves counterclockwise around the island of Gotland. The salt water which flows over the 17 m deep sill at Darss into the Baltic follows the deepest connections between the different basins in the Baltic. When the basin closest to the entrance is filled with salt water up to the sill depth to the next basin, the salt water begins to stream down over the sill filling up the basin to the sill depth of the next basin, and so on. The 55 m deep Arkona basin west of Bornholm is first filled up to the 45 m deep sill to the 105 m deep Bornholm basin east of Bornholm. The sill is located between the Swedish coast and Bornholm. When this relatively large basin is filled with salt water up to the 60 m level, the water can proceed over the Stolpe sill to the large eastern Gotland basin with the 249 m deep Gotland Deep. From this basin the water may continue over a probably 115 m deep sill to the northern Central basin which extends from the Gulf of Finland to Landsort. It includes the 459 m deep Landsort Deep, the deepest spot of the Baltic. From the northern Central basin the water may still proceed south to the areas west of Gotland over a 100 m deep sill. From there the deep water cannot continue further without mixing in the surface water, because of the small water depth south of Gotland and Öland. The Gulf of Bothnia is isolated from the Baltic by a 45 m sill which prevents deep water from penetrating further north.

The amount of salt water inflow is regulated by the amount of inflowing water. The inflowing water expels the lighter old water from the basin. If the following inflow contains lighter water, it will stream over the heavier water which therefore may stay in the basin for years. Through diffusion and turbulence in the boundary layer its density slowly decreases. Eventually it may be expelled by heavier water.

The expelled water spreads from the eastern Gotland basin towards the north. In the northern Central basin it is divided into two arms. One goes toward the Gulf of Finland and is slowly mixed into the surface water which there mainly is a mixture of water from the Neva, the Narva and the Kymijoki rivers. The water of the second arm flows to the west down into the Landsort Deep and from there to the area between Gotland and Öland. There the remaining water is mixed into the surface water. The expelled water has a high concentration of nutrient salts. Therefore it "fertilizes" the surface water which has a very low nutrient content (Fonselius, 1967).

The water which flows into the Baltic, forming deep and bottom water, cannot effectively renew its oxygen content.This is prevented by the halocline which acts as a barrier to gas exchange. Therefore the oxygen concentration will decrease in the deep water during its way counterclockwise around Gotland. This is due to the fact that organic compounds in the water through bacterial processes are oxidized to such simple inorganic oxides as carbon dioxide (CO_2), water (H_2O) and to ions such as nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (H_2SiO_3). Organic compounds are brought to the deep water from the surface layers by the sinking of dead microorganisms as, e.g., plankton. The supply of dead matter is dependent on the production in the surface layers. When the production is high, the amount of dead matter increases in the deep water. This increases also the oxygen utilization there. Water with unusually high salinity and therefore also an unusually high density, may remain in some of the deep basins for a long time. The oxygen in such water may then become completely exhausted. There are always bacteria in nature and of course also in sea water. When the free oxygen has been almost completely used up, certain denitrification bacteria become active. They can use the oxygen from nitrate ions to oxidize organic compounds. The nitrate ions are converted to nitrite ions and then to free nitrogen molecules. There is also the possibility that a part is transformed to ammonia. The concentration of nitrate in sea water is relatively low. Thus the nitrate ions are quickly used up. When this has happened, a new oxidation process begins, in which sulphate-reducing bacteria use the oxygen from sulphate ions for the oxidation of organic matter. The sulphate is reduced to sulphide ions. What generally is called hydrogen sulphide, is formed in the water. It is recognized by its repulsive smell even in very small concentrations. Hydrogen sulphide is a poisonous gas which dissolves in water and kills all higher life. Therefore hydrogen sulphide formation is a real catastrophe for the bottom fauna in the area. Once started, hydrogen sulphide formation proceeds rapidly.

Such a development as that described above has taken place in the Baltic during recent years. The hydrogen sulphide formation began in the Gotland basin towards the end of 1967 and during 1968 hydrogen sulphide was present in the deep water of the Bornholm basin, the eatern Gotland basin, the northern Central basin and the western Gotland basin. Such an extensive hydrogen sulphide poisoning has never been observed before in the deep basins of the Baltic. This is the final result of the decreasing oxygen concentration in the deep water of the Baltic, which has been observed since the beginning of the present century (Fonselius, 1969).

