One hundred years of hydrographic measurements in the Baltic Sea

Stig Fonselius†, Jorge Valderrama*

SMHI Oceanographic Laboratory, Nya Varvet 31, S-426 71 Västra Frölunda, Sweden

Received 15 January 2002; accepted 15 August 2002

Abstract

The first measurements of salinity of the deep water in the open Baltic Sea were made in the last decades of the 1800s. At a Scandinavian science meeting in Copenhagen in 1892, Professor Otto Pettersson from Sweden suggested that regular measurements of hydrographic parameters should be carried out at some important deep stations in the Baltic Sea. His suggestion was adopted and since that time we have rather complete hydrographical data from the Bornholm Deep, the Gotland Deep, and the Landsort Deep and from some stations in the Gulf of Bothnia. The measurements were interrupted in the Baltic Proper during the two World Wars. At the beginning only salinity, temperature and dissolved oxygen were measured and one or two expeditions were carried out annually, mostly in summer. In the 1920s also alkalinity and pH were occasionally measured and total carbonate was calculated. A few nutrient measurements were also carried out. After World War II we find results from four or more expeditions every year and intercalibration of methods was arranged. Results of temperature, salinity and dissolved oxygen measurements from the Bornholm Deep, the Gotland Deep, the Landsort Deep and salinity measurements from three stations in the Gulf of Bothnia, covering the whole 20th century are presented and discussed. The salinity distribution and the variations between oxygen and hydrogen sulphide periods in the deep water of the Gotland Deep and the Landsort Deep are demonstrated. Series of phosphate and nitrate distribution in the Gotland Deep are shown from the 1950s to the present and the effects of the stagnant conditions are briefly discussed. Two large inflows of highly saline water, the first during the First World War and the second in 1951, are demonstrated. The 20th century minimum salinity of the bottom water in the Baltic Proper in 1992 is discussed.

© 2003 Published by Elsevier Science B.V.

Keywords: Baltic Sea; Hydrographic parameters; Nutrients; Long-time series; Gotland Deep; Stagnation

1. Introduction

The first hydrographic measurements in the Baltic Sea were carried out in the 1700s. Temperature and density were measured and later salinity was calculated from the density. Also some direct salinity determinations were carried out by evaporation of the water and weighing the salt residue. In the middle of the 1800s, titration of the salinity was introduced (Forchhammer, 1865).
In the last decades of the 1800s, series of hydrographic measurements were started in several Baltic Sea countries at coastal stations and lightships, mostly by individual scientists. Also some deep-sea expeditions were carried out, in 1871 by Germany (Meyer et al., 1873) and in 1877 by Sweden (Pettersson, 1893).

A Nautical-Meteorological Conference on Regular Hydrographical Measurements on Ships on Regular Routes, Lightships and Coastal Stations was held in Copenhagen in 1878 (Anonymous, 1878). Scientists from Denmark, Norway and Sweden participated. Common principles for observations, performance, data processing and publication of results were discussed and it was agreed that the work should be divided between the countries and that nautical-meteorological institutions should be established.

At the 14th Scandinavian Science Meeting in Copenhagen in 1892, Professor Otto Pettersson from Sweden in a resolution suggested an international co-operation between the various countries in order to conduct a rational investigation of the Baltic Sea. This resolution was adopted. In that year the Danish and Swedish Hydrographical Commissions were established and hydrographical-biological investigations were started in both countries (Anonymous, 1892). When Professor Otto Krümmel in Germany heard about this co-operation, he joined in the work (Fonselius, 2001).

At the 15th Scandinavian Science Meeting in Stockholm in July 1898, the Danish, Finnish and Swedish hydrographers agreed on simultaneous investigations in different parts of the Baltic Sea on a regular basis (Hölmén, 1907). Prof. Otto Pettersson and Dr. Gustaf Ekman had in 1897 concluded that the state and variations of the Baltic Sea could be tracked by collecting hydrographical data at just a few deep stations (Pettersson and Ekman, 1897). It would, therefore, be easy to follow such variations from season to season and year to year by measuring the main hydrographical parameters regularly at the main stations, e.g. the Bornholm Deep, the Gotland Deep, the Landsort Deep, the Åland Deep, the Ulvö Deep and the Bjurö Deep. Germany and Russia joined in this work, but Russia had to delegate the work to Finland, which at that time was under Russian rule. The Barents Sea had been included in the international co-operation and Russia, which had taken the responsibility for that region, therefore had no research ship available for the Baltic Sea (Fonselius, 2001).

