REPORT OCEANOGRAPHY No. 80, 2024

Oxygen Survey in the Baltic Sea 2024

- Extent of Anoxia and Hypoxia, 1960-2024

Front: View towards Gotland from R/V Svea during the Baltic International Acoustic Survey (BIAS) in the Baltic Proper organized by SLU-Aqua. During the fishing surveys, before or after each trawl, a CTD-profile and water samples are collected for analysis. Dissolved oxygen and concentration of hydrogen sulphide are two examples of the parameters that are collected. Data from the ICES co-ordinated trawl surveys are well suited for concurrent oxygen surveys because of randomized sampling and since surveys are performed by different countries almost simultaneously, a vast sea area can be monitored. Photo by Anna-Kerstin Thell, October 2024.

ISSN: 0283-1112

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Oxygen Survey in the Baltic Sea 2024
- Extent of Anoxia and Hypoxia, 1960-2023

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Summary

In 2011, SMHI published *Report Oceanography No. 42*, a climatological atlas detailing the oxygen status in the deep waters of the Baltic Sea. Since then, annual updates have been released as new data are reported to the International Council for the Exploration of the Sea (ICES) data center. This report provides an update for 2023 and presents the preliminary results for 2024. The oxygen data for 2024 were collected from various sources, including ICES coordinated trawl surveys, national monitoring programmes, and research projects involving Poland, Estonia, Latvia, Denmark, Sweden, and Finland.

For the autumn period, each profile in the dataset was analyzed 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 to produce two surfaces that represent the depths at which hypoxic and anoxic conditions are present, respectively. The volume and area of hypoxia and anoxia were then calculated and the results transferred to maps and diagrams to visualize the annual autumn oxygen situation during the analyzed period.

The updated results for 2023 and the preliminary results for 2024 show that the severe oxygen conditions in the Baltic Proper after the regime shift in 1999 continues. In 2023 anoxia was found at 19% of the bottom areas and 33% suffered from hypoxia including anoxic areas. Preliminary results for 2024 show that anoxia affected 18% of the bottom areas and 34% suffered from hypoxia (including anoxic areas). The concentration of hydrogen sulphide is record high in all the basins around Gotland. In the Eastern and Western Gotland Basin hydrogen sulphide in the bottom water has reached levels not recorded before. The inflows that occurred during 2023 had a short-term positive effect that could be seen in the Southern Baltic Proper but not further into the Baltic Proper than to the Eastern Gotland basin at intermediate depths. Unfortunately, these pulses of oxygenated water are too small to have any major positive impact on the overall oxygen situation. In late 2024 two inflows occurred that might improve the oxygen situation in 2025 in the southern Baltic Proper.

Sammanfattning

År 2011 publicerade SMHI *Report Oceanography No. 42*, en klimatologisk atlas som beskriver syreförhållandena i djupvattnet i Östersjön. Sedan dess har årliga uppdateringar publicerats i takt med att nya data rapporteras till Internationella havsforskningsrådets (ICES) datacenter. Denna rapport utgör en uppdatering för 2023 och presenterar preliminära resultat för 2024. Syredata för 2024 har insamlats från flera olika källor, inklusive trålundersökningar samordnade av ICES, nationella övervakningsprogram och forskningsprojekt i samarbete mellan Polen, Estland, Lettland, Danmark, Sverige och Finland.

För höstperioden analyserades varje profil i datasetet med avseende på förekomst av hypoxi (syrebrist) och anoxi (helt syrefritt). De djup där hypoxi och anoxi inträffar interpolerades mellan provtagningsstationer för att generera två ytor som representerar de nivåer där respektive tillstånd förekommer. Därefter beräknades volym och utbredning av hypoxi och anoxi, och resultaten visualiserades i kartor och diagram för att illustrera syresituationen under hösten för den analyserade perioden.

De uppdaterade resultaten för 2023 och de preliminära resultaten för 2024 visar att de allvarliga syreförhållandena i Egentliga Östersjön, som följde efter regimskiftet 1999, består. Under 2023 uppmättes anoxi på 19% av bottenytorna, medan 33% av bottenarealen drabbades av hypoxi (inklusive anoxiska områden). De preliminära resultaten för 2024 indikerar att 18% av bottenytorna var påverkade av anoxi och att hypoxi (inklusive anoxiska områden) omfattade 34%.

Koncentrationen av svavelväte har nått rekordhöga nivåer i samtliga bassänger runt Gotland. I Östra och Västra Gotlandsbassängen har svavelvätehalterna i bottenvattnet uppnått nivåer som tidigare inte har registrerats. De inflöden som inträffade under 2023 hade en kortvarig positiv effekt som kunde observeras i Södra Egentliga Östersjön, men de påverkade inte Östersjön längre än till den Östra Gotlandsbassängen på intermediära djup. Dessa inflöden av syrerikt vatten är dessvärre alltför små för att ha någon betydande förbättrande effekt på den övergripande syresituationen. Under slutet av 2024 inträffade två inflöden som potentiellt kan förbättra syresituationen i Södra Egentliga Östersjön under 2025.

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1 Background

The deep central regions of the Baltic Proper are characterized by persistently low oxygen levels, a condition largely shaped by the sea's unique geography. Its semi-enclosed, fjord-like structure naturally limits oxygen renewal, while water exchange with the North Sea is restricted by the narrow straits and shallow sills of the Belt Sea and the Sound.

Extensive freshwater runoff from the Baltic Sea's vast catchment area creates a predominantly outward flow through the Sound and Belt Sea into the Kattegat and North Sea. However, shifts in wind patterns, atmospheric pressure, and sea levels can occasionally reverse this flow, allowing rare but significant inflows of oxygen-rich, saline water.

These inflows, though beneficial, do not reach all deep-water layers due to the strong stratification caused by differences in salinity and density. As a result, oxygenation of deeper waters remains limited, while the continuous decomposition of high amounts of organic matter depletes existing oxygen supplies. This process leads to critically low oxygen levels, endangering marine life and promoting the expansion of oxygen-depleted zones.

However, large inflow events or series of small inflows, can supply the deep water of the Baltic Proper with dissolved oxygen, as inflowing water usually is well-oxygenated. The inflow either form a layer that follows the sea floor or is interleaved at intermediate depths, depending on its density. Inflows can only reach the deep basins of the central basin in the Baltic Proper if the volume is large enough to move over the sills between the different basins of the Baltic Proper, and the density is high enough to settle the inflow along the bottom. Major Baltic Inflows (MBI) are rare, with the latest large MBI occurring as a series of large inflows during 2014-2016 [Mohrholz et. al. 2015].

The oxygen situation in the Baltic Proper has become increasingly problematic because large inflows don't occur every year and due to large nutrient inputs over time, mainly between the 1950s and the late 1980s, resulting in escalating eutrophication with increasingly severe symptoms to the Baltic Sea's ecosystem [HELCOM, 2018]. The more organic matter that is supplied to the deep water, the more oxygen is consumed, resulting in oxygen deficiency and if the bottom water is not renewed this will escalate to anoxia. 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 an extended period, hydrogen sulphide (H_2S) is formed, which is toxic to all higher marine life. Only bacteria and fungi can survive in a water environment with total absence of oxygen.

The pool of hydrogen sulphide found in the deep parts of the Baltic Proper must be oxidized by oxygen-rich inflowing water or pushed above the permanent stratification where oxygen is available before a new inflow can have any effect on the oxygen concentrations. During anoxic conditions, sediments release nutrients such as phosphate and silicate to the water column, which, due to vertical mixing or upwelling events, can reach the surface layer and the photic zone. High concentrations of nutrients in surface waters favour phytoplankton growth, especially cyanobacteria during summer, which can further enhance oxygen depletion as the bloom sinks to the bottom and consumes oxygen when it is decomposed - a vicious circle has formed [Vahtera et al. 2007].

These natural factors, combined with external human pressures on the Baltic Sea, form the basis for the increasingly problematic low-oxygen conditions and the "dead zones" or oxygen minimum zones (OMZ) found in the Baltic Sea. Total absence of oxygen and oxygen deficiency in the deep water or at intermediate depths throughout the year are mainly found in the central deep basins in the Baltic Proper and the Gulf of Finland. Seasonal lack of oxygen is generally found in the southern parts of the Baltic Proper.

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. Literature studies [Vaquer-Sunyer & Duarte, 2008] shows that the sublethal concentration ranges from 0.06 ml/l to 7.1 ml/l. The mean for all experimental assessments was 1.8 +/- 0.12 ml/l. The same study also suggests that the commonly used threshold for acute hypoxia around 2.0 mg/l (1.4 ml/l) is below the empirical sublethal and lethal oxygen concentrations for half of the species tested.

The dominant demersal fish population in the Baltic Sea, the Baltic cod (*Gadus morhua*), has been shown to avoid oxygen concentrations below 1 ml/l [Schaber et al., 2012]. However, already at 4.3 ml/l the condition and growth of cod starts to be affected [Chabot and Dutil,1999]. It has also been shown that Baltic Sea 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,]. With this background the limit of acute hypoxia, in this report, is set to 2.0 ml/l.

This report presents a time series of the 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 2024. The time series was first published in 2011 and the results have been updated annually as new additional data have become available at International Council for the Exploration of the Sea (ICES) [ICES, 2009]. In the report from 2011 and in a newly published article a distinct regime shift in the oxygen situation in the Baltic Proper was found to occur around 1999 [Hansson et al, 2011; Almroth et al., 2021]. 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.

In this report results from 2023 and 2024, in form of maps and diagram of bottom areas affected by oxygen deficiencies, has been added to the time series starting in 1960. The complete and updated time series can be found as figures in this report and as maps in Appendix 2, which can be used as a climatological atlas describing the historical development and the present oxygen situation in the Baltic Proper.

2 Data

2.1 Oxygen data

The oxygen data for the analysis of 2024 are based on oxygen data collected during the annual trawl surveys coordinated by the ICES in the Baltic Sea and North 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, Poland, Denmark and Sweden. See all data contributors in the Acknowledgement below.

Oxygen data have not been fully quality controlled; only preliminary checks have been performed. The time series and the results presented for 2024 will be updated when additional data are reported to ICES in 2025/2026. In this report the results for 2023 has been updated with all available bottle and CTD data retrieved from the dataset on ocean hydrography at ICES (http://www.ices.dk, last access: 2025-02-19).

Trawl survey data, oxygen CTD and bottle, are particularly well suited for concurrent oxygen assessments due to the randomized sampling approach and the near-simultaneous execution of cruises by multiple countries. As a result, almost the entire offshore Baltic Proper is covered with extensive spatial distribution, offering a comprehensive snapshot of the oxygen conditions. These surveys are conducted during late summer and autumn, from August to October, a period when oxygen depletion is typically at its peak. Thus, they provide a crucial contribution of oxygen data, complementing the routine national and regional monitoring carried out 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 northern part (Viken) and the southern part (Klagshamn) of the Sound [Håkansson et. al. 1993, Håkansson 2022]. The results, as accumulated inflow, from 1977 to present are presented in Swedish at the SMHI website under the title “Vattenåret”. To improve the yearly summary of inflow/outflow events the calculations has been revised. Inflow/outflow events are added together but small inflows/outflows, < 0.5 days and <1 km^3, that would interrupt and ongoing inflow/outflow, has been added or removed from inflow/outflow events to get at better overview of the size and duration of inflow and outflow events. For the years 2023 and 2024 see Figure 5 and 6 for accumulated inflow and inflow/outflow events [SMHI, 2025].

Another estimate of the flow through the Sound and the Belt Sea has been presented by [Mohrholz, 2018] and is continuously updated. Simplified, the calculations are based on the mean sea level at Landsort and river discharge to the Baltic Sea. In Figure 1, the two estimates of the flow through the Sound are compared. The results from the two calculations are generally similar and in the same range. The results by [Mohrholz, 2018] is usually higher but the SMHI inflows are often divided into several inflow events. Larger inflows seem to correlate better. However, there are some inflows in both time series that do not correlate at all. For example, during late 1980s and 1990s in [Mohrholz, 2018] and in early 1990s in the SMHI timeseries. The difference could be explained by the local [SMHI, 2025] and regional [Mohrholz, 2018] perspectives of the two methods.

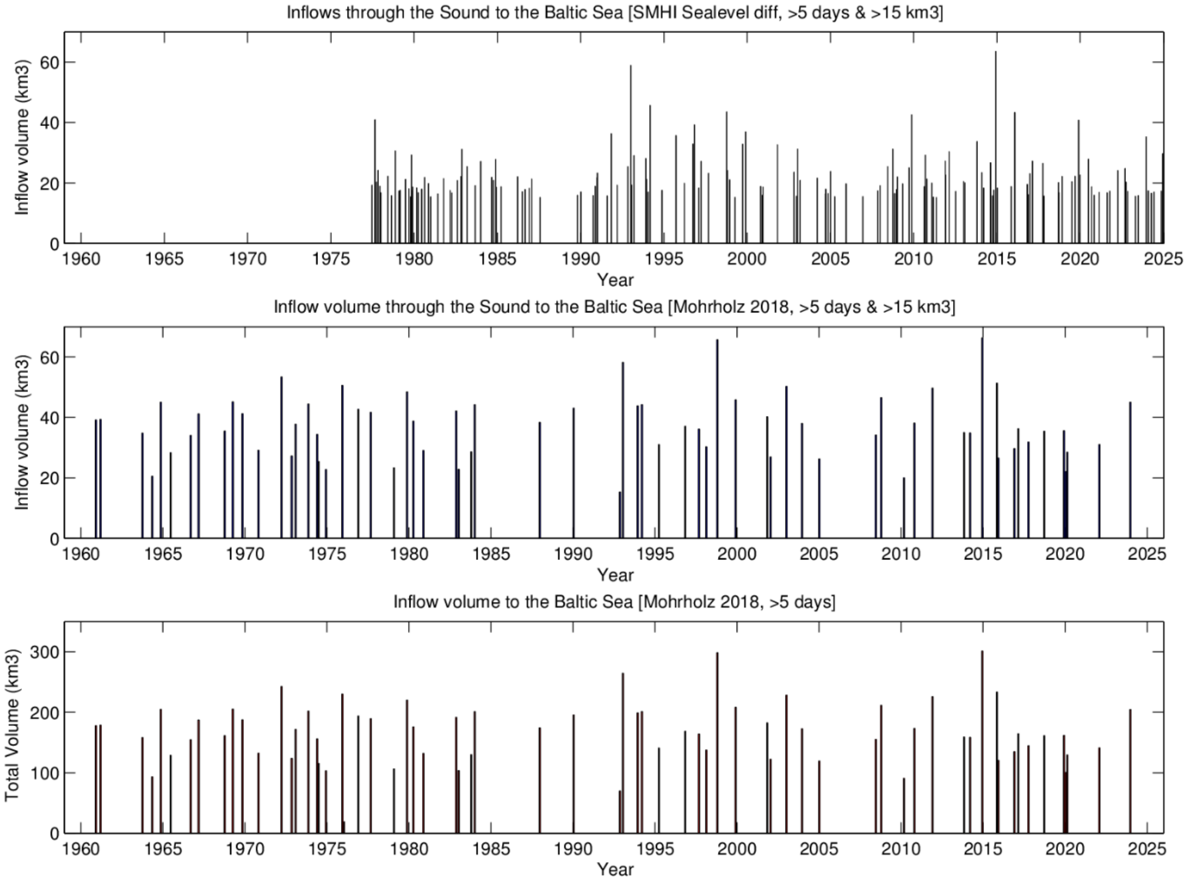

Figure 1. Two different estimations of inflow to the Baltic Sea through the Sound (Öresund). Top: Inflow through the Sound estimated from 1977-2024 by SMHI. [Revised summary of inflow events, SMHI, 2025]. Middle: Inflow through the Sound 1960-2023 estimated by [Mohrholz, 2018]. Bottom: Total volume transport through the Sound and the Danish Straits to the Baltic Sea for inflows, 1960-2023 [Mohrholz 2018, updated 2025-03-17]. Note that the SMHI results are only available from 1977 to 2024 and that by the time for publication Mohrholz had not updated the time series with 2024 data.

3 Method

For the late summer and autumn period, August to October, 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 profiles had to be filtered out: for example, when data was missing in the deep water, when correct data from a shallow area obviously negatively affects the interpolation results in nearby deep areas 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 was 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 was 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 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. On the other hand, the oxygenated zones below the intermediary layer, does influence the sediment to water nutrient exchange [Hall et al., 2017 and Sommer et al., 2017].

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].

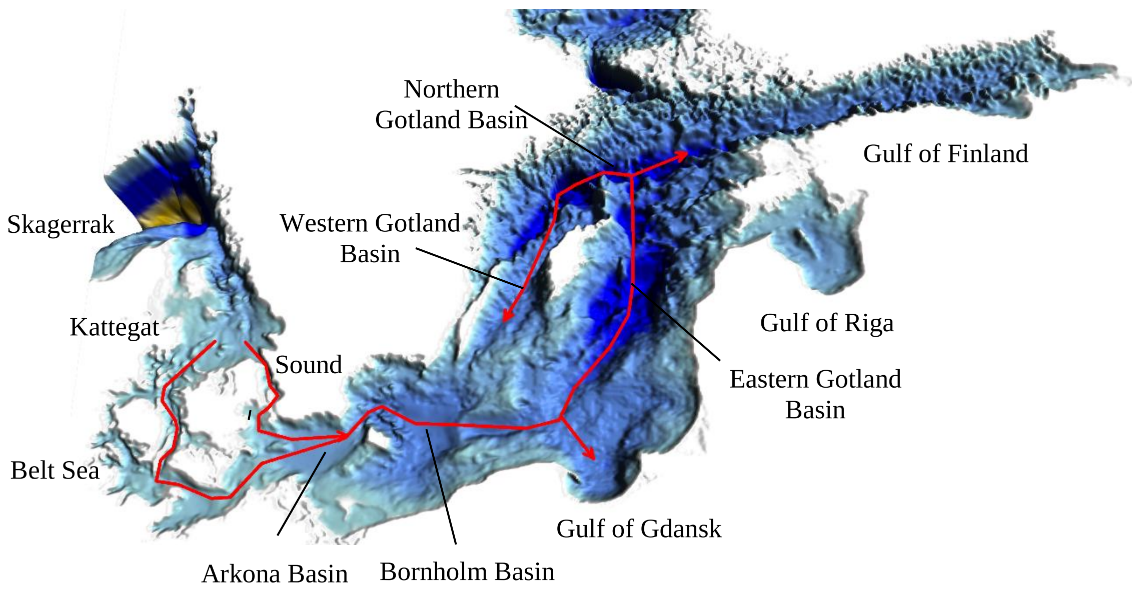

Figure 2. Bathymetry [Seifert, 2001] of the south Baltic Sea and pathways of inflowing deep-water during inflows. The Baltic Proper includes the Arkona Basin, the Bornholm Basin, the Gulf of Gdansk, the Gulf of Riga and the Eastern-, Western- and Northern Gotland Basin [Fonselius, 1995].

4 Result

Extent and volume affected by hypoxia and anoxia during the period 1960 - 2024 are presented in Figures 3 and 4, respectively. Maps presenting bottom areas affected by hypoxia and anoxia during the autumn period 2023 and 2024 can be found in Appendix 2. The mean, maximum and minimum areal extent and volume affected by hypoxia and anoxia before and after the regime shift in 1999 [Hansson et. al, 2011]) and the preliminary results for 2024 are presented in Table 1. Note that the hypoxic area and volumes are defined as all area/volume with oxygen concentration below the limit for acute hypoxia, thus it includes both hypoxic and anoxic areas/volumes.

The preliminary results for 2024 are all above mean for the period 1999-2023.

Table 1. Mean, max and min 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.

in %	1960 – 1998		1999 – 2023		2024 (Preliminary)	
	Hypoxia	Anoxia	Hypoxia	Anoxia	Hypoxia	Anoxia
Mean Areal extent	22	5	30	17	34	18
Max Areal extent (Year)	27 (1970)	14 (1969)	35 (2022)	24 (2018)	-	-
Min Areal extent (Year)	9 (1993)	1 (1994)	25 (1999)	10 (2000)	-	-
Mean Volume	13	2	19	10	22	11
Max Volume (Year)	19 (1965)	8 (1969)	22 (2019)	15 (2018)	-	-
Min Volume (Year)	5 (1993)	0.1 (1994)	15 (2000)	4 (1999)	-	-

Areal extent of hypoxia and anoxia

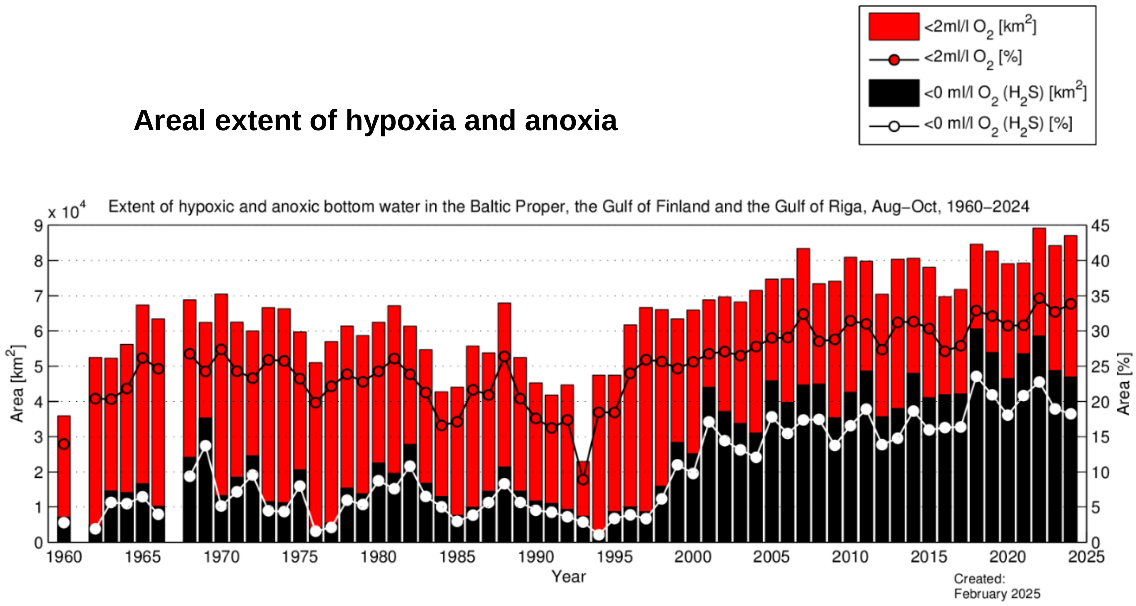

Figure 3. Areal extent of anoxic and hypoxic conditions in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins. Note that the hypoxic area is defined as all area with oxygen concentration below the limit for acute hypoxia, thus it includes both hypoxic and anoxic areas.

Water volume affected by hypoxia and anoxia

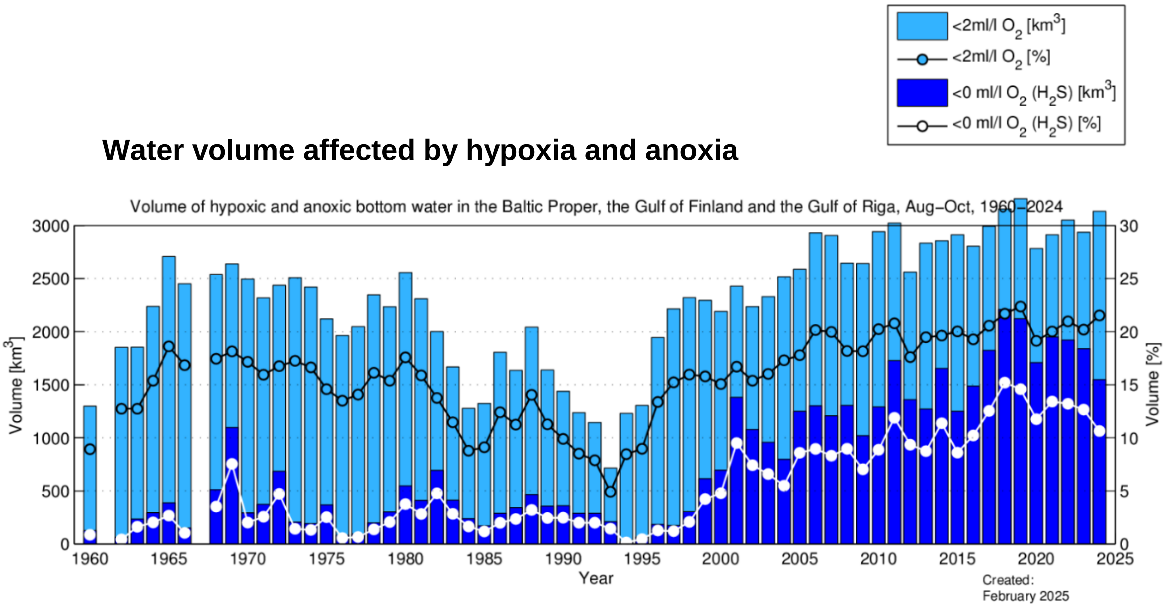

Figure 4. Volume of anoxic and hypoxic deep water in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins. Note that the hypoxic volumes are defined as all volume with oxygen concentration below the limit for acute hypoxia, thus it includes both hypoxic and anoxic volumes.

4.1 Updated results for 2023

The result for 2023 has been updated as additional hydrographic data has been reported to ICES. Overall the update resulted in minor increase of the total areas and volumes of both anoxia and hypoxia. After the update the anoxic and hypoxic area increased in the Gulf of Gdansk and in the central basins around Gotland.

The proportion of areas affected by anoxia increased from 18% to 19% and the hypoxic areas was increased from 32% to 33%. The proportion of volume affected by anoxia increased from 12% to 13% and for hypoxia it was unchanged at 20%.

The results for 2023 are all above the mean for the period after the regime shift in 1999, see Table 1. The areal extent and volume of anoxia and hypoxia continues to be elevated and the oxygen development in the Baltic Proper that has prevailed since the regime shift in 1999 continues, see Figure 3-4.

In 2023, three inflow events occurred through the Sound, each with a volume of approximately 20-40 km^3. The last in 2023, in December, was the largest, just below 40 km^3. This inflow was followed by a series of smaller inflows that might be able to improve the oxygen situation in the southern Baltic during 2024, since it was cold, well oxygenated and had a relatively high salinity.

The total inflow to the Baltic Sea through the Sound during 2023 was 327 km^3 which is just above the mean for the time period 1977-2022, 318 km^3. The outflow was 633 km^3, which is higher than the mean for the same period as above, 622 km^3. The accumulated inflow through the Sound (Öresund) during 2023, compared to the mean inflow 1977-2023 can be seen in Figure 5.

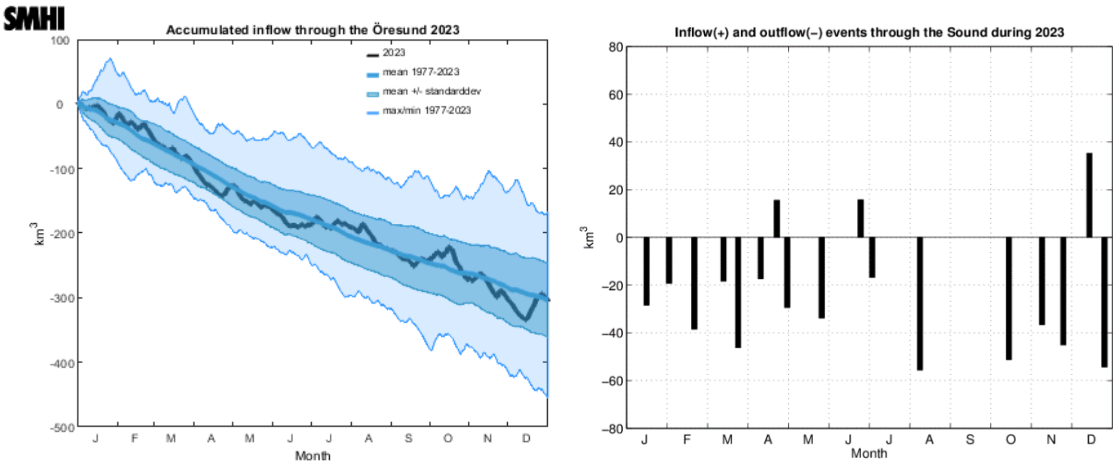

Figure 5. Left: Accumulated inflow (volume transport) through the Sound (Öresund) during 2023 in comparison to mean inflow/outflow 1977-2023. Right: Inflow (+) and outflow (-) events during 2023 that was longer than 5 days and larger than 15 km^3. [Revised summary of inflow events, SMHI, 2025].

4.2 Preliminary results for 2024

The latest major inflow to the Baltic Sea occurred in late 2014. After that a series of inflows occurred during the period 2015-2016, but during 2017-2018 only minor inflows was observed. In late 2019, one somewhat larger inflow (~40 km^3) was noted. During 2020-2024 the frequency of inflows ranged from 3-4 per year and the majority was small inflows. An inflow in December 2023, was somewhat larger, just below 40 km^3 and another in December 2024 (~30 km^2). The latest inflow was followed by another inflow over the new year 2024/2025 of about 12 km^2 that might be able to improve the oxygen situation in the southern Baltic during 2025, since it was cold, well oxygenated and relatively high salinity. See Figure 6.

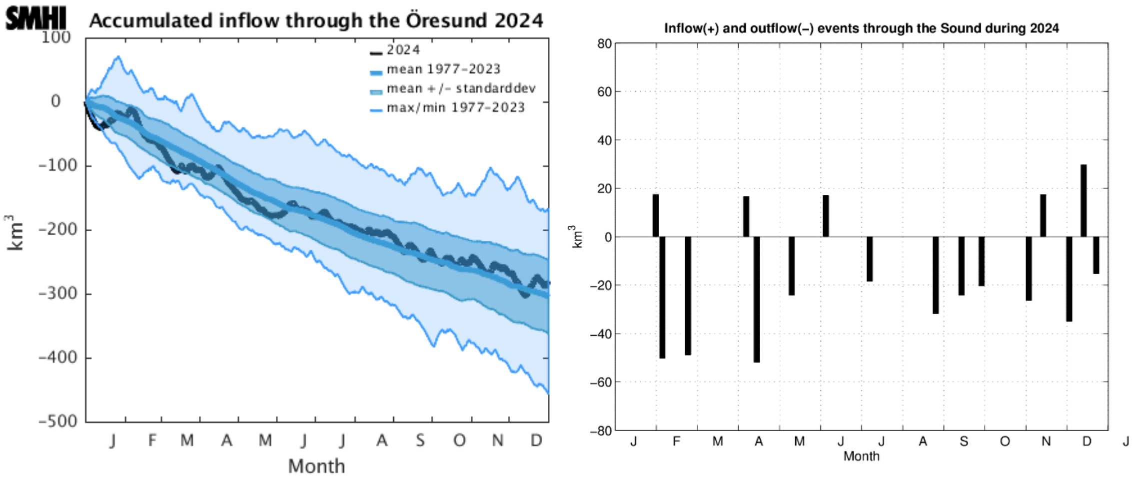

Figure 6. Left: Accumulated inflow (volume transport) through the Sound (Öresund) during 2024 in comparison to mean inflow/outflow 1977-2023. Right: Inflow (+) and outflow (-) events during 2024 that was longer than 5 days and larger than 15 km^3. [Revised summary of inflow events, SMHI, 2025].

The deep water oxygen conditions in the Arkona Basin normally follow an annual cycle with well oxygenated conditions during winter and spring, followed by decreased oxygen concentrations during summer and recovery during late autumn and winter. In 2024 the oxygen situation followed the same pattern. Low oxygen levels prevailed between June to October. At sampling station BY1 acute hypoxia was observed in June and August and almost oxygen free conditions were measured in September, which is rare at this site in the Arkona basin. At station BY2, further east in the basin, acute hypoxia was first seen in September and October and no near anoxic conditions were noted. See station locations in Figure 7. [SMHI, 2025]

In the Hanö Bight at station Hanöbukten the deep-water oxygen was hypoxic throughout the year. The only exceptions were found in January and December, which due to ongoing inflows originating from December 2023 and November-December 2024, had oxygen concentrations exceeding 2 ml/l. The bottom water was near-anoxic, with oxygen concentrations close to 0 ml/l, in July and October-November. In the Bornholm Basin, at station BY4 and BY5, the positive effects of the inflow in December 2023 were also observed from January-April as oxygen concentrations in deep water remained above 2 ml/l. But during the following months the oxygen concentration decreased to acute hypoxia and from July near anoxic conditions prevailed throughout the year. See station locations in Figure 7. [SMHI, 2025]

Further into the southeastern Baltic Proper at station BCSIII-10 the pulse of the December 2023 inflow had reached the area in May or possibly April (The visits to this sea area was cancelled in April due to uncertain safety conditions in the Baltic region). The oxygen concentrations near bottom was up to 3 ml/l. However, this was only a brief event of better oxygen conditions as the bottom water suffered from either acute hypoxic or anoxia during the rest of the year. [SMHI 2024]

At the Gotland Deep monitoring station, BY15, in the Eastern Gotland Basin, concentrations of hydrogen sulphide was constantly high during the year. The concentrations continued to increase during 2024. From depths exceeding 225 meters the concentrations of hydrogen sulphide varied between 147 - 244 µmol/l over the year. The maximum concentration was found in November, which is the highest concentration ever recorded at BY15. [SMHI, 2025]

In September, 2023 the measured concentration of hydrogen sulphide at 239 meters depth was 213 µmol/l. This was the highest concentration noted in the Eastern Gotland Basin during the analyzed period 1960-2023. However, in November 2024 another record was noted when 244 µmol/l hydrogen sulphide was measured at 225 meters, surpassing the previous record. See Figure 7, Appendix 1 and SMHI cruise reports from 2024 [SMHI, 2025].

The oxygen conditions further up in the water column, just below the permanent halocline, remained stable over the year, with only minor exceptions. The December 2023 inflow reached the area in June and could be found as an intermediate layer with an oxygen peak with concentration up to ~1.5 ml/l around 100 meters depth. Already in July this peak was more or less gone and near anoxic conditions prevailed at this depth throughout the year. Acute hypoxic conditions, below 2 ml/l, was found at approximately 70 meters depth. From 80-125 meters depth near anoxic conditions prevailed with oxygen concentrations near zero or low concentrations of hydrogen sulphide.

The oxygen situation in the deep water in the Northern Gotland Basin shows similar development as in the Eastern Gotland Basin. The concentration of hydrogen sulphide in the bottom water also continues to increase, but concentrations are lower than in the Eastern Gotland Basin. At depths exceeding 150 meters the concentration ranged from 31-58 µmol/l compared to 37-53 µmol/l in 2023. See Figure 7.

Also, in the Western Gotland Basin the severe stagnation continues. The concentrations of hydrogen sulphide is higher than normal and are at a record high levels for this basin, never measured before, see appendix 1. At station Landsort Deep, BY31, the hydrogen sulphide concentration in the deep water exceeding 400 meters depth ranged from 43-64 µmol/l compared to from 35-49 µmol/l during 2023. Similar values were found in the deep water at station Norrköpings Deep, station BY32, further south in the Western Gotland Basin, 42-77 µmol/l. Acute hypoxia was found from 60-80 meters depth and anoxic conditions from 60-90 meters depth.