There have been several attempts to try to explain the oxygen decrease that has taken place since about 1900. It is known that the salinity of the Baltic has increased, and is greater in

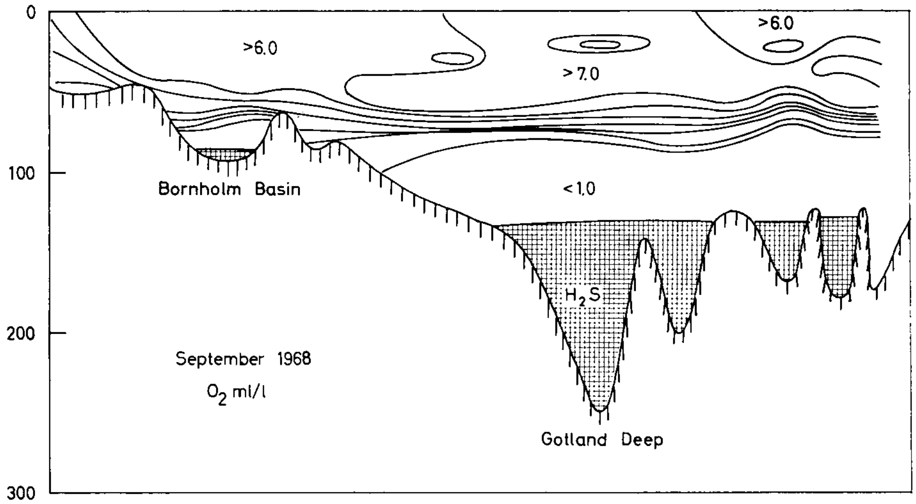

Fig. 2. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in September 1968.

the deep water than in the surface water (Fonselius, 1969). This may have increased the stability of the halocline. Therefore a decrease of the oxygen supply through the halocline to the deep water may have taken place. It has also been observed that the temperature of the deep water has increased by more than 1°C during the last 50 years (Fonselius, 1969), probably due to the fact that the temperature of the ocean water being supplied to the Baltic through the Danish sounds has increased during the century. This may have increased the oxidation rate (i.e. the decomposition rate of the organic matter in the water, Van't Hoff's principle). It has been shown that in fresh water a 10° increase of the temperature may increase the oxidation rate to double or almost to triple. It is therefore possible that a 1° temperature increase increases the oxidation rate by about 10%. This would of course be unimportant if the supply of organic matter were the limiting factor for the oxidation process. Waste water from communities and industries have, however, "fertilized" the sur-

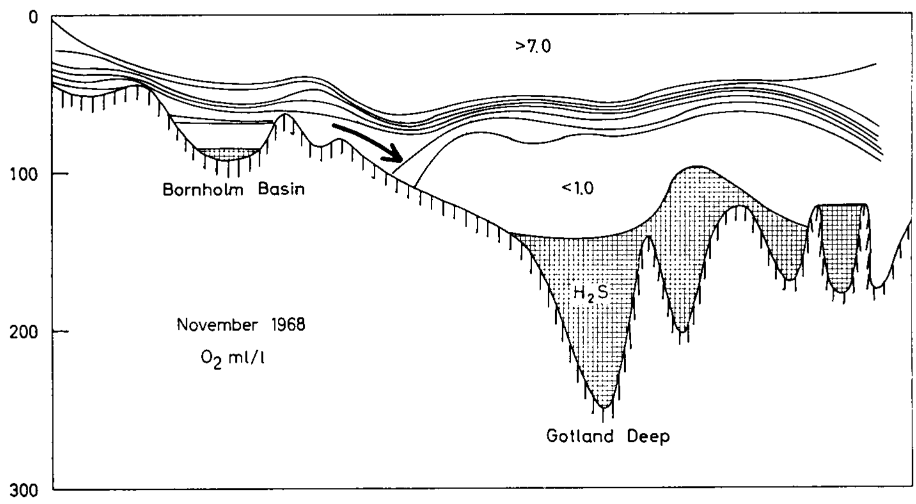

Fig. 3. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in November 1968.

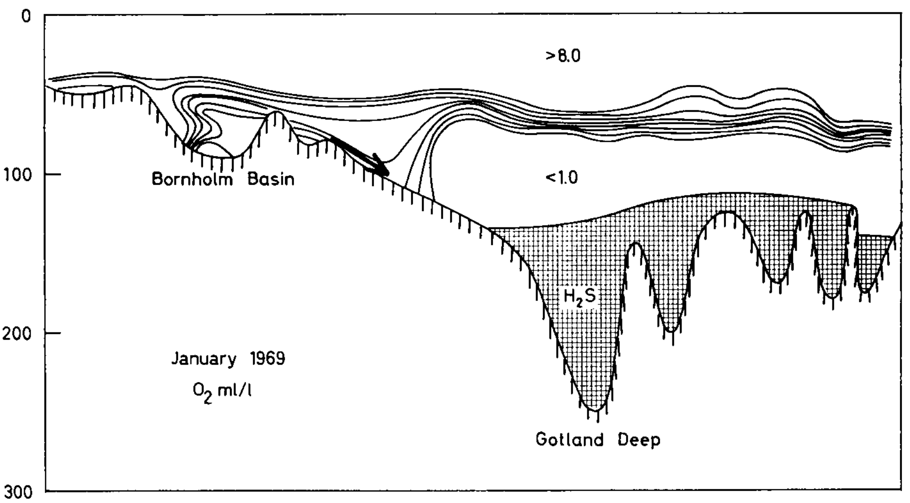

Fig. 4. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in January 1969.

face water and thereby increased the primary production. This may have caused a greater transport of dead organic matter to the deep water. The oxygen supply may now be the limiting factor for the oxidation.

