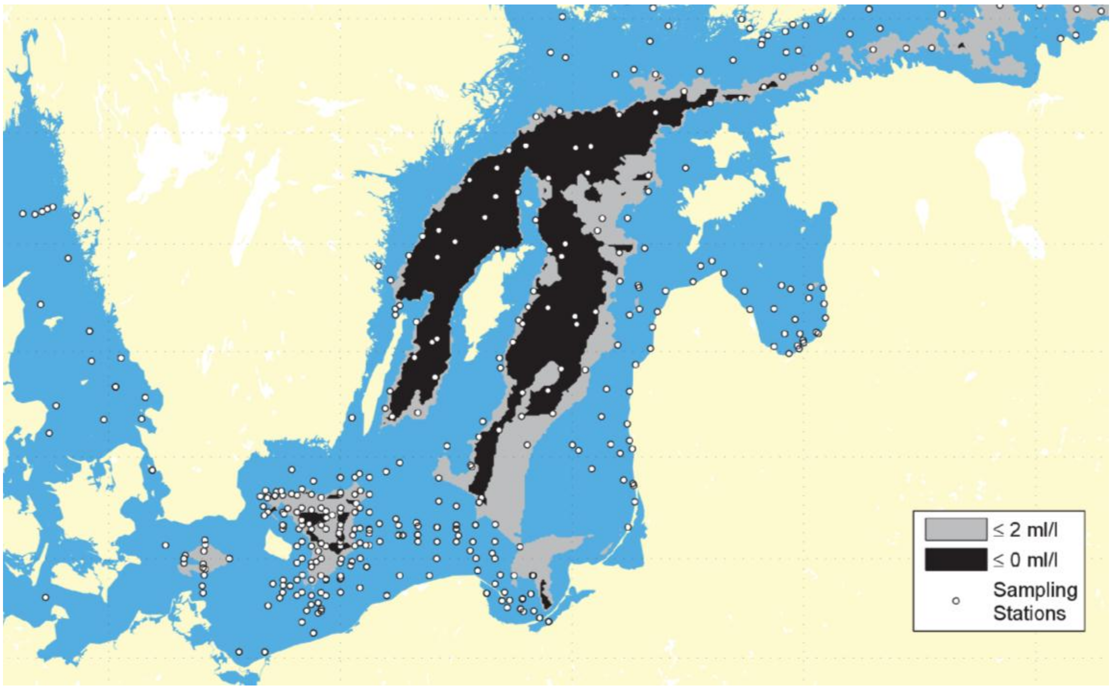
REPORT OCEANOGRAPHY No. 42, 2011

Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011



Front: Areal extent of hypoxia (grey), anoxia (black) and sampling stations (dots) in the Baltic Sea during autumn 2010.

ISSN: 0283-1112

REPORT OCEANOGRAPHY No. 42, 2011

Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011

Martin Hansson, Lars Andersson, Philip Axe

Summary

A climatology atlas of the oxygen situation in the deep water of the Baltic Sea from 1960 to 2011 has been created based on all available data from ICES. Additional data collected during the Baltic International Acoustic Survey (BIAS) have been added to the year 2011. For the autumn period, each profile in the data set was examined for the occurrence of hypoxia (oxygen deficiency) and anoxia (total absence of oxygen). The depths of the onset of hypoxia and anoxia were then interpolated between sampling stations producing two surfaces representing the depth at which hypoxic and anoxic conditions are found. The volume and area of hypoxia and anoxia have been calculated and the results have then been transformed to maps and diagrams to visualize the annual autumn oxygen situation during the analysed period.

From the analysed oxygen data 1960-2011 a distinct regime shift has been identified in 1999. During the first regime, 1960 to 1999, hypoxia affected large areas and volumes while anoxic conditions affected only minor deep areas. After the regime shift in 1999 both the areal extent and volume of hypoxia and anoxia are elevated to levels never recorded before.

Excluding the results from 2011, which are preliminary, the largest areal extent of anoxia, 18%, in the Baltic Proper (including the Gulf of Finland and the Gulf of Riga) was recorded in 2005 and the largest affected water volume, 10%, was recorded in 2001.

The cause and ecosystem effects of the new behaviour of the Baltic Sea that has been recognized after the regime shift, with continuously extreme oxygen conditions, are still not fully understood. However, there are several likely contributory and concurrent causes to the recent development such as changes in winds, changes in frequency and characteristics of inflows, increased loading of organic matter to the deep water, altered vertical mixing and stratification, and changed freshwater runoff.

