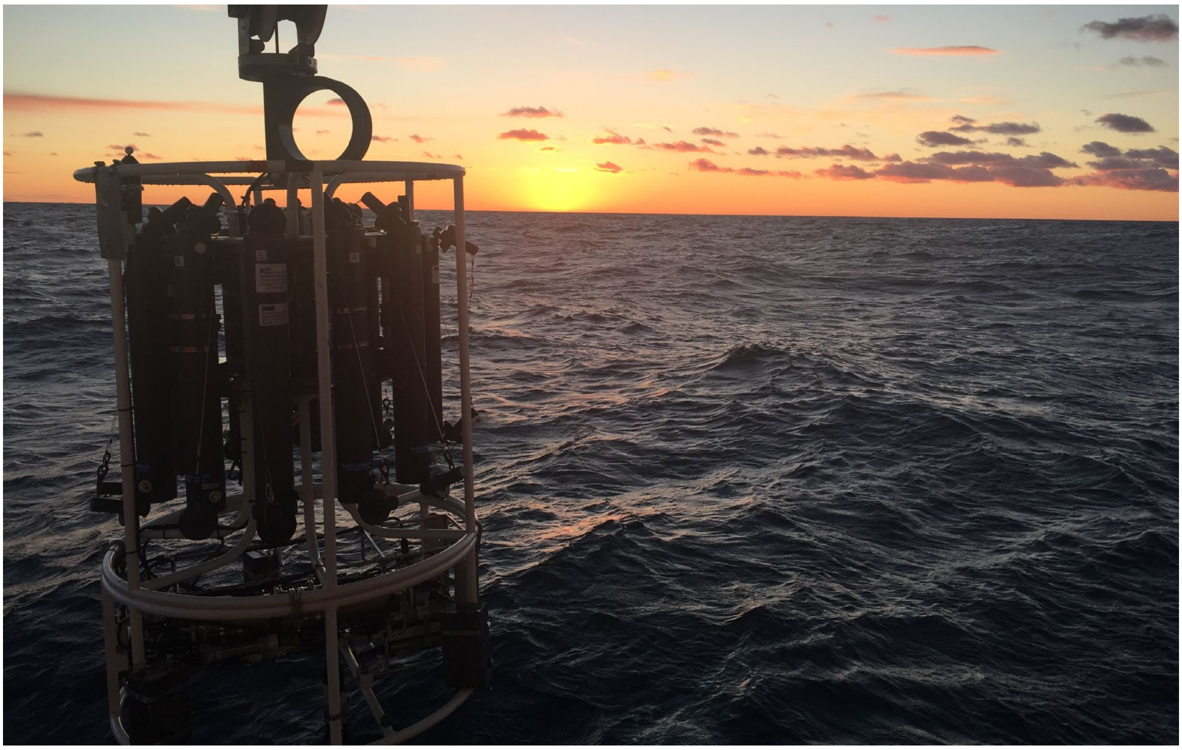
REPORT OCEANOGRAPHY No. 65, 2018

Oxygen Survey in the Baltic Sea 2018

- Extent of Anoxia and Hypoxia, 1960-2018



Front: The photo was taken on-board R/V Aranda during SMHIs September cruise in 2018 somewhere in the Western Gotland Basin.
Photo by Örjan Bäck

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Oxygen Survey in the Baltic Sea 2018
- Extent of Anoxia and Hypoxia, 1960-2018

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Summary

A climatological atlas of the oxygen situation in the deep water of the Baltic Sea was first published in 2011 in SMHI Report Oceanography No 42. Since 2011, annual updates have been made as additional data have been reported to the ICES data center. In this report the results for 2017 has been updated and the preliminary results for 2018 are presented. Oxygen data from 2018 have been collected from various sources such as international trawl survey, national monitoring programmes and research projects with contributions from Poland, Estonia, Latvia, Russia, Denmark, Sweden and Finland.

For the autumn period each profile in the dataset was examined for the occurrence of hypoxia (oxygen deficiency) and anoxia (total absence of oxygen). The depths of onset of hypoxia and anoxia were then interpolated between sampling stations producing two surfaces representing the depth at which hypoxic and anoxic conditions respectively are found. The volume and area of hypoxia and anoxia have been calculated and the results have then been transferred to maps and diagrams to visualize the annual autumn oxygen situation during the analysed period.

The updated results for 2017 and the preliminary results for 2018 show that the severe oxygen conditions in the Baltic Proper after the regime shift in 1999 continue. Both the areal extent and the volume with anoxic conditions have, after 1999, been constantly elevated to levels only observed occasionally before the regime shift. Despite the frequent inflows to the Baltic Sea during the period 2014-2016 approximately 22% of the bottom area was affected by anoxia and 32% by hypoxia during 2018. The preliminary results indicate that this is the largest area affected by anoxia during the analysed period, starting 1960. The hydrogen sulphide that had disappeared from the Eastern and Northern Gotland Basin due to the inflows in 2014-2016 is now steadily increasing in the deep water again.

Sammanfattning

En klimatologisk atlas över syresituationen i Östersjöns djupvatten publicerades 2011 i SMHIs Report Oceanography No 42. Sedan 2011 har årliga uppdateringar gjorts då kompletterande data från länder runt Östersjön har rapporerats till ICES datacenter. I denna rapport har resultaten från 2017 uppdaterats och preliminära resultat för 2018 tagits fram. Resultaten för 2018 baseras på data insamlade under internationella fiskeriundersökningar, nationell miljöövervakning och forskningsprojekt med bidrag från Danmark, Estland, Lettland, Sverige, Finland, Ryssland och Polen.

Förekomsten av hypoxi (syrebrist) och anoxi (helt syrefria förhållanden) under höstperioden, har undersökts i varje mätprofil. Djupet där hypoxi eller anoxi först påträffas i en profil har interpolerats mellan provtagningsstationer och kombinerats med en djupdatabas för beräkning av utbredning och volym av hypoxiska och anoxiska förhållanden. Resultaten har överförts till kartor och diagram för att visualisera syresituationen i Östersjöns djupvatten.

Resultaten för 2017 och de preliminära resultaten för 2018 visar att de extrema syreförhållanden som observerats i Egentliga Östersjön, efter regimskiftet 1999, fortsätter. Utbredningen av anoxi fortsätter att vara konstant förhöjd till nivåer som bara observerats i Östersjön enstaka år före 1999. Trots ett flertal inflöden under perioden 2014-2016 beräknas ungefär 22% av bottnarna i Egentliga Östersjön, Finska viken och Rigabukten vara påverkade av anoxiska förhållanden och omkring 32% av hypoxi under 2018. De preliminära resultaten från 2018 indikerar att de anoxiska områdena är de största som har noterats under den analyserade perioden, som startar 1960. Mängden svavelväte, som på grund av inflödena 2014-2016, helt försvann från Östra och Norra Gotlandsbassängerna, ökar åter i dessa bassängers djupvatten.