Further south in the Western Gotland Basin, at the station BY38 the hydrogen sulphide at depth exceeding 100 meters depth has also increased, from 15-62 µmol/l in 2023 to 34-84 µmol/l in 2024. [SMHI, 2025]

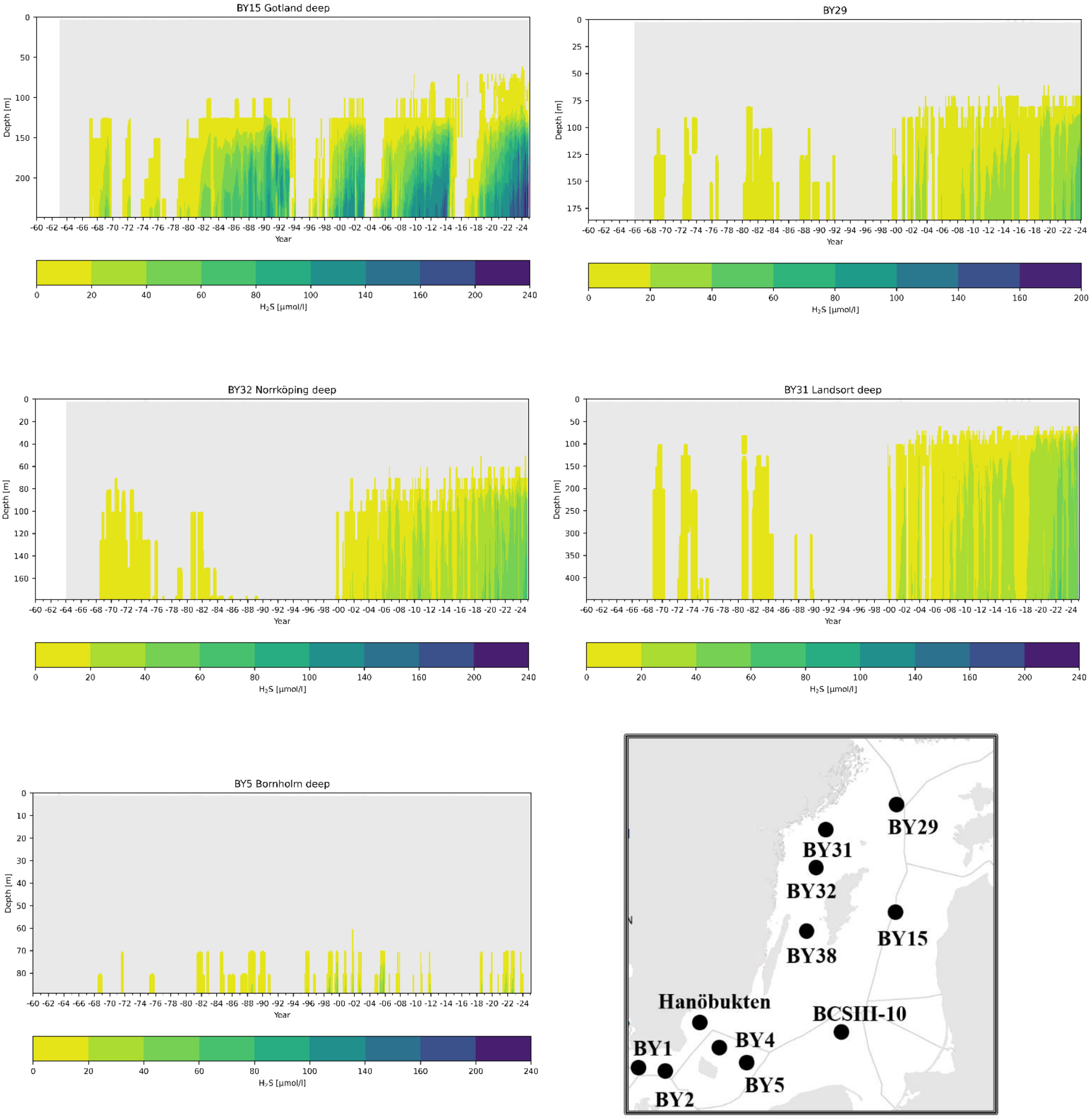

Figure 7. Concentration of hydrogen sulphide (H2S) in the Baltic Proper, 1960-2024. Grey color signifies no hydrogen sulphide present and white indicate that data is missing.
Top left: Gotland Deep (BY15) in Eastern Gotland Basin. Top right: Northern Baltic Proper (BY29). Middle left: Norrköping Deep (BY32). Middle right: Ladsort Deep (BY31), in the Western Gotland Basin. Lower left: Bornholm Deep (BY5) in the Bornholm Basin. Lower right: Map of monitoring stations in the Baltic Proper.

In November and December 2024 two small inflows occurred, cold and relatively high saline and well oxygenated, that could possibly improve the oxygen situation in the southern Baltic Proper similar to the inflow that occurred in December 2023.

Note that the 2024 results are preliminary; however, the results are based on extensive data sets with essential data contributions from almost all countries around the Baltic Proper.

The updated results for 2023 and the preliminary results for 2024 show that the severe oxygen conditions in the Baltic Proper after the regime shift in 1999 continues. The areal extent of anoxia and hypoxia is more or less similar to previous years only with small differences. The situation in both the Eastern and Western Gotland Basin continues to deteriorate as the concentration of hydrogen sulphide continues to increase with new record high concentrations. The positive effect of the inflow that do occur can be seen in the Southern Baltic Proper but these pulses of oxygenated water are too small to have any major impact on the overall oxygen situation. A major inflow or a series of medium inflows are needed to have a real positive impact on the oxygen situation in Baltic area.

5 Conclusions

- The severe oxygen conditions in the Baltic Proper continues. The areal extent and volume of anoxia are still elevated and follow the development that have prevailed since the regime shift in 1999.

- In 2023 anoxia was found at ~19% of the bottom areas and ~33% suffered from hypoxia during the autumn period.

- Preliminary results for 2024 shows similar results as 2023. About ~18% of the bottom areas suffer from anoxia and approximate ~34% suffered from hypoxia.

- The concentration of hydrogen sulphide is above normal in all the basins around Gotland. In the Eastern and Western Gotland Basin hydrogen sulphide in the bottom water has continued to increase and have reached extreme levels, never recorded before.

- The inflows that occurred in December 2023 did have an effect on the oxygen situation in southern parts of the Baltic Proper and reached intermediate depth in the Eastern Gotland basin. However, no inflows reached the Western or Northern Gotland Basins. In late 2024 two inflows occurred, how this will affect the oxygen situation will be investigated in the next annual oxygen reports.

6 Acknowledgement

We would like to extend our heartfelt thanks to Tycjan Wodzinowski from the National Marine Fisheries Research Institute in Poland for generously providing data from surveys conducted as part of the " Polish Multiannual Fisheries Data Collection Program".

A special thanks to Māris Skudra, a researcher at the Latvian Institute of Aquatic Ecology, for providing CTD data from the Gulf of Riga and the Eastern Baltic Proper.

Our appreciation also goes to David Rytter at the Institute for Bioscience, Aarhus University, Denmark, for sharing the extensive "Iltsvind" dataset from 2024.

We are also grateful to Taavi Liblik from Tallinn University of Technology, Department of Marine Systems, Estonia, for contributing data from the Estonian National Monitoring Programme.

Furthermore, we sincerely thank Jakob Walve and Svante Nyberg at Stockholm University's DEEP Marine Pelagic Ecology Laboratory for sharing data from the coastal and offshore stations along Sweden's east coast, as part of the Swedish National Marine Monitoring Programme.

We would also like to express our gratitude to Heini Jalli at the Finnish Meteorological Institute (FMI) for generously sharing CTD data collected during the Combine1, Kevatseuranta (Spring), Combine2, Combine3 monitoring cruises and LUKE:s ICES-BIAS 2024 cruise.

We extend our appreciation to the Swedish Agency for Marine and Water Management (HaV) for their support of SMHI and the Swedish National Marine Monitoring Programme.

Lastly, many thanks to the SMHI crew aboard R/V Svea for their dedicated work in collecting data for the Swedish National Marine Monitoring Programme, as well as during the Swedish BIAS and IBTS cruises organized by SLU-Aqua.

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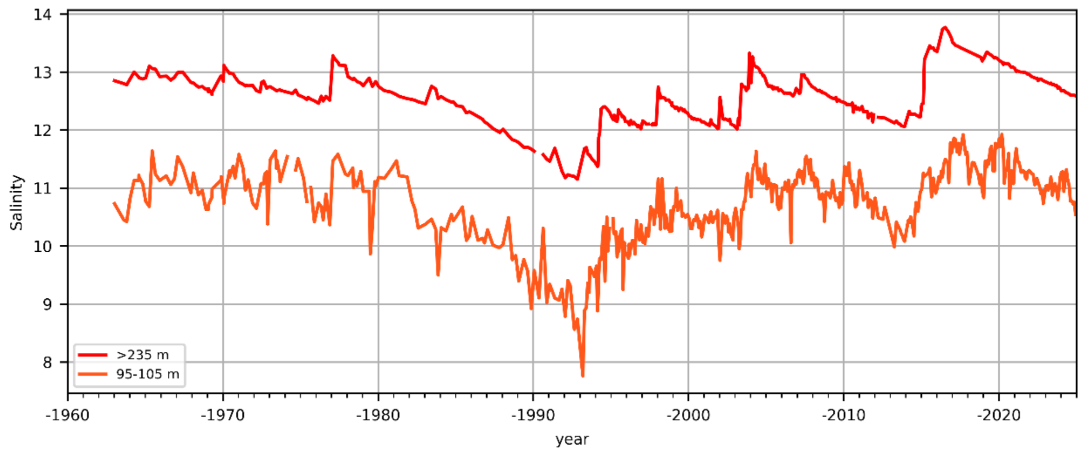
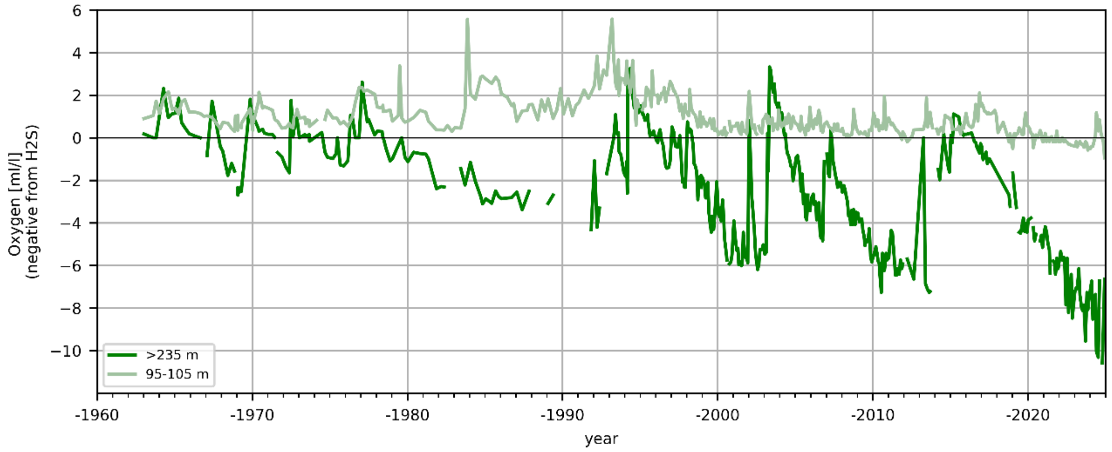
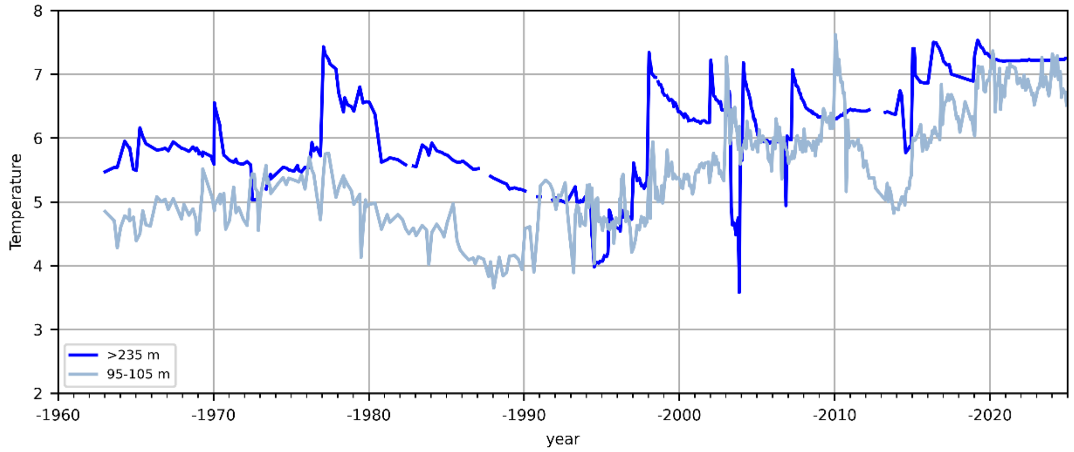
Appendix 1

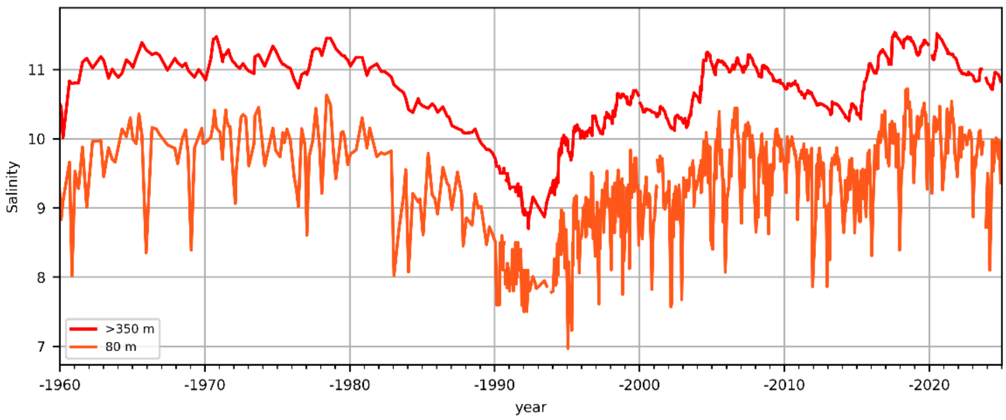
Temperature, salinity and oxygen in the Eastern Gotland Basin at station BY15 Gotland Deep, 1960-2024

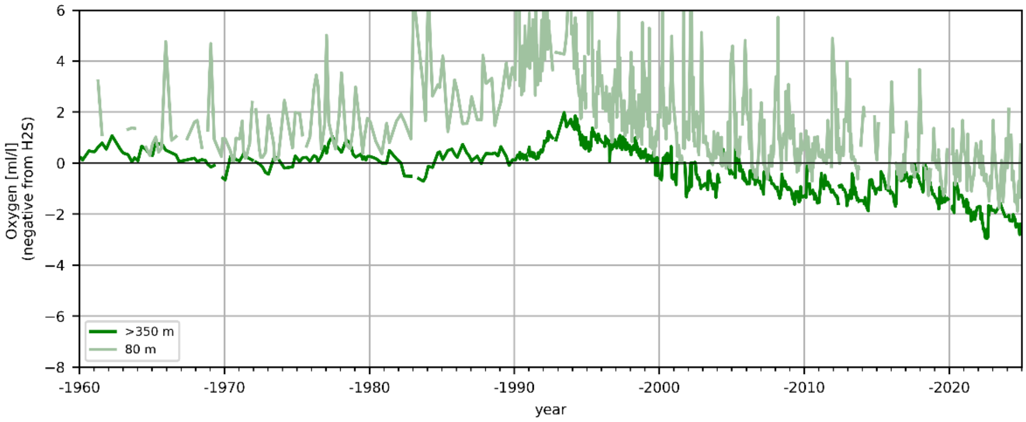


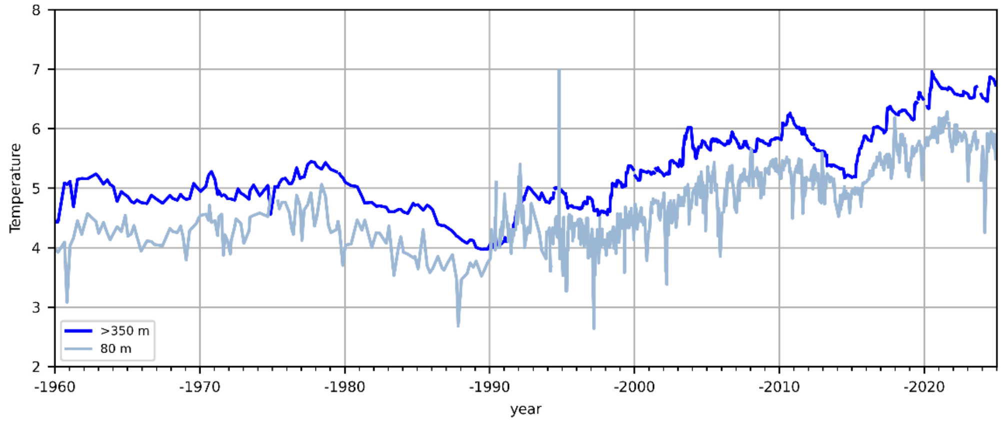




Temperature, salinity and oxygen in the Western Gotland Basin at station BY31 Landorts Deep, 1960-2024







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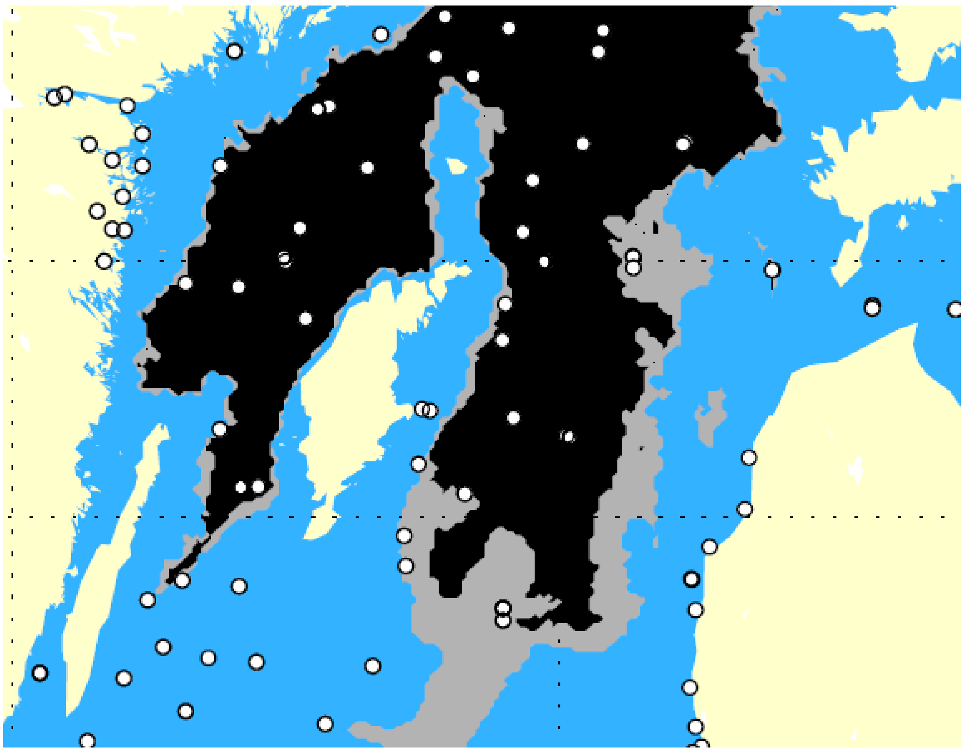
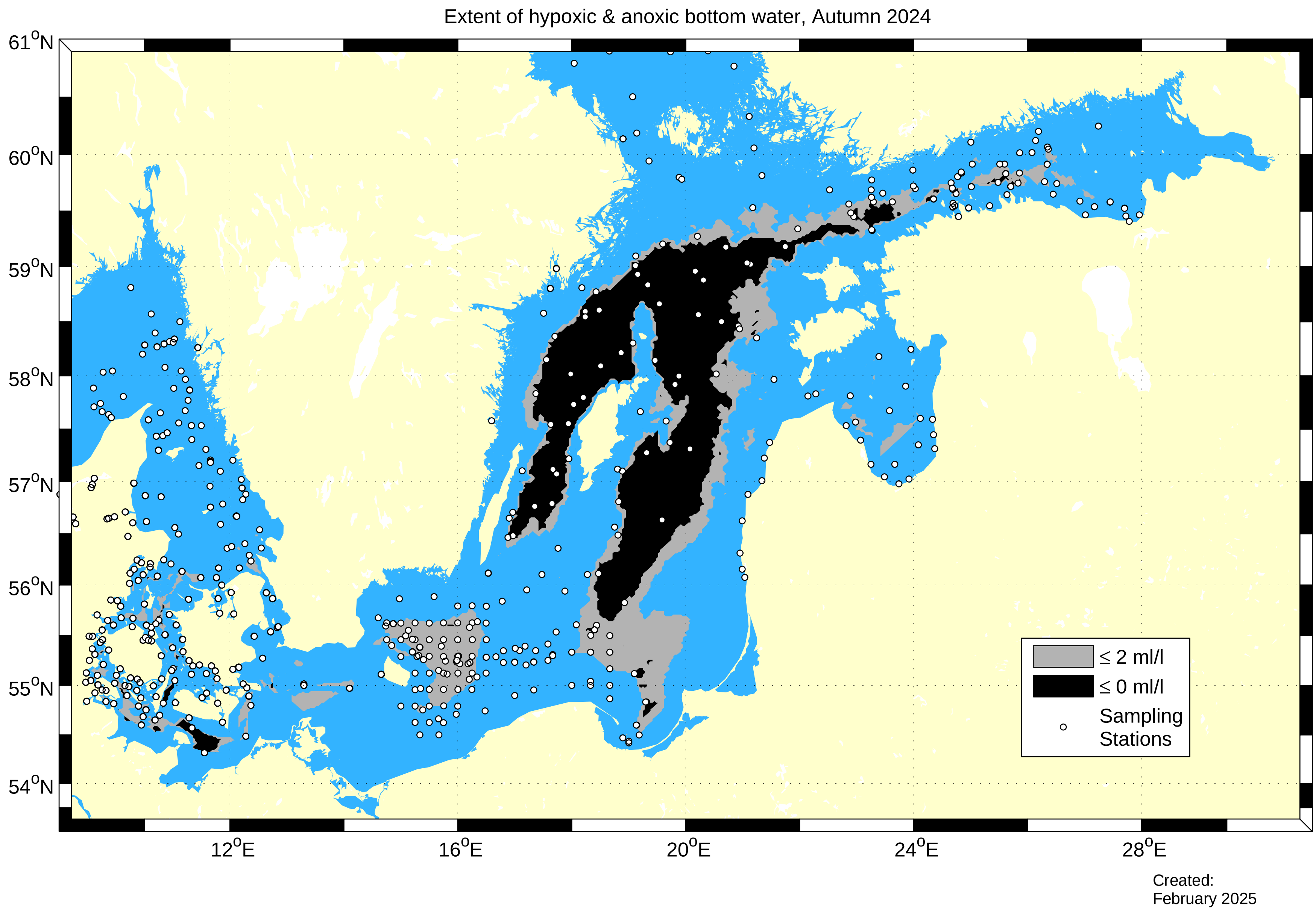
Appendix 2 - Anoxic and hypoxic areas in the Baltic Sea

- updated maps 1960-2024




Extent of hypoxic & anoxic bottom water, Autumn 2024
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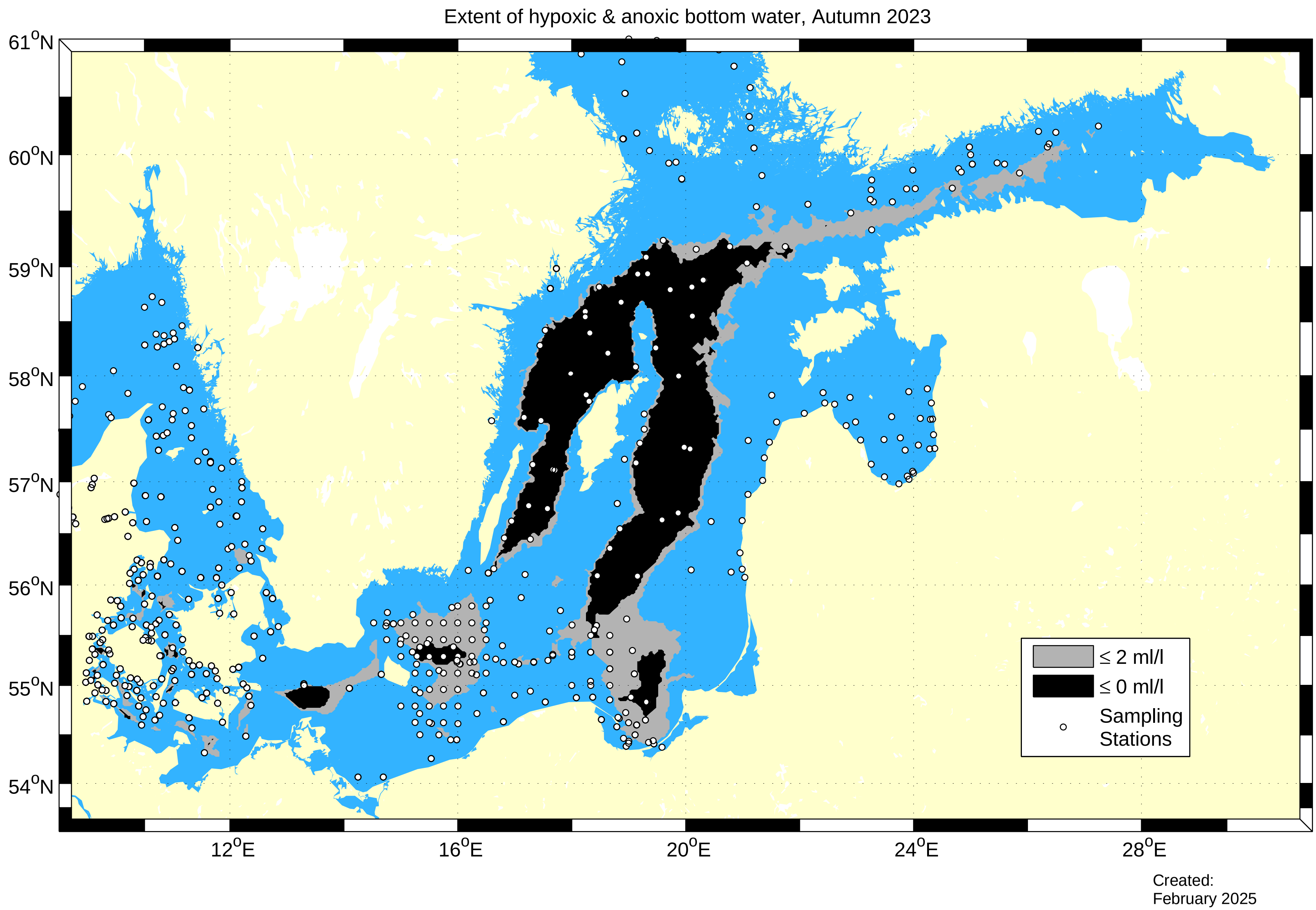
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created:
February 2025



Extent of hypoxic & anoxic bottom water, Autumn 2023
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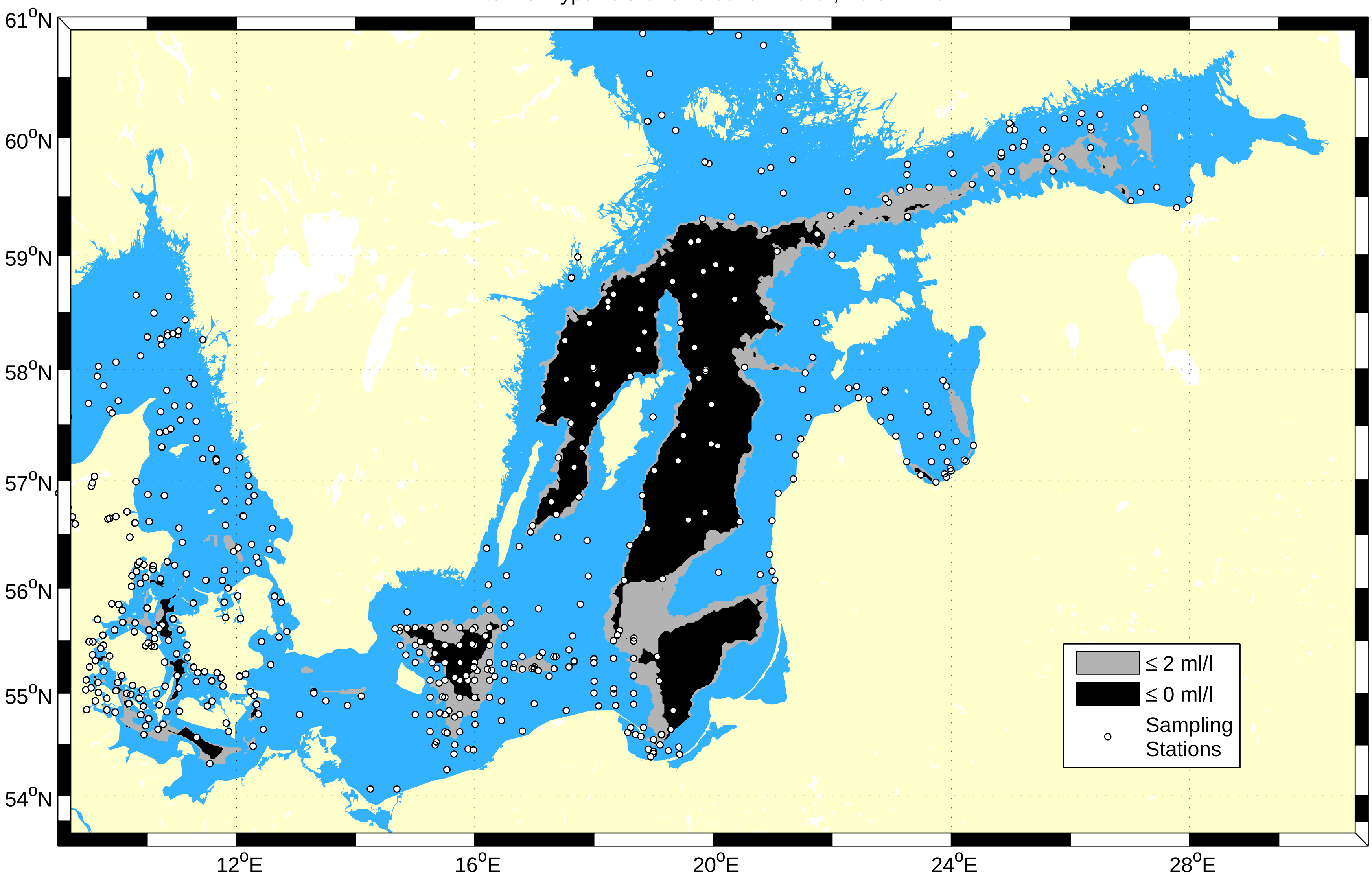
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created:
February 2025

Extent of hypoxic & anoxic bottom water, Autumn 2022



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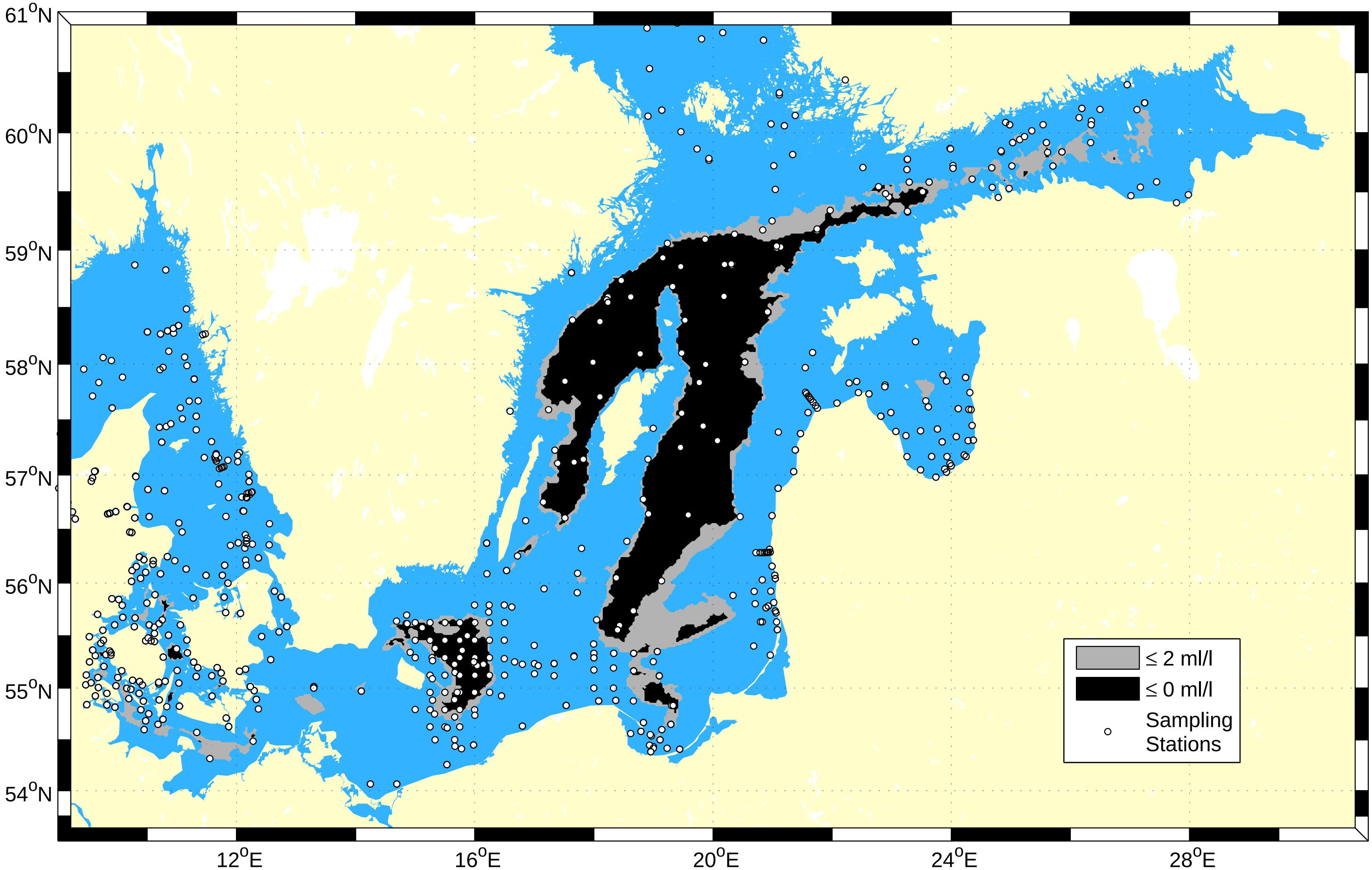
Extent of hypoxic & anoxic bottom water, Autumn 2021



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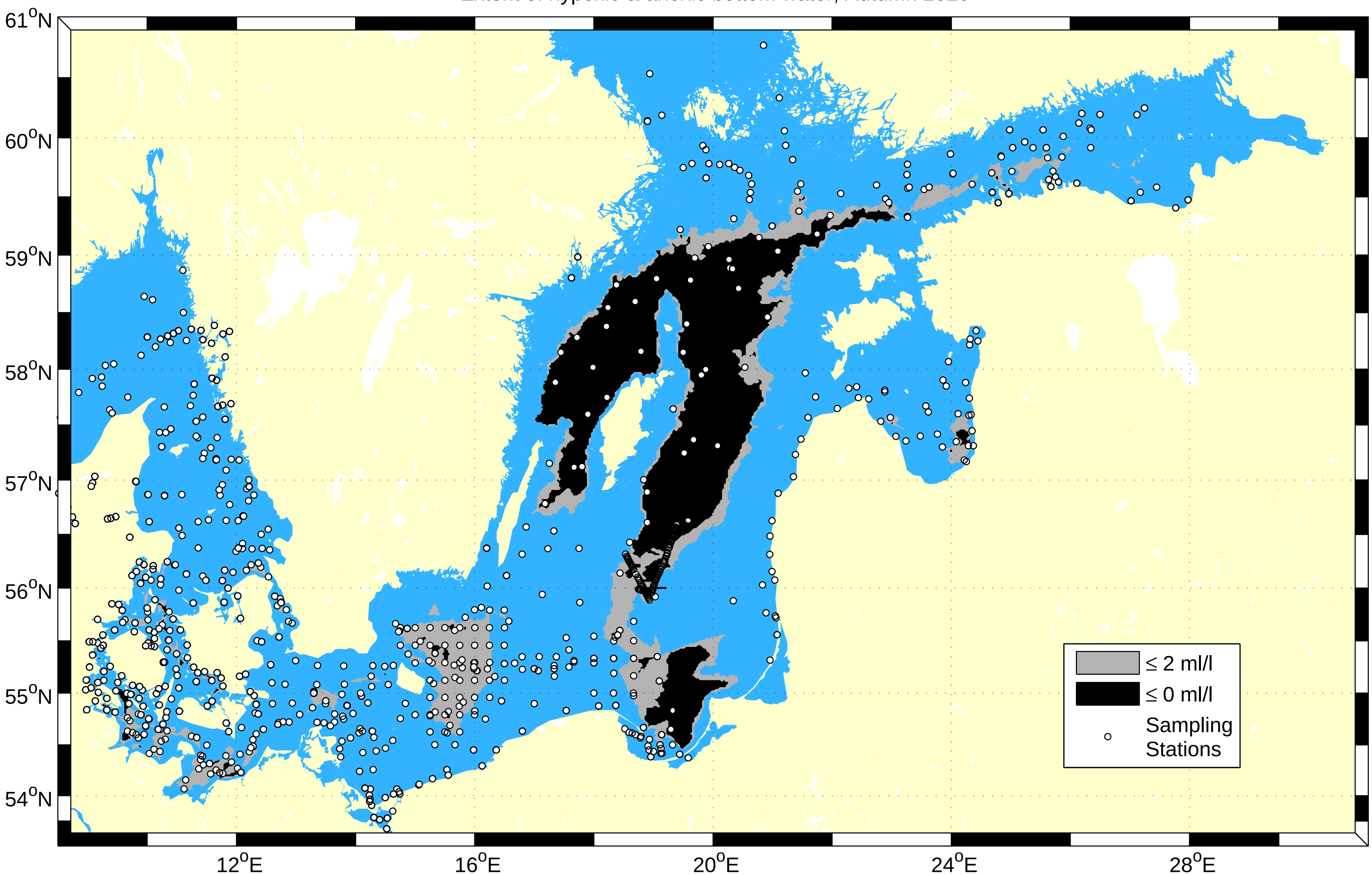
Extent of hypoxic & anoxic bottom water, Autumn 2020