The main stations were named and numbered according to a system where the stations designated to Denmark got Da-numbers, the Finnish stations F-numbers, the German stations D-numbers, the Swedish stations S-numbers etc. Unfortunately, some stations used by several countries were named differently by these countries and we may find stations with several names and numbers. During the Baltic Year 1969–1970 all stations used in the IBY-programme were designated BY-numbers in order to avoid confusion. The BY-numbers, which covered almost the whole Baltic Proper, became very popular and were used by most countries until the Helsinki Commission again introduced a new numbering for the stations included in their network. Therefore we find for instance for the Gotland Deep the numbers F 81, BY 15 and BPEX21. In the present paper we have used the BY-numbers for the stations in the Baltic Proper and F-numbers for stations in the Gulf of
Bothnia. Fig. 1 shows the position of the main stations used in the present paper.

The data used are from Sweden and other Baltic countries; they were submitted to and quality controlled by ICES and our own laboratory. It is possible to access to them by ICES Oceanographic Database (www.ICES.dk/ocean).

2. Long-term series of salinity

A few studies on the salinity changes in the Baltic Sea were published during the 1950s by Segerstråle (1953) and Lindquist (1959), but these papers were mainly concerned with the biology in special areas and did not include changes in the deep water. One of the

Fig. 2. a. Long-term salinity variations in the surface (▲), deep water (100 m, ■) and bottom water (♦) at the Stations F 9, F 26 and F 64. b. Long-term salinity variations in the surface (▲), deep water (100 m, ■) and bottom water (♦) at the stations BY 5, BY 15 and BY 31.
present authors in 1962 published a paper showing the salinity, temperature and oxygen changes in the deep water of the Bornholm Deep, the Gotland Deep and the Landsort Deep from the beginning of the 20th century to 1961 (Fonselius, 1962). This paper was followed by a second paper (Fonselius, 1969), where the conditions in the deep and bottom water of the main stations were described and studied in detail. These papers aroused wide interest in long-term series in all the Baltic Sea countries. Important examples are Soskin (1963), Hela (1966), Fonselius et al. (1984), Launiainen and Vihma (1990) and the very extensive works of Matthäus and co-workers (Matthäus, 1979, 1990, 1995; Matthäus and Franck, 1992) etc.

Because the series now cover more than 100 years it may be appropriate to discuss the results achieved. The long series of salinity at the main deep stations may serve as a good example. Fig. 2 (a and b) shows the salinity variations in the surface water and deep water in the Bornholm Deep (BY 5), the Gotland Deep (BY15), the Landsort Deep (BY 31), the Åland Deep (F 64), the station F 26 and the Bjurö Deep (F 9) from 1902 to 2000. There exist a few salinity series from the 1800s (1871, 1877, 1893, 1898 and 1899). These are not included in the figure because the results are questionable and separated by several years without measurements. In 1901 the Knudsen tables were published and subsequently used by all Baltic Sea countries (Knudsen, 1901). Regular measurements started in 1901 and continued until 1914, when the outbreak of WW I interrupted all open sea work. Generally only one expedition was carried out every year. The measurements were carried out by Finnish, German, Russian and Swedish ships. The war and revolutions destroyed the infrastructure of some of the participating countries and the hydrographic work had to be reorganised. The investigations were again started in 1921. Finland covered almost every year until 1939, when WW II again interrupted the measurements. Latvia joined the investigations in 1933. We also find some German and Swedish results. Most of the work was carried out during the summer. Between 1901 and 1939 we find only one series from December, one from April and no results at all from January, February or March.