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1 Background

The Baltic Sea is suffering from oxygen deficiency. Total absence of oxygen and lack of oxygen in the deep water are mainly found in the central deep basins in the Baltic Proper, Gulf of Finland and Gulf of Riga, but is also found seasonally at intermediate depth and at shallow areas. Limited inflows of high saline and oxygen rich water from the North Sea through the Belt Sea and the Sound together with the high freshwater input from land and precipitation cause a strong stratification of the water column that prevents ventilation of the deep water. The strong stratification in combination with eutrophication forms the basis for the problematic low-oxygen conditions that are found in the Baltic Sea.

Anoxia is the condition when all oxygen has been consumed by microbial processes and no oxygen is left in the water. If the water stays anoxic for a longer period of time hydrogen sulphide (H_2S) is formed, which is toxic for all higher marine life. Only bacteria and fungi can survive in a water environment with total absence of oxygen. During anoxic conditions nutrients, such as phosphate, are released to a higher extent from the sediments to the water column, which, due to vertical mixing, can reach the surface layer and the photic zone. High concentrations of phosphate in surface waters favour phytoplankton growth, especially cyanobacteria in the Baltic Sea during summer which can further enhance the oxygen depletion as the bloom sinks to the bottom and consume oxygen when it is decomposed.

Oxygen depletion or hypoxia occurs when dissolved oxygen falls below the level needed to sustain most animal life. The concentration at which animals are affected varies broadly and literature studies [Vaquer-Sunyer & Duarte, 2008] show that the threshold for hypoxia range from 0.2 ml/l to 2.8 ml/l. However, the sublethal concentration ranges from 0.06 ml/l to 7.1 ml/l. The mean and median for all experimental assessments was 1.8 +/- 0.12 ml/l and 1.6 ml/l +/- 0.15 respectively. It has also been shown that Baltic cod eggs need at least 2 ml/l oxygen for successful development [MacKenzie et al., 2000; Nissling, 1994; Plikshs et al., 1993; U.S. EPA, 2003; U.S. EPA, 2000,]. In this report the limit of hypoxia is set to 2.0 ml/l.

This report presents a time series of the bottom areal extent and water volume of anoxic and hypoxic autumn conditions of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, for the period 1960 to 2018. The time series were first published in 2011 and the results have been updated annually as new additional data have become available at ICES[1]. In the report from 2011 a distinct regime shift in the oxygen situation in the Baltic Proper was found to occur around 1999. During the first regime, 1960-1999, hypoxia affected large areas while anoxic conditions were found only in minor deep areas. After the regime shift in 1999, both areal extent and volume of anoxia have been constantly elevated to levels that only occasionally have been observed before 1999. [Hansson et. al, 2011]

The report includes maps of bottom areas affected by oxygen deficiencies during 2017 and 2018. The complete and updated time series from 1960 can be found at; http://www.smhi.se, which can be used as a climatological atlas describing the historical development and the present oxygen situation in the Baltic Proper.

[1] ICES Dataset on Ocean Hydrography. The International Council for the Exploration of the Sea, Copenhagen 2009.

2 Data

2.1 Oxygen data

The results for 2018 are preliminary and based on oxygen data collected during the annual trawl surveys in the Baltic Sea; The Baltic International Acoustic Survey (BIAS), International Bottom Trawl Survey (IBTS) and Polish Multiannual Fisheries Data Collection Programme complemented by data from national and regional marine monitoring programmes and mapping projects with contributions from Finland, Estonia, Latvia, Russia, Poland, Denmark and Sweden.

These data have not been fully quality controlled, only preliminary checks have been performed (timing, duplicates, position and range checks). Usually data from the period August to October is used in the analysis but since an extensive data from Latvia was available from the end of July this data was also included. The time series and the results presented for 2018 will be updated when additional data are reported to ICES in late 2019. In this report the results for 2017 have been updated with all available data collected at ICES.

Data from the ICES trawl surveys are well suited for concurrent oxygen surveys because of randomized sampling and since cruises are performed by different countries. Hence, almost all parts of the offshore Baltic Proper are monitored with a vast spatial distribution providing a synoptic view of the oxygen situation. The surveys are also performed during the late summer/autumn period, August to October, when the oxygen situation usually is most severe. Consequently, this is an essential contribution of oxygen data, complementing the regular national and regional monitoring performed monthly at fixed stations.

2.2 Inflow data

The inflow through the Belt Sea and the Sound to the Baltic Sea is an important factor influencing the oxygen development in the deep water in the southern and central basins of the Baltic Proper.

SMHI calculates the flow through the Sound based on the sea level difference between two sea level gauges situated in the norther part (Viken) and the southern part (Klagshamn) of the Sound [Håkansson et. al. 1993]. The results, as accumulated inflow, from 1977 to present are presented at the SMHI web. For the years 2017 and 2018 see also Figure 5 and 6. [SMHI, 2019]

A continues time series of major inflows events to the Baltic Sea from 1887 to present was reconstructed using long term data series from the Belt Sea and the Sound by [Fischer & Matthäus, 1996]. This time series of major inflows has frequently been used for comparing the recent development with the past. Several updates have also been done since the first publication (Figure 1). However, a recent publication comparing this time series with new calculations using sea level, river discharge and salinity from the Belt Sea and the Sound suggests that there is a significant difference due to lack of appropriate data between 1976 and 1991 and the change in observations afterwards, which cause a bias in the inflow statistics. [Volker 2018]

The newly published time series for inflows to the Baltic Sea presents the amount of salt transported and flow into the Baltic Sea. The two time series can be compared in Figure 1.