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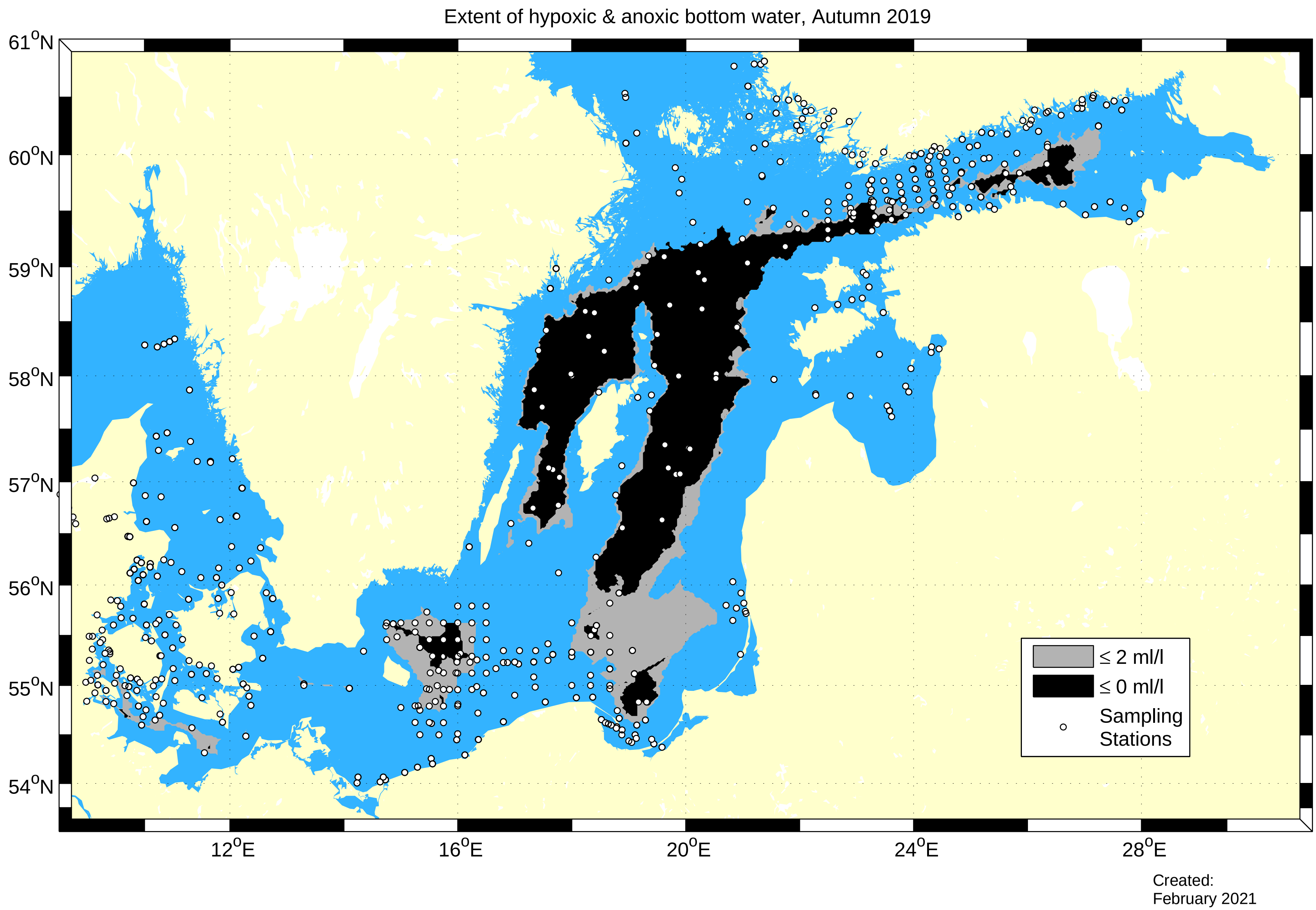

Extent of hypoxic & anoxic bottom water, Autumn 2019
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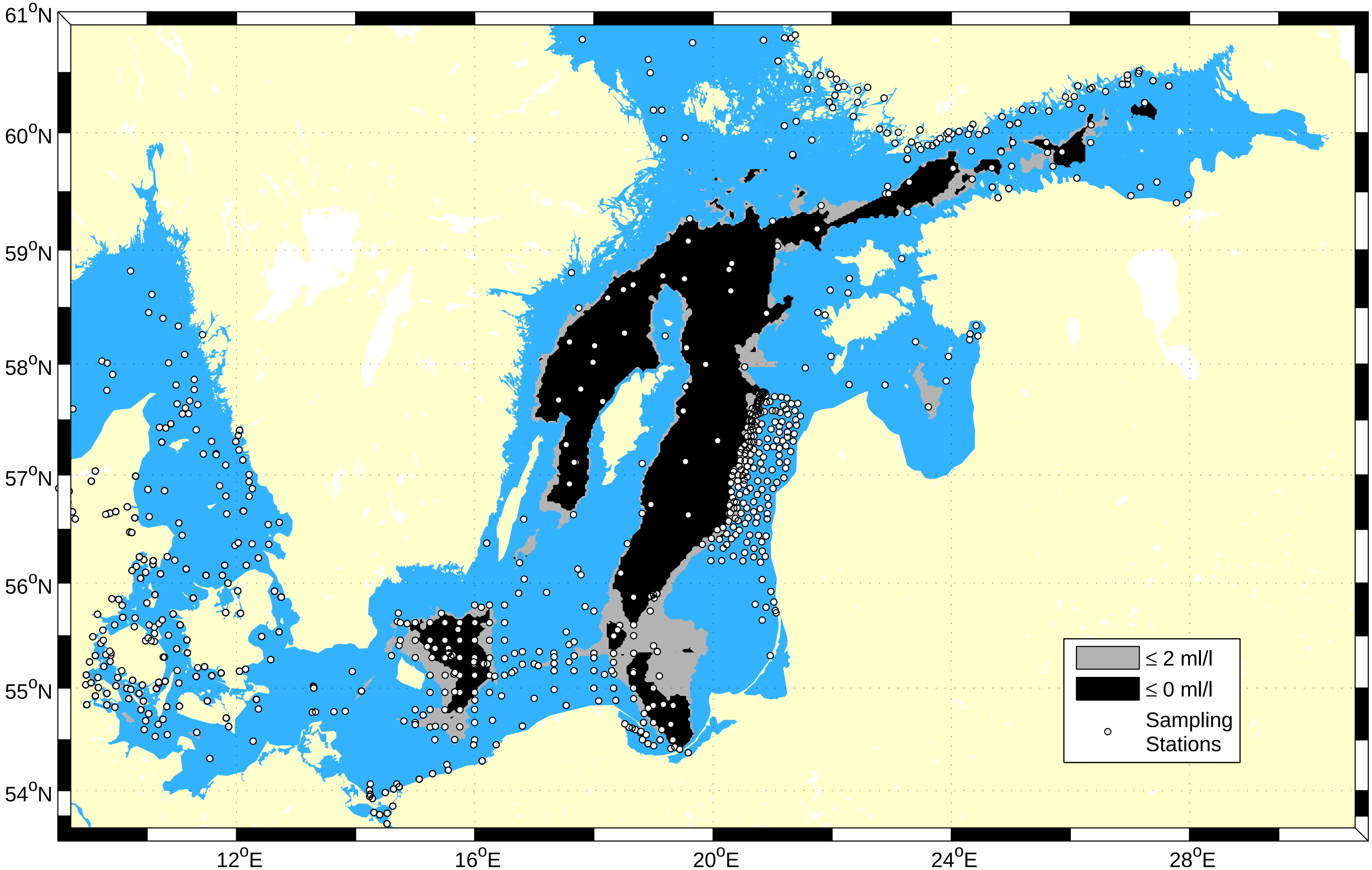
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created:
February 2021

Extent of hypoxic & anoxic bottom water, Autumn 2018



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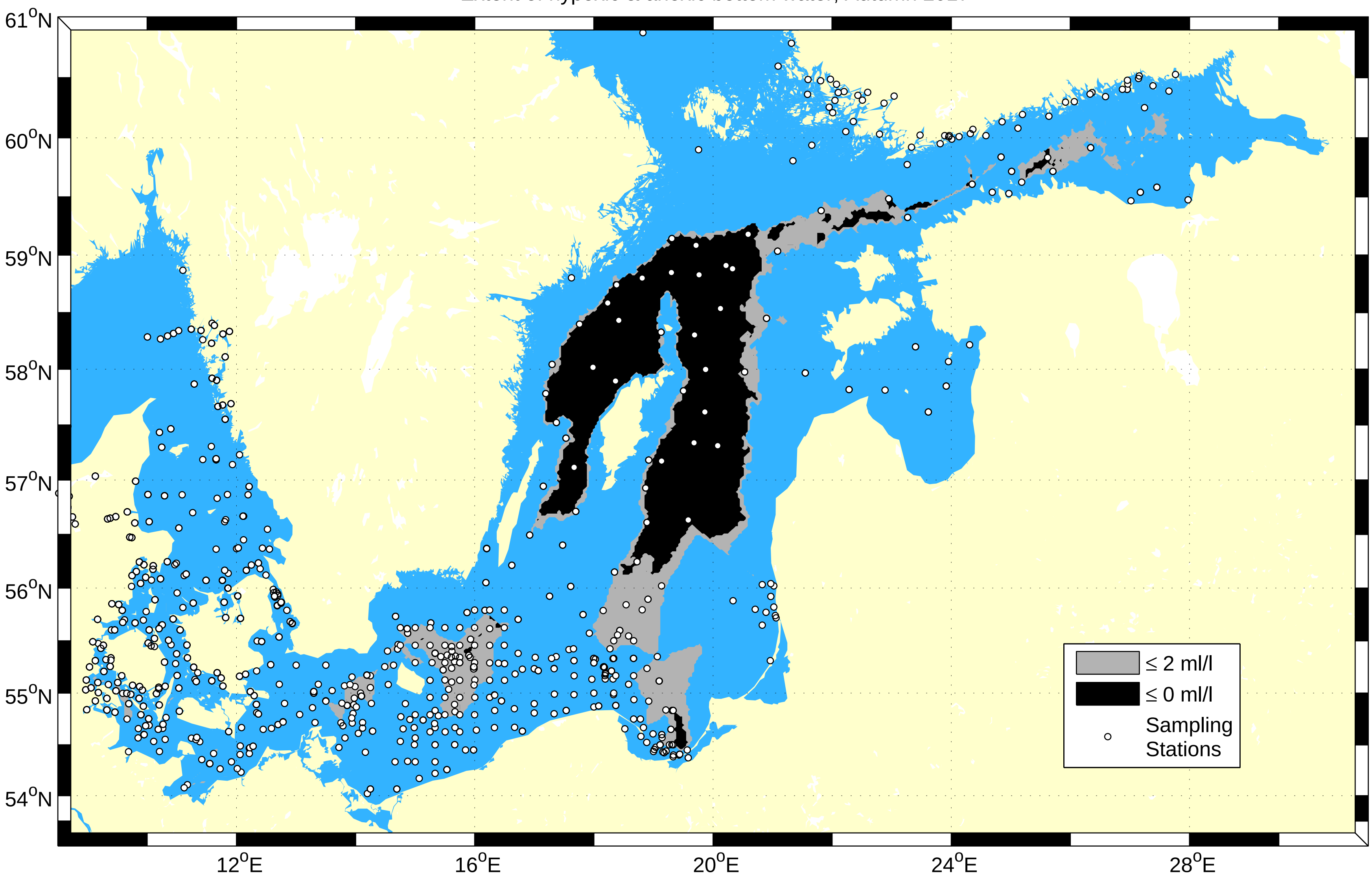
Extent of hypoxic & anoxic bottom water, Autumn 2017



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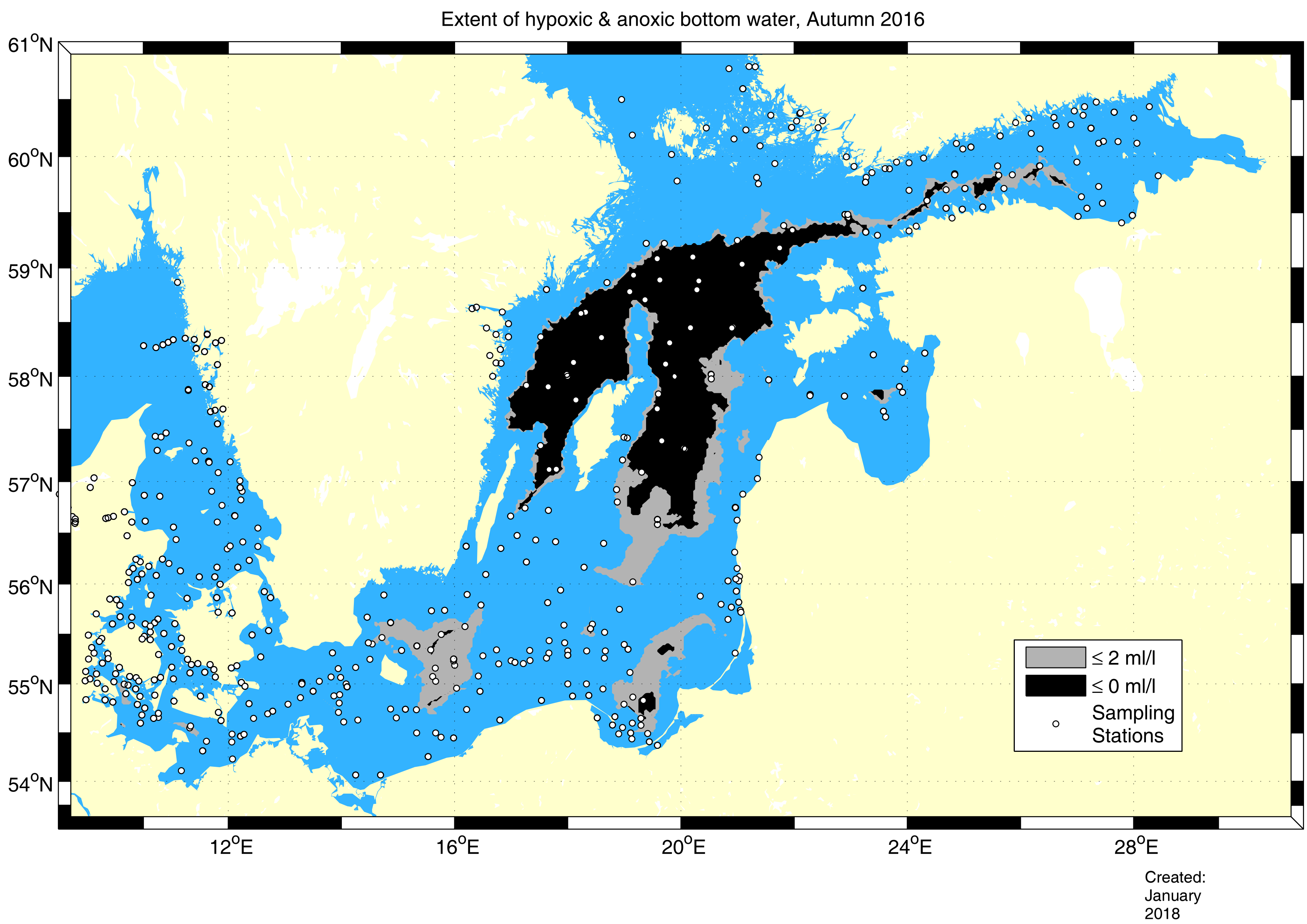

Extent of hypoxic & anoxic bottom water, Autumn 2016
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58°N
57°N
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54°N
12°E
16°E
20°E
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28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
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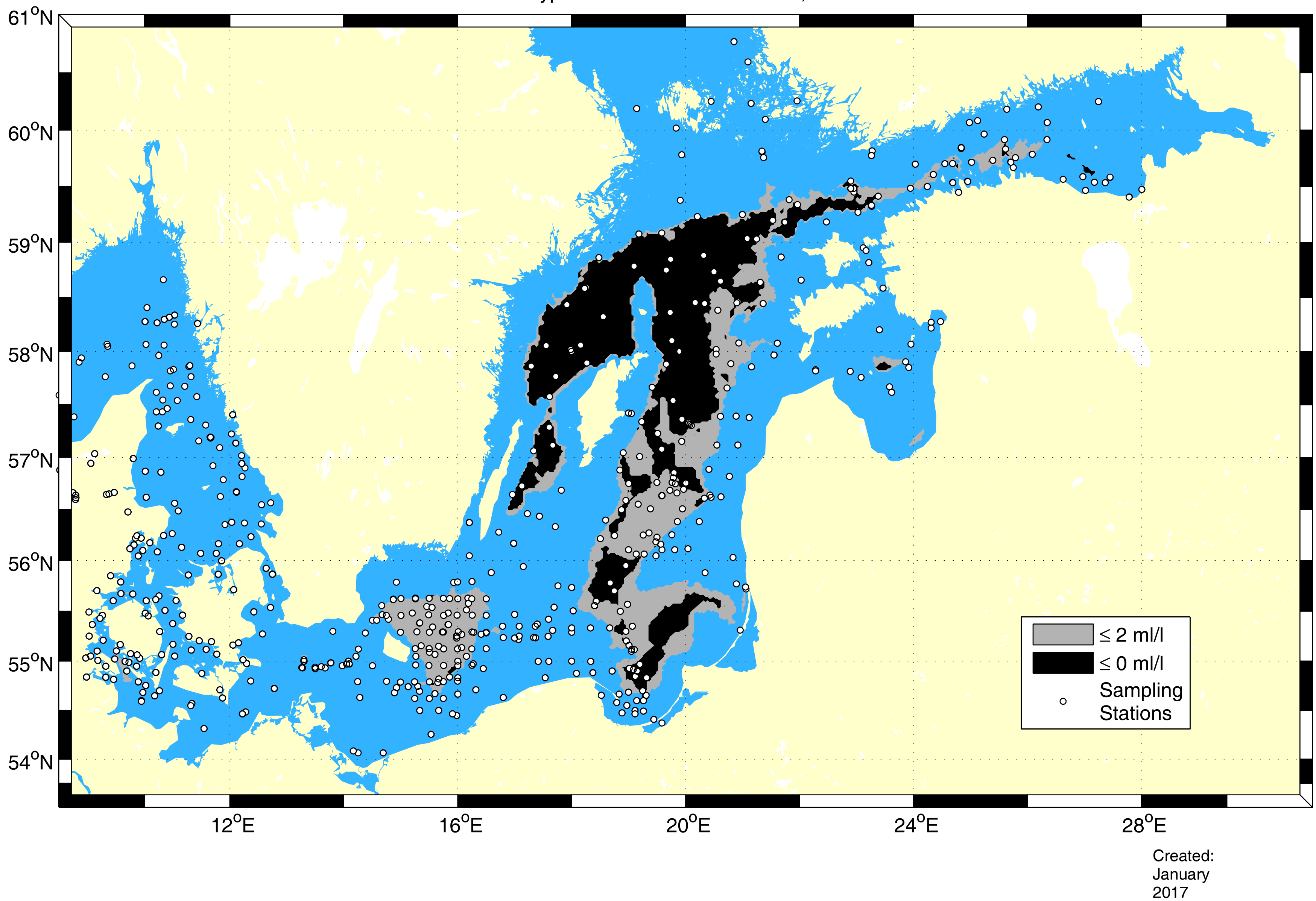
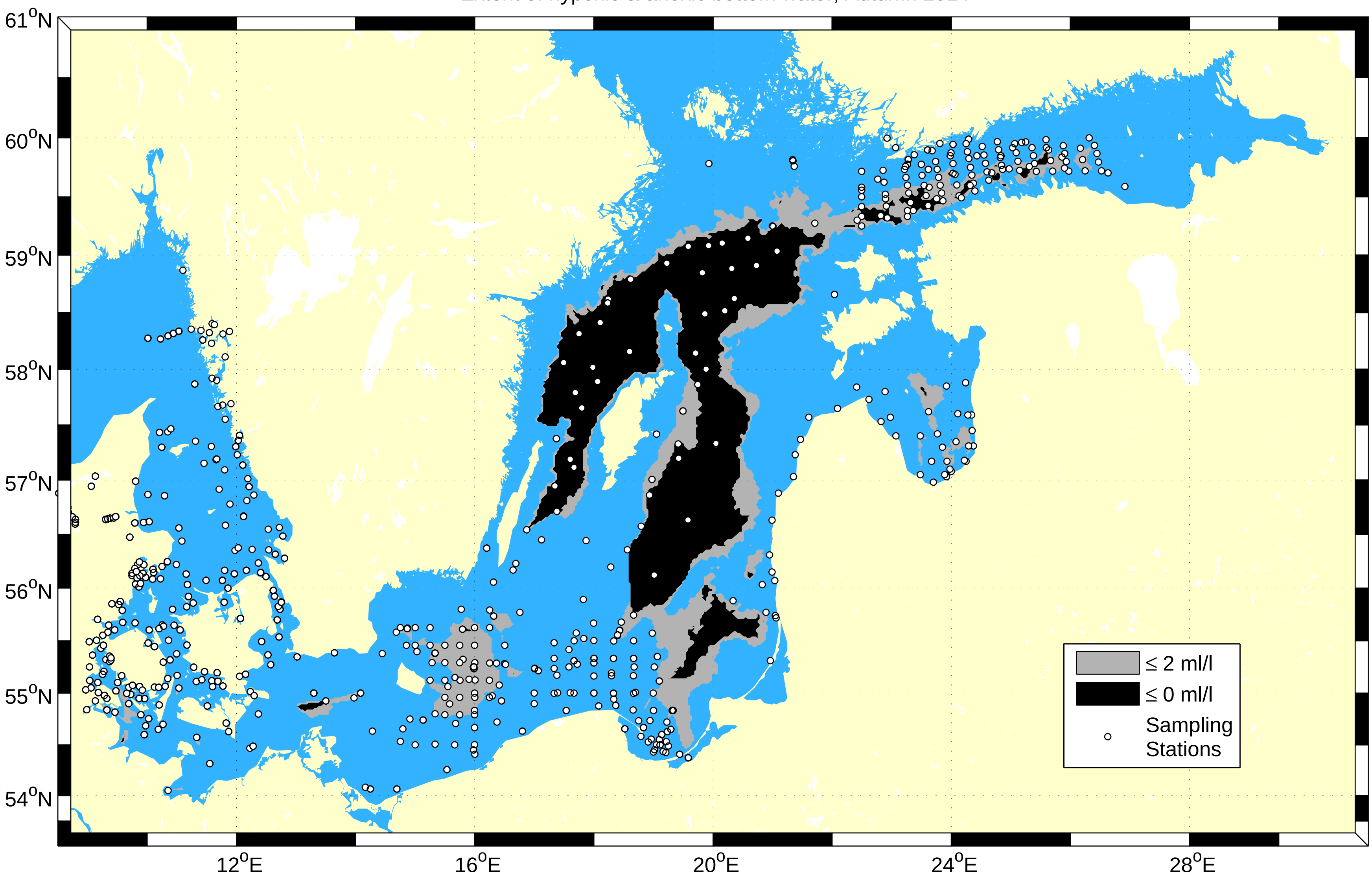
Extent of hypoxic & anoxic bottom water, Autumn 2015



Extent of hypoxic & anoxic bottom water, Autumn 2014



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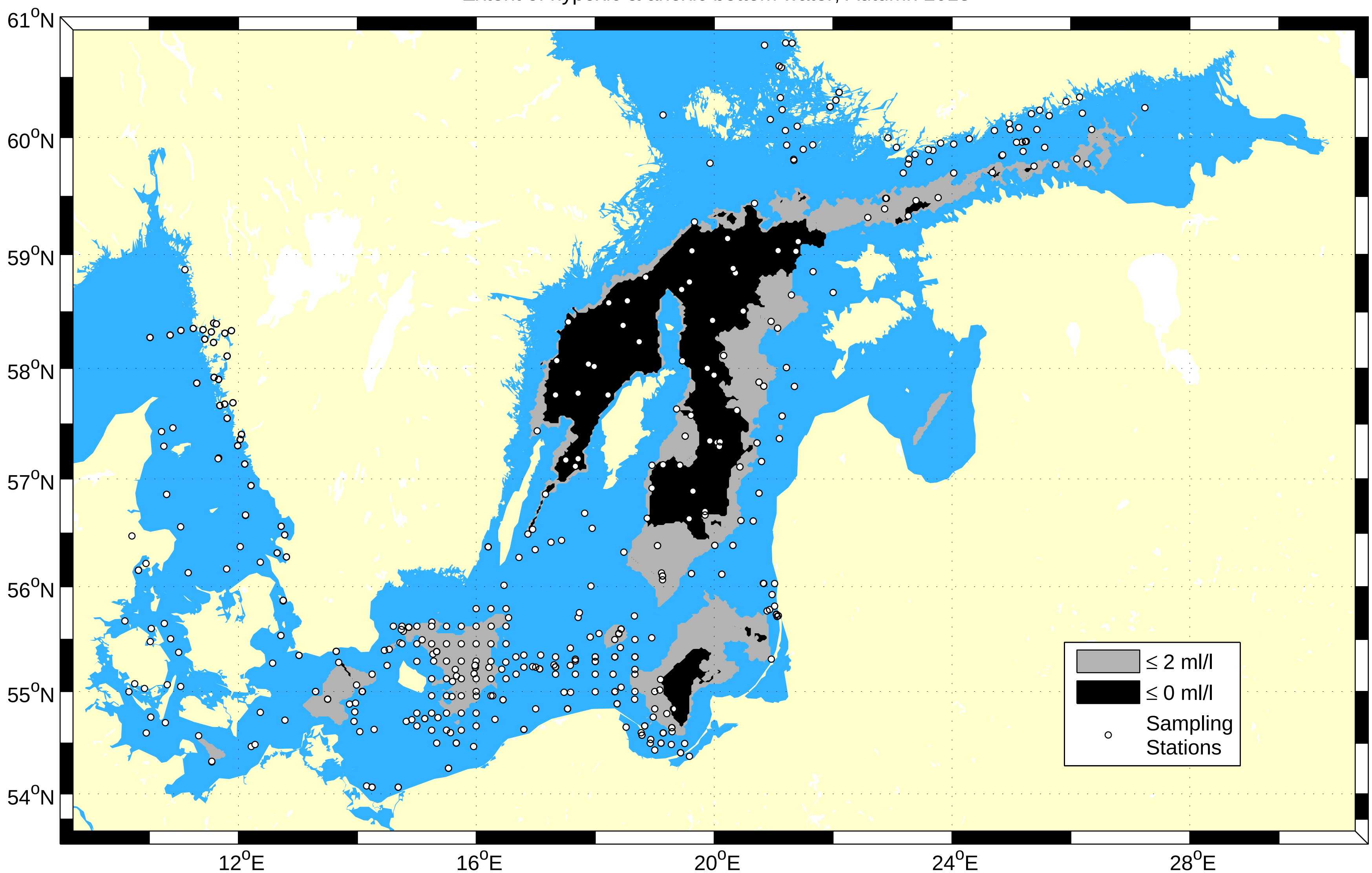
Extent of hypoxic & anoxic bottom water, Autumn 2013



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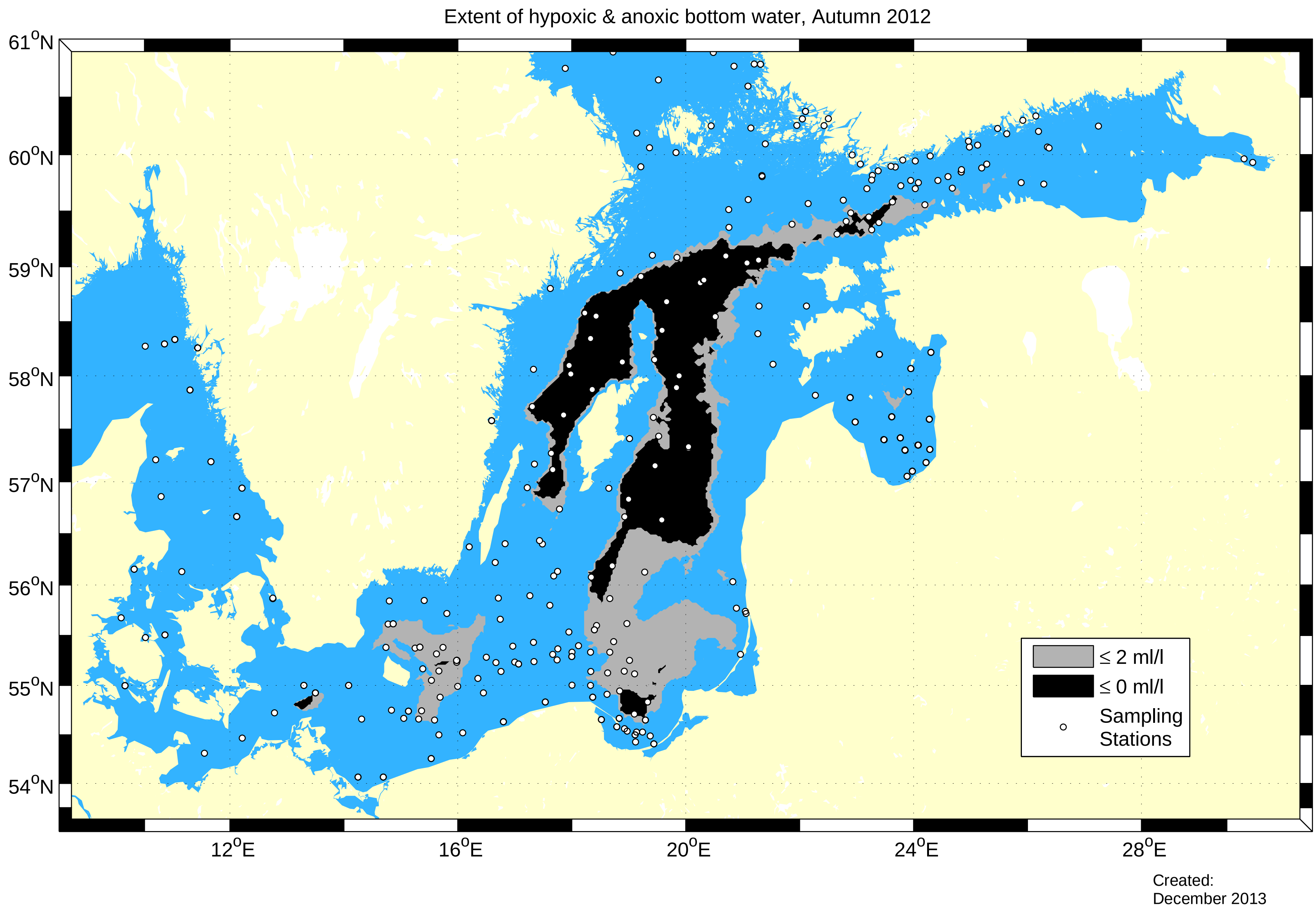
Extent of hypoxic & anoxic bottom water, Autumn 2012
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59°N
58°N
57°N
56°N
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24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
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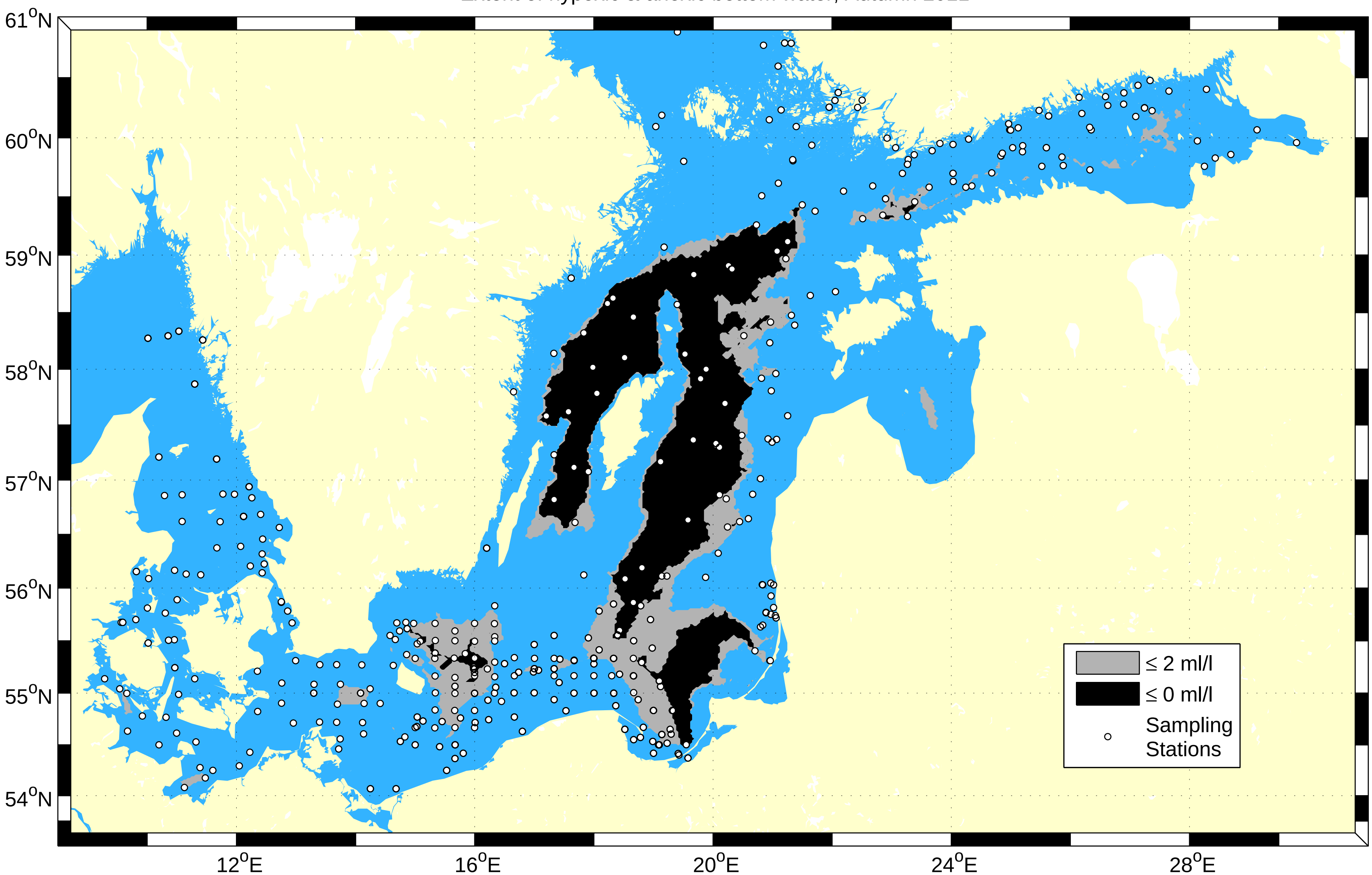
December 2013