Again it took a long time to start the hydrographic work. Sweden was the first country to begin the expeditions in 1951. Fortunately the Swedish navy had a small fishing vessel, the ‘Orion’, which was used for hydrographic work, and from 1947 onwards measurements were made available for science. RV ‘Skaigerak’ started its expeditions in 1952 and was soon joined by Polish vessels. In 1954 Finland obtained RV ‘Aranda’ for hydrographic work in summer. In 1956 the FRG (Federal Republic of Germany) and the USSR (Union of Soviet Socialist Republics) joined the investigations, and in 1964 the GDR (German Democratic Republic) followed suit. As mentioned, the results until 1958 contain mostly one measurement per year. If we use single measurements for the work after WW II, we would in some cases end up with more than 100 results per year for example at BY 15, which would give these years an enormous preponderance. In the deep water there are hardly any seasonal variations. Also the surface salinities show only small seasonal variations. Therefore a single measurement may be considered to be relatively representative of a year. The salinity shows a very weakly increasing trend at all stations with the exception of BY 31 during the century in the surface water, at 100 m and close to the bottom. The salinity changes can be traced through the whole Baltic Sea.

3. Long-term series of temperature

We have not included long-term temperature series of surface water, because of their large seasonal variations. Fig. 3 (a and b) shows the temperature variations in the deep water at the stations mentioned above. This water is not influenced by the seasons. There is a very clear increase in deep-water temperature during the century. An inflow of unusually warm water occurred in 1977. The temperature of the bottom water in the Gotland Deep was around 7 °C. In the Gulf of Bothnia, and especially in the Bothnian Bay, the vertical convection during winter may reach almost to the bottom, where the temperature will then fall to near zero.

4. Long-term series of dissolved oxygen and hydrogen sulphide

The salinity and oxygen conditions in the Baltic deep water are characterised by irregular inflows of
Fig. 3. a. Long-term temperature variations in the deep water (100 m, ■) and bottom water (♦) at the stations F 9, F 26 and F 64. b. Long-term temperature variations in the deep water (100 m, ■) and bottom water (♦) at the stations BY 5, BY 15 and BY 31.

oxygen-rich and high-saline water through the Danish sounds. This water fills the deep basins, expelling the old bottom water. Due to the high density of the new water, it remains in the deep basins until the density has decreased so much that it can be replaced by new higher-saline water. During the stagnation period, all oxygen may be utilised for oxidising dead organic material. Hydrogen sulphide is formed in the sediment surface and may spread upwards in the water. Such inflows can be traced at all the main stations in the whole Baltic Sea, but stagnation and hydrogen sulphide formation have only been observed at the deepest stations in the Baltic Proper (Fig. 4a and b). The hydrogen sulphide is expressed as ‘negative oxygen’ (Fonselius, 1969). In annual means the hydrogen sulphide may
Fig. 4. a. Long-term oxygen variations in the deep water (100 m, ■) and bottom water (♦) at the stations F 9, F 26 and F 64. b. Long-term oxygen and hydrogen sulphide variations in the deep water (100 m, ■) and bottom water (♦) at the stations BY 5, BY 15 and BY 31. The hydrogen sulphide is expressed as ‘negative oxygen’ (Fonselius, 1969).

not show up if the concentration is low and the period shorter than a year. The surface water is normally saturated with oxygen and is therefore not discussed here. A strong negative trend may be seen in the bottom water in the Baltic Proper. In the Gulf of Bothnia the negative trend is weak due to thermohaline convection during winter (see Fig. 3).
5. Long-term series of nutrients

A few phosphate and nitrate analyses were carried out already before WW I, but these results are very unreliable and have not been used in our figures. Between the two World Wars we find some phosphate, nitrate and ammonium results at BY 15, which we have included in our diagrams. For F 64 and F 26 we find some phosphate results and for F 64 some nitrate results. Also for nutrients we have excluded the surface series, because they are much influenced by biological activities in the water. Fig. 5 (a and b) shows the phosphate concentration in the deep water at the different stations. During the stagnation periods phosphate is accumulated in the bottom water, mainly due to the effect of hydrogen

![Graphs showing long-term phosphate variations](image)
sulphide. The trend is positive with the exception of the Bothnian Bay, where the phosphate concentration is extremely low in the deep water and phosphate is obviously the limiting factor for primary production (Fonselius, 1978).