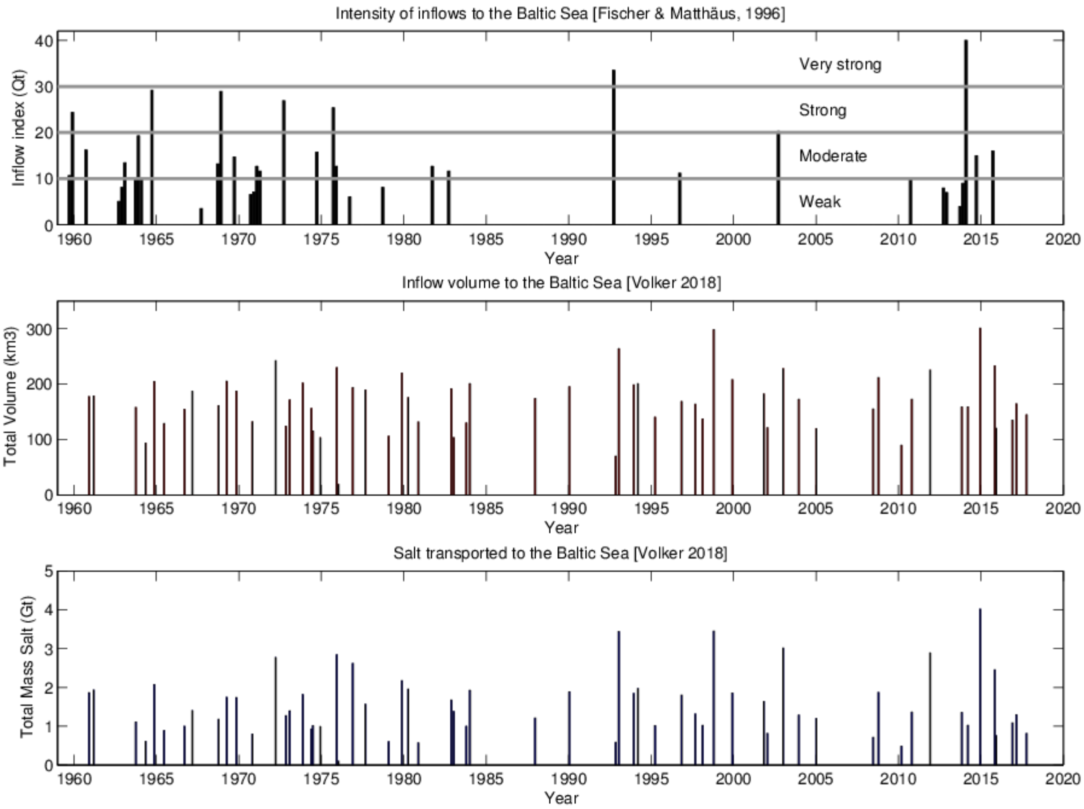

Figure 1. Two different estimations of major inflow to the Baltic Sea. Top: Intensity of inflows to the Baltic Sea, 1960-2018. [Fischer & Matthäus, 1996, Mohrholz et al. 2015, Feistel et al. 2016] Revised and updated. Middle and Lower: Total volume and salt transport to the Baltic Sea for inflows that last more than 5 days [Volker 2018].

3 Method

For the late summer and autumn period, August to October (in 2018 July was also included), each vertical profile including at least three data points, was examined for the occurrence of hypoxia (<2 ml/l) and anoxia (<0 ml/l). To find the depth of the onset of hypoxia and anoxia in each vertical profile, interpolation between discrete measurements in the profile was used. If hypoxia or anoxia was not found in the profile, the two deepest measurements in the profile were used to linearly extrapolate the oxygen concentration down towards the bottom. If two or more profiles were found at the same position an average profile was calculated for that position. To process the dataset a few station profiles had to be filtered out: for example when data was missing in the deep water or when questionable data were found.

The depths of the onset of hypoxia and anoxia were gridded with linear interpolation (Delaunay triangulation) between sampling stations, producing a surface representing the depth at which hypoxic and anoxic conditions are found. The surface has then been compared with bathymetry data, [Seifert, 2001] see Figure 2, to exclude profiles where the hypoxic and anoxic depths were greater than the actual water depth. After filtering the results, the affected area and volume of hypoxia and anoxia have been calculated for each year.

The calculations do not account for the existence of oxygenated water below an anoxic or hypoxic layer. Hence, during inflow situations when an intermediate layer with low oxygen concentrations or hydrogen sulphide can be found above oxygenated water, the method then overestimates the area and volume. However, these oxygenated zones are still problematic for most benthic animals and fish since they are trapped below an anoxic or hypoxic layer that also prevents migration and recolonization. However, the oxygenated zones below the intermediary layer, does influence the sediment to water nutrient exchange.

Areal extent and volumes are presented in relation to the area and volume of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, see Figure 2 [Fonselius, 1995].

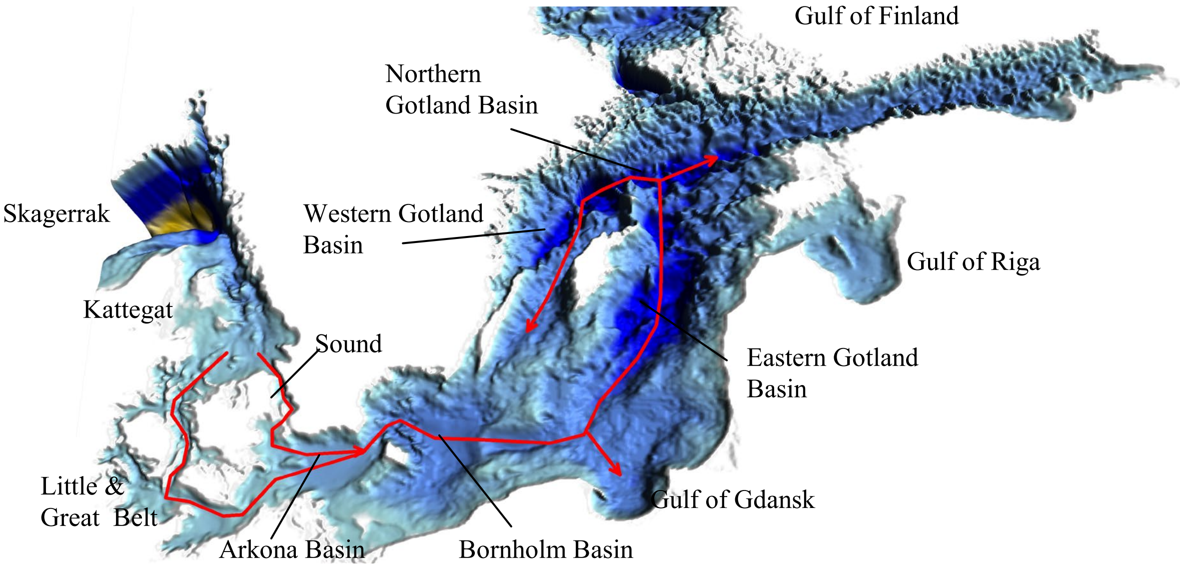

Figure 2. Bathymetry [Seifert, 2001] of the south Baltic Sea and pathways of inflowing deep water during inflows. The Baltic Proper includes the Arkona Basin, the Bornholm Basin, the Gulf of Gdansk, the Gulf of Riga and the Eastern-, Western- and Northern Gotland Basin [Fonselius, 1995].

4 Result

Extent and volume affected by hypoxia and anoxia during the period 1960 - 2018 are presented in Figures 3 and 4, respectively. Maps presenting bottom areas affected by hypoxia and anoxia during the autumn period 2017 and 2018 can be found in Appendix 2.The mean areal extent and volume affected by hypoxia and anoxia before and after the regime shift in 1999 (see Background section or [Hansson et. al, 2011]) and the preliminary results for 2018 are presented in Table 1.