Extent of hypoxic & anoxic bottom water, Autumn 2011



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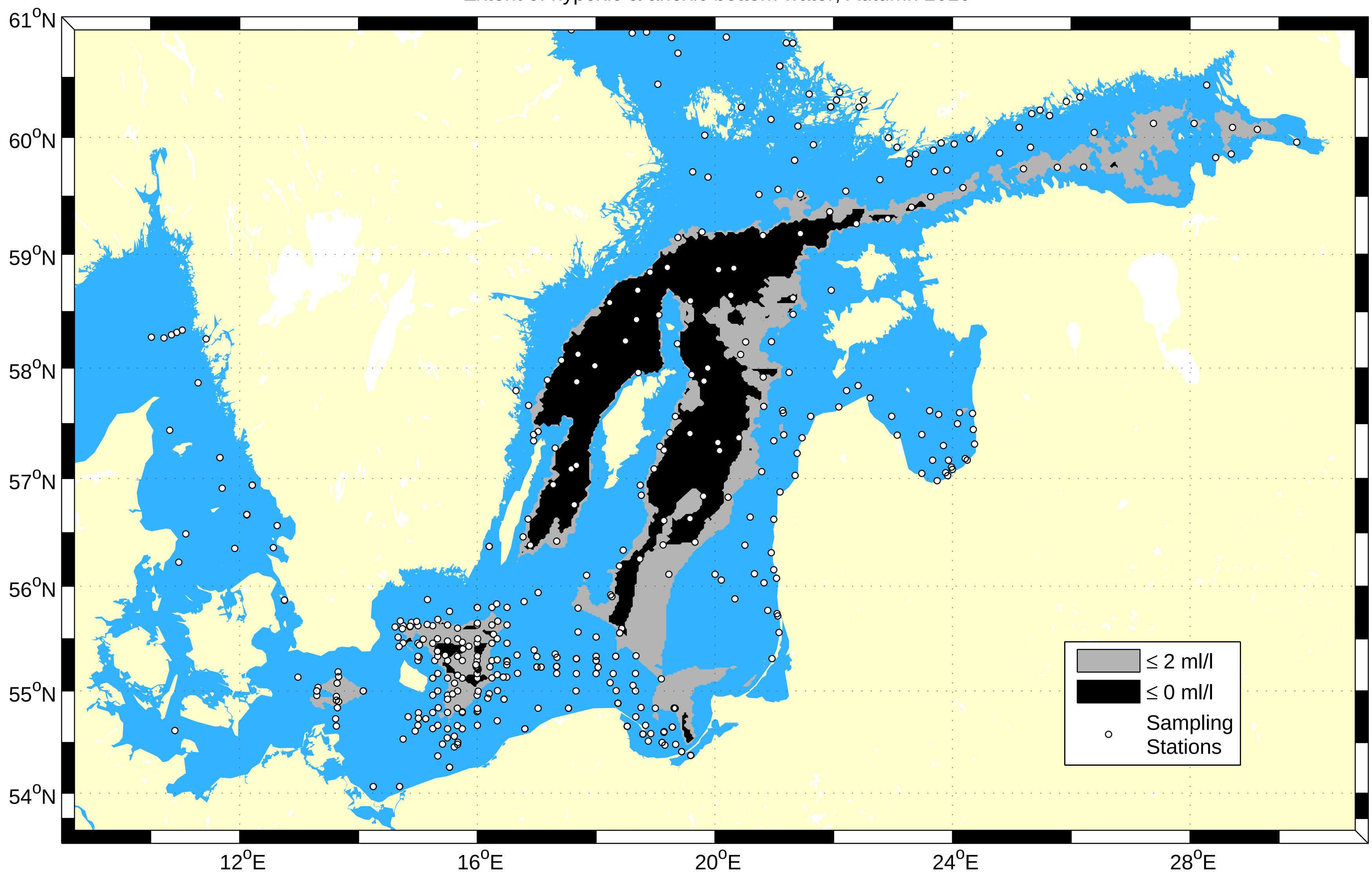
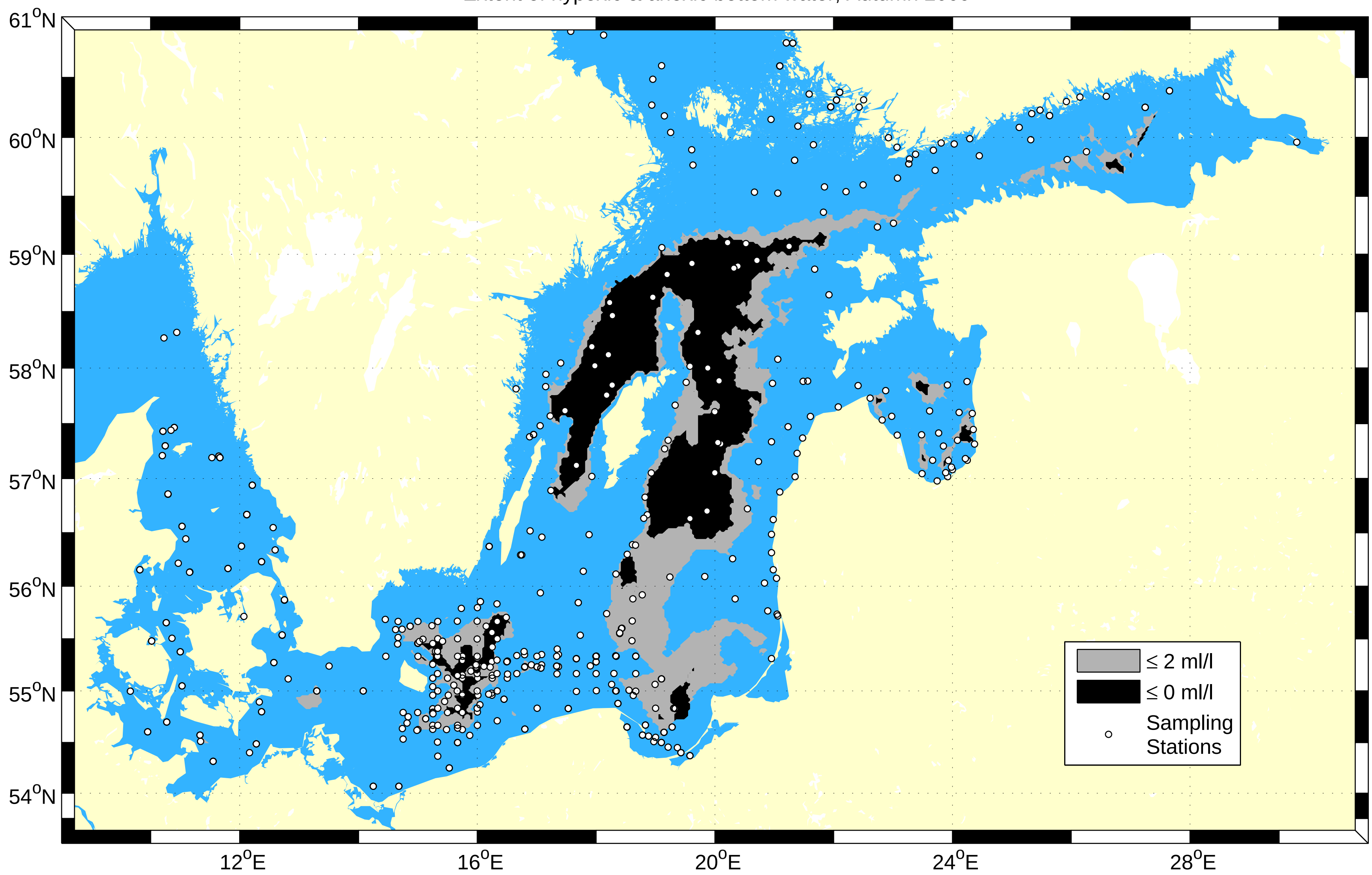
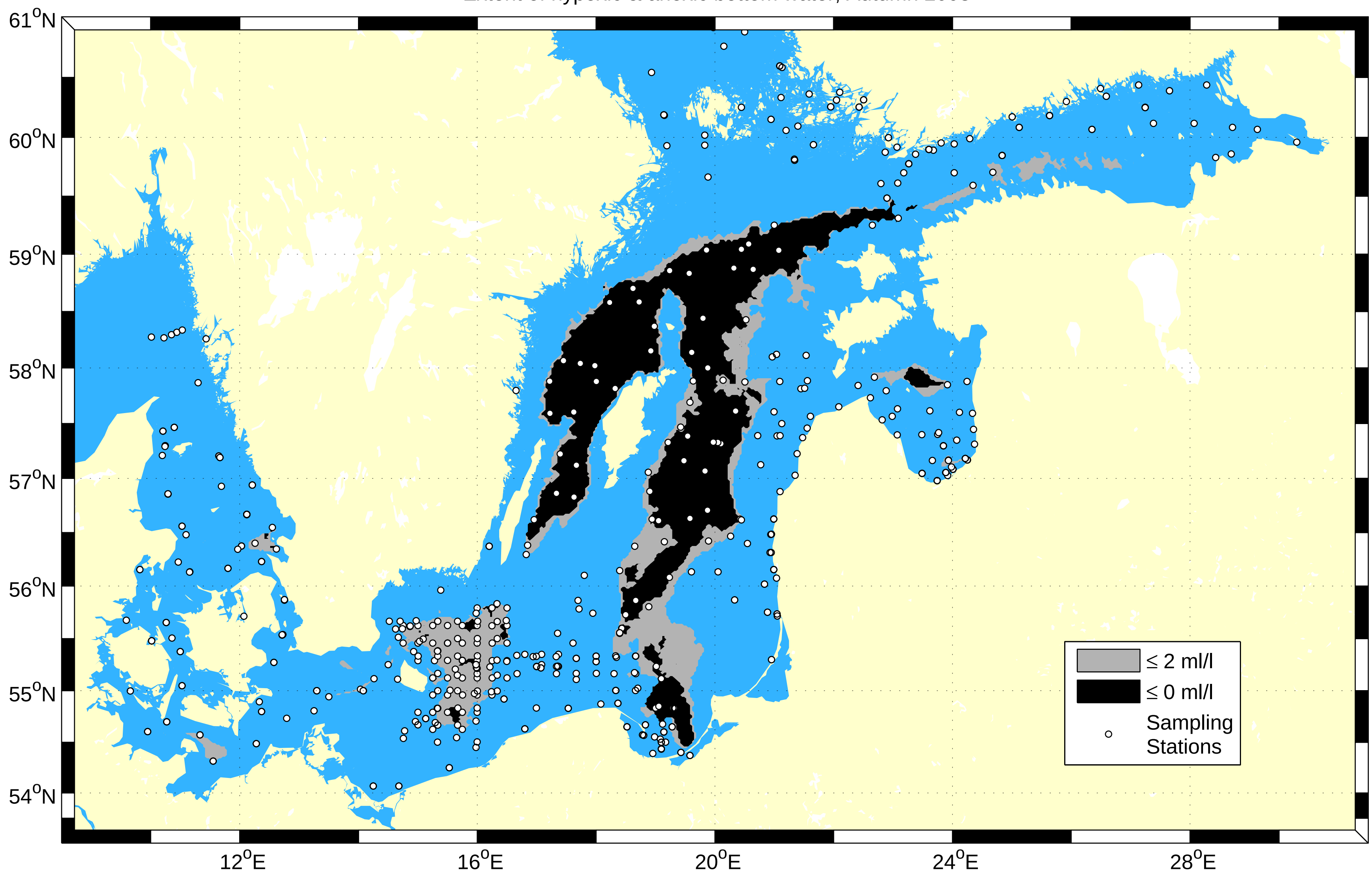
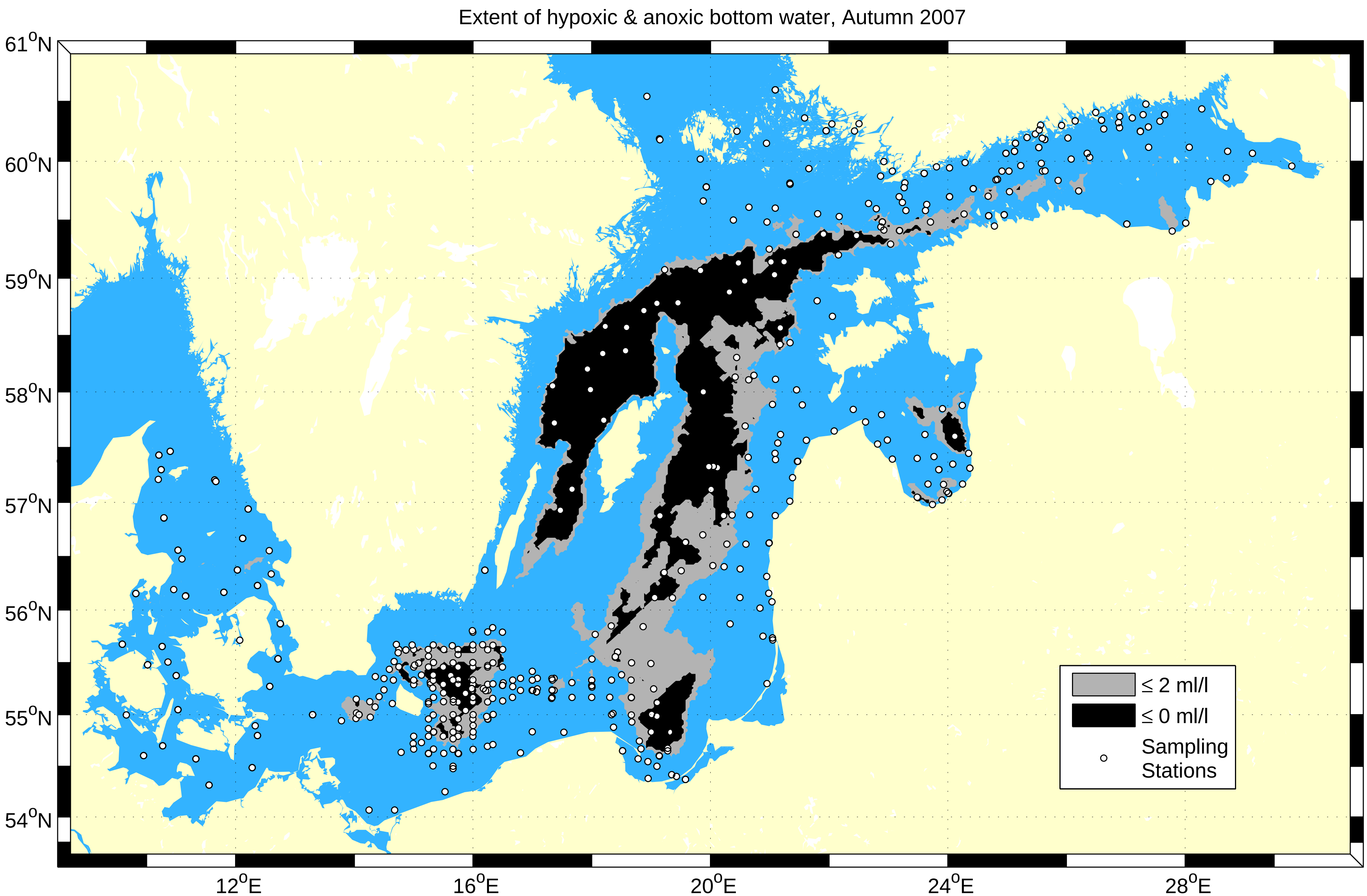


Extent of hypoxic & anoxic bottom water, Autumn 2009



Extent of hypoxic & anoxic bottom water, Autumn 2008




Extent of hypoxic & anoxic bottom water, Autumn 2007
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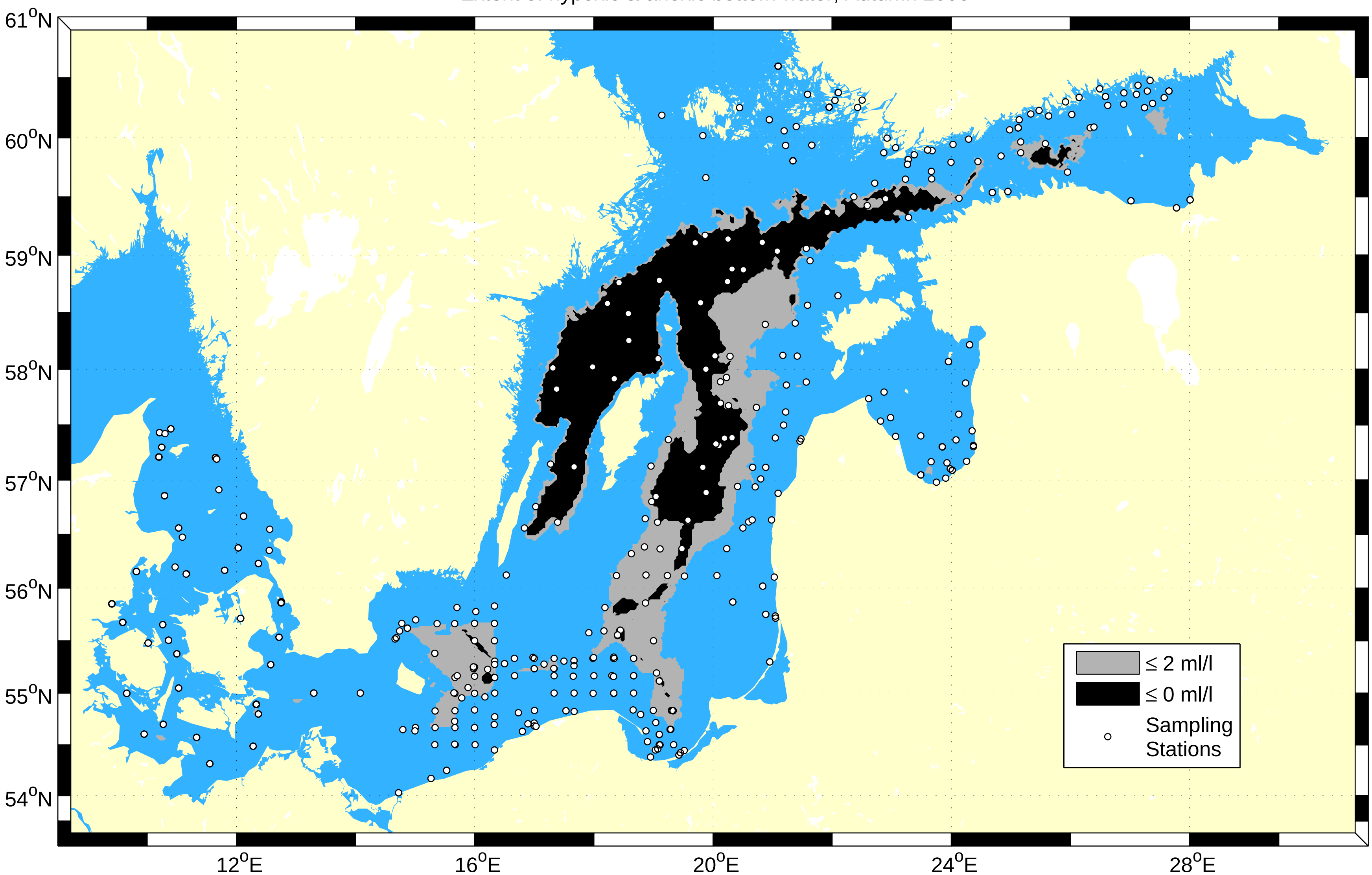
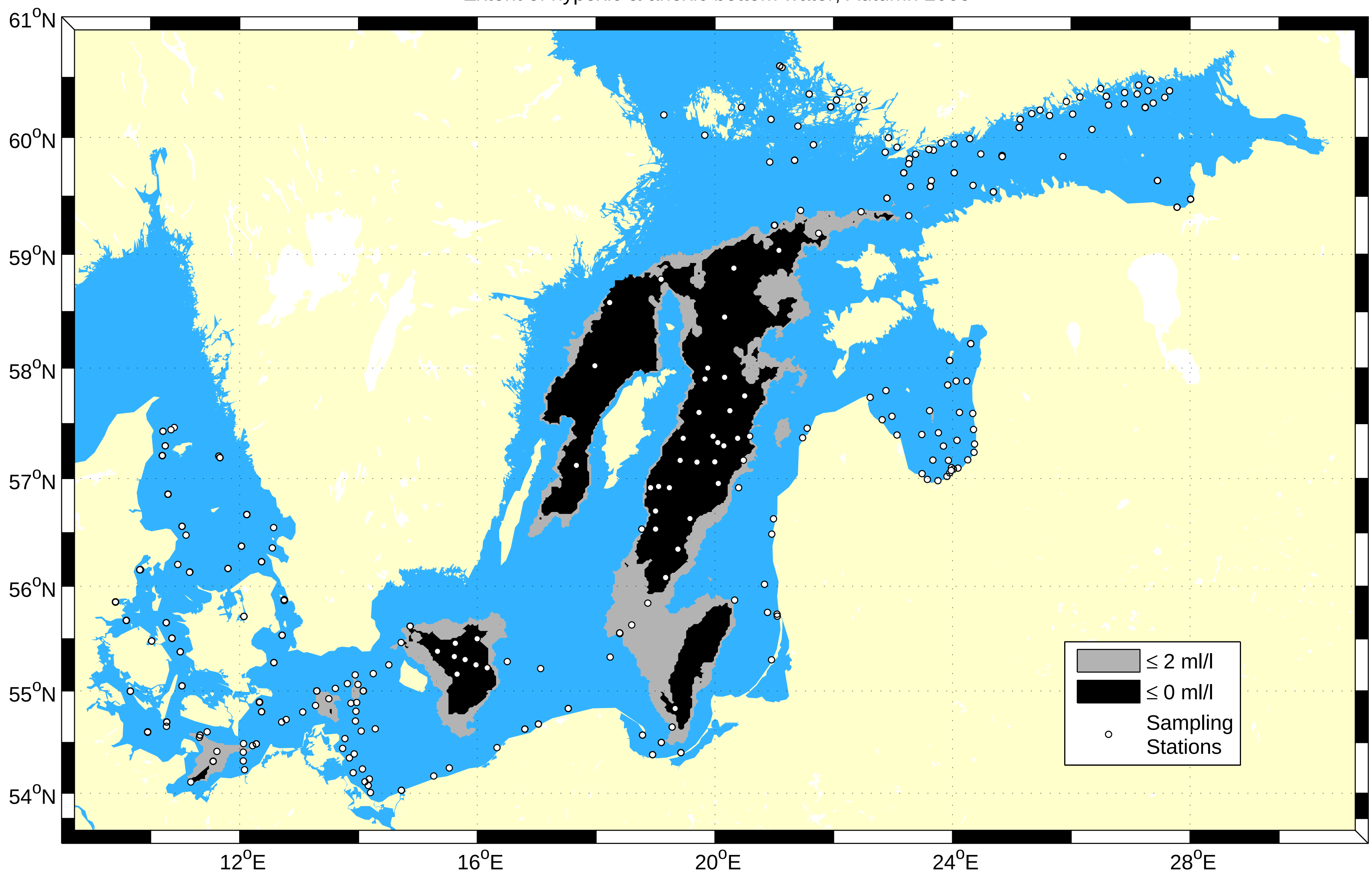
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 2006



Extent of hypoxic & anoxic bottom water, Autumn 2005



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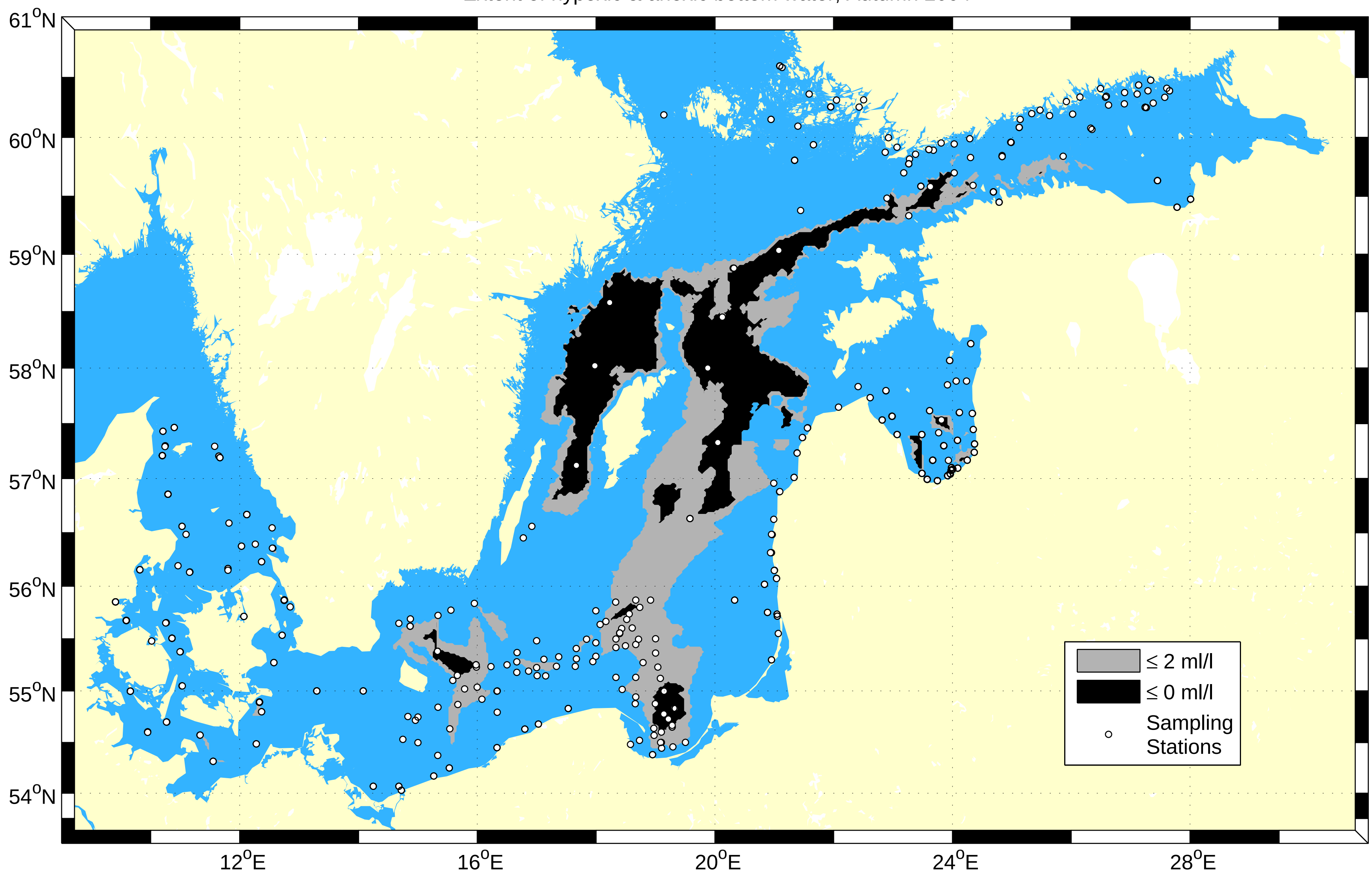

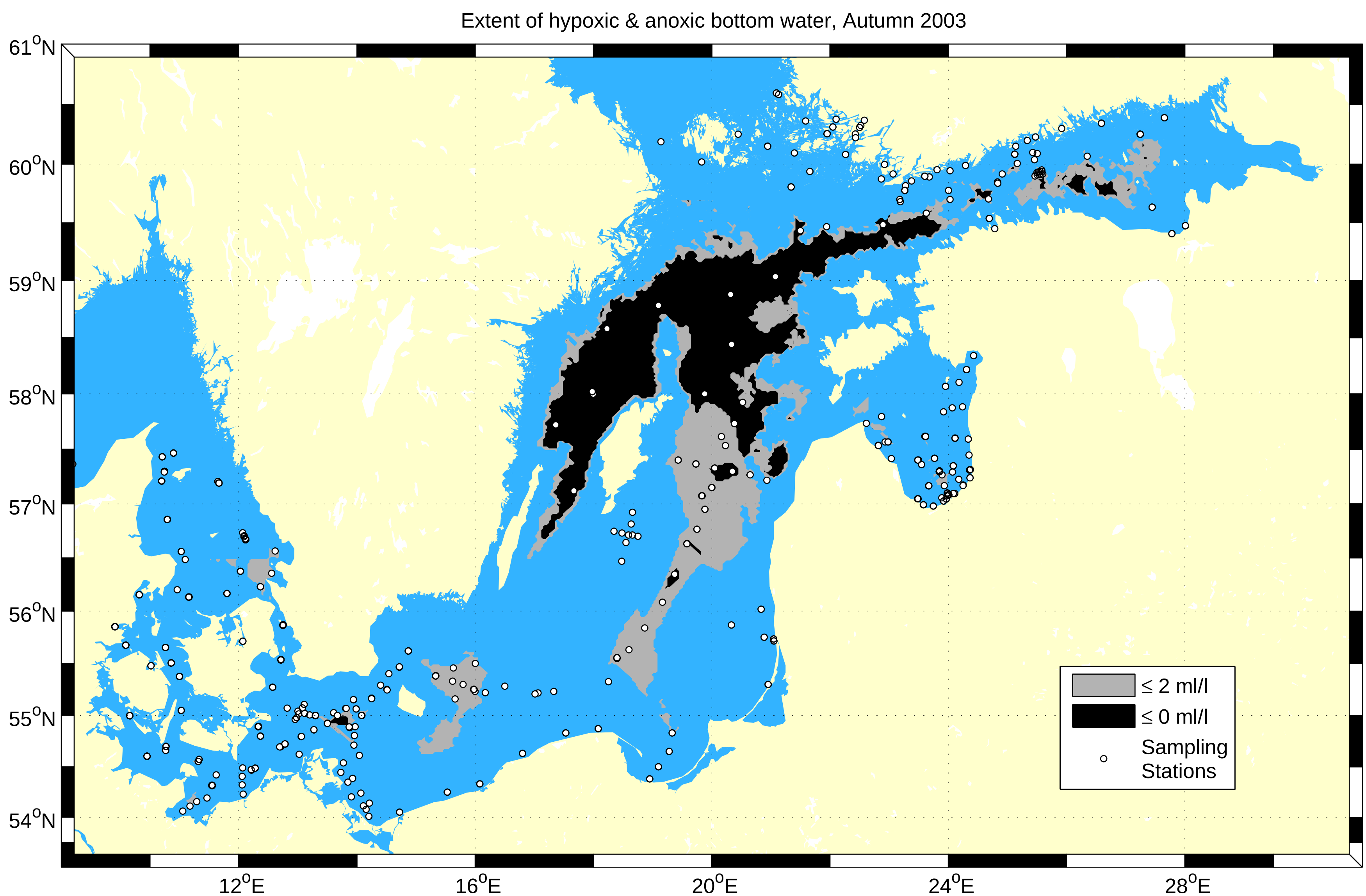

Extent of hypoxic & anoxic bottom water, Autumn 2003
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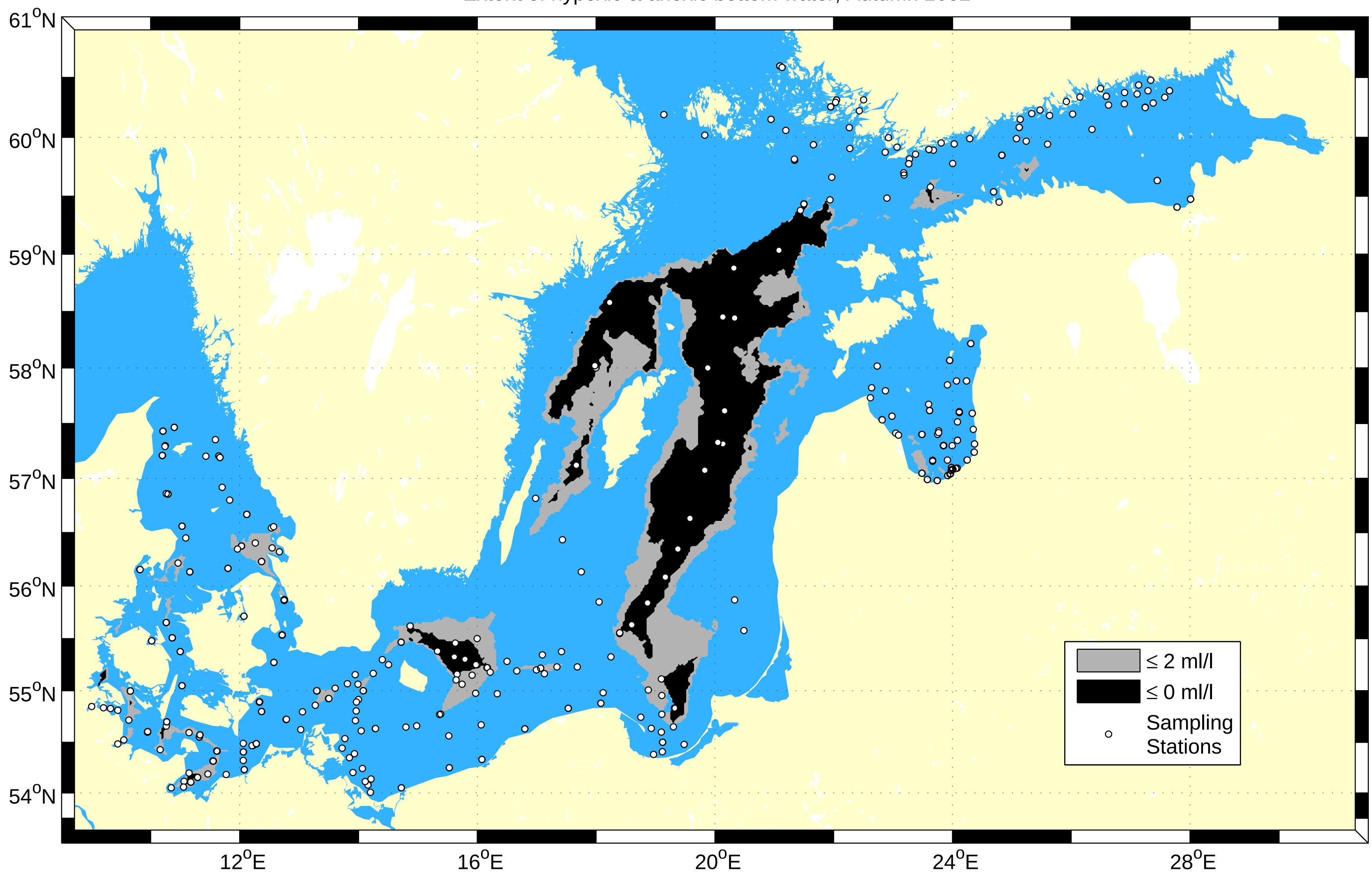
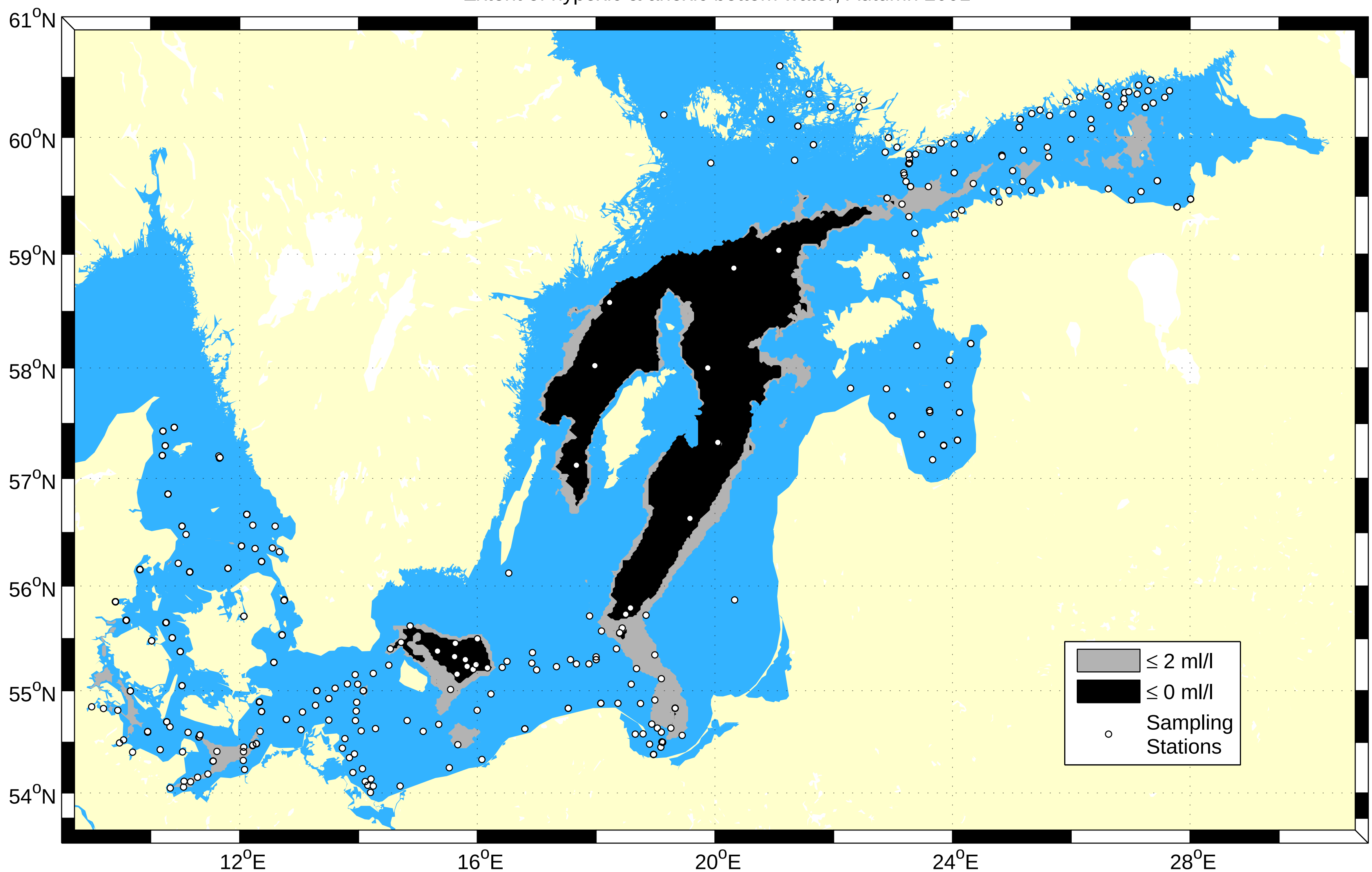
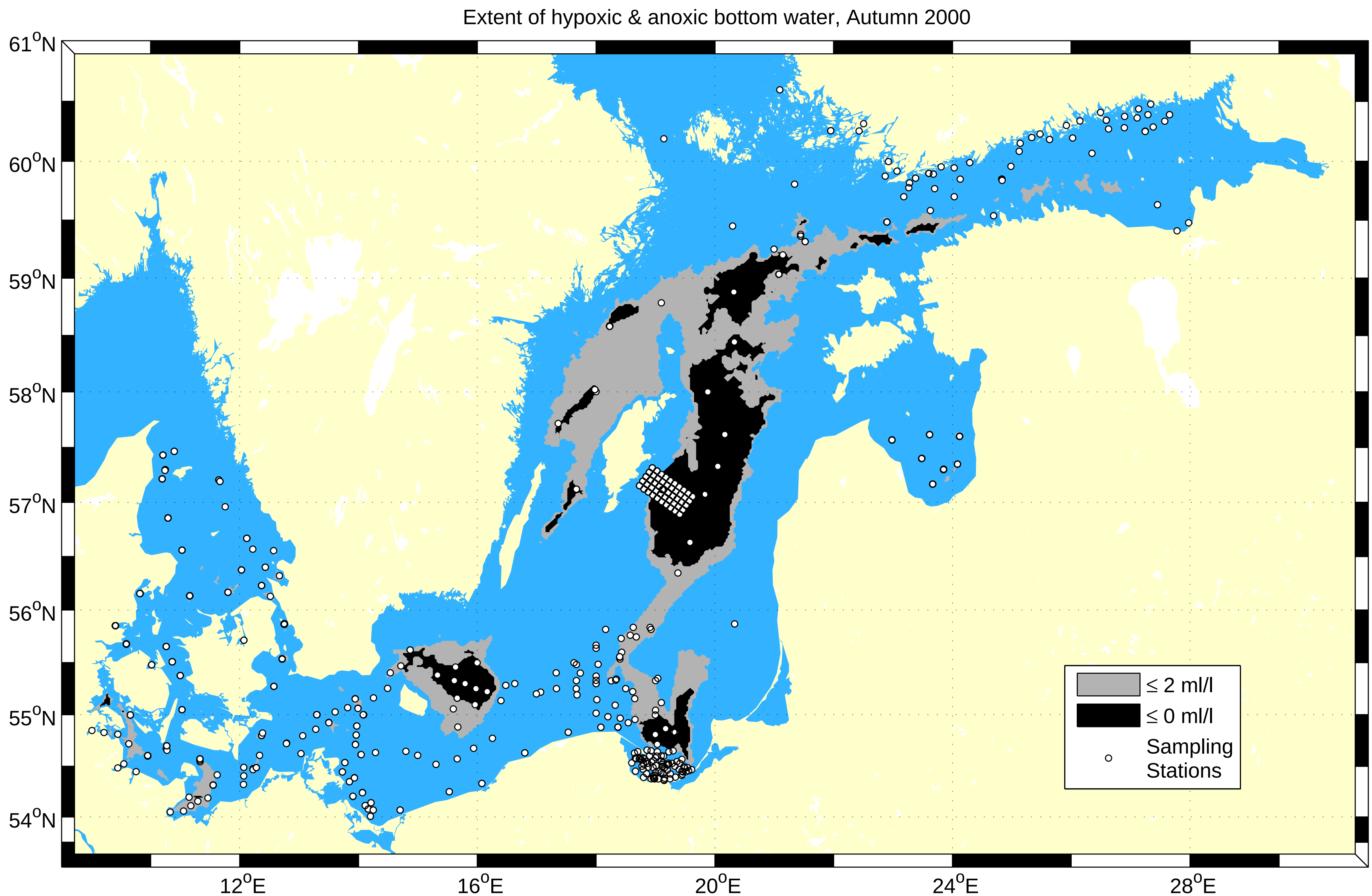
≤ 0 ml/l
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 2002