Nitrate (here shown as the sum of nitrate and nitrite) and ammonia were also measured from 1928 and 1933, respectively. Generally the nitrate concentration is increasing in the Baltic Sea due to pollution. Especially in the Bothnian Bay the values are extremely high in comparison with the phosphate values. When the salinity decreases due to stagnation and hydrogen sulphide is formed (negative oxygen), the phosphate and ammonium concentrations rise and the nitrate concentration falls to zero (Figs. 6a,b, 7a,b). The nitrate disappears due to reduction to ammonia and therefore nitrate there shows an opposite trend to phosphate. Fig. 7 (a and b) shows that normally, when oxygen is present, the ammonia concentration in the water is extremely low. In the

Fig. 6. a. Long-term nitrite + nitrate variations in the deep water (100 m, ■) and bottom water (♦) at the stations F 9, F 26 and F 64. b. Long-term nitrite + nitrate variations in the deep water (100 m, ■) and bottom water (♦) at the stations BY 5, BY 15 and BY 31.
Baltic Proper, values higher than 2 μmol/l show the presence of hydrogen sulphide in the water. Especially in the Gulf of Bothnia, where the water always contains oxygen, we find very low ammonia values. A few higher values are certainly caused by contamination during the analysis. When the salinity in the bottom water increases due to a new inflow, the oxygen content and the nitrate content also go up. The ammonia is mixed into the deep water and the concentration sinks to values below 2 μmol/l. The ammonia values measured in the deep water of BY 15 in the 1930s are doubtful because the analytical methods were probably not sufficiently developed at that time. Silicate is also accumulated during stagnation periods, but the silicate results show large variations due to analytical variations and silicate results are therefore not shown here. The method was improved during the 1990s.

Fig. 7. a. Long-term ammonia variations in the deep water (100 m, ■) and bottom water (♦) at the stations F 9, F 26 and F 64. b. Long-term ammonia variations in the deep water (100 m, ■) and bottom water (♦) at the stations BY 5, BY 15 and BY 31.
6. A closer study of stagnation periods

Matthäus (1995) has worked out an intensity index for inflows of highly saline and oxygenated Kattegat water between 1880 and 1994 (Fig. 8). The index was prepared by using salinity measured at Gedser Rev and Drogden plus Baltic Sea level data. A diagram showing the salinity variations in the bottom water of the Gotland Deep has been inserted above the intensity index in Fig. 8.

Fig. 8 shows at least five major inflows during that period. The first occurred in 1914, but because of WWI no salinity measurements could be carried out in the open Baltic Sea for seven years. The first measurements in the Gotland Deep after the war show a high salinity, which continuously decreased until 1932. Also the oxygen concentration (see Fig. 4) fell to values around zero. The smell of hydrogen sulphide was observed in the bottom water samples. The stagnant water was replaced by new water through a strong inflow in 1933. During WW II no important inflows seem to have occurred. Of course no open sea expeditions could be carried out during the war. Below we will discuss the development at 200 m depth in the Gotland Deep after WW II (Fig. 9). In 1951 a major inflow filled the Gotland Deep with water with a salinity around 14, the highest ever recorded there (Fig. 9). During the long stagnation period that followed, the oxygen disappeared in the bottom water and hydrogen sulphide was observed (Fig. 9). The stagnation lasted for ten years until a moderate inflow replaced the stagnant water in 1961. Between 1961 and 1977 several minor inflows were observed. In 1977 a major inflow of unusually warm high-saline water occurred. Very high concentrations of hydrogen sulphide were observed during the 1980s.