Table 1. Mean and maximum areal extent and volume of anoxia and hypoxia before and after the regime shift. Results are given as part (%) of the area and volume of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga. Updated table from Hansson et. al., 2011. Note that the results for 2018 are preliminary.

in %	1960 – 1998		1999 – 2017		2018	
	Hypoxia	Anoxia	Hypoxia	Anoxia	Hypoxia	Anoxia
Mean Areal extent	22	5	29	15	32	22
Max Areal extent (Year)	27 (1970)	14 (1969)	32 (2007)	19 (2011)	-	-
Mean Volume	13	2	18	9	20	15
Max Volume (Year)	19 (1965)	8 (1969)	21 (2011)	13 (2017)	-	-

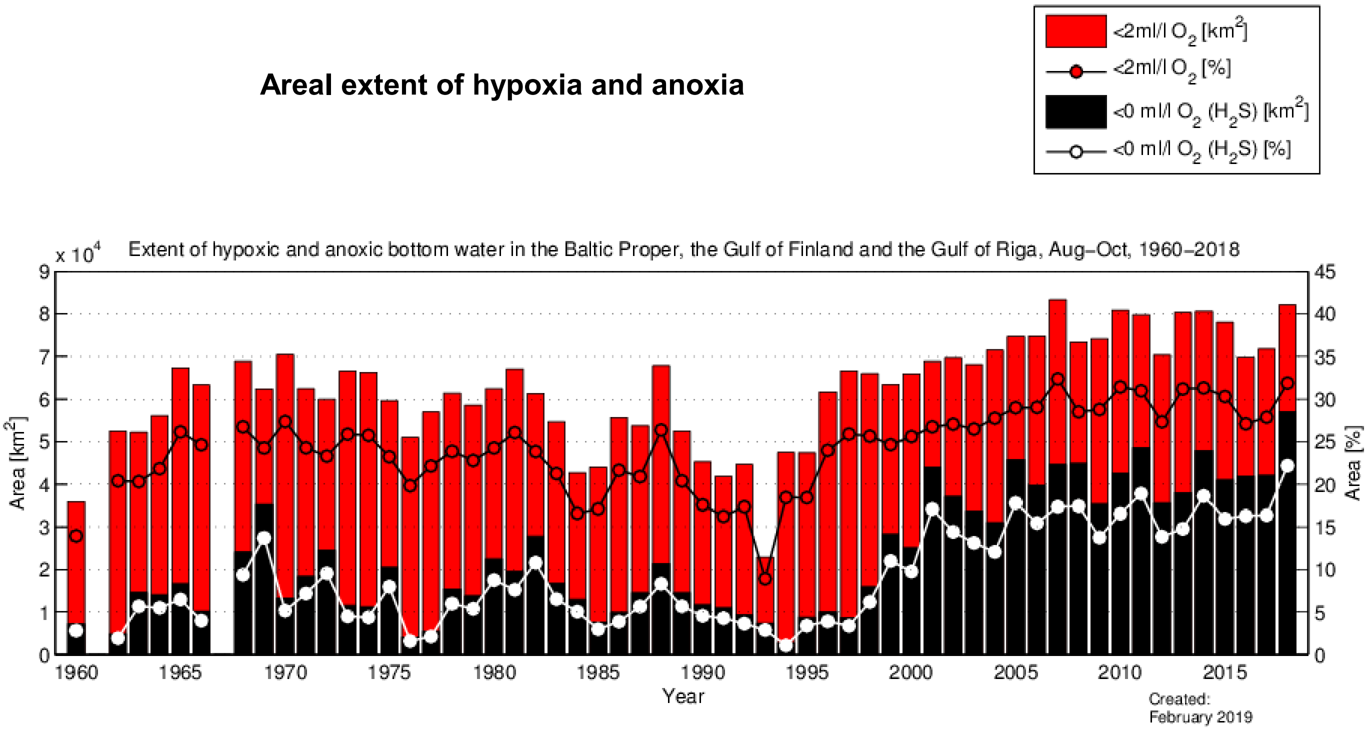

Figure 3. Areal extent of anoxic and hypoxic conditions in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins.

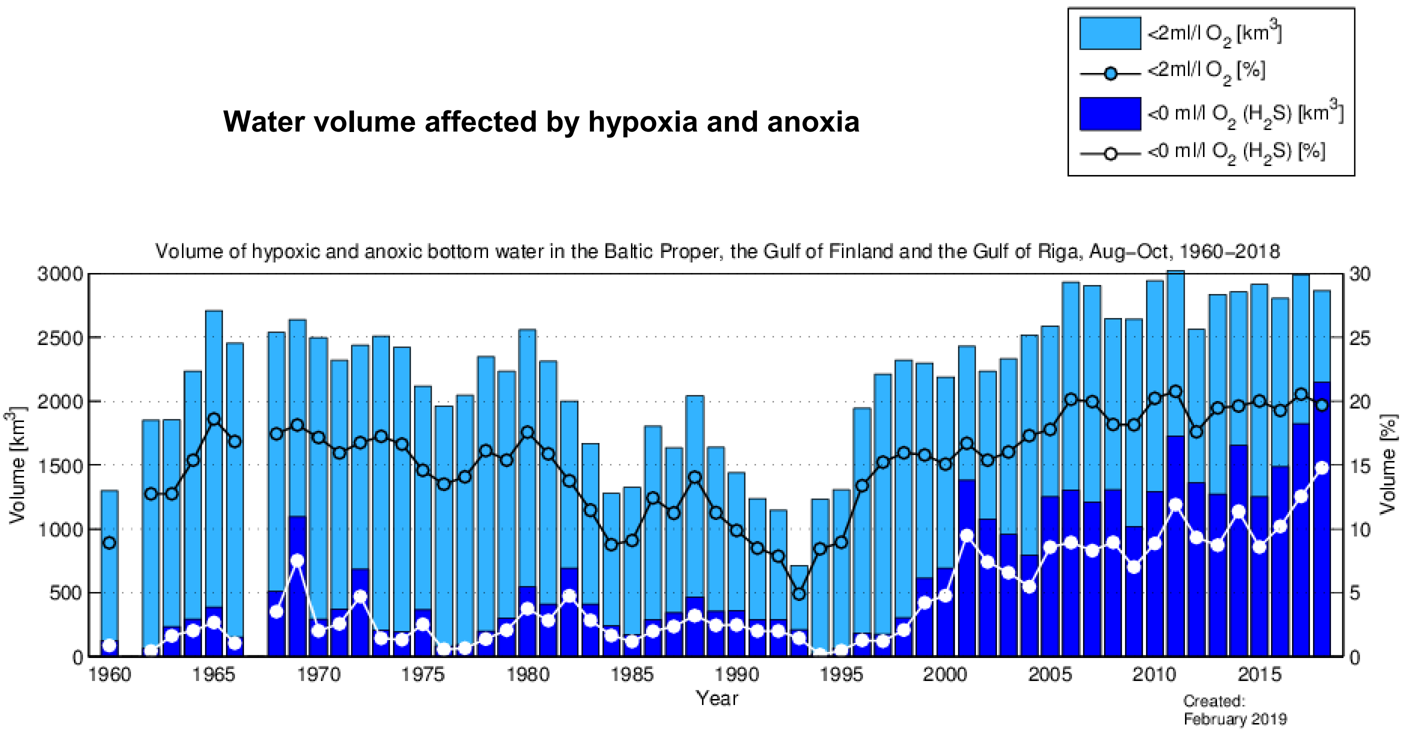

Figure 4. Volume of anoxic and hypoxic deep water in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins.