Historically, the oxygen development in the deep water of the Baltic Sea has been investigated in detail and most of the processes involved, both physical and chemical, have been described. But the development during the 2000s is alarming and should be investigated thoroughly. The areal extent and volume of hypoxia have today probably reached the maximal possible extent due to the permanent stratification in the Baltic Proper. However, the extent and volume of anoxic conditions can still increase, which further can enhance the eutrophication of the Baltic Sea due to released phosphorus from sediments that previously have been oxygenated.

Sammanfattning

En klimatologisk atlas av syresituationen i Östersjöns djupvatten från 1960 till 2011 har skapats baserad på all tillgänglig data från ICES. Ytterligare data från Baltic International Acoustic Survey (BIAS) har inkluderats separat för 2011. Förekomsten av hypoxi (syrebrist) och anoxi (helt syrefria förhållanden) under höstperioden har undersökts i varje mätprofil. Djupet då 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.

Utifrån analyserade data från perioden 1960-2011 har ett distinkt regimskifte skett 1999. Under den första regimen, från 1960 till 1999, påverkade hypoxi stora områden och volymer, medan anoxi enbart påverkade mindre djupområden. Efter regimskiftet 1999 har andelen hypoxi och anoxi förhöjts till nivåer som aldrig tidigare observerats i Östersjöns djupvatten.

Den största utbredningen av anoxi, 18%, i Egentliga Östersjön (inklusive Finska viken och Rigabukten) observerades 2005 och den största påverkade vattenvolymen, 10%, noterades 2001.

Utvecklingen i Östersjön med fortsatt extrema syreförhållanden efter regimskiftet och dess orsaker och konsekvenser för Östersjöns ekosystem är idag inte helt klarlagd. Det finns emellertid flera troliga orsaker som kan samverka såsom; förändrade vindförhållanden, förändrad frekvens och karaktäristik av inflöden, ökad belastning av organiskt material till djupvattnet, förändrad vertikal omblandning samt skiktning och ändrad tillrinning till Östersjön.

Historiskt så har syreförhållanden i Östersjön undersökts i detalj och de flesta processer, både fysiska och kemiska finns beskrivna. Men utvecklingen under 2000-talet är alarmerande och måste noggrant undersökas. Utbredningen och volymen av hypoxi har idag (2011) antagligen nått den övre gränsen för vad som är fysiskt möjligt med den permanenta skiktning som finns i Östersjön. De anoxiska förhållandena kan dock fortsatt öka om den negativa utvecklingen fortsätter, vilket ytterligare kan förvärra övergödningsproblematiken i Östersjön då mer fosfor kan frigöras från bottnar som tidigare varit syresatta.

Table of contents

1 Background

Oxygen is essential to sustain the life of higher organisms, including fish and invertebrates living in aquatic habitats. The exchange between atmosphere and the ocean surface together with phytoplankton photosynthesis normally make the ocean surface layer saturated with oxygen. The dissolved oxygen in the surface layer is mixed or diffused into the lower water column where it is consumed by organisms, especially by microorganisms. When oxygen supply to the deep layers is reduced due to stratification or if there is a high consumption rate, oxygen concentrations become depleted.

Hypoxia is a condition that occurs when dissolved oxygen falls below the level needed to sustain most animal life. The concentration at which various animals are affected varies, but generally effects start to appear when oxygen drops below 2.8-3.4 ml/l (4- 4.8 mg/l) and acute hypoxia is usually defined between 1.4 – 2.1 ml/l (2-3 mg/l) [Rabalais, 2001; Diaz & Rosenberg, 1995; Aertebjerg et al. 2003]. 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, Swedish EPA, 2007]. In this report the limit for hypoxia is set to 2.0 ml/l.

Anoxic conditions are the state of oxygen depletion with total absence of oxygen. When all oxygen is consumed by microbial processes hydrogen sulphide is formed, which is toxic for all higher marine life. Anoxic conditions lead to release of phosphate and silicate 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 favour phytoplankton growth, especially cyanobacteria in the Baltic Sea during summer. This phenomenon could clearly be seen after the inflow 2003 when intermediate water was mixed into the surface layer. Phosphate concentrations in the Northern and Western Gotland Basin during early 2004 were elevated to levels never observed before in the surface water of the Baltic Proper [R/V Argos cruise reports, SMHI 2004].