It has been observed that the concentration of nutrients increases rapidly in the stagnant water. This is caused by the fact that more and more organic matter is brought to the deep water and is decomposed there. The nutrient salts set free during the oxidation process are accumulated in the stagnant water and when hydrogen sulphide formation begins, the environment changes from oxidizing to reducing. Nutrient salts are also dissolved from the bottom sediments, increasing the nutrient concentration still more (Fonselius, 1969).

When the water in the deep basins is renewed by a new inflow of saltwater with a higher density, the old water is forced out from the basin. It is spread northwards into the deep basins north and west of Gotland. Finally this nutrient-rich water will be mixed up into the surface water, "fertilizing" it. When

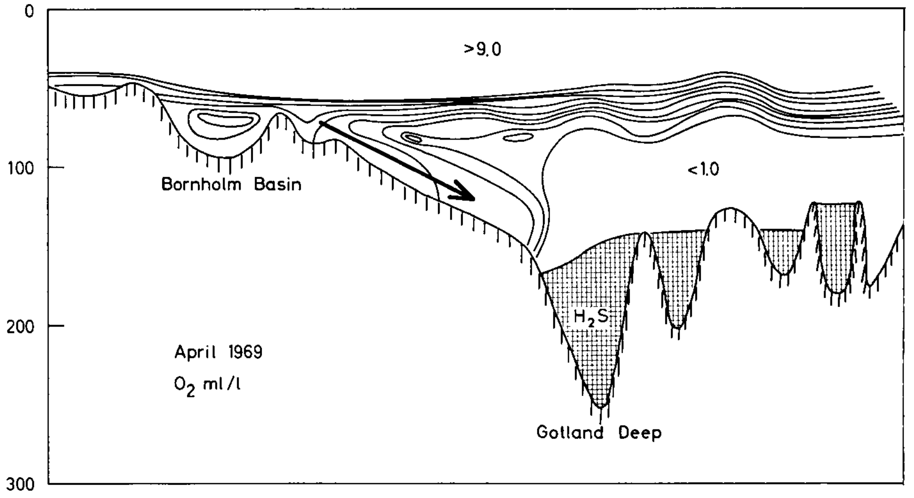

Fig. 5. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in April 1969.

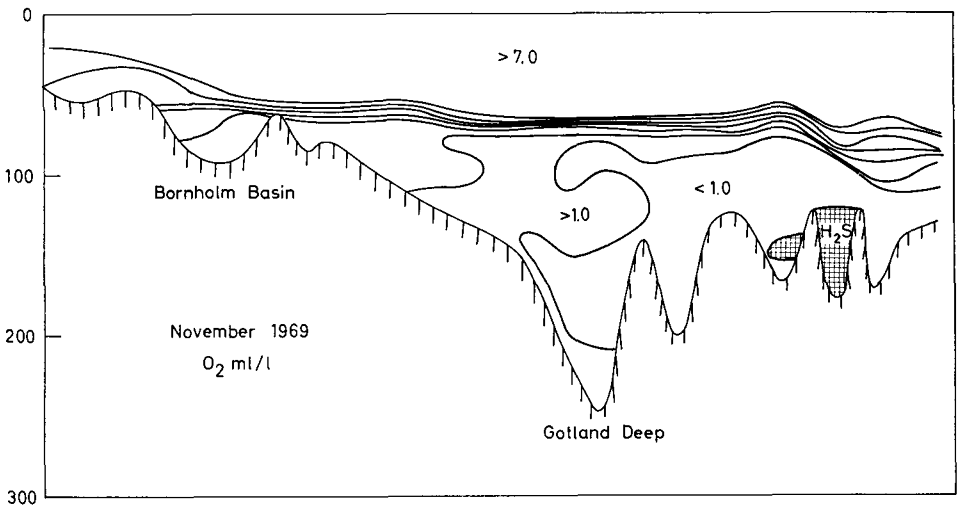

Fig. 6. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in November 1969.

hydrogen sulphide-containing water is mixed with oxygen-containing water, the two dissolved gases will react, forming sulphate ions or free molecular sulphur (Fonselius, 1969). This of course will decrease the oxygen content of the water which is mixed with the stagnant water. Furthermore the "fertilization" of the surface water increases the primary production. This again increases the oxygen utilization in the deep water by the increase of organic matter. We get alternating oxygen and hydrogen sulphide periods in the water. The situation deteriorates until a steady state is reached. It seems that it is difficult for Nature to restore normal conditions once hydrogen sulphide formation has started (Fonselius, 1969).