4.1 Updated results for 2017

As additional data was reported to ICES the results for 2017 was updated. The area affected by anoxia and hypoxia showed only minor changes. The anoxic areas in the outer parts of the Gulf of Finland decreased but new areas were found in the central parts. In the Eastern Gotland Basin anoxic areas increased and a new anoxic area was also found in the Gulf of Gdansk. Hypoxic areas showed similar small changes.

The proportion of areas affected by anoxia was after the update more or less unchanged (18% to 16%). However, as different areas were affected, the volume did show a small increase from 12% to 13%. This is the largest volume that has been recorded during the investigated period 1960-2017. No changes were found for the proportion of areas suffering from hypoxia, the results remained at 28%. However, the volume of hypoxic water slightly decreased from 22% to 21%. The updated results for 2017 follow the oxygen development that has prevailed since the regime shift in 1999.

The total outflow from the Baltic Sea through the Sound during 2017 was 736 km^3, which is 100 km^3 larger than normal when compared to the time period 1977-2016. There were no major inflows through the Sound (Öresund) that reached the deep basins but several minor inflows. The two largest occurred in February and October and brought approximately 20 km^3 each. There was also, as normal for the season, a couple of small inflows during summer. The inflows during 2017 only temporally improved the oxygen situation in the Bornholm Basin and the southern part of Eastern Gotland Basin.

Compared to previous years with high inflow activity with both major Baltic inflows and several smaller events the year 2017 is characterized as a weak inflow year [Naumann et. al. 2018]. This is clearly seen in Figure 5 that show the accumulated inflow volume through the Sound (Öresund), where the inflow curve of 2017 runs below the minimum of the reference period 1977-2016 during large parts of the year. Hence, outflow from the Baltic Sea prevailed during most parts of the year and no major inflow was recorded.

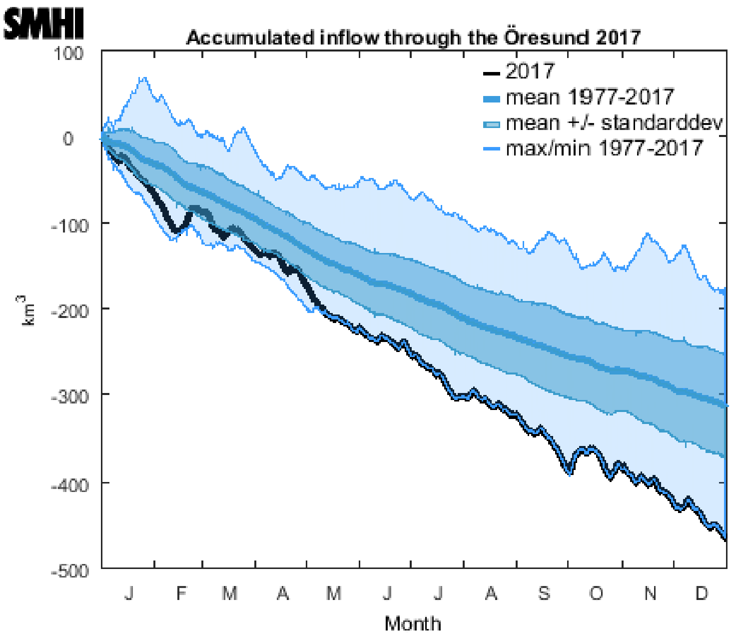

Figure 5. Accumulated inflow (volume transport) through the Sound (Öresund) during 2017 in comparison to mean inflow/outflow 1977-2017 [SMHI, 2019].

4.2 Preliminary results for 2018

The frequency of inflows to the Baltic Sea increased during the period 2014-2016. However, no large inflows were noted during 2017. In 2018 a small inflow through the Sound was noted in mid-June (~20 km^3) and later in mid-September a larger inflow (~40 km^3) occurred. Another inflow through the Sound (~30 km^3) was recorded in the beginning of December.

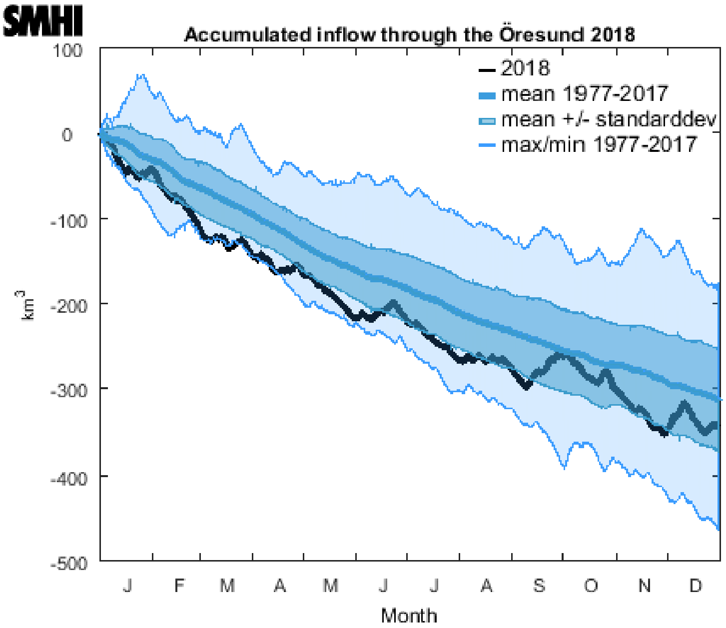

Figure 6. Accumulated inflow (volume transport) through the Sound (Öresund) during 2018 in comparison to mean inflow/outflow 1977-2017. [SMHI, 2019]

In comparison with 2017 the oxygen situation in the deep water of all basins generally deteriorated during 2018. The deep water in the Arkona Basin are usually well oxygenated during winter and early spring, but during 2018 the near bottom oxygen concentrations in January and March was much lower than normal, and varied between 4-5 ml/l. The bottom oxygen concentration reached its highest values in April, thereafter decreasing concentrations followed from early summer, resulting in hypoxia in August and almost anoxic conditions in September. The inflow in mid-September improved the conditions by raising the oxygen concentration in Arkona to normal levels. [SMHI 2018]

The oxygen conditions in the bottom water at Hanö Bight were near anoxic with oxygen concentrations close to 0 ml/l throughout the year. Anoxic conditions, with hydrogen sulphide present, were found during summer. Hypoxia was generally found from depth exceeding 60 meters but in February already from 50 meters depth.