The oxygen conditions in the deep water of the Baltic Sea are strongly influenced by inflows of saline oxygenated water from the Skagerrak and the Kattegat. These inflows are limited by narrow and shallow sills in the Little and Great Belts and the Sound. Only large inflows, which occur sporadically due to certain oceanographic and meteorological conditions, are able to renew the deep water of the central Baltic Proper. Inflowing deep water propagates through the Arkona Basin and reaches the Bornholm Basin. When this basin is filled the deep water continues along the Slupsk channel into the Eastern Gotland Basin, propagating counter clockwise around the Gotland island to the Western Gotland Basin, see Figure 1. As deep water flows into the central parts of the Baltic Proper, salinity decreases due to mixing and the oxygen concentration decreases due to both mixing and consumption. However, conditions in the deep basins improve and the amount of oxygen increases. The increase varies depending on both the oxygen content and the salinity of the inflowing deep water, and the present oxygen situation in the different deep basins.

As the initial effect of major inflows leads to increasing oxygen concentrations, it also causes increased stability of the stratification due to high salinity and low temperature, consequently followed by decreased vertical mixing and stagnation of the deep water. However, in the deep basins of the Baltic Proper, oxygen concentrations usually increase during the later phase of a stagnation period. This increase is caused by intensified advection at intermediate depths and by increasing vertical exchange as the stratification becomes weaker [Feistel et al., 2005].

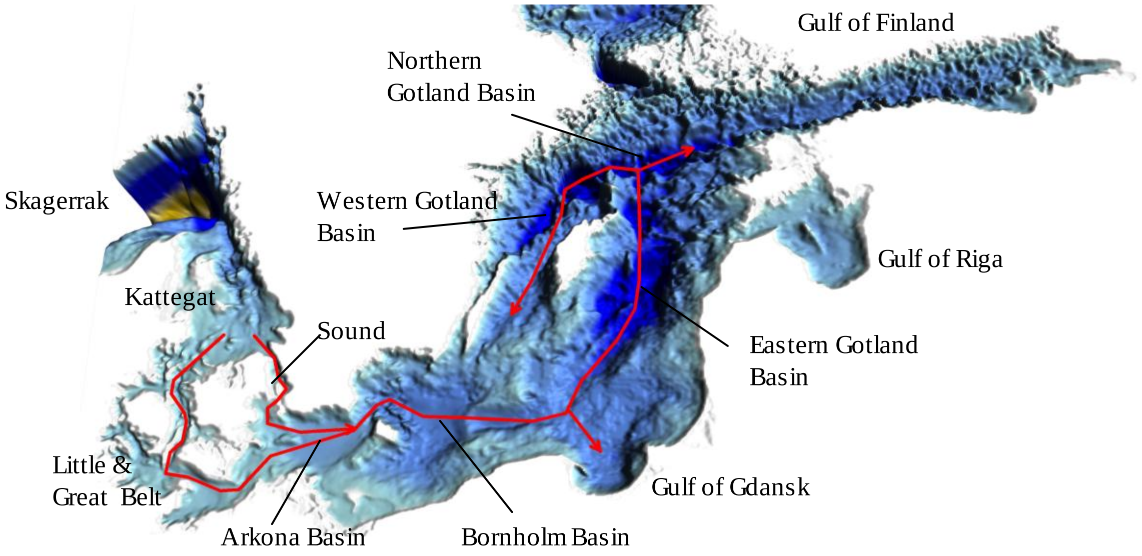


Figure 1. Bathymetry of the south Baltic Sea and pathway of inflowing deep water during inflows. The Baltic Proper includes the Arkona Basin, the Bornholm Basin, the Gulf of Gdansk and the Eastern-, Western- and Northern Gotland Basin [Fonselius, 1995].

The permanent halocline is located at a depth of about 60-80 meters in the main part of the Baltic Proper. During wintertime when the thermocline weakens the upper layer becomes well mixed and oxygenated down to the halocline. This sets the upper limit for the areal extent and volume of hypoxia and anoxia, see Figure 2.

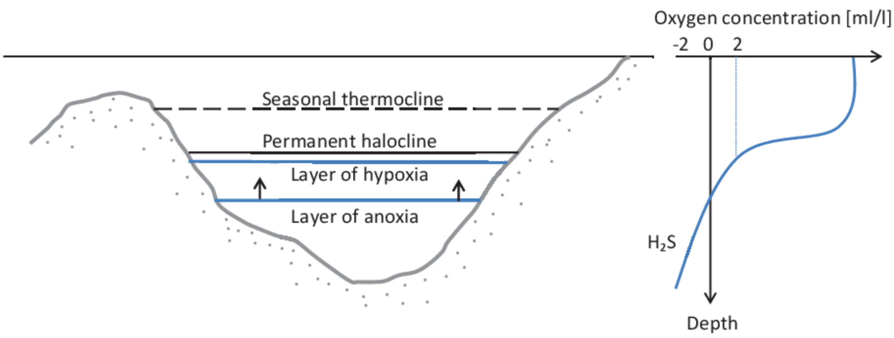


Figure 2. Principle sketch of the stratification in the Baltic Proper and the general oxygen concentration, during recent years.