2. Deep water renewal in 1968 and 1969

It was mentioned above that there was hydrogen sulphide in all the deep basins of the Baltic proper during 1968. Fig. 2. shows a vertical section through the different deep basins of the Baltic from the Arkona basin to the

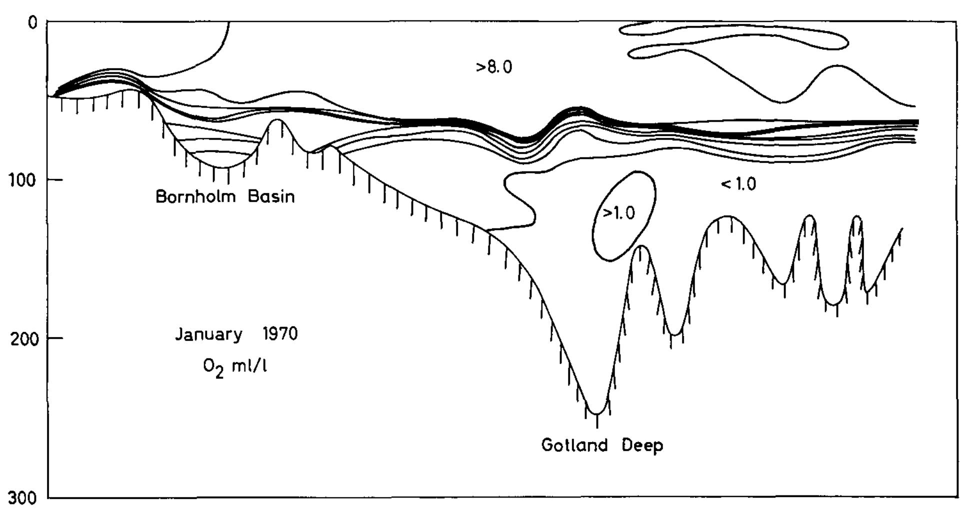

Fig. 7. Longitudinal section through the Baltic from the Arkona Basin to the mouth of the Gulf of Finland, showing the distribution of dissolved oxygen and hydrogen sulphide in January 1970.

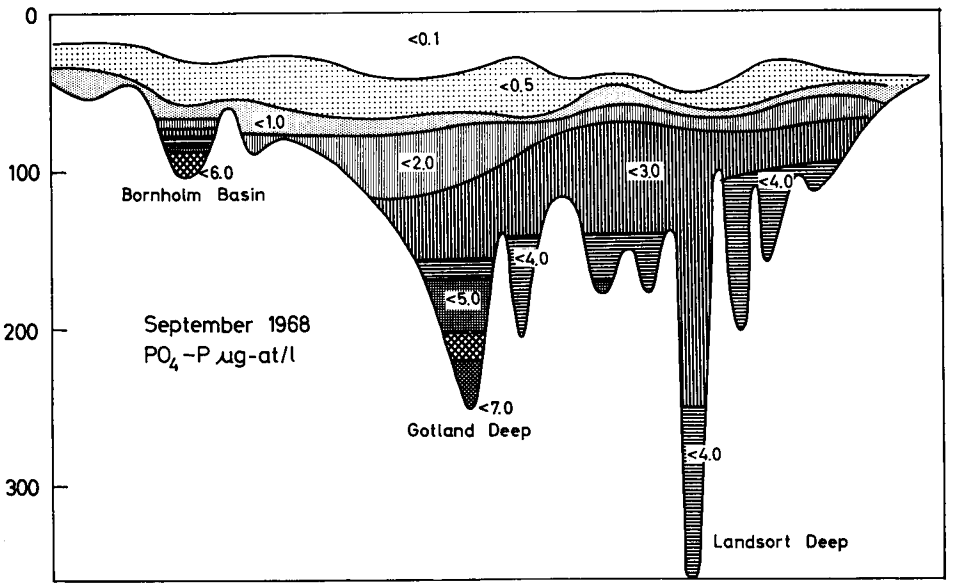

Fig. 8. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate-phosphorus in September 1968.

mouth of the Gulf of Finland in September 1968. The isolines for oxygen are drawn and the areas with hydrogen sulphide are shaded. It can be seen that there is hydrogen sulphide in the Bornholm basin, the Gotland basin, the Fårö Deep and in the deep areas of the northern Central basin. Fig. 3 shows the same section in November 1968. New water with a higher oxygen content has now started to flow in over the Darsser Sill at the left in the figure. It does not have, however, a density high enough to renew the deep water of the Bornholm Basin. It flows above the stagnant water in the Gotland basin and has peeled off the top layer of hydrogen sulphide and pushed it to the north.