In the Bornholm Basin hypoxia was found at 60 and 70 meters depth and anoxic condition or close to 0 ml/l from about 80 meters depth throughout the year. However, the inflow in September could be seen at BY5 as a pulse of water with oxygen concentrations just above 2 ml/l in October. During the end of the year the oxygen conditions dropped below 2 ml/l and anoxic conditions close to zero oxygen was observed in December.

Further into the Southern Baltic Proper, at the station BCSIII-10, anoxic condition or oxygen concentrations close to 0 ml/l were found from 80 meter depth throughout the year. Hydrogen sulphide has rarely been seen at this station but was now found from June to October. A pulse of the September inflow could be found at 80 meters depth at BCSIII-10 in November and December.

In the central parts of the Eastern Gotland Basin - Gotland Deep (BY15) anoxic conditions with hydrogen sulphide present or oxygen concentrations close to zero were found from 80-200 meters depth during the first half of 2018. After summer the hydrogen sulphide concentration in the deep water, exceeding 150 meters depth, increased, see Figure ~~5~~ 7 and Appendix 1. Hypoxia was present just below the stratification starting at 70-80 meters depth. [SMHI 2018]

The Northern Gotland Basin and the Eastern Gotland Basin show similar development in the deep water. The improved oxygen situation that was noted after the pulse of inflowing water 2014-2016 is slowly deteriorating since no large inflow has occurred during 2017-2018. Figure 7 show the development of hydrogen sulphide over time. From this figure it is clear that the anoxic conditions, with hydrogen sulphide present but at low concentrations, after the inflow period 2014-2016 has moved shallower compared to previous years.

The severe stagnation in the Western Gotland Basin continues with high concentrations of hydrogen sulphide. Anoxic conditions were found already from 60 meters depth in October at Norrköpings Deep and hypoxia from ~50 meters depth. [SMHI 2018]

The preliminary results for 2018, focusing solely on the extent and volumes of anoxia and hypoxia, suggest that the severe oxygen situation that has prevailed since 1999 continues. The anoxic conditions, both area and volume, are the largest noted during the analyzed period from 1960. The proportion of areas affected by anoxia remains at the same level ~22% and the hypoxic areas affect ~32%. See Table 1. The large increase is mainly due to the anoxic areas found in the Bornholm Basin and that anoxia is found even shallower in the central basins.

I should be noted that the 2018 results are preliminary; however the results this year are based on an extensive data set with data contributions from most countries around the Baltic region.

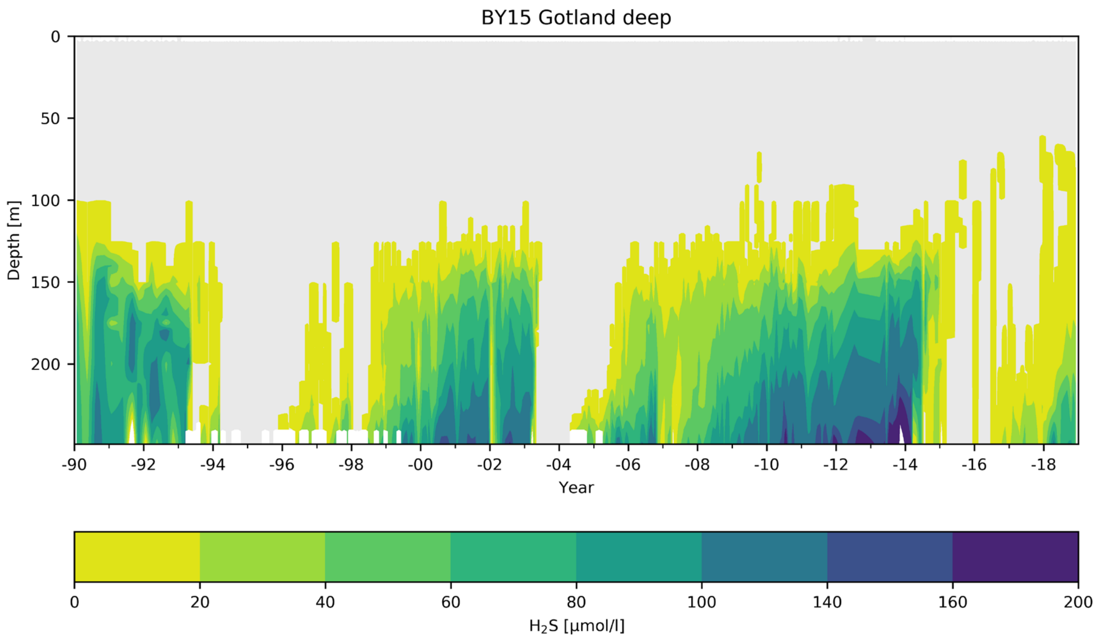

Figure 7. Concentration of hydrogen sulphide (H_2S) at Gotland Deep (BY15) in Eastern Gotland Basin from 1990-2018. Grey signifies no hydrogen sulphide present.

The reason for the large volume of anoxia during 2018 is still not clear but the extremely warm and calm weather during the spring and summer might have favoured extremely high biological production [Rehder G, 2018], resulting in a larger proportion of organic material to be degraded in the deep water during the late summer and autumn.

5 Conclusions

- Similar to previous year, the severe oxygen conditions in the Baltic Proper continued during 2018. The areal extent and the volume of anoxia and hypoxia have since the regime shift in 1999 been constantly elevated.

- Preliminary results for 2018 shows that anoxic conditions are the largest noted during the analysed period from 1960. Anoxic conditions affected ~22% of the bottom areas and about 32% suffered from hypoxia.

- The reason for the large volume of anoxia during 2018 is still not clear but the extremely warm and calm weather during the spring and summer and the resulting large biological production might have enhanced the oxygen consumption in the deep water as organic material is degraded.

- A series of inflows to the Baltic Sea occurred between 2014 and 2016. The recent inflows have reduced the large pool of hydrogen sulphide that was present in the Eastern and Northern Gotland Basin. However, oxygen concentrations in the deep water are near zero below the permanent stratification and conditions near bottom has become increasingly anoxic during 2017.