In the central and northern parts of the Baltic Proper the oxygen situation in the deep water, below the permanent halocline, is relatively stable throughout the year. In the southern parts, however, there is a clear annual cycle in the oxygen concentration in the deep water, due to the direct effect of inflows and a smaller volume of deep water compared to the central and northern basins, see Figure 3. Since the oxygen situation is most severe during autumn (August-

October), this period has been chosen in the analysis of the areal extent and volume of hypoxia and anoxia.

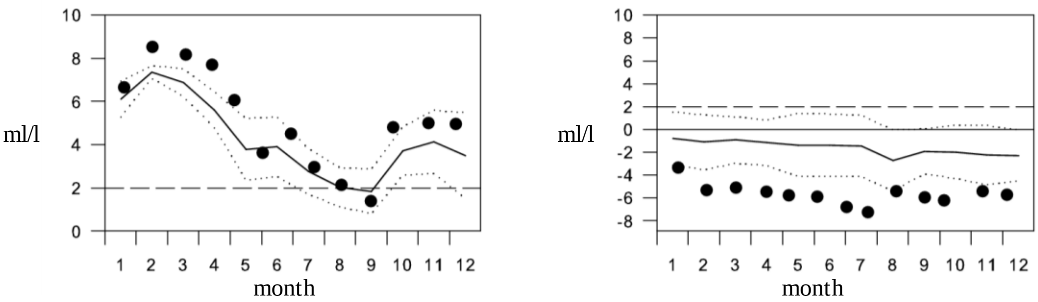


Figure 3. Annual cycle of oxygen in bottom water at the stations BY2 in Arkona (left) and BY15 in the eastern Gotland Basin (right). 10 year mean (solid line) and measurements during 2010 (dots). Hydrogen sulphide recalculated to negative oxygen. Limits for hypoxia (2 ml/l) shown as a dashed line and anoxia (0 ml/l) as a solid line. [R/V Argos cruise report, December 2010]

In this report a time series of the bottom areal extent and deep water volume of anoxic and hypoxic autumn conditions of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, are presented for the period 1960 to 2011. The report includes maps of bottom areas affected by oxygen deficiencies which can be used as a climatological atlas describing the historical development and the present oxygen situation in the Baltic Proper.

2 Data

Oxygen measurements from the Baltic Sea are available from the 1890s, but are sparse and also uncertain due to the measuring technique [Fonselius, 1995]. Since 1902 to present, oxygen has been measured using basically the same method, Winkler titration [Grasshoff, 1999]. Hydrogen sulphide is measured using colorimetric determination as methylene blue and has in this analysis been recalculated to negative oxygen [Fonselius, 1969].

Until the 1950s there are only a few sampling occasions each year, hence there are not enough data to generate distribution maps of the oxygen situation.

During the 1960s and 1970s, the quantity, quality and spatial distribution of oceanographic data improved. Much a result of the initiatives taken during the International Baltic Year (IBY) 1969-1970, which main objective was to investigate the deterioration of the oxygen conditions in the Baltic Sea. Due to the success of the IBY it was recommended at the conference in Helsinki in 1970 the voluntary continuation of the IBY programme for the following years.

In 1974, the Helsinki Commission (HELCOM) was formed and the IBY programme was followed by the Baltic Monitoring Programme (BMP) in 1979. To harmonize the different programmes into a common structure, the Cooperative Monitoring in the Baltic Marine Environment (COMBINE) was instituted in 1992. This included a manual defining the contribution made by all contracting parties and regulates all measuring methods used, which further has improved the data quality. [Feistel et al., 2005, HELCOM, 2010]

For the period 1960 to 2010, the analysis is based on data from the ICES Dataset on Ocean Hydrography[1]. Although results from the 1960s are presented in this report it should be noted that the amount and spatial distribution of data available are low during some years. The available data are concentrated to the southern and western Baltic Proper. During 1961 and 1967, questionable data were found