The "Baltic Year"

This programme began in January 1969. It is a cooperative effort with participants from all the countries around the Baltic. About every third week a research ship from one of the participating laboratories goes out in the Baltic in accordance with an established programme. In addition to ordinary hydrographic work, water samples for nutrient salt analysis are taken in all deep basins of the Baltic proper. The Hydrographic Department of the Fishery Board of Sweden acts as coordinator for the work. The "Baltic Year" began with an expedition of the *Skagerak* in January 1969. Fig. 4. shows the results from this expedition in the form of a longitudinal section similar to those shown above. Now the stagnant water of the Bornholm basin has been replaced with oxygen-rich water. The heavy, oxygen-rich water proceeds towards the Gotland deep. The isolines for oxygen are almost vertical in front of the new water. Fig. 5 shows the same section in April 1969. The new water has now reached the edge of the Gotland deep and has begun to stream down along the slope. The oxygen content of the bottom water in the Bornholm basin on this occasion was about 6 ml/l.

Unfortunately the results from the expeditions of the other participating countries are not available at present, but some important information is given in the cruise reports. The Finnish research ship *Aranda* observed in June (1969) that hydrogen sulphide was present sporadically in the deep water of the Gulf of Finland. The Danish vessel *Dana* reported that in August hydrogen sulphide was found in the deep water of all stations in the Gulf of Finland west of Hogland. Large concentrations of hydrogen sulphide were observed north and

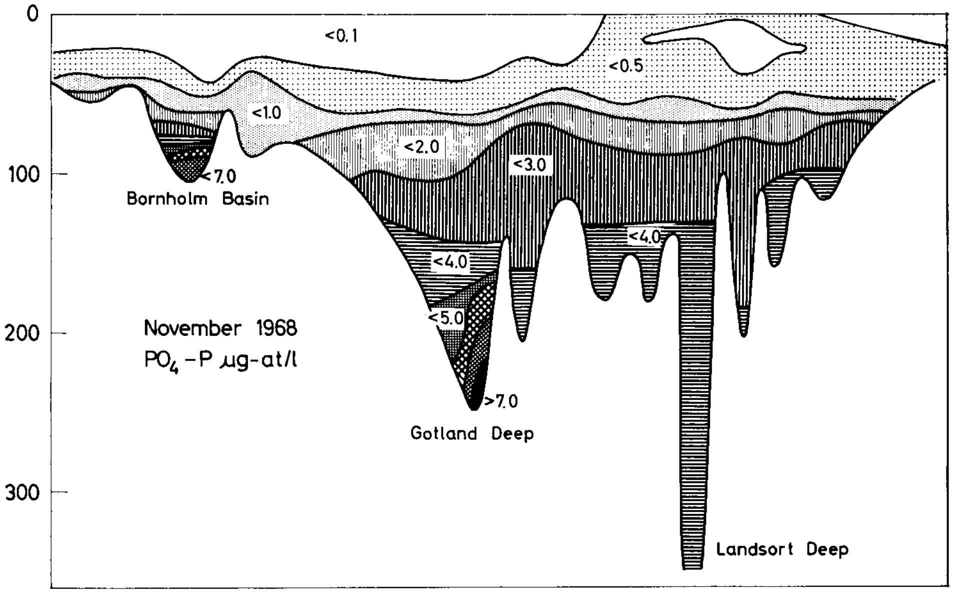

Fig. 9. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate-phosphorus in November 1968.

west of Gotland. The hydrogen sulphide layer began at 100 m in the Landsort Deep. The *Professor Albrecht Penck* from Warnemünde reported that in October the oxygen concentration in the Bornholm basin had decreased to about 3 ml/l, which indicates that the inflow had now stopped. According to the programme the ship was anchored at the Gotland Deep for 5 days, carrying out measurements every third hour. Oxygen was observed to be present sporadically in the bottom water alternating with hydrogen sulphide. The deep water seemed to move back and forth. The new water had apparently now reached the Gotland Deep and the stagnant water was driven out. In the Gulf of Finland the hydrogen sulphide had disappeared at this time. Hydrogen sulphide was found on all stations north and west of Gotland. West of Gotland the hydrogen sulphide layer even began at 70 m on some of the stations.