- The amount of hydrogen sulphide is increasing in the Eastern and Northern Gotland Basins in the deep water. New major inflows are needed to prevent further deterioration of the oxygen situation, with the formation of higher hydrogen sulphide concentrations as a result.

6 Acknowledgement

Many thanks to Tycjan Wodzinowski, National Marine Fisheries Research Institute in Poland, for sending data from two surveys “Polish Multiannual Fisheries Data Collection Programme” (September) and “Relations between recruitment of selected fish species and driving forces as hydro-meteorological factors and food availability” (August).

We are also very grateful to David Rytter and Jens Würgler Hansen at the Institute for Bioscience, Aarhus Universitet, Denmark for providing the large “Iltsvind” dataset.

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We also acknowledge Māris Skudra at the Latvian Institute of Aquatic Ecology for sharing their extensive data set from their national project: "Improvement of knowledge about sea ecosystem, environmental status of the sea and loads affecting it".

Thanks also to Marina Ulyanova at Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS) Atlantic Branch for sharing data collected with support of the state assignment of the Ministry of Science and Higher Education of the Russian Federation (theme No 0149-2018-0012).

Many thanks also to the Finnish Environment Institute and Finnish Meteorological Institute for sharing CTD-data.

The ICES Dataset on Ocean Hydrography was used for updating the result for 2017. The data was collected at the excellent web service at the International Council for the Exploration of the Sea (ICES). Many thanks to the ICES crew for always good support.

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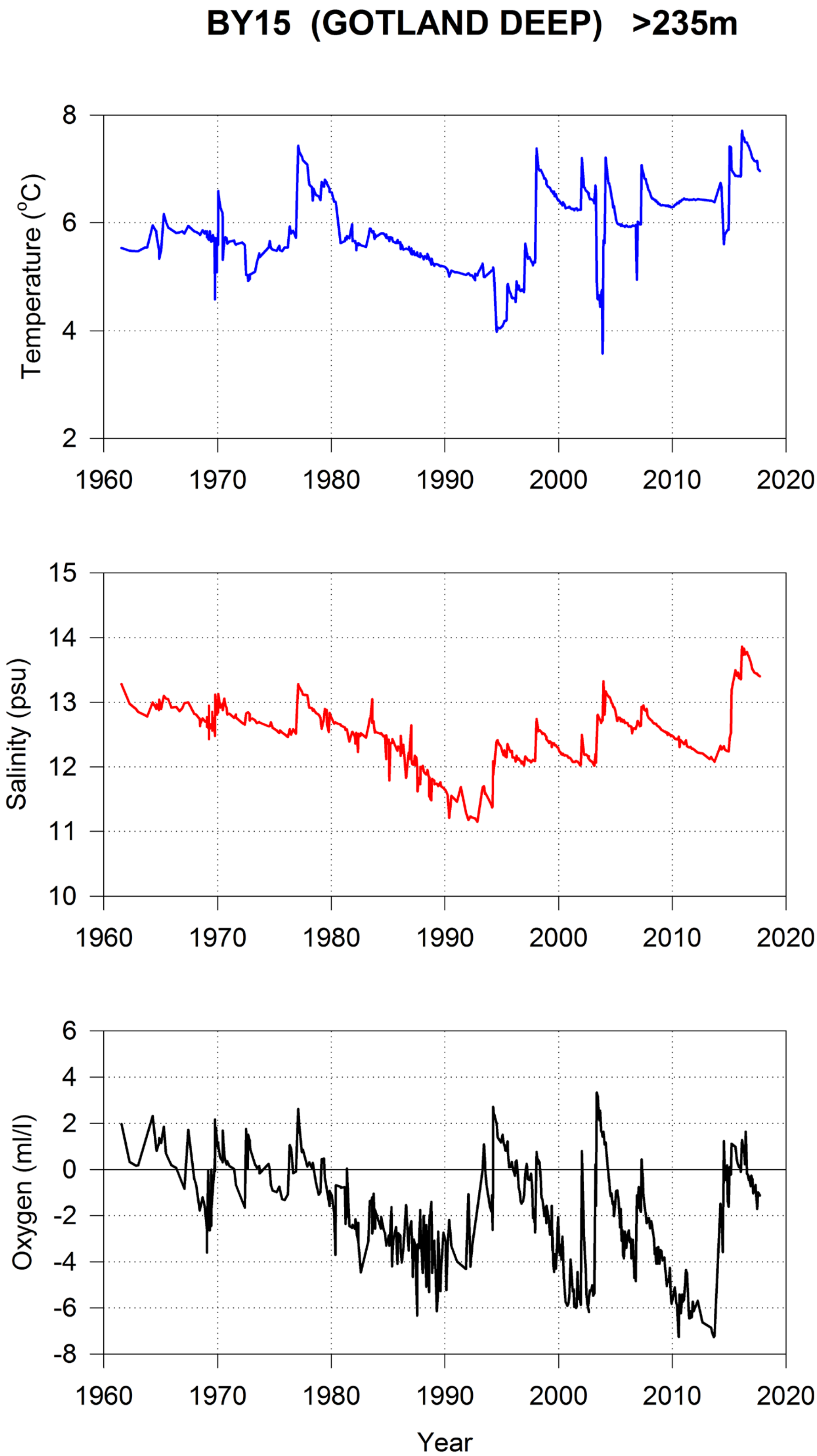
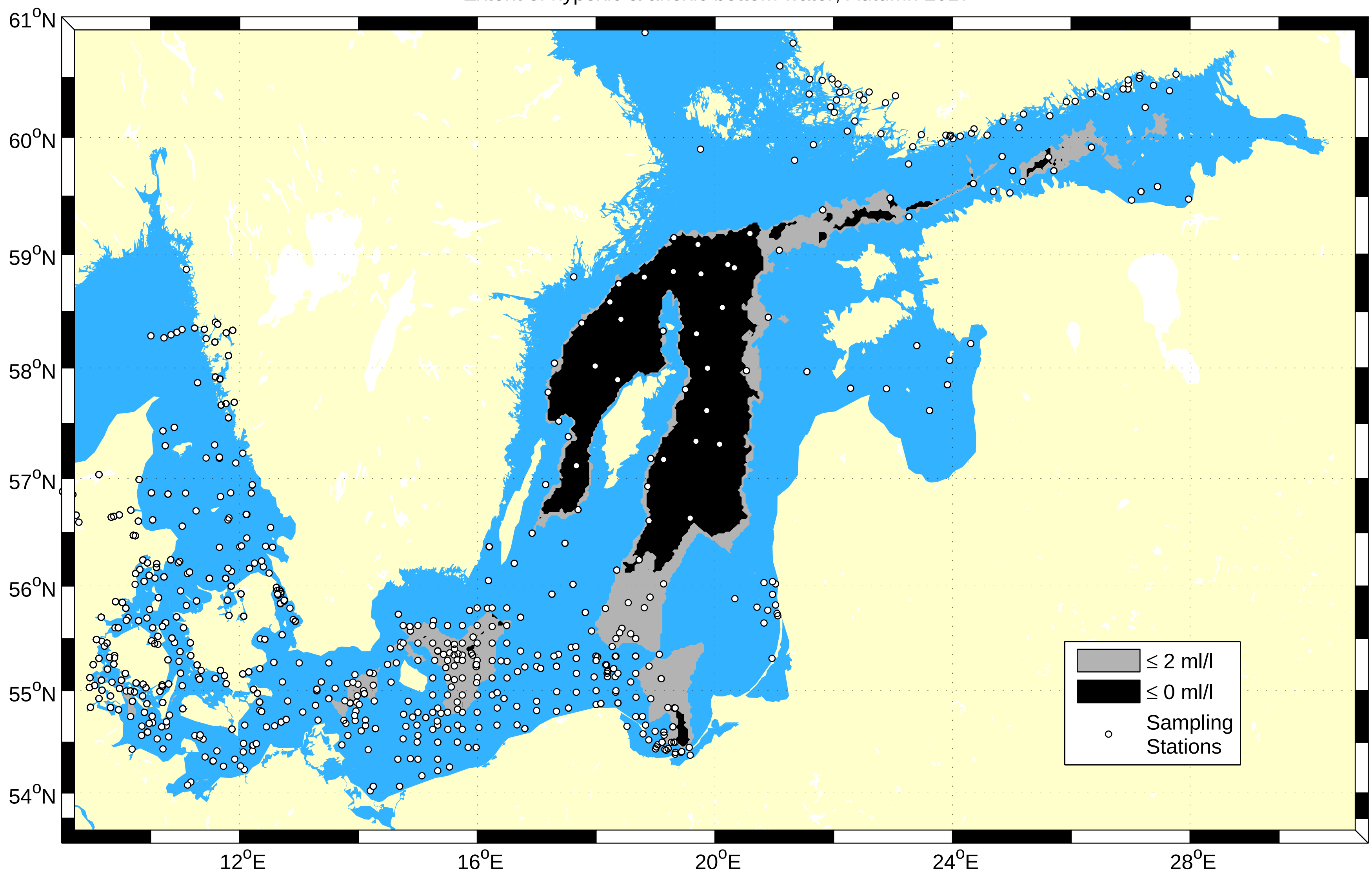
Appendix 1 – Temperature, salinity and oxygen in Eastern Gotland Basin at station BY15, 1960-2018