![Fig. 8. Intensity diagram showing the inflow of high-saline water into the Baltic Sea between 1880 and 1994, characterised by an intensity index Q (above) and by inflow clusters (below) (Matthäus, 1995). The top diagram shows salinity variations in the bottom water of BY 15, from 1901 to 2000.](image-url)
and the stagnation lasted until 1993. The salinity decreased from 13 to 11 during this period. The inflow in 1993 raised the oxygen concentration to 2 ml/L, but the oxygen again disappeared in 1998 and at present the hydrogen sulphide concentration is higher than ever in the deep water of the Baltic Proper. Fig. 9 shows how high salinity (inflow) corresponds to high temperature and high concentrations of oxygen and nitrate because the inflowing Kattegat surface water is relatively warm, saturated with oxygen and has a high nitrate content. During the following stagnation, the salinity, temperature, oxygen and nitrate decrease while the phosphate and ammonia concentrations increase. The salinity falls due to dilution until the density is so low that new water can replace it. Also the temperature drops due to dilution with colder bottom water. The oxygen disappears from the water due to oxidation of dead organic matter, and hydrogen sulphide (here expressed as negative oxygen) is formed. The reducing conditions in the sediment surface transform sedimented ferriphosphate into soluble ferrophosphate, which dissolves and accumulates (Fig. 9) in the stagnant water (Fonselius, 1969). The nitrate disappears from the water (Fig. 9) and ammonia is formed through denitrification when the oxygen of the nitrate ions is used for oxidation of dead matter. Therefore we find high ammonia concentrations in the stagnant water (Fig. 9).
7. Conclusions

Examination of the distribution of hydrographic parameters in the deep water at the main stations mentioned here shows that all stations follow the same pattern. The inflows of high-saline water can be traced all the way to the Bothnian Bay (the Bjurö Deep). The very weak salinity trend at all stations indicates that no important changes occurred during the 20th century. Therefore it is hardly justified to conclude that the salinity will continue to fall in the future, as has been claimed by some Swedish scientists (Anonymous, 2001).

The salinity was extremely high during the 1950s. It then dropped to an all-time minimum in 1992–1993, but is now back at the same level as at the beginning of the century.

The relatively strong temperature trend shows a clear rise in the temperature of the deep water in the Baltic Proper, which may influence the oxidation of dead organic matter and the oxygen conditions in the water. The oxygen trend is clearly negative at all stations mentioned. Hydrogen sulphide is only found in the deep stations of the Baltic Proper. The Swedish expeditions in 2001 reported very high hydrogen sulphide concentrations in the Gotland Deep extending from the bottom up to 125 m. Phosphate is increasing in the deep water. In the Bothnian Bay, however, the concentrations are so low that it is difficult to draw conclusions. Nitrate is also increasing at all stations where no hydrogen sulphide has been observed. The increase is also strong in the Gulf of Bothnia. At stations with hydrogen sulphide (the Gotland Deep) nitrate is decreasing in the stagnant bottom water due to denitrification. Therefore the ammonia concentration is also rising in the bottom water of BY 15. Normally the ammonia concentration is low in the deep water. The silicate results are varying and so uncertain that it is difficult to draw conclusions.

The salinity variations in the Baltic Sea are most probably natural oscillations in the water regime. Irregular inflows of Kattegat water, caused by special weather conditions and variations in the freshwater supply, seem to be the main cause of the stagnation periods in the Baltic Sea (Schinke and Matthäus, 1998). The Baltic Sea is a young sea which has gone through several stages since the last ice age. First it was a freshwater lake at the edge of the melting ice, then it was transformed into a sea, then back into a lake and then again into a brackish-water lake. The present Baltic Sea is a continuation of the Limnea Sea, which had a much higher salinity. The salinity has slowly decreased from that period and we cannot tell if the salinity seen in an aspect of several hundred years is increasing or decreasing. The Baltic Sea stage has lasted for around 3000 years. Our observation series cover only the last one hundred years. That is too short a period for drawing definite conclusions on future development.

Acknowledgements

We thank Jan Szaron for providing the data series from the Swedish Data Bank (SHARK).

References

Launiainen, J., Vihma, T., 1990. Meteorological, ice and water