The *Skagerak* again went to the Baltic in November 1969. Fig. 6 shows the oxygen conditions in the Baltic during this expedition. The hydrogen sulphide had now completely disappeared from the Gotland basin and only small amounts were found in some of the deep areas of the northern Central basin. In the Gotland basin the oxygen content at the bottom was 1.8 ml/l. Above this water there was a layer with almost oxygen-free water. West of Gotland there were still great amounts of hydrogen sulphide. Fig. 7 finally shows the results from the *Skagerak*'s expedition in January 1970. The hydrogen sulphide has now completely disappeared from all basins visible in the section. The oxygen concentration has again begun to decrease in the bottom water of the Gotland basin and is now around 0.9 ml/l. The intermediate layer has still a low oxygen content around 175 m. There are still small amounts of hydrogen sulphide in the Landsort Deep from 300 m downwards. West of Gotland hydrogen sulphide was found at only two stations, in small amounts.

The following figures show a longitudinal section through the deep basins along the course that the inflowing water is believed to take around Gotland. The figures illustrate the changes in the phosphate concentration during the period September 1968 – January 1960. Fig. 8 shows the condition in September 1968. It can be seen that the phosphate concentration increases toward the bottom of the deep basins. In the bottom water of the Gotland basin the phosphate values are above 6 μg-at/l. The

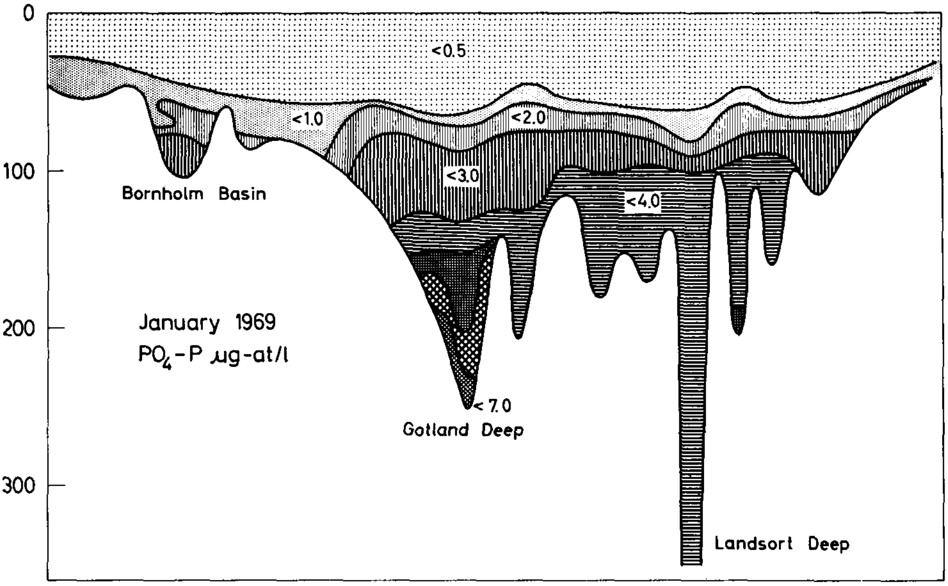

Fig. 10. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate–phosphorus in January 1969.

phosphate concentration increases in the intermediate water below the primary halocline counterclockwise around Gotland. This is due to the fact that this water slowly circulates around Gotland. It is "peeling" off the boundary layer to the stagnant hydrogen sulphide-containing water, thereby transferring phosphate to the deep water. It can also be seen that during the summer almost all phosphate has been used up by organisms above the

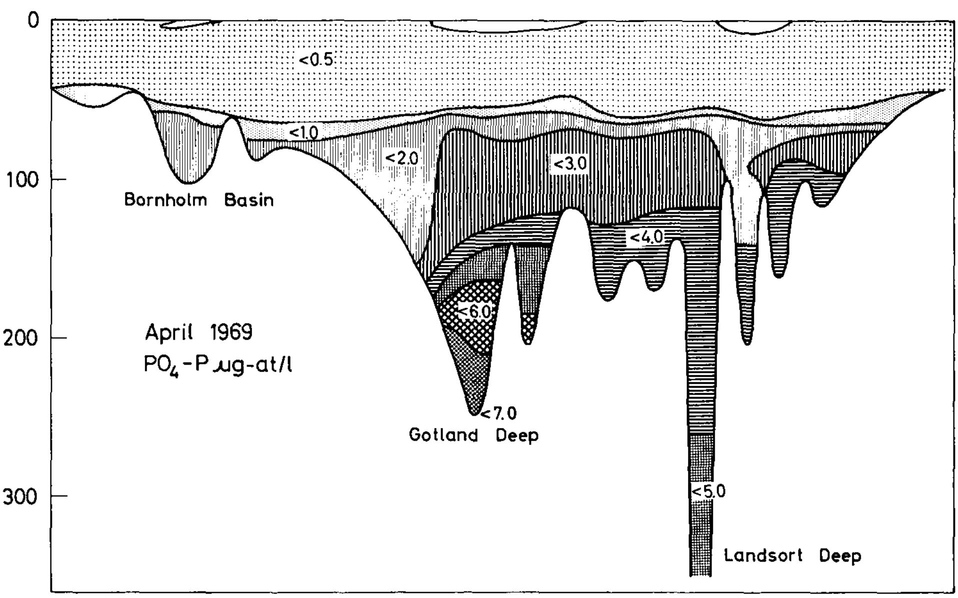

Fig. 11. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate–phosphorus in April 1969.

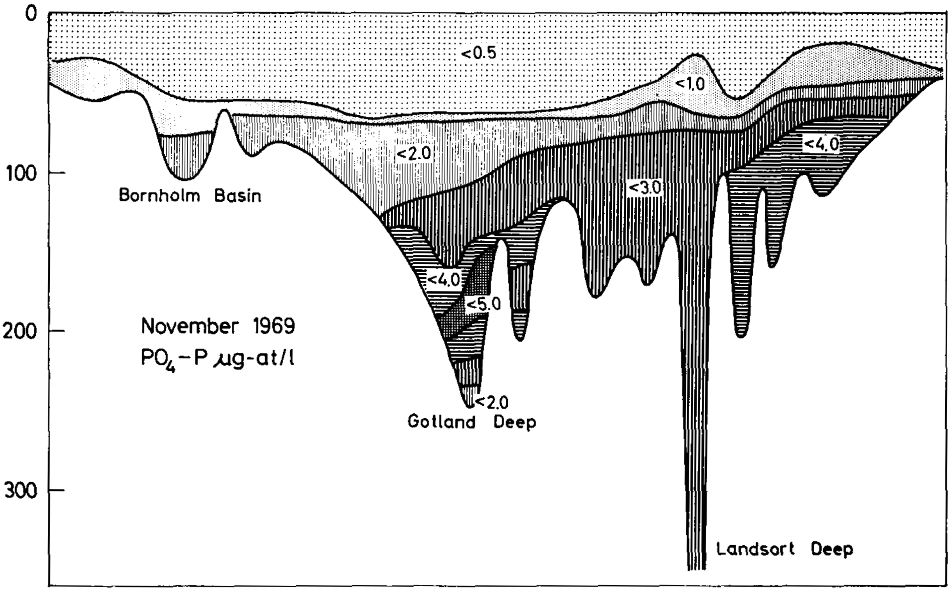

Fig. 12. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate–phosphorus in November 1969.

thermocline. Fig. 9. shows the conditions in November 1968. It can be seen as in the corresponding oxygen section, that the phosphate is "peeled" off by the strong inflow of new water in the intermediate layer. One can also see that the bottom water of the Gotland Deep to some degree is affected by the inflow. Also it is apparent that a certain winter convection has begun in the northernmost parts. Nutrients are transported to the surface. The January sec-

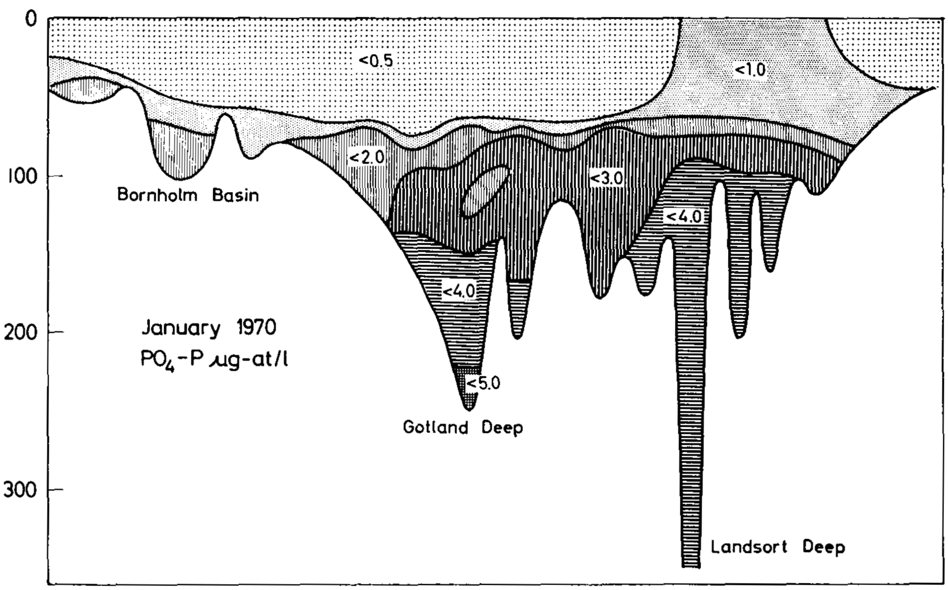

Fig. 13. Longitudinal section through the Baltic around the island of Gotland along the line: Arkona Basin – Bornholm Basin – Gotland Basin – Northern Central Basin – Landsort Deep – Karlsö Deep, showing the distribution of phosphate–phosphorus in January 1970.

tion for 1969 (Fig. 10) shows that the phosphate concentrations increase north and west of Gotland and that new water has penetrated to the bottom of the Bornholm basin. The isoclines for phosphate are almost vertical ahead of the inflowing water. The vertical convection has now "fertilized" the surface water in the whole Baltic. The phosphate concentrations in the surface water are between 0.10–0.50 μg-at/l. The section for April 1969 (Fig. 11) shows how the inflow continues and that new water now begins to flow down into the Gotland Deep. In the surface water the spring production has begun and at some places the phosphate values are below 0.10 μg-at/l. Fig. 12 shows the conditions in November 1969. The phosphate concentration in the bottom water of the Gotland Deep is now below 2 μg-at/l and higher concentrations are found above, in the deep water. The autumn has been colder than in 1968 and production has almost stopped in the surface water. The phosphate values are between 0.10 and 0.50 μg-at/l on all stations. In Fig. 13 it can be seen that the stagnation again begins in the deep water. The phosphate values increase in all deep basins. The surface water west of Gotland is "fertilized" with phosphate and the values exceed 0.50 μg-at/l. A large primary production may be expected during the spring.

3. Tentative conclusion

The results from these expeditions indicate clearly that the old stagnant water in the southern and middle parts of the Baltic proper have been forced towards the north and into the Gulf of Finland and counterclockwise around Gotland to the area west of Gotland. The hydrogen sulphide concentrations in these areas increased at first but decreased later during the autumn. In the Gulf of Finland all hydrogen sulphide has now disappeared and only very small amounts remain in the Landsort Deep and west of Gotland. The hydrogen sulphide has mixed with oxygen-containing water and has been destroyed. All the nutrients accumulated in the stagnant water have been washed out from the bottom areas of the deep basins and will eventually be mixed up into the surface water. This may even be happening now during the winter and spring of 1970, or possibly during the winter of 1971. This new "fertilization" of the surface water will most probably cause an enormous plankton bloom in the surface water. That will again increase the amounts of dead organic matter sinking down into the deep water. The result will then be a new formation of hydrogen sulphide close to the bottom. If the water remains for some time in the basins, the conditions will be still worse than during 1968.

One easily gets the impression that the increasing discharge of waste water into the Baltic is a secondary reason for the oxygen deficit in the deep water. The Baltic has been "overstrained". It can no longer recover from the hydrogen sulphide shocks in a natural way. The oxygen in the instreaming bottom water is almost completely used up before it reaches the northern areas of the Baltic proper. Man has "speeded up" the stagnation so that Nature cannot now restore normal conditions. It is therefore necessary to limit or stop the discharge of untreated waste water from communities and industries in order to give the Baltic a fair chance to recover.

Data

The data used are results from the expeditions with the R/V *Skagerak* from the Fishery Board of Sweden. They will be published in *Meddelande från Havsfiskelaboratoriet*, Lysekil.

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О ЗАСТОЕ И НЕДАВНЕМ ОБНОВЛЕНИИ ВОДЫ В БАЛТИКЕ

Дается краткое описание гидрографии и водного баланса Балтийского моря. Описываются различные пикноклины собственно Балтийского моря, приток соленой воды через Датские проливы и развития застойных явлений в глубоких бассейнах моря. Обсуждается обновление застойных глубоких вод и «удобрение» поверхностных вод питательными веществами. Описывается потребление кислорода и накопление питательных веществ путем распада органического материала в глубоких водах. Кратко объясняется образование в застойных водах сульфидов аммиака, азота и водорода. Обсуждается уменьшение кислорода в глубоких водах Балтики в течение этого столетия и возможные причины этого явления. Описывается с помощью графиков недавние обновления застойных и глубоких вод, происходившее в течение 1969 г. Описана программа «Года Балтики» и обсуждаются некоторые ее результаты. Указывается на накопление фосфатов в застойных водах и на их распространение в глубоких водах в течение обновления вод в 1969 г., также как и на «удобрение» поверхностных вод в этот период. Дается прогноз об увеличении количества первичных организмов в поверхностных водах и о дальнейшей эволюции содержания кислорода. Делается вывод, что человек увеличил потребление кислорода в глубоких водах путем сброса огромных количеств неочищенной промышленной и другой загрязненной воды, и поэтому Балтийское море находится в «перенапряженном» состоянии. В заключение предлагается, что необходимо принять меры против будущих сбросов отходов, чтобы дать Балтике шанс оздоровиться.