Appendix 2 - Anoxic and hypoxic areas in the Baltic Sea, 2017-2018

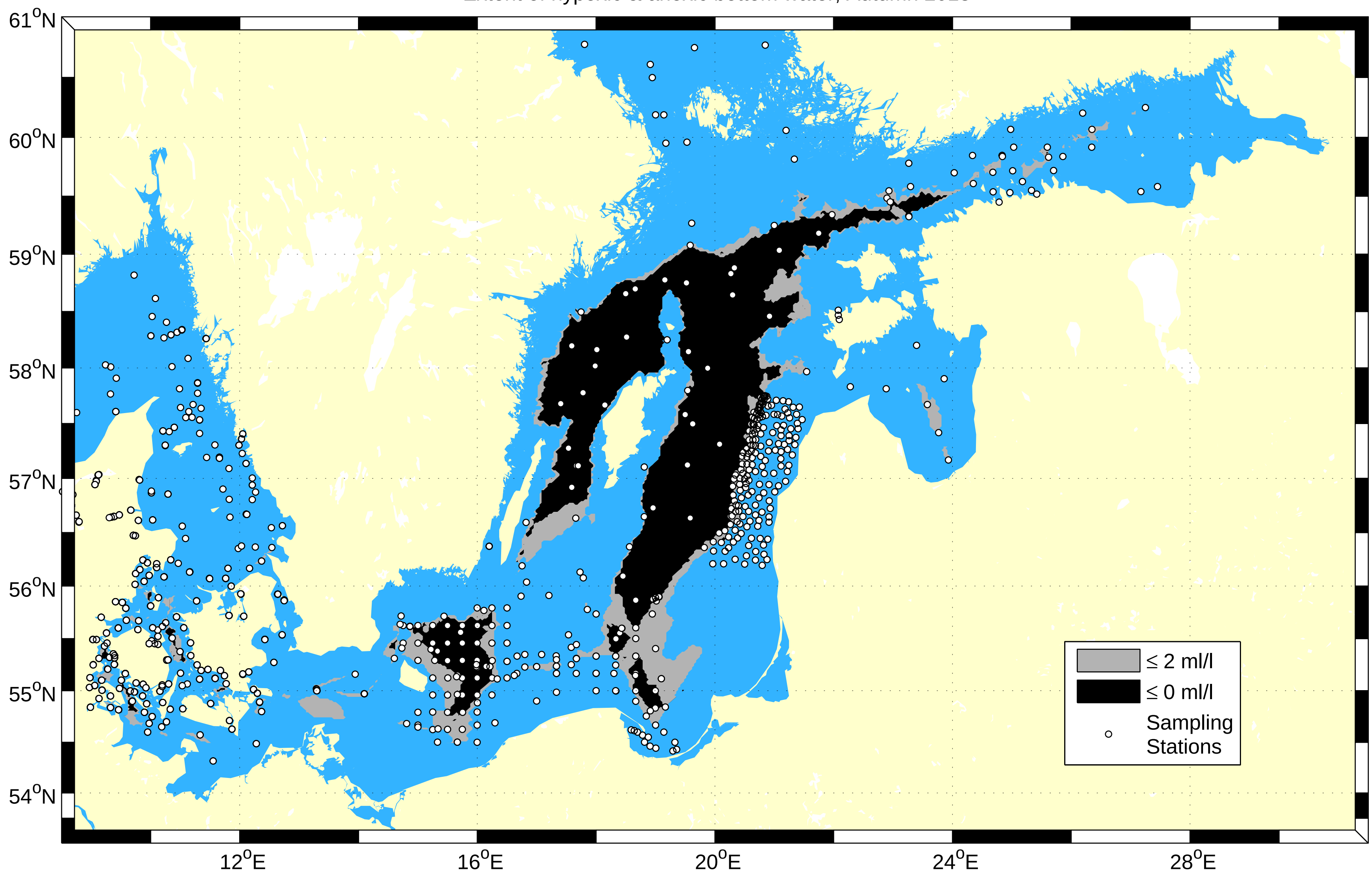
(The complete and updated time series can be found in on http://www.smhi.se)

Extent of hypoxic & anoxic bottom water, Autumn 2017



Created:
January 2019

Extent of hypoxic & anoxic bottom water, Autumn 2018



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