Extent of hypoxic & anoxic bottom water, Autumn 2001




Extent of hypoxic & anoxic bottom water, Autumn 2000
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55°N
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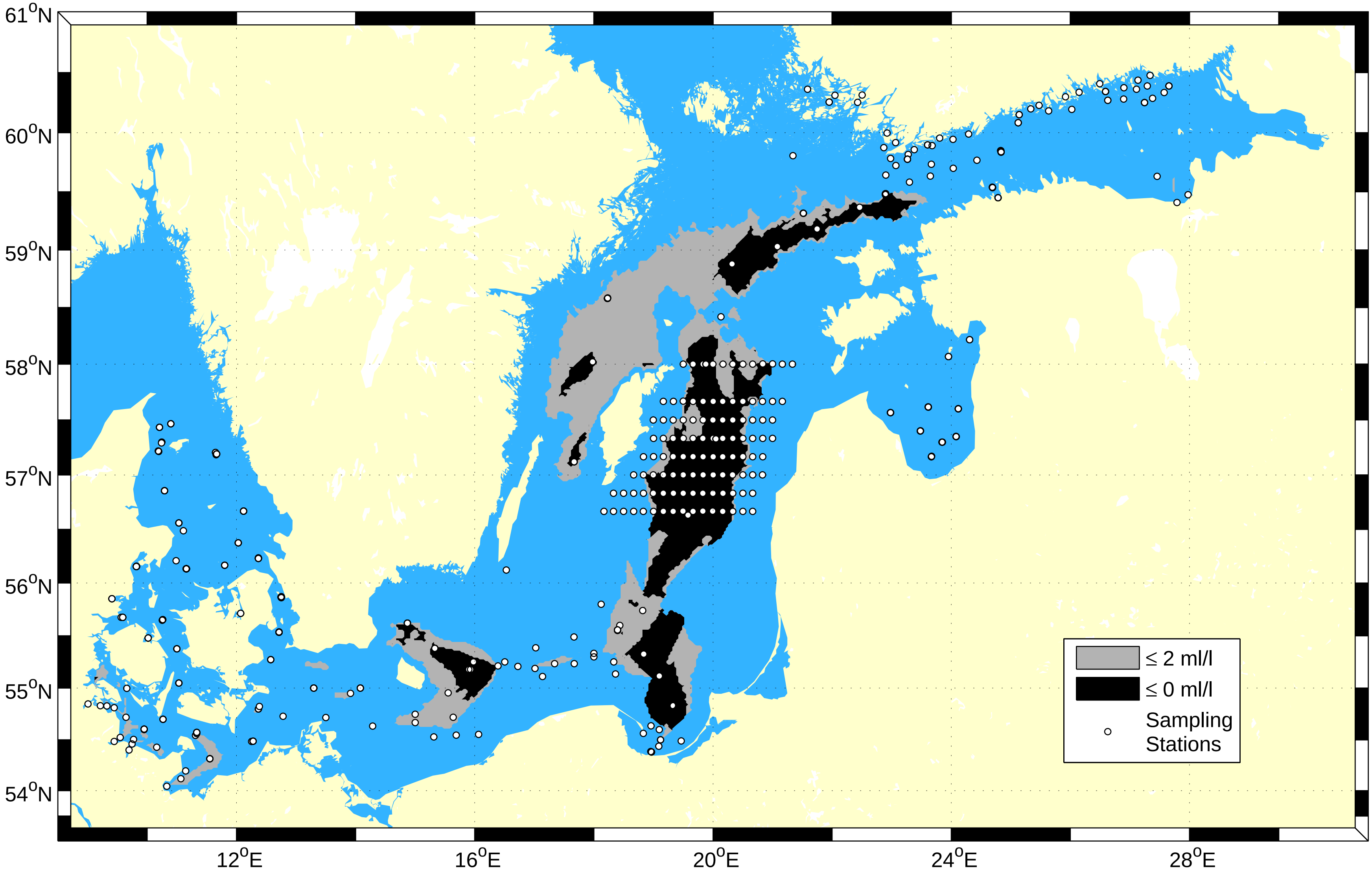
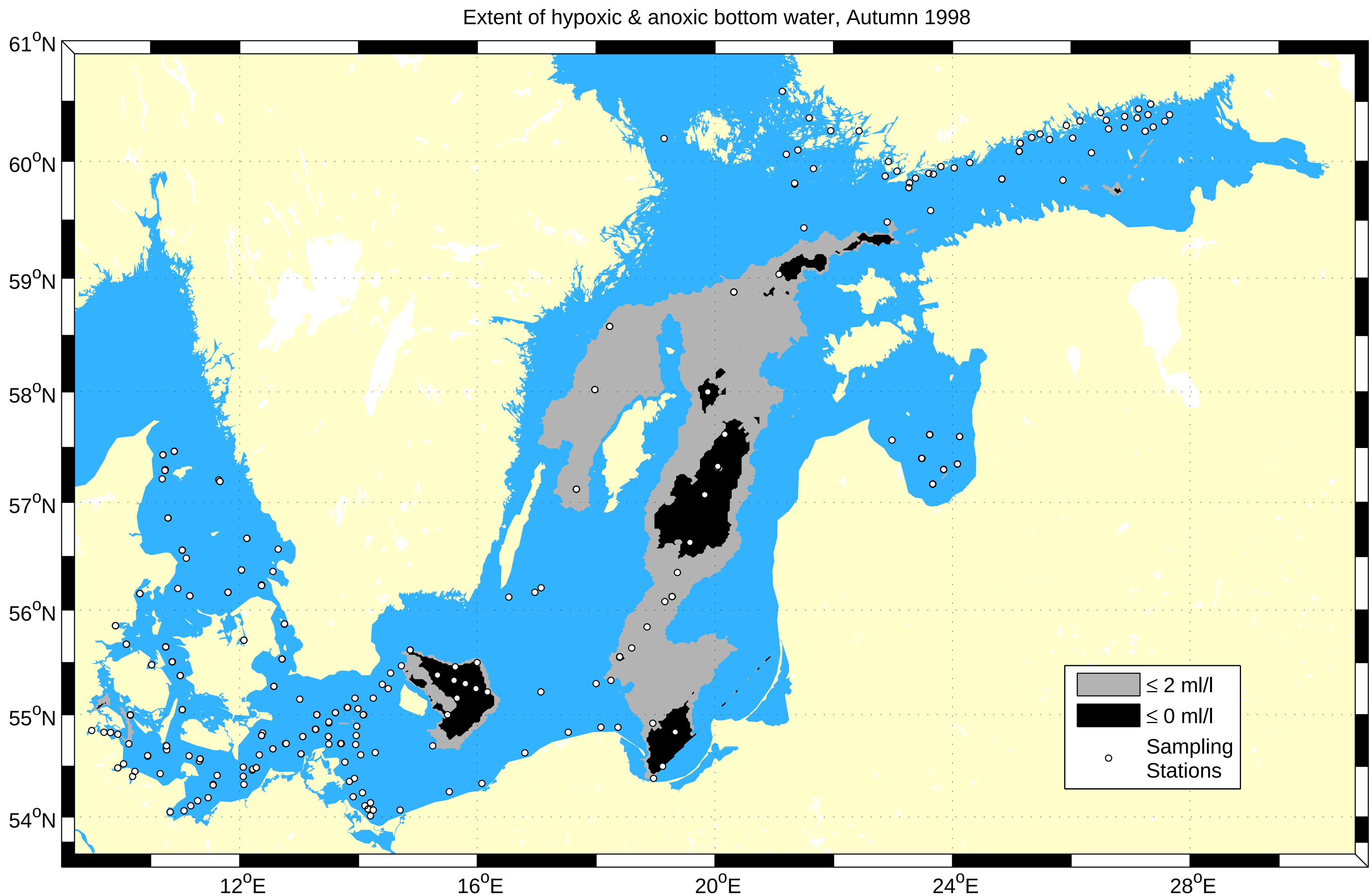
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1999





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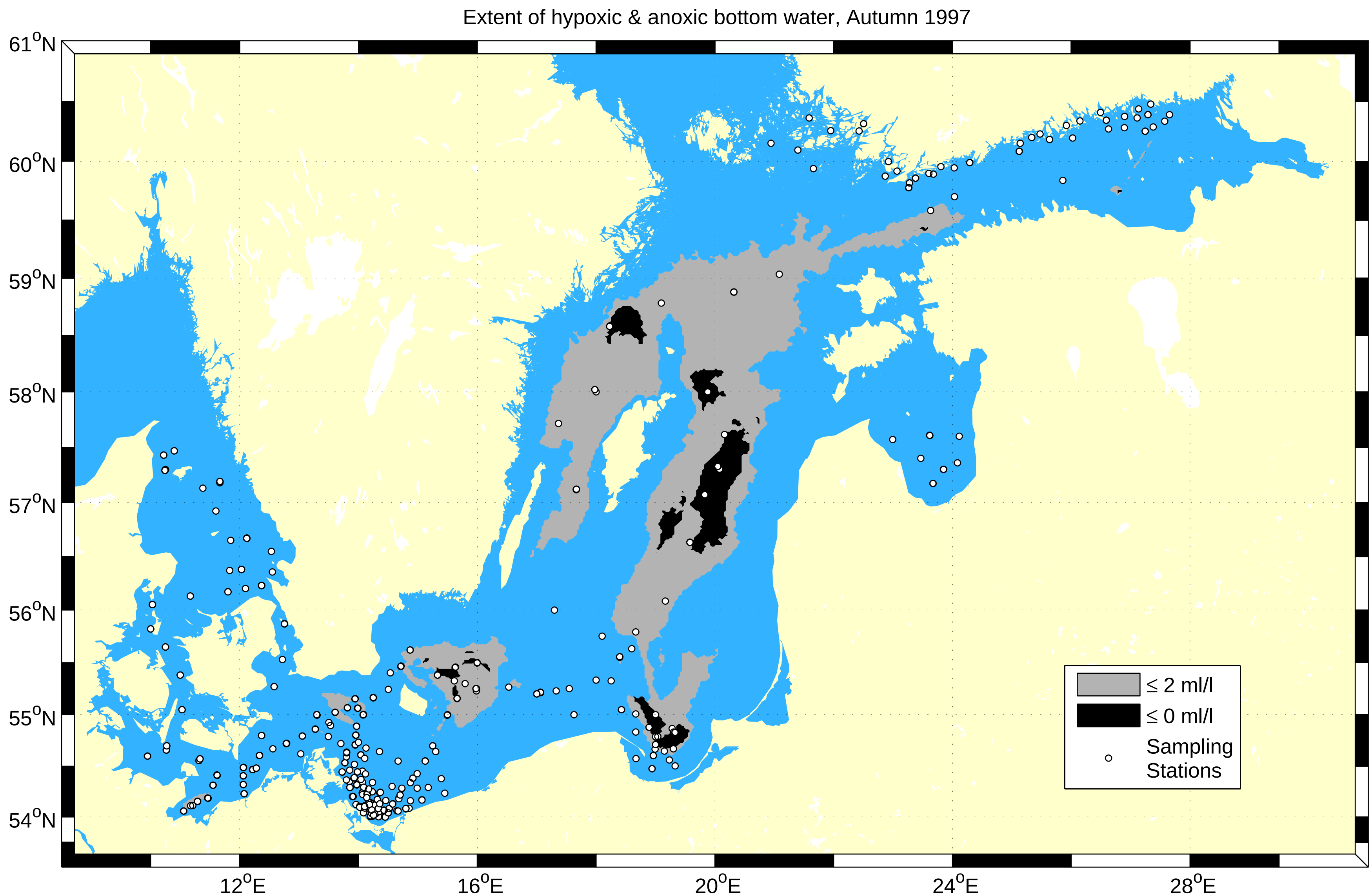
Sampling Stations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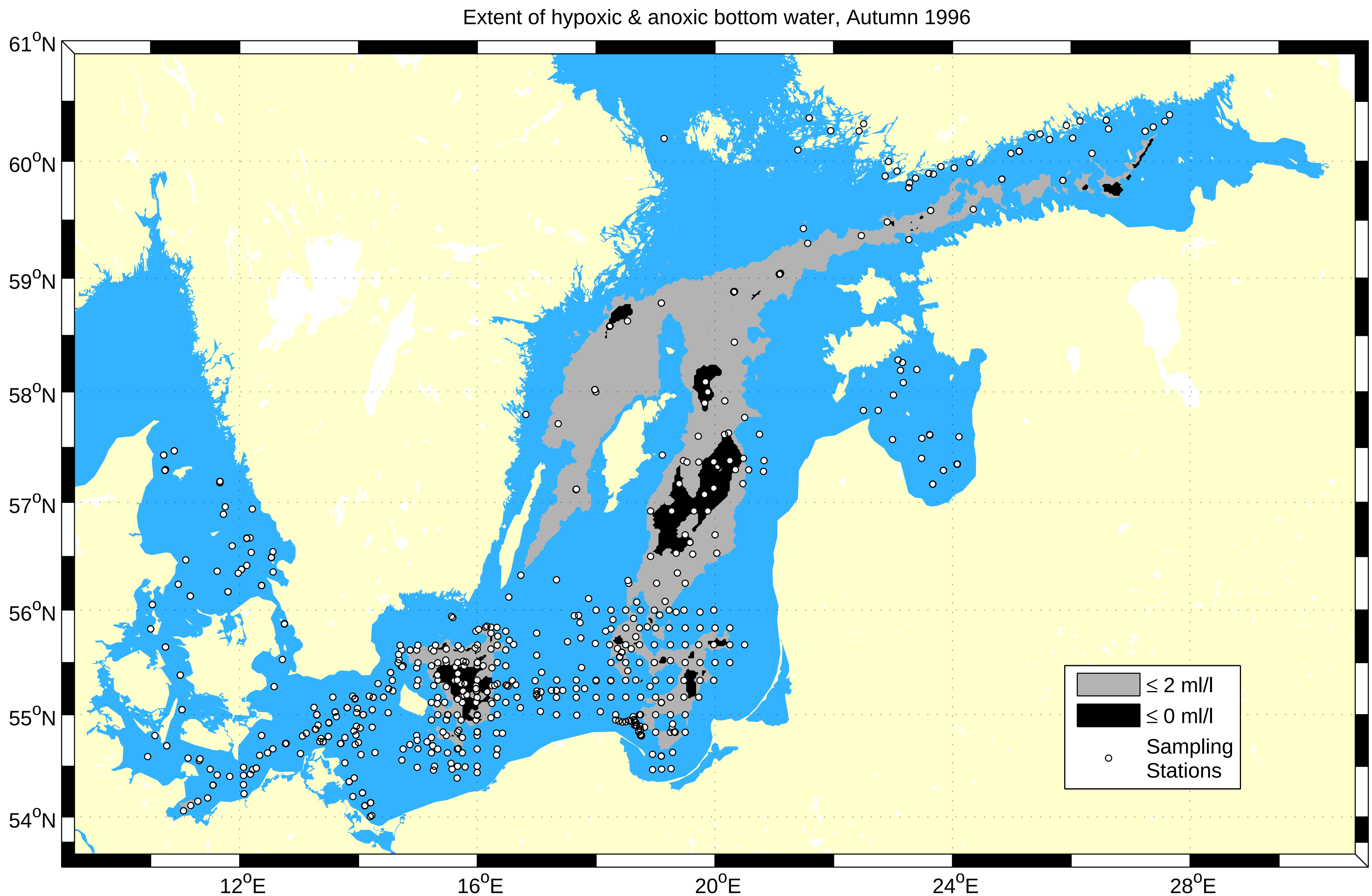
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations


Extent of hypoxic & anoxic bottom water, Autumn 1996
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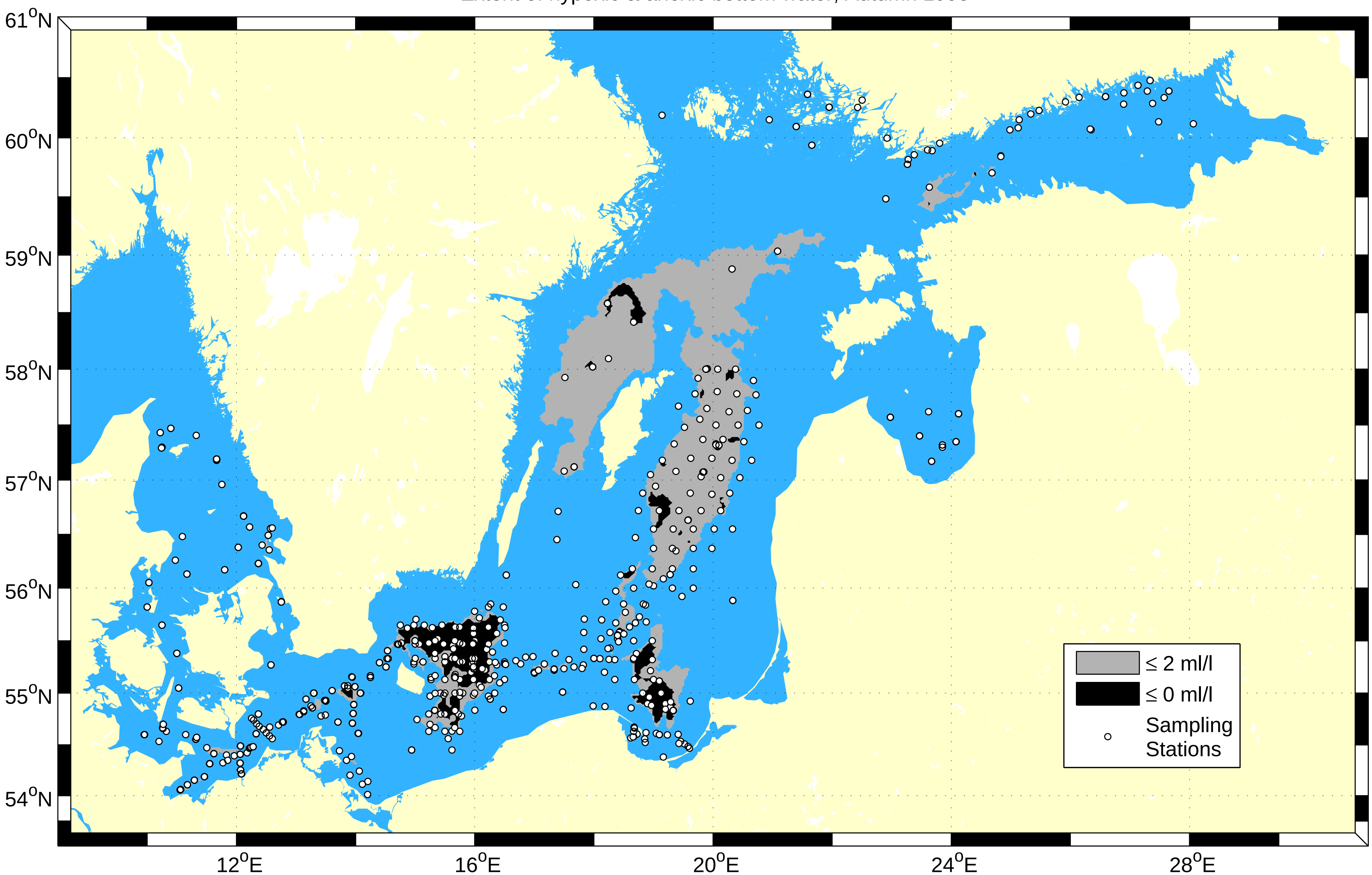
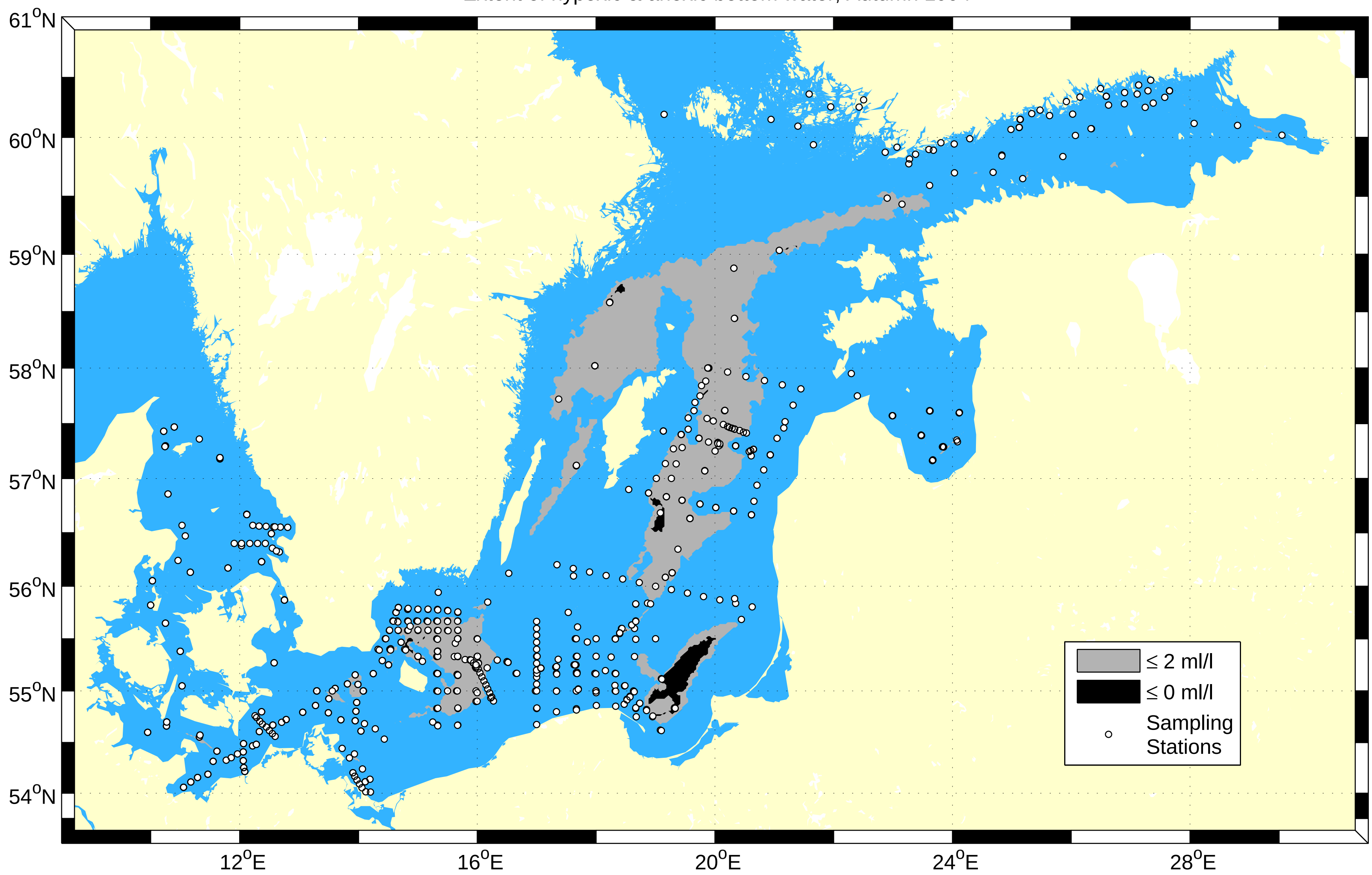
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1995



Extent of hypoxic & anoxic bottom water, Autumn 1994



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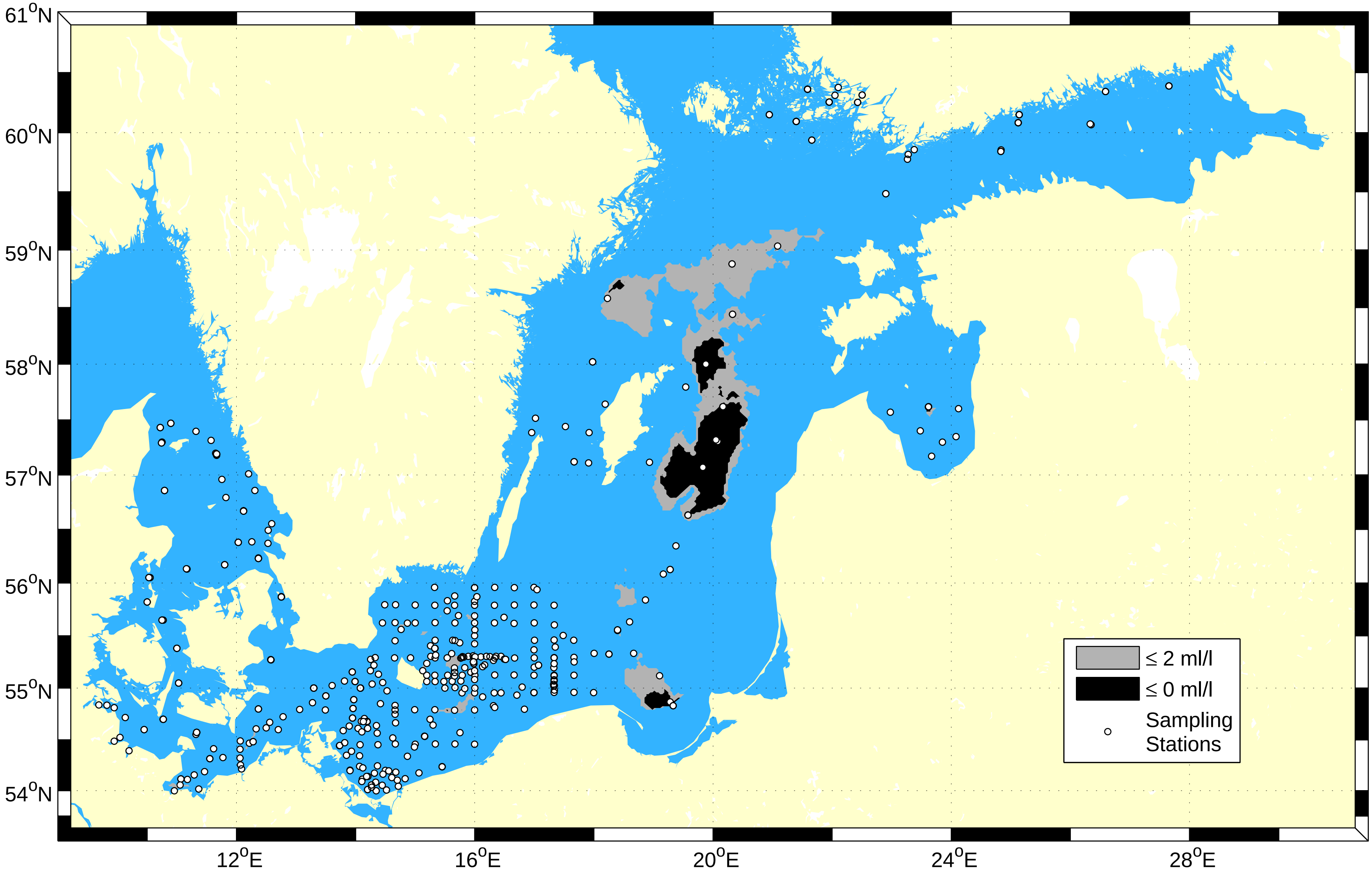
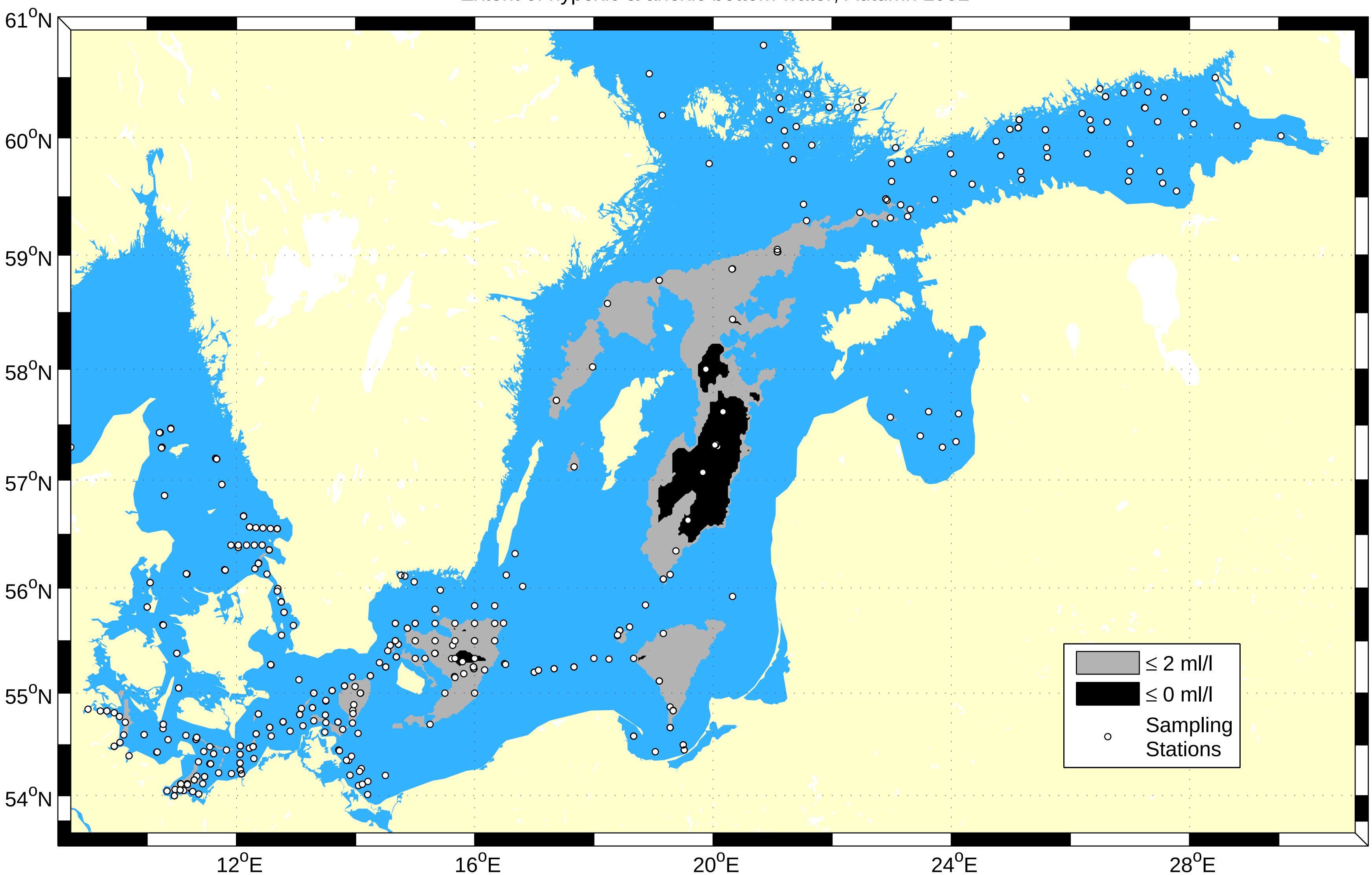
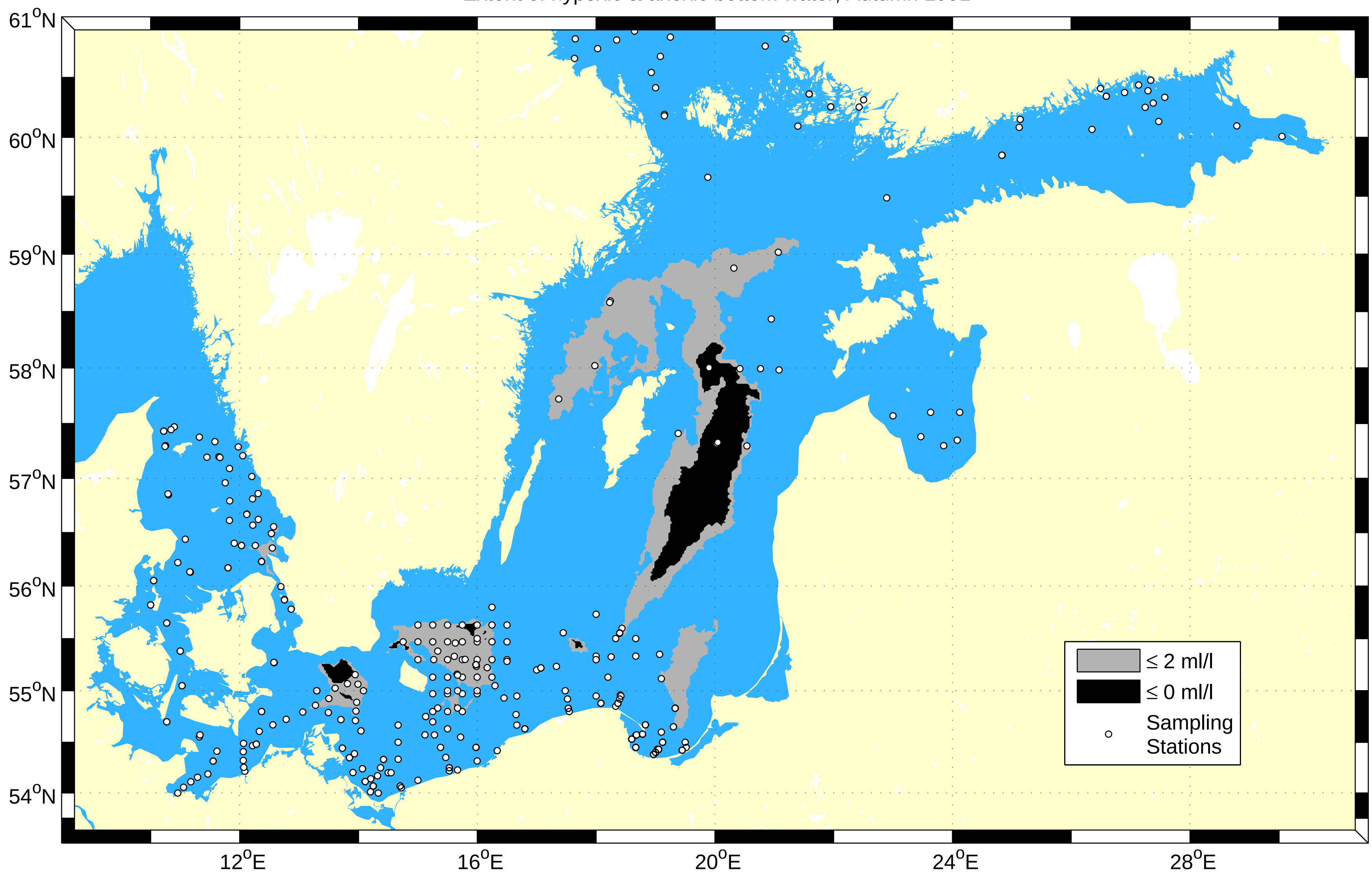


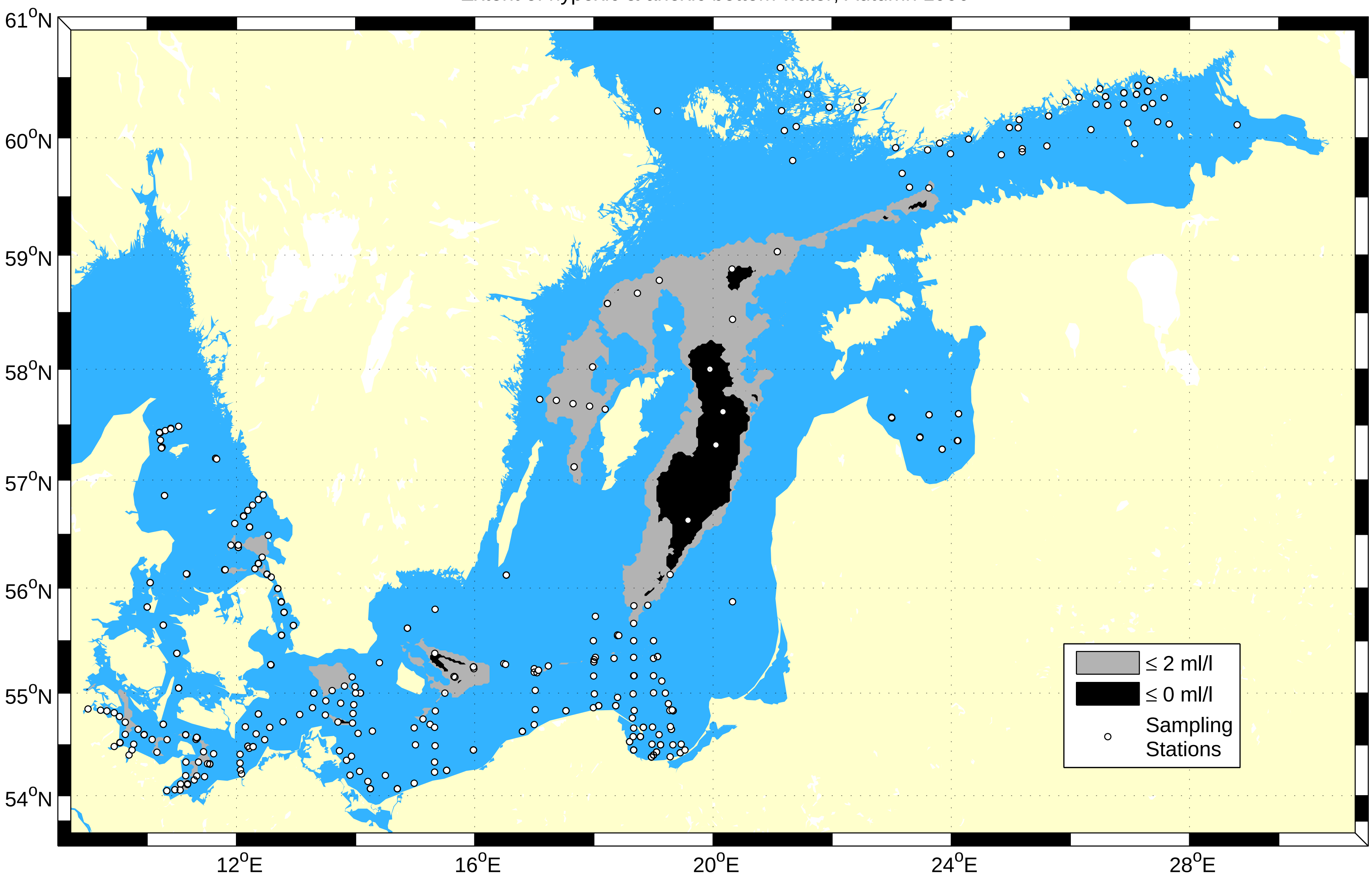
Extent of hypoxic & anoxic bottom water, Autumn 1992



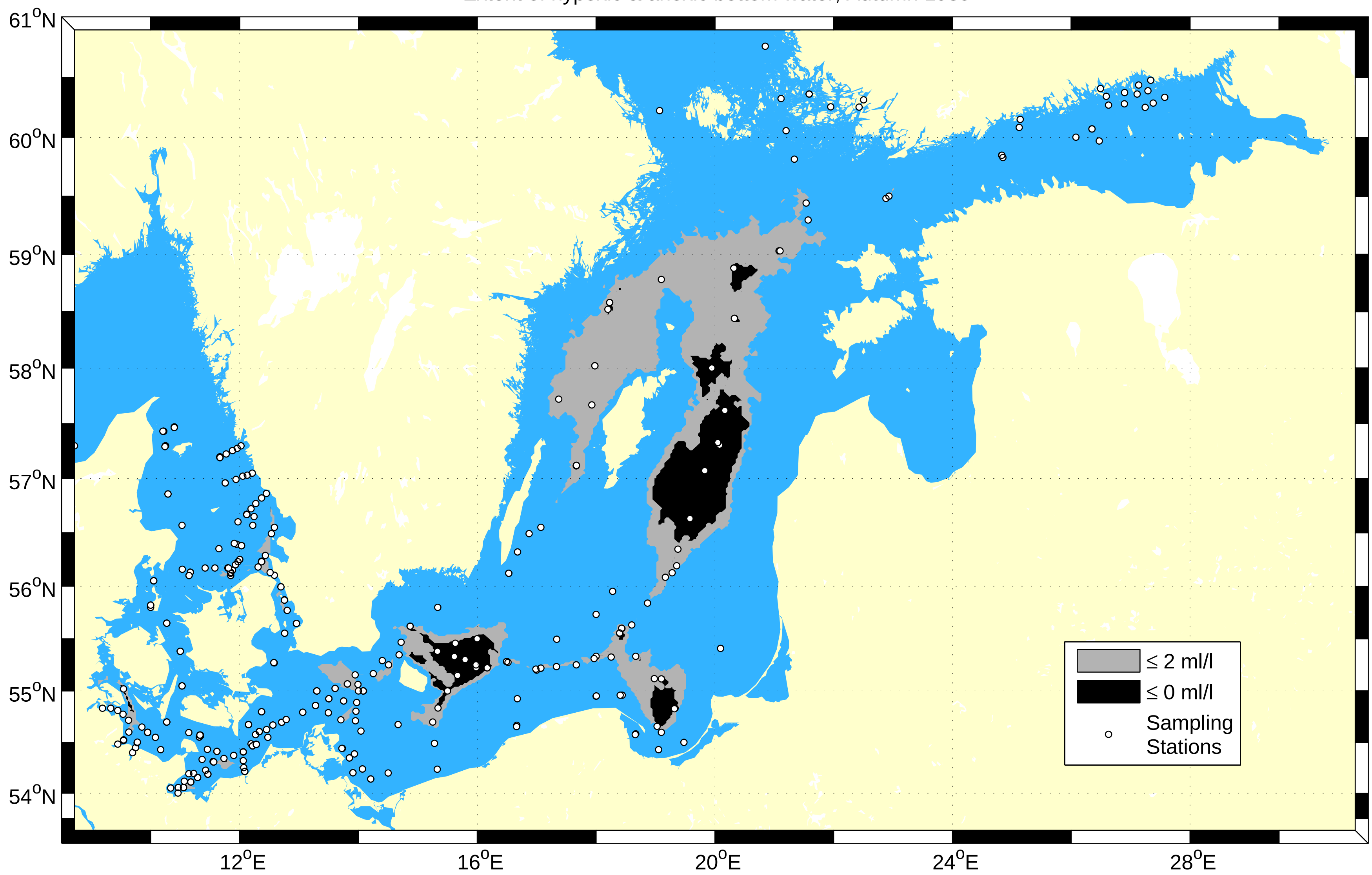
Extent of hypoxic & anoxic bottom water, Autumn 1991



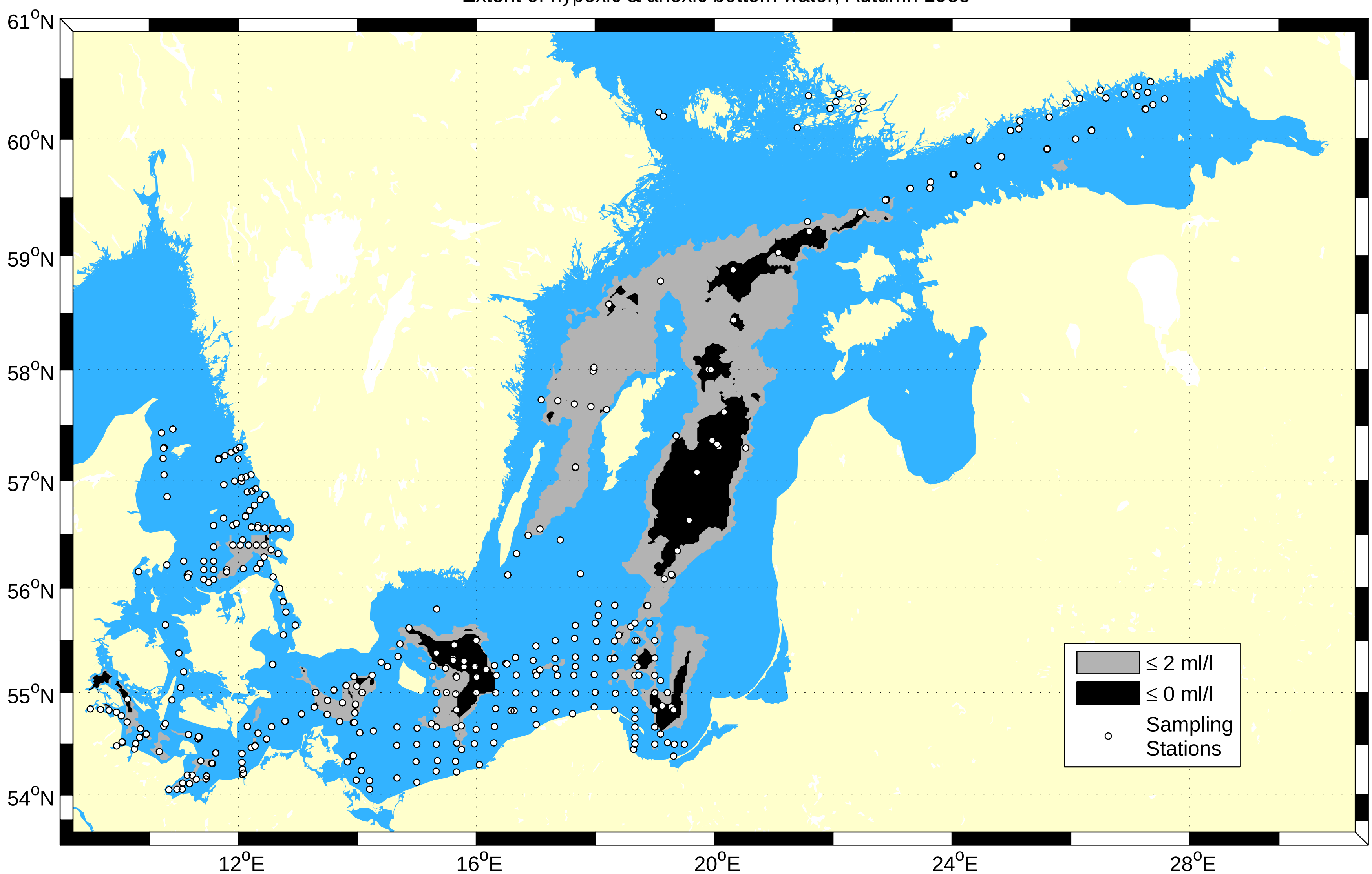
Extent of hypoxic & anoxic bottom water, Autumn 1990



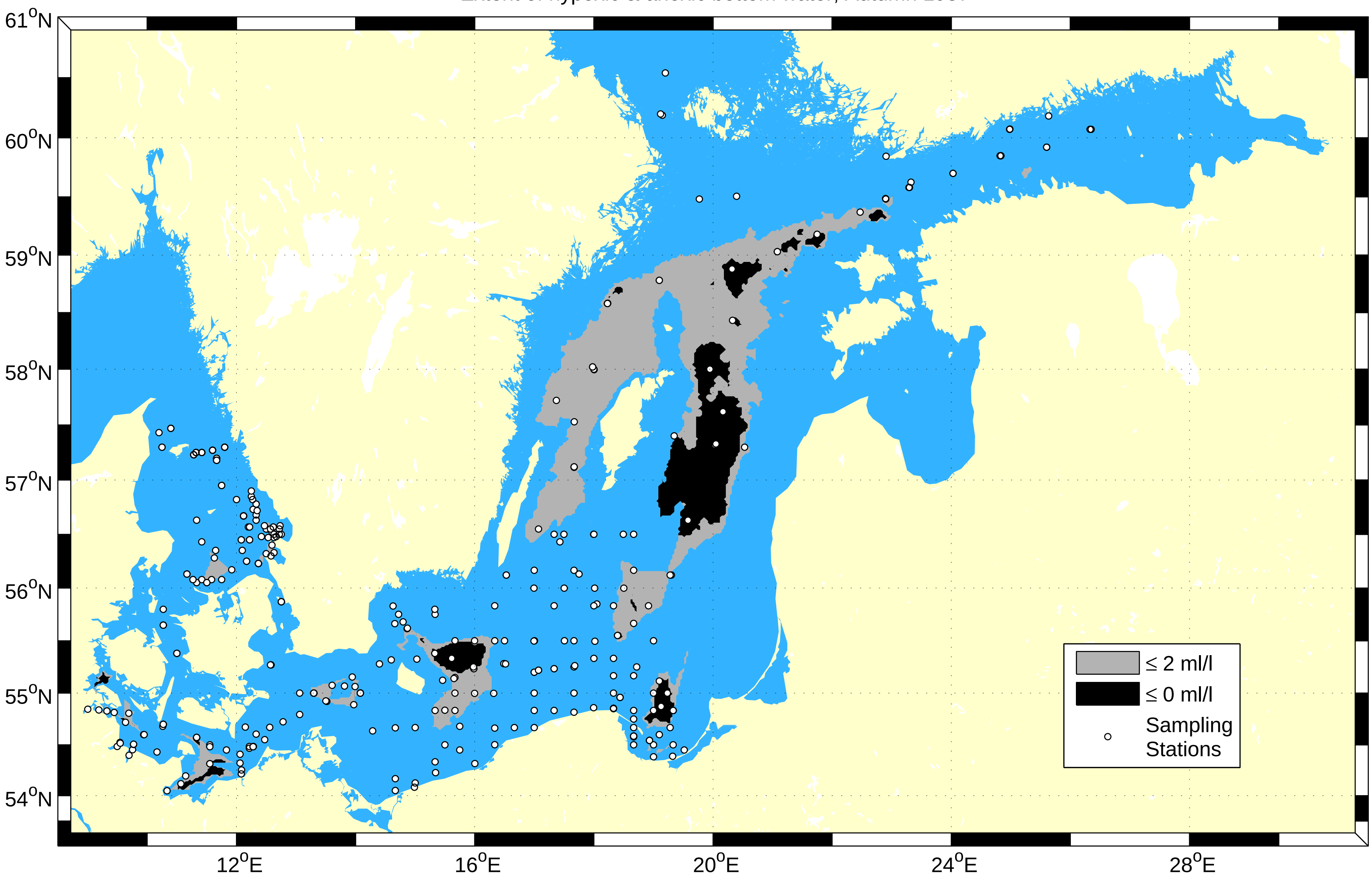
Extent of hypoxic & anoxic bottom water, Autumn 1989

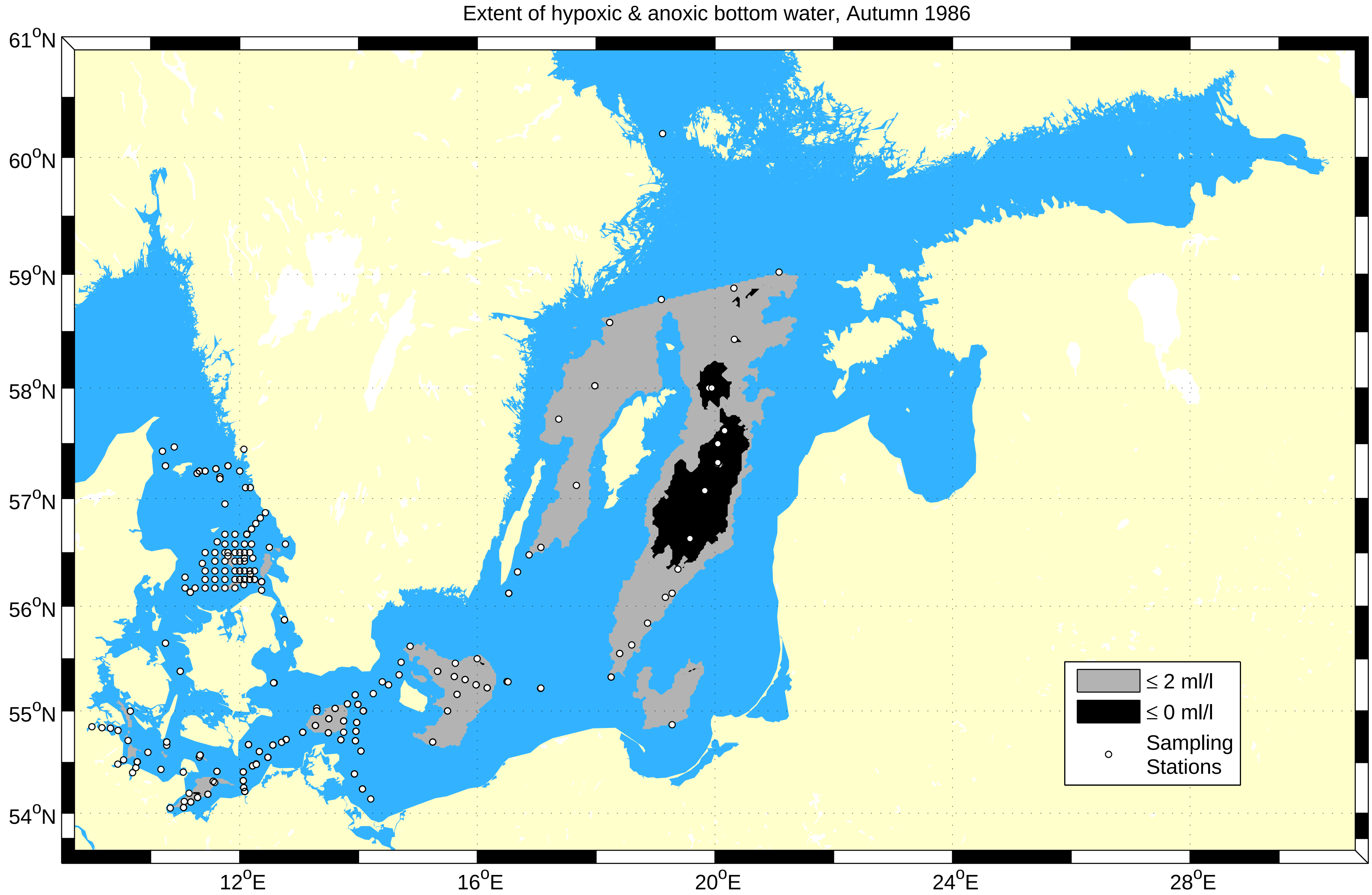


Extent of hypoxic & anoxic bottom water, Autumn 1988

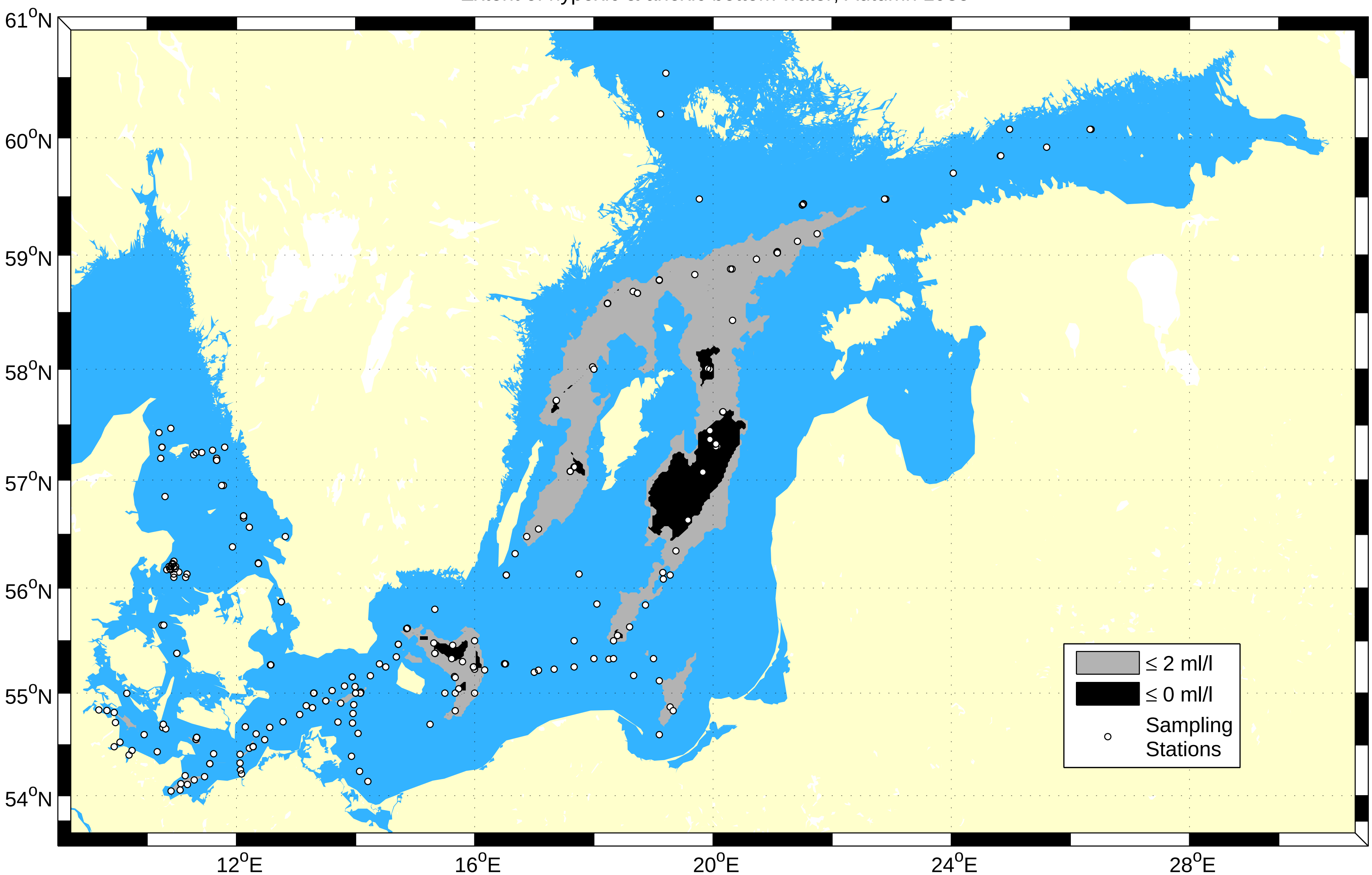


Extent of hypoxic & anoxic bottom water, Autumn 1987

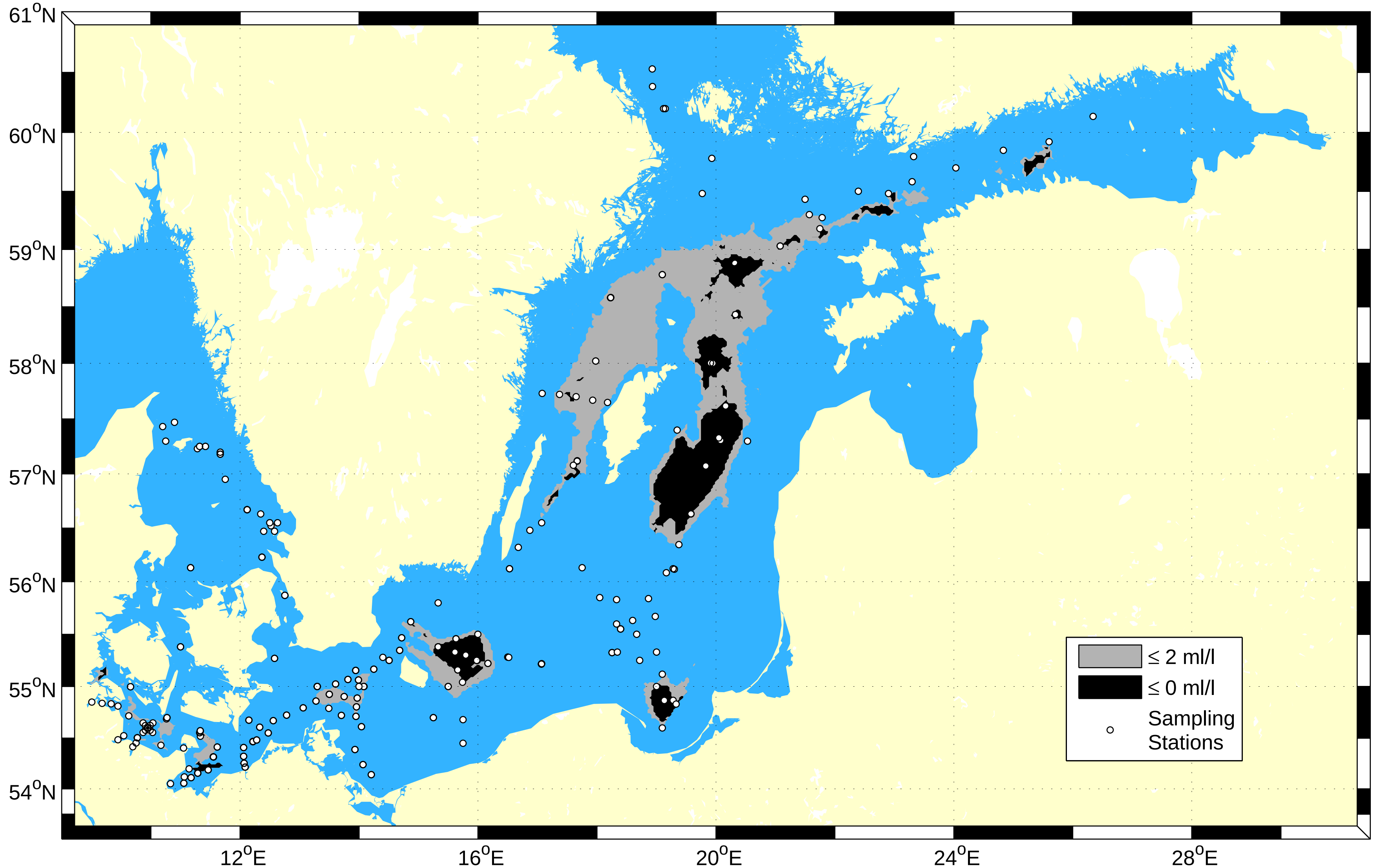



Extent of hypoxic & anoxic bottom water, Autumn 1986
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

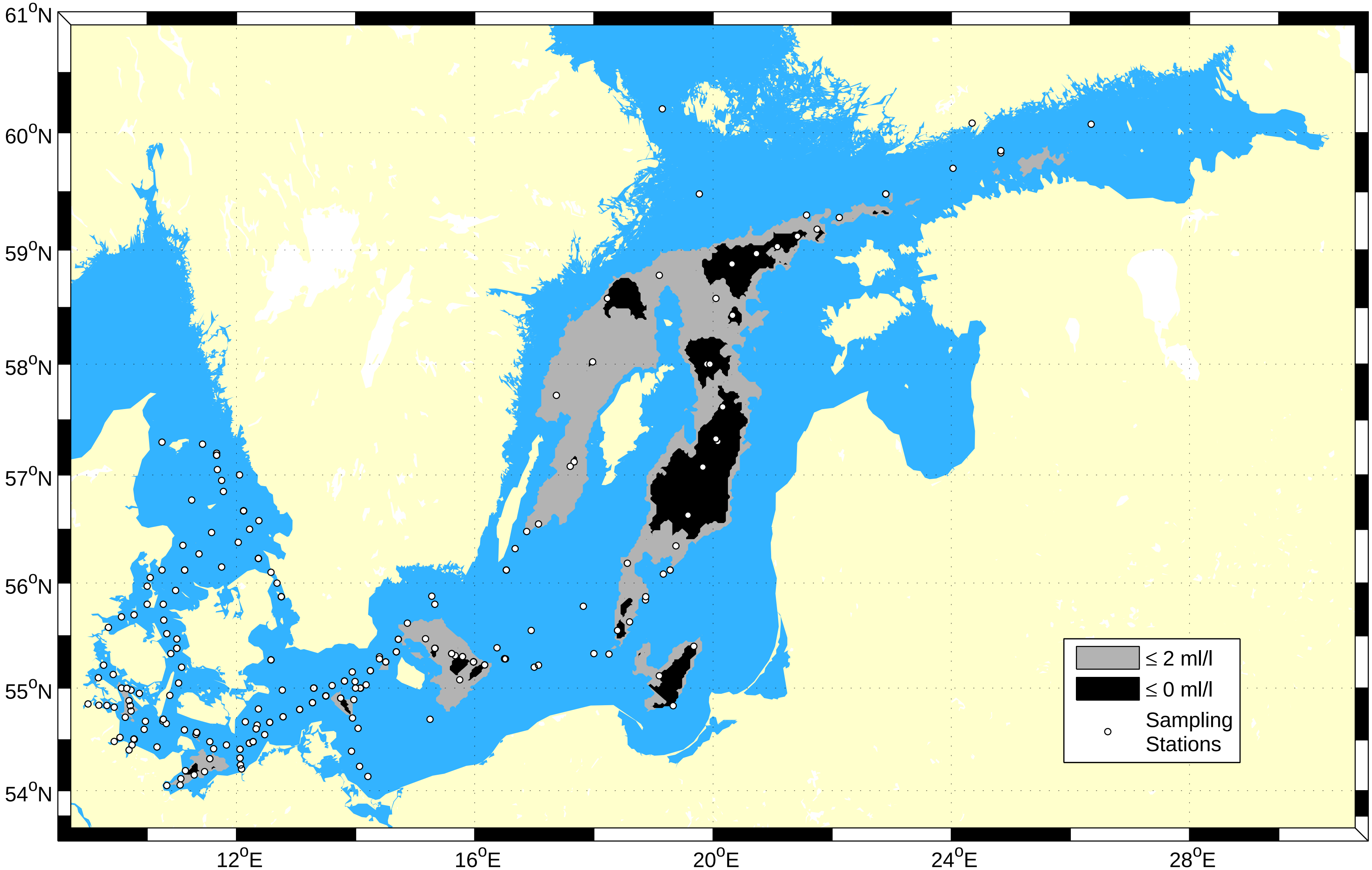
Extent of hypoxic & anoxic bottom water, Autumn 1985



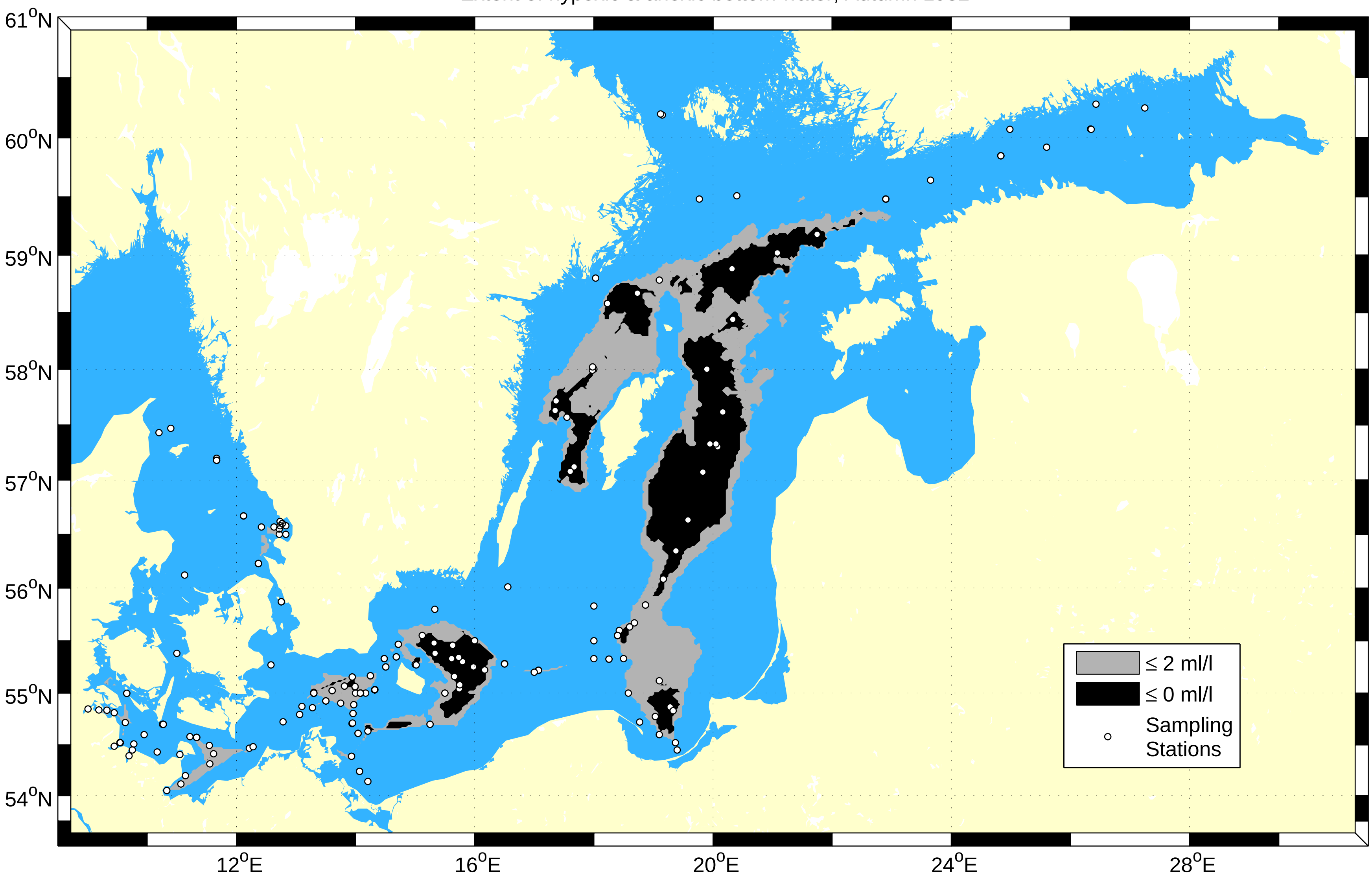
Extent of hypoxic & anoxic bottom water, Autumn 1984



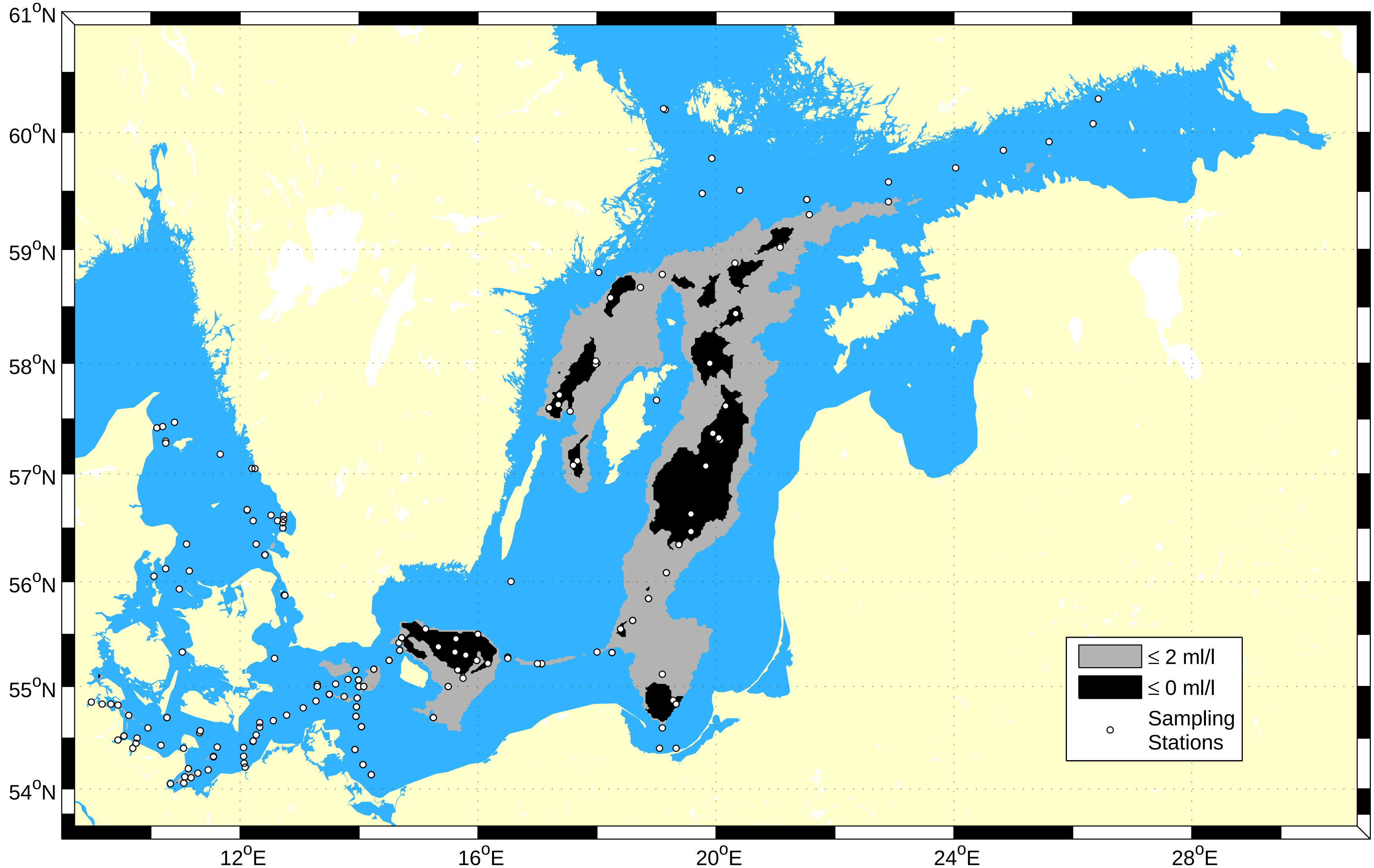
Extent of hypoxic & anoxic bottom water, Autumn 1983



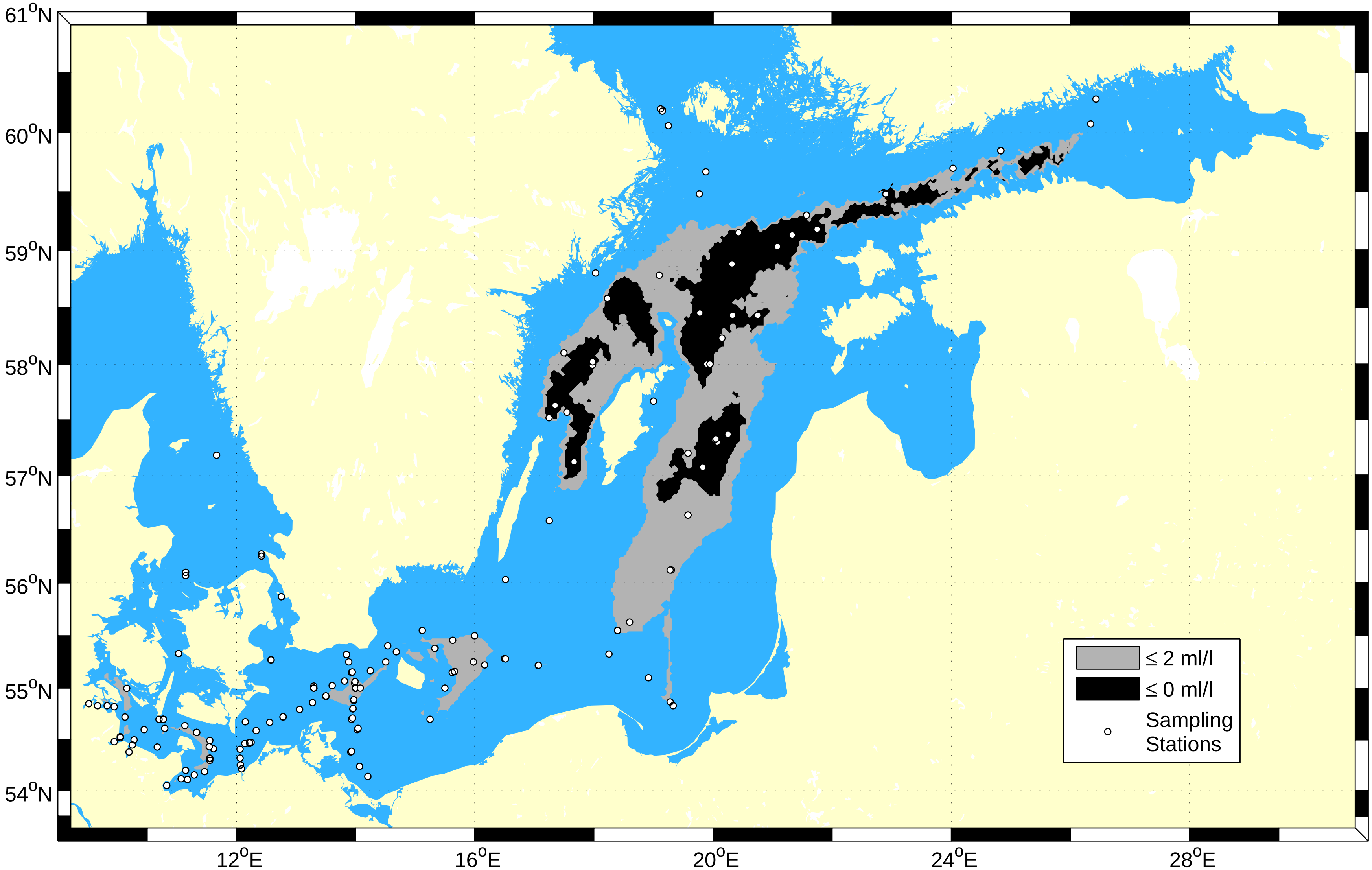
Extent of hypoxic & anoxic bottom water, Autumn 1982



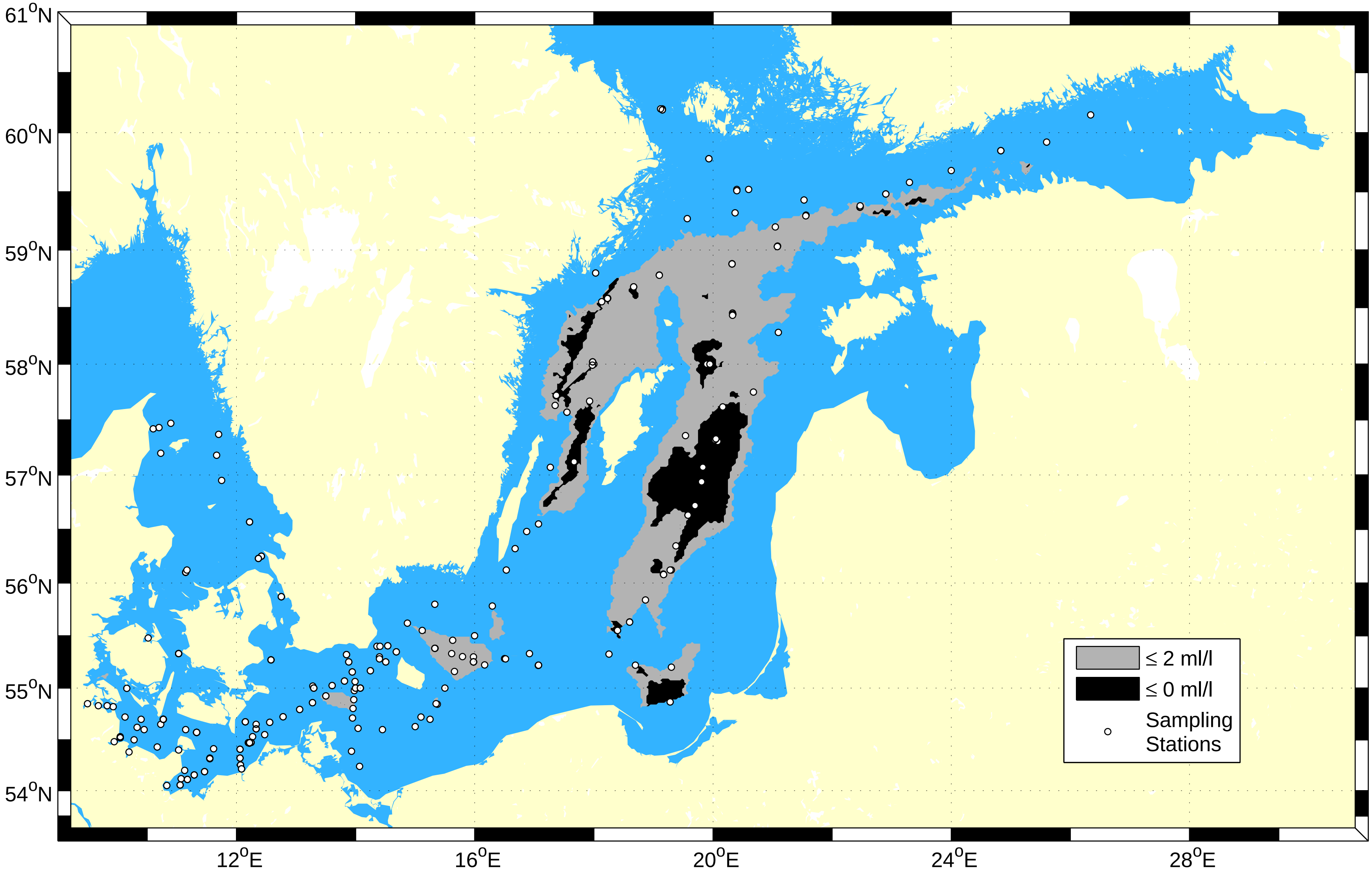
Extent of hypoxic & anoxic bottom water, Autumn 1981



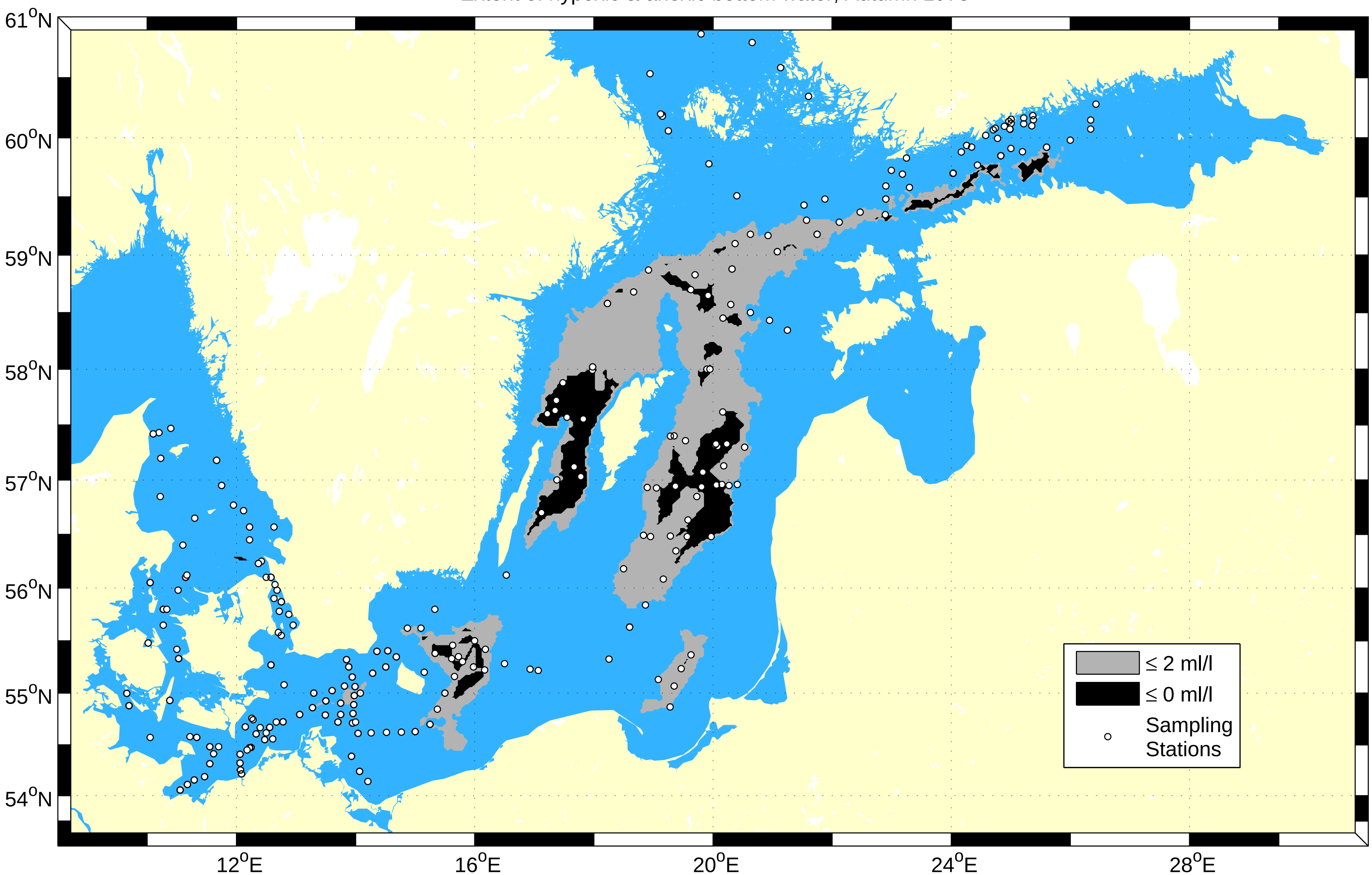
Extent of hypoxic & anoxic bottom water, Autumn 1980



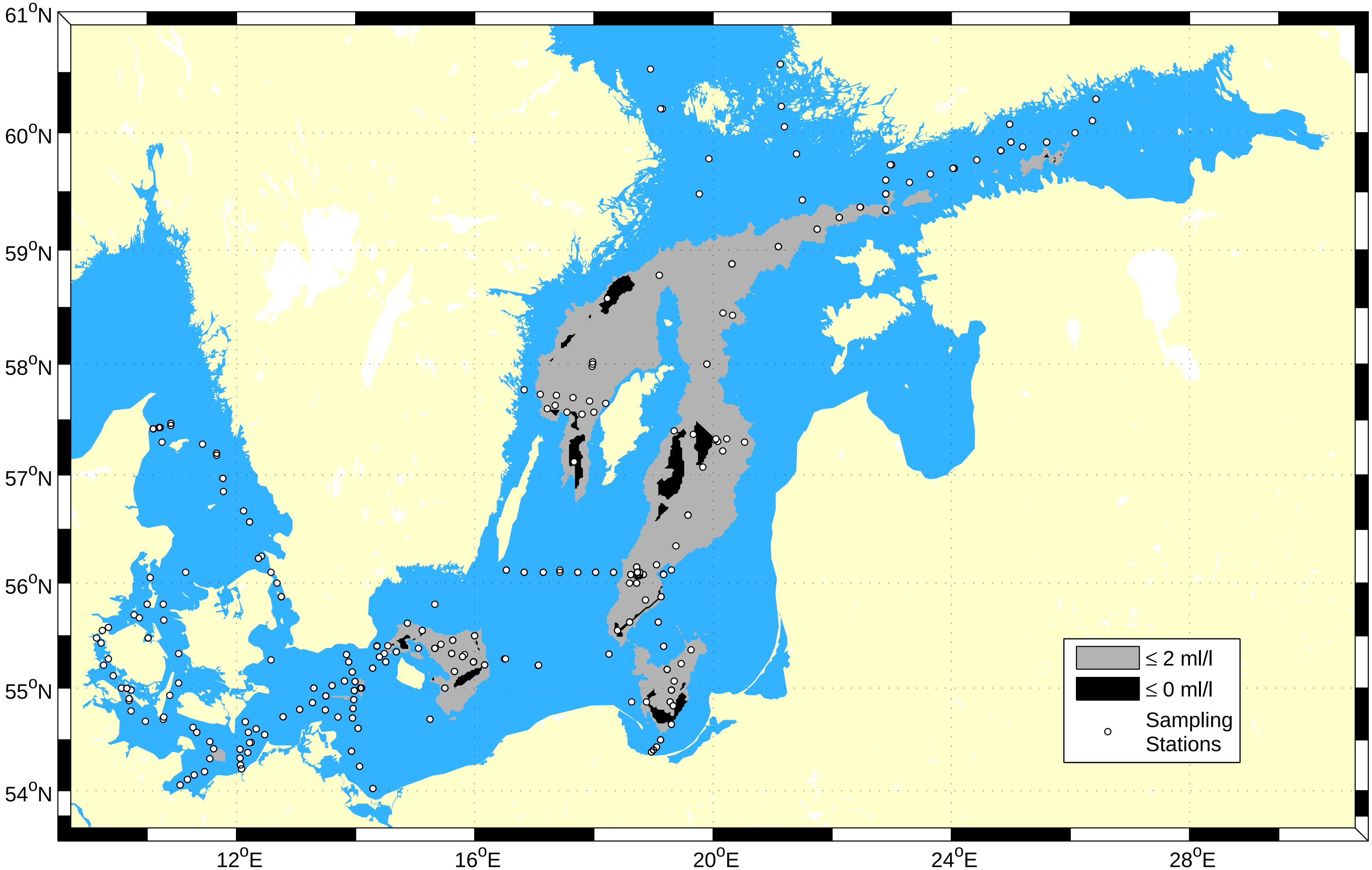
Extent of hypoxic & anoxic bottom water, Autumn 1979



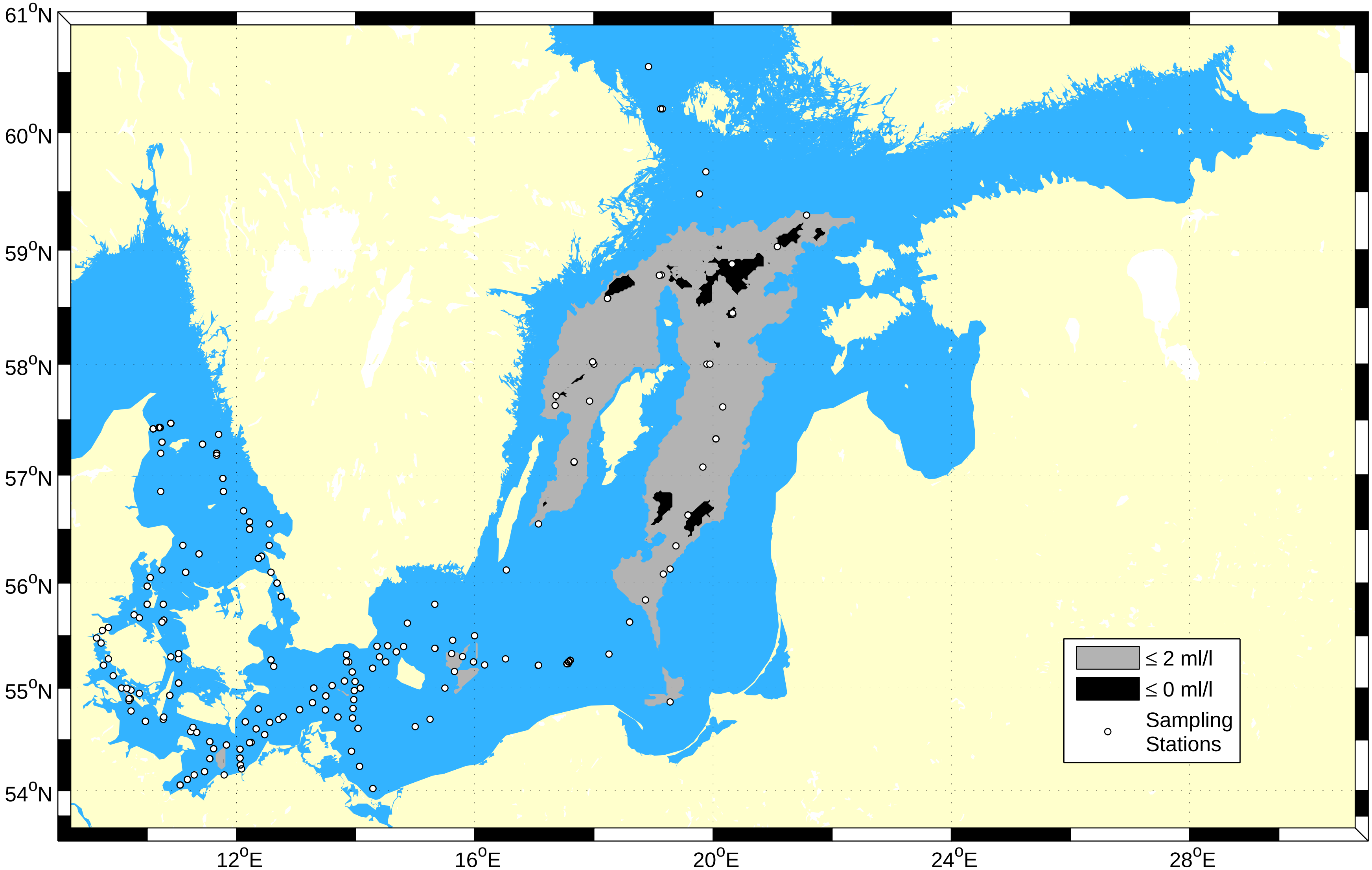
Extent of hypoxic & anoxic bottom water, Autumn 1978

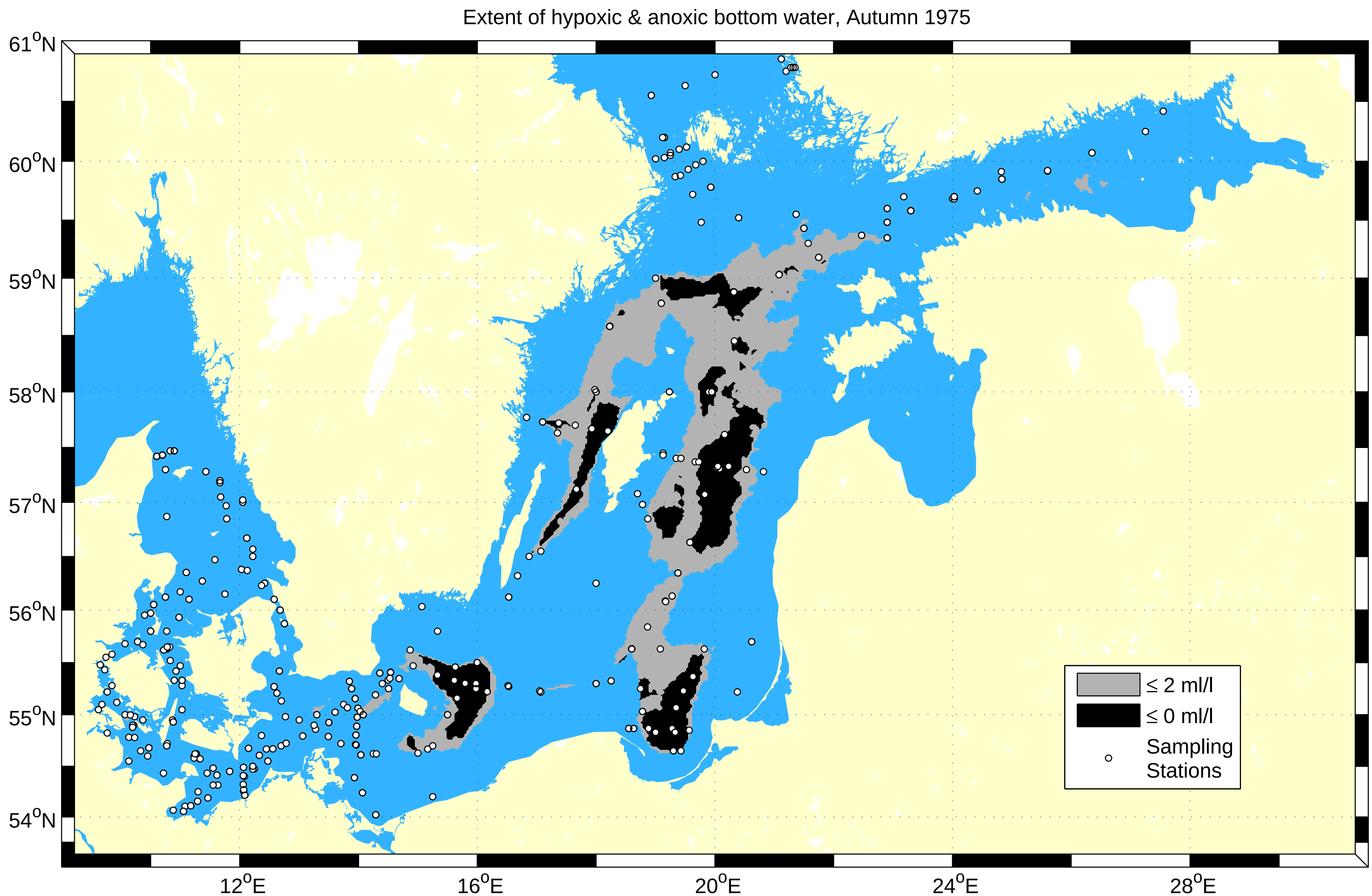


Extent of hypoxic & anoxic bottom water, Autumn 1977

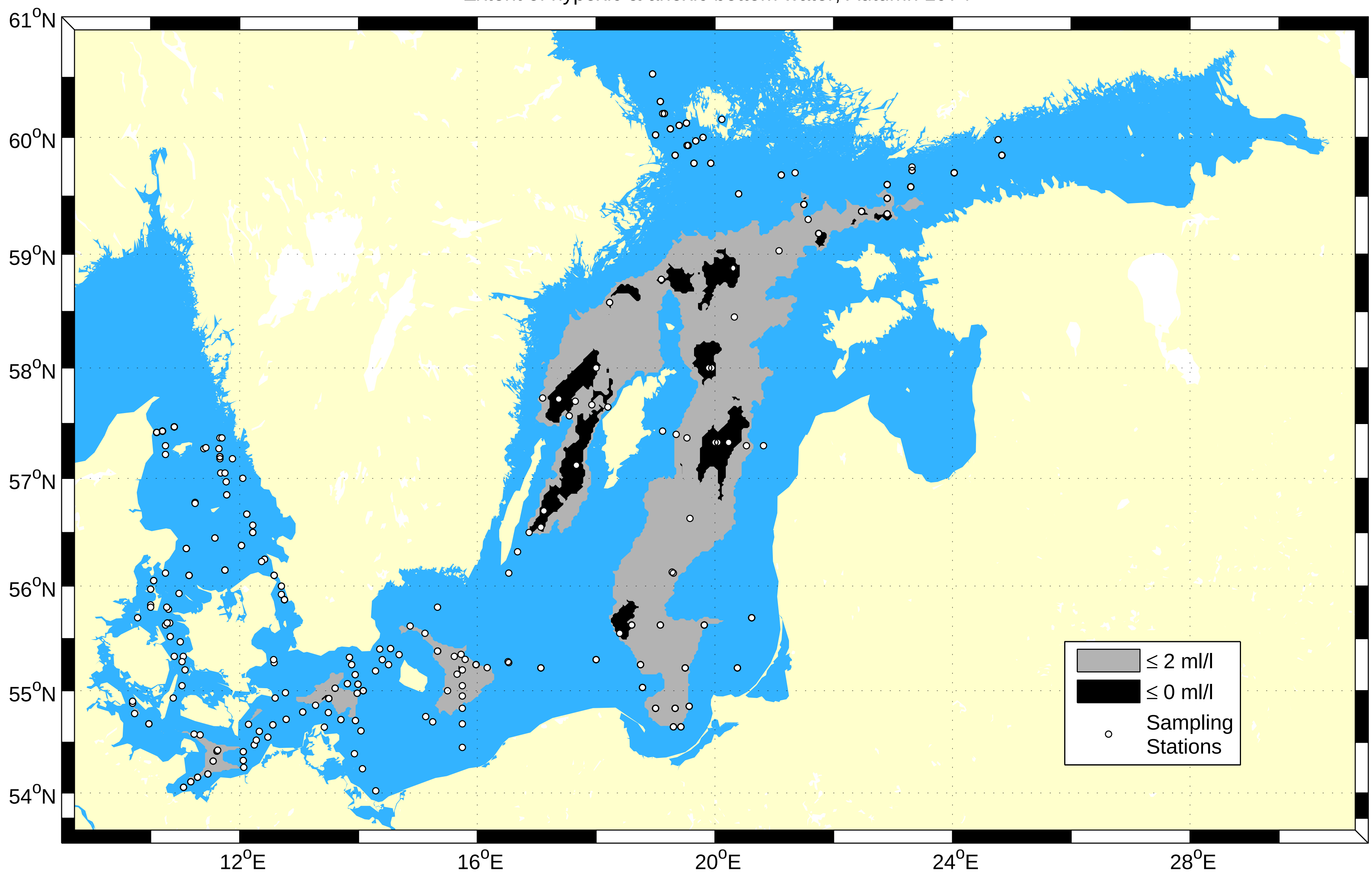


Extent of hypoxic & anoxic bottom water, Autumn 1976

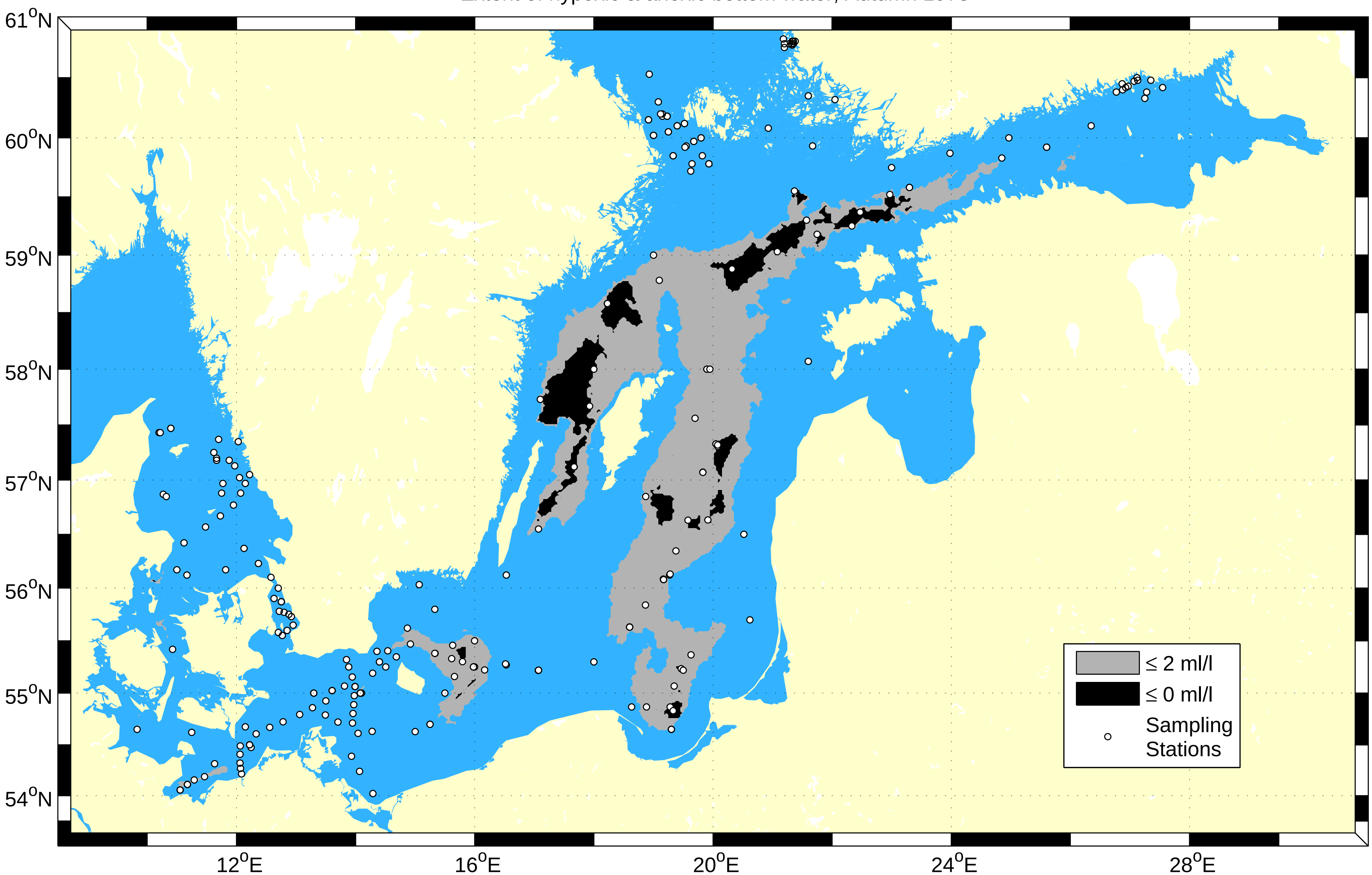



Extent of hypoxic & anoxic bottom water, Autumn 1975
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

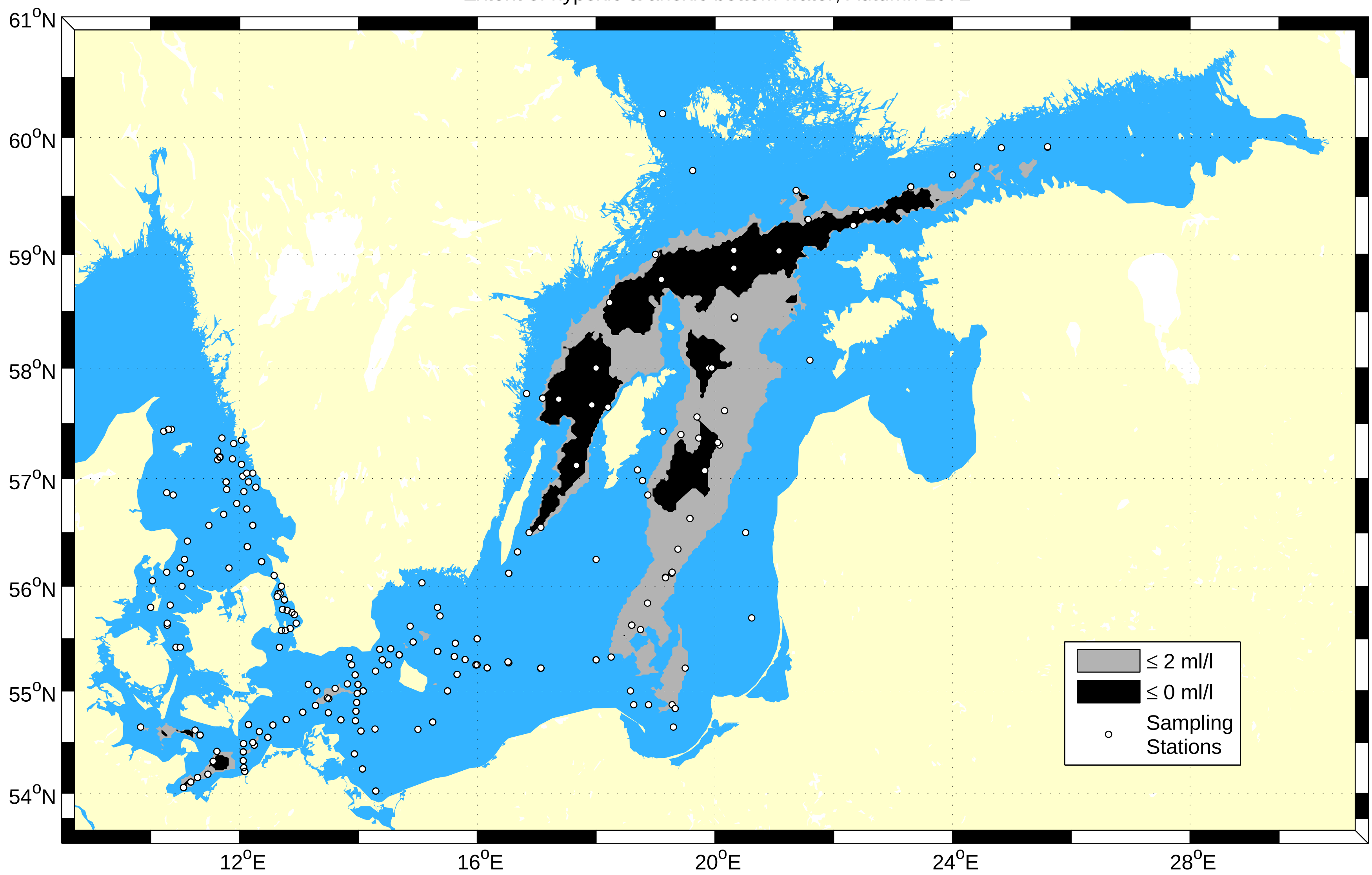
Extent of hypoxic & anoxic bottom water, Autumn 1974



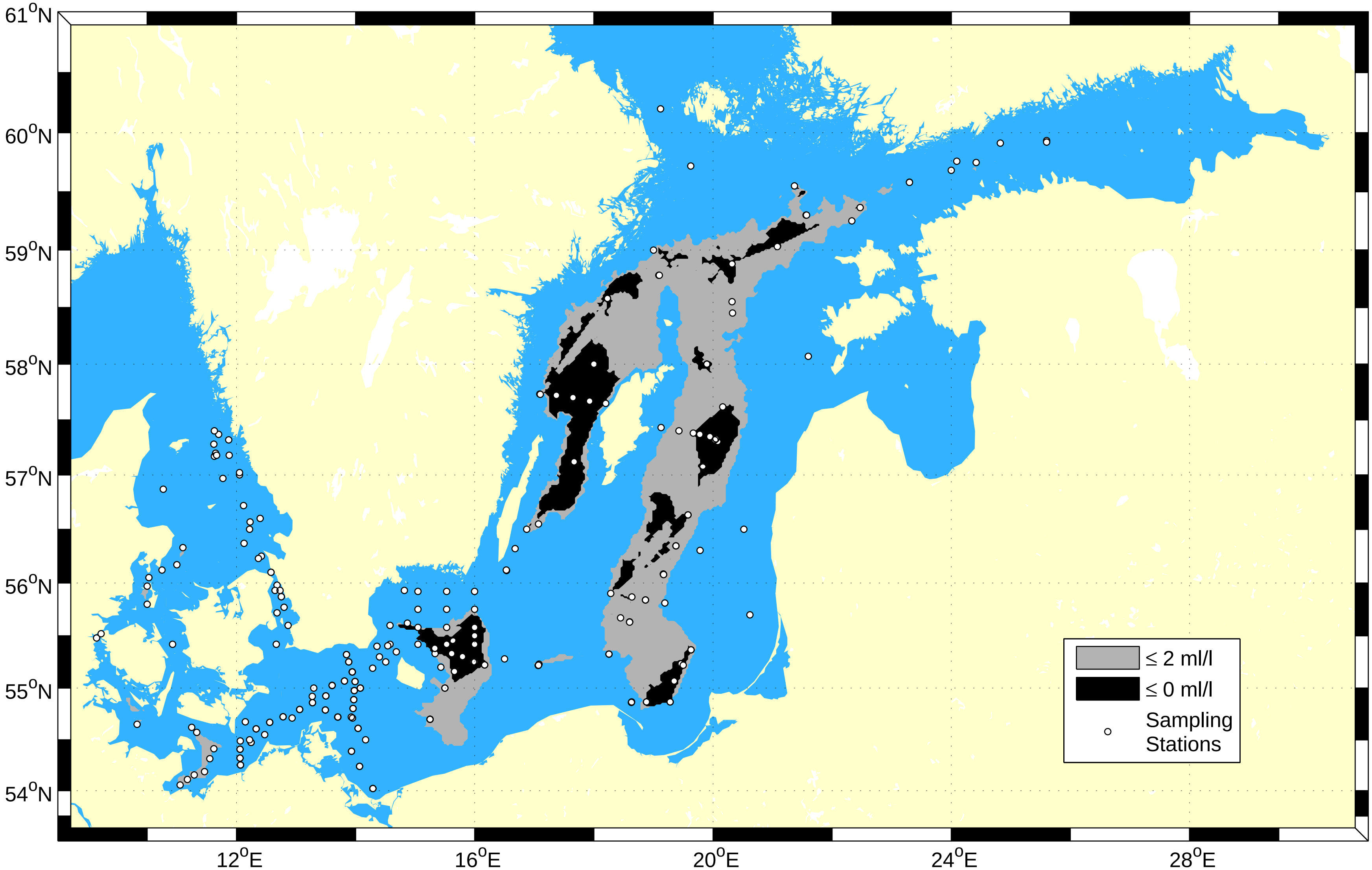
Extent of hypoxic & anoxic bottom water, Autumn 1973

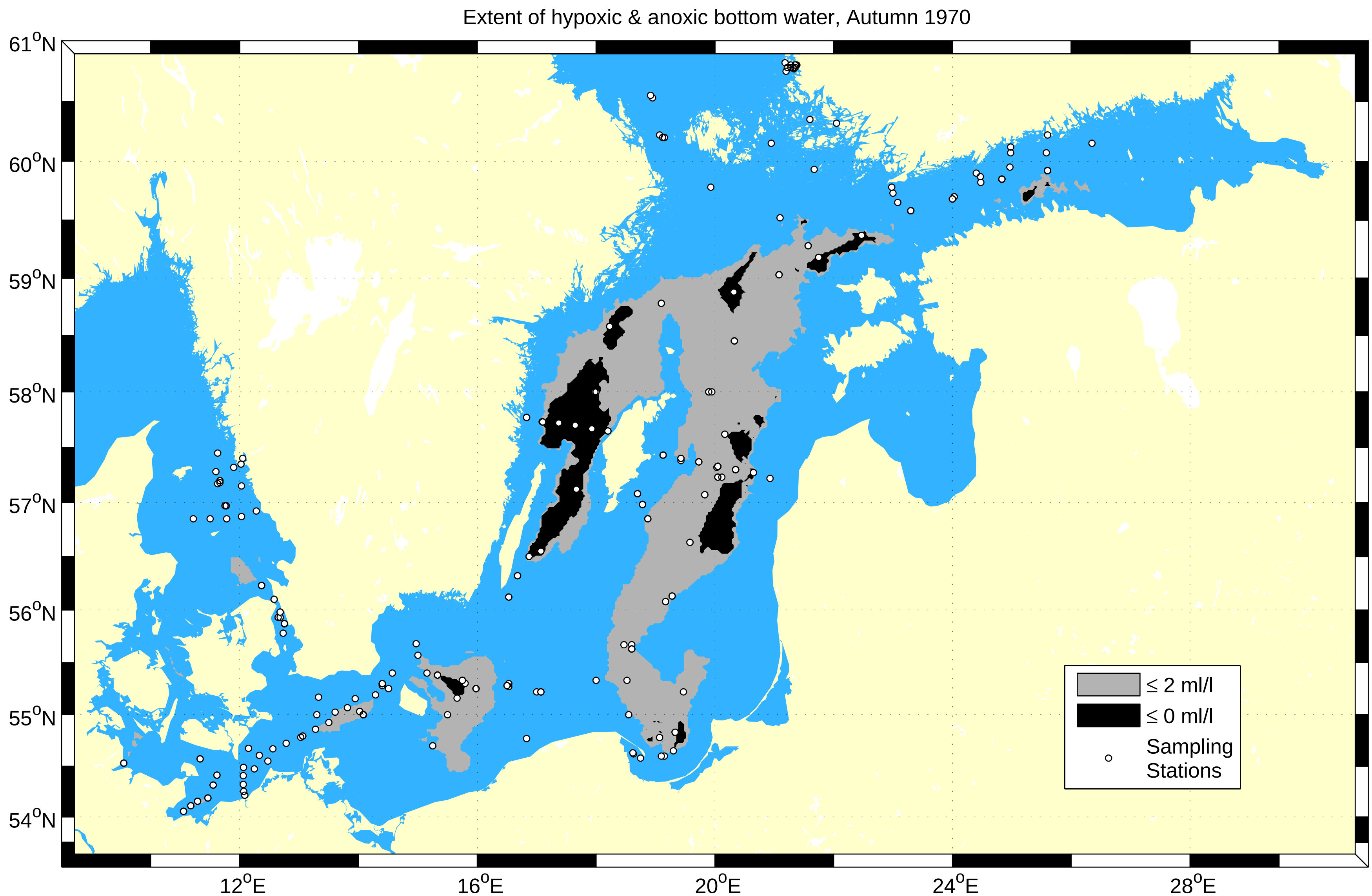


Extent of hypoxic & anoxic bottom water, Autumn 1972



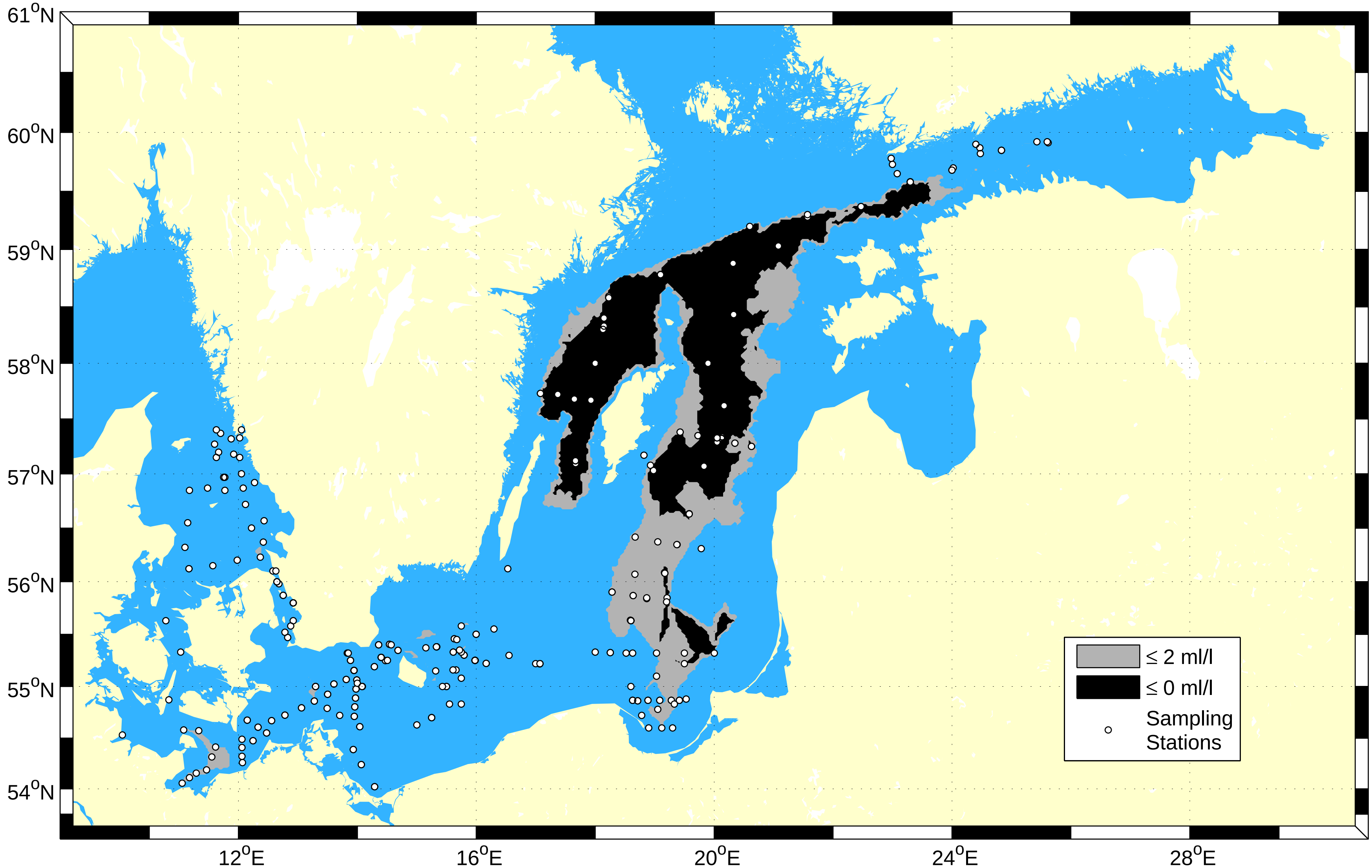
Extent of hypoxic & anoxic bottom water, Autumn 1971



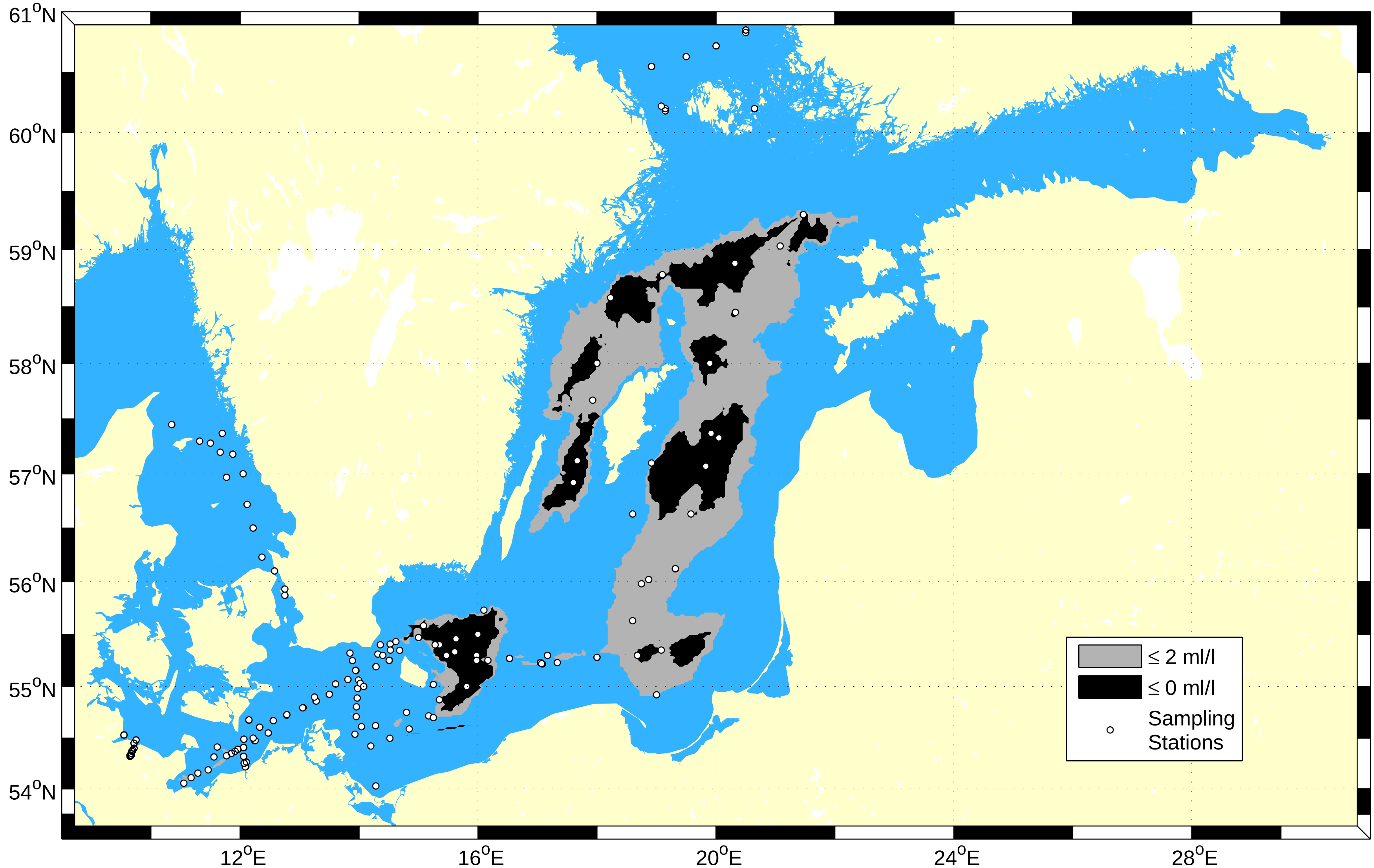


Extent of hypoxic & anoxic bottom water, Autumn 1970
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

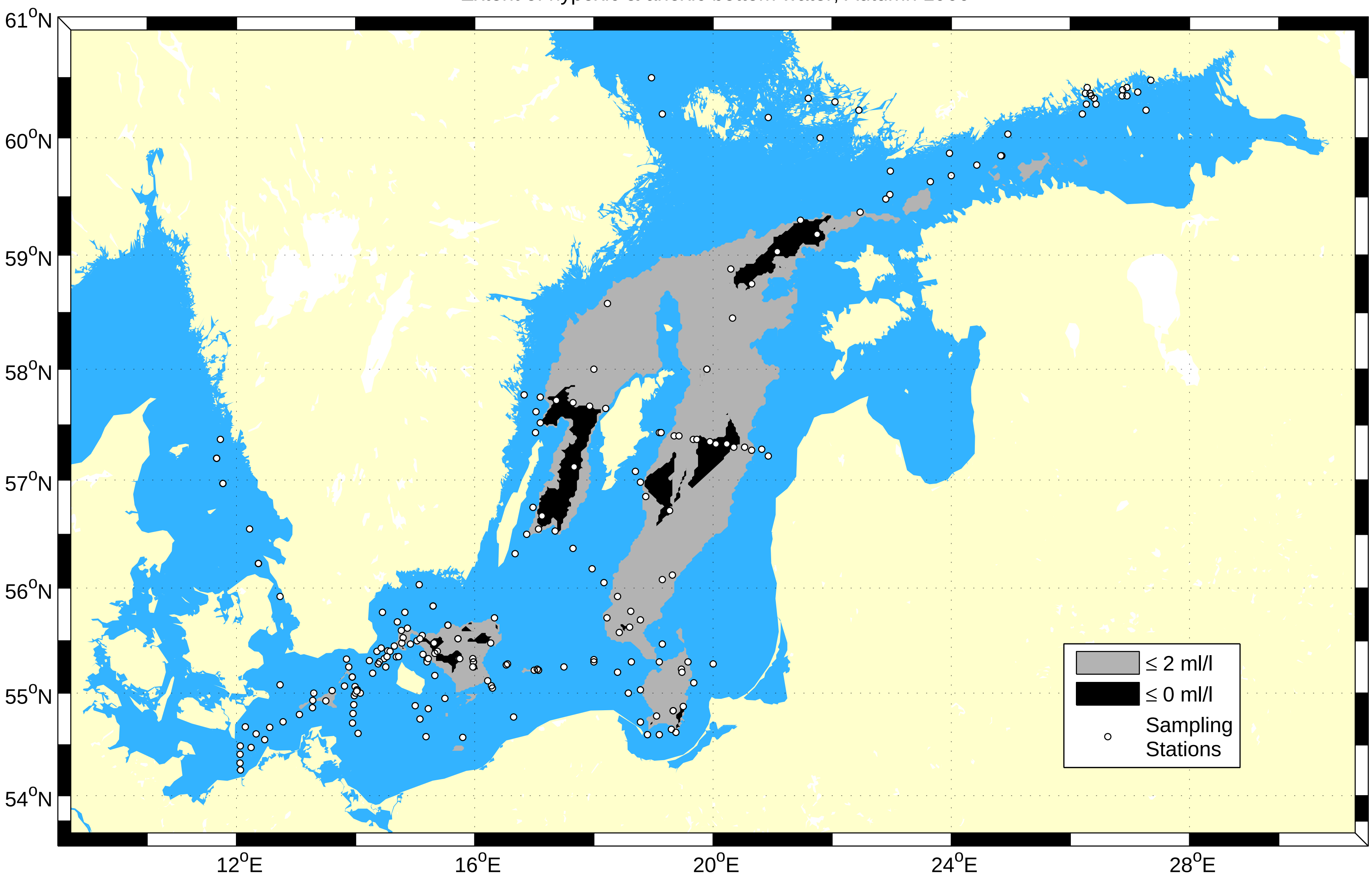
Extent of hypoxic & anoxic bottom water, Autumn 1969



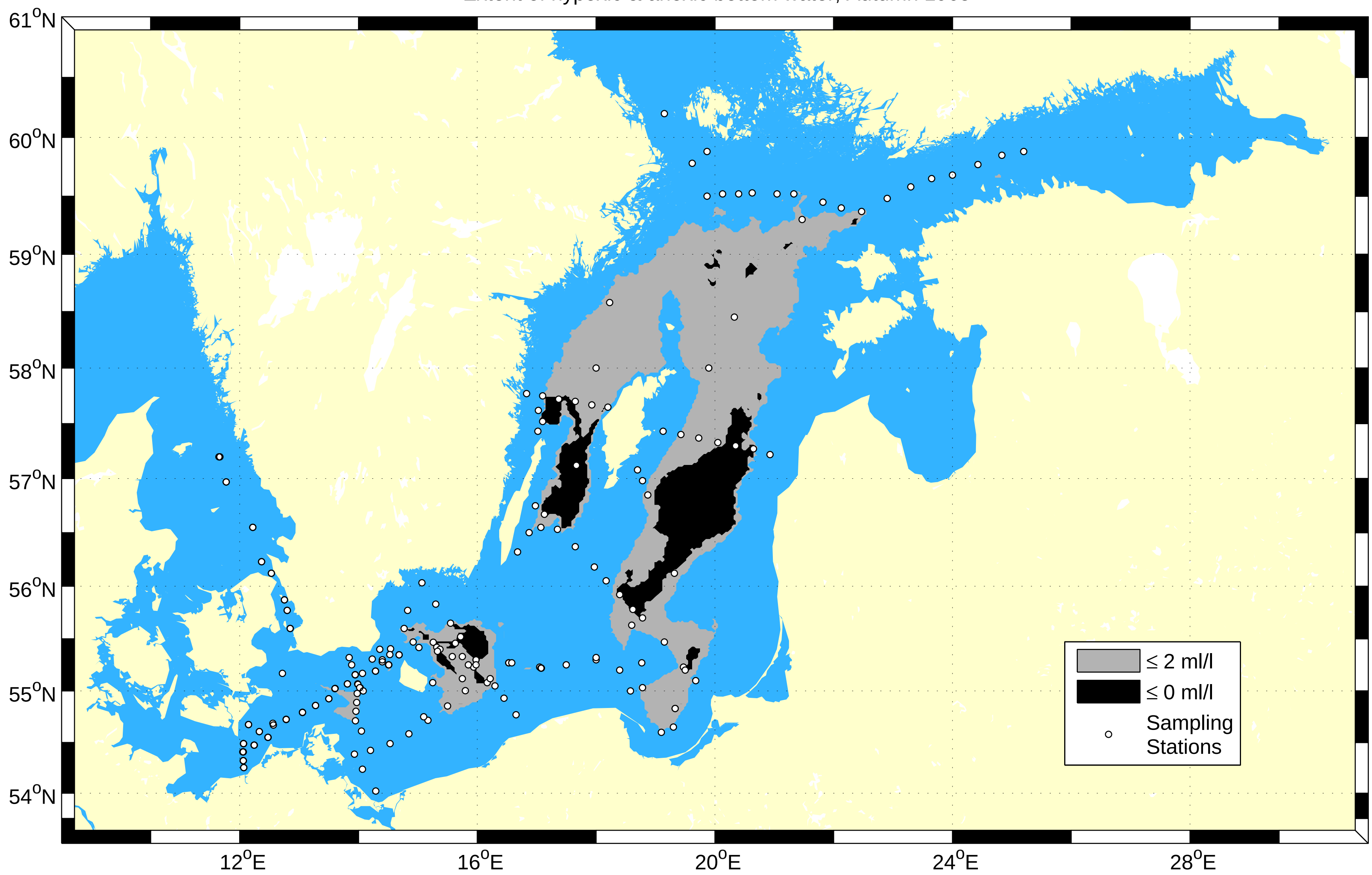
Extent of hypoxic & anoxic bottom water, Autumn 1968



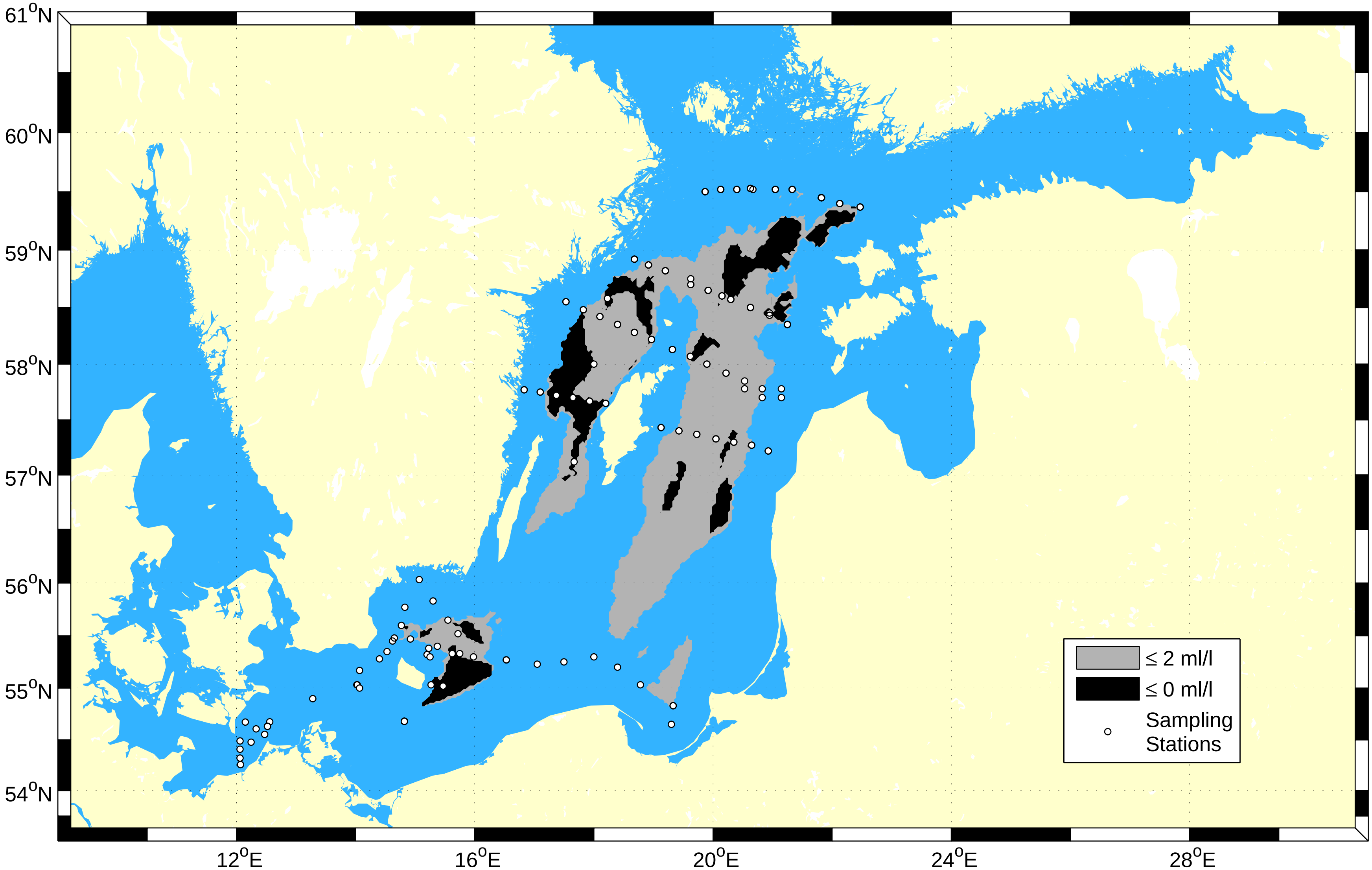
Extent of hypoxic & anoxic bottom water, Autumn 1966

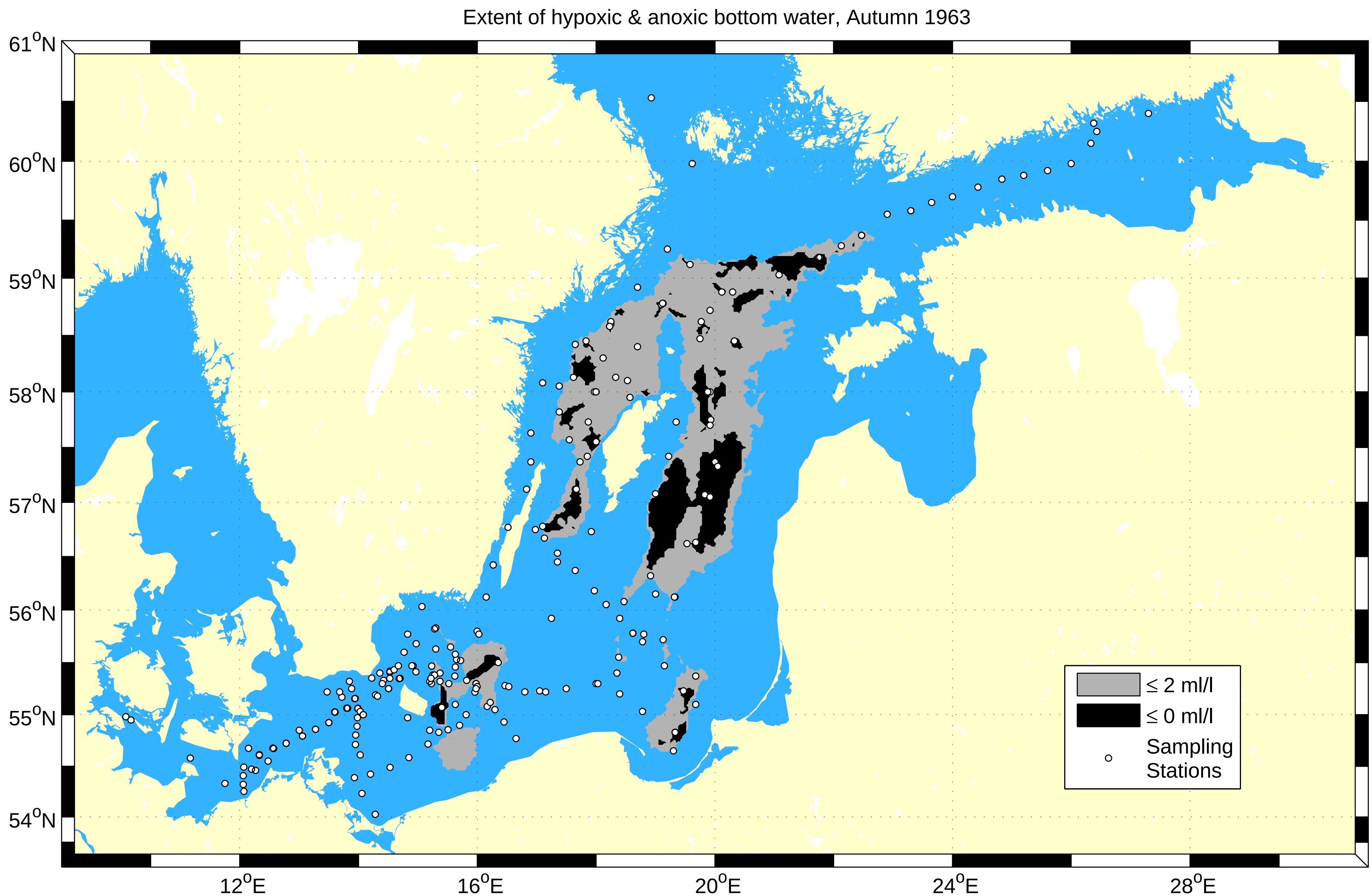


Extent of hypoxic & anoxic bottom water, Autumn 1965

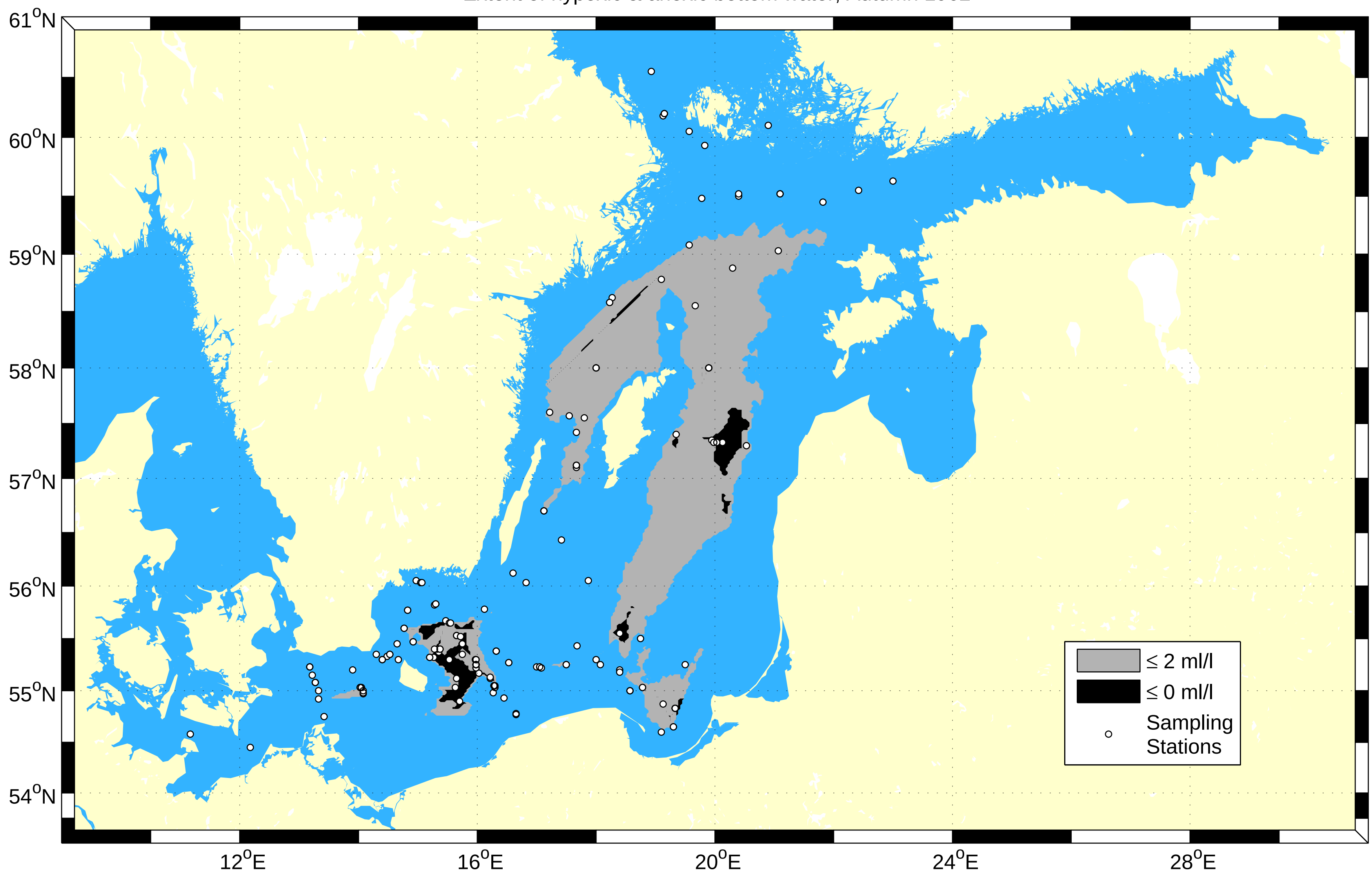


Extent of hypoxic & anoxic bottom water, Autumn 1964

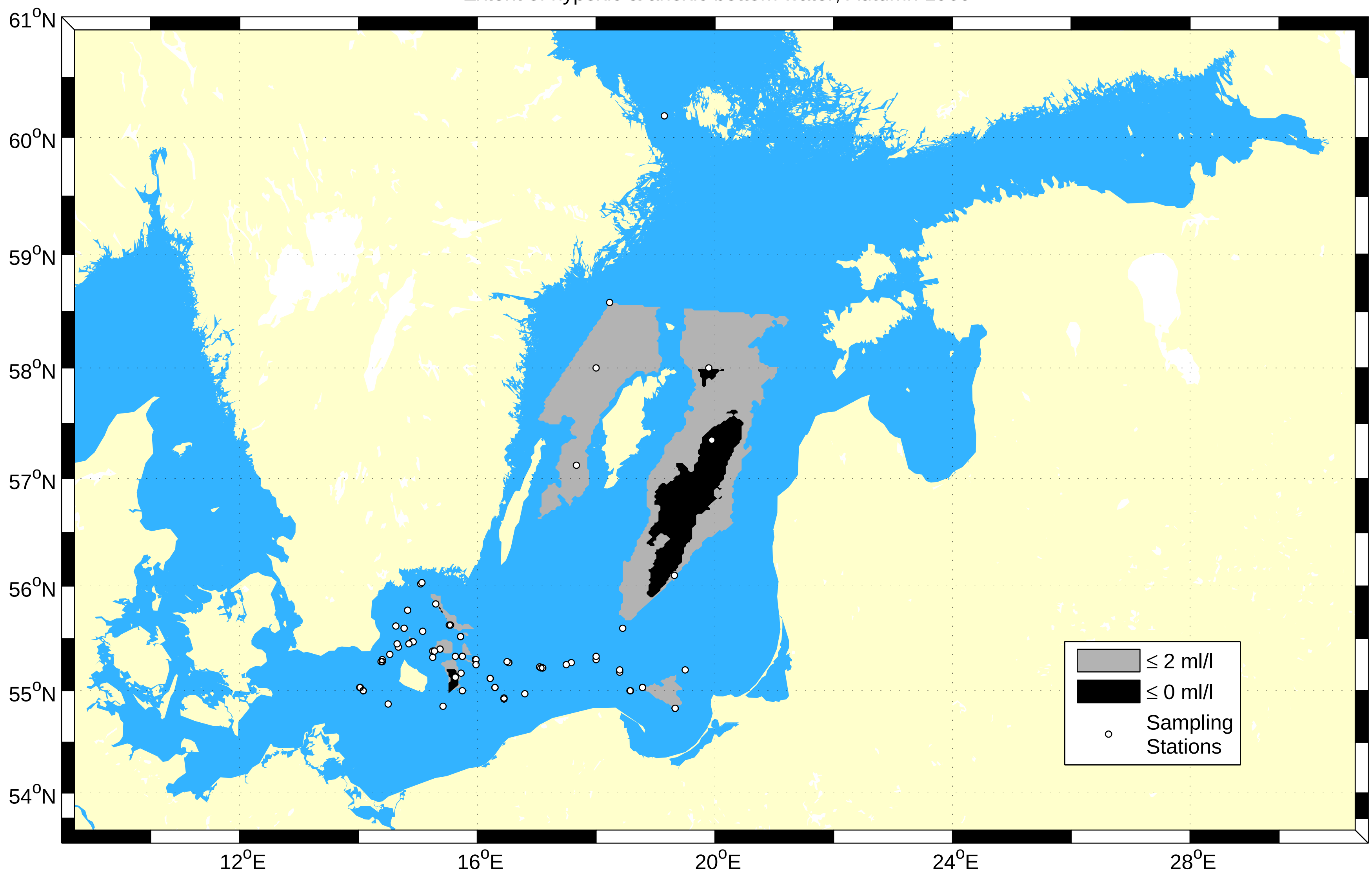



Extent of hypoxic & anoxic bottom water, Autumn 1963
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1962



Extent of hypoxic & anoxic bottom water, Autumn 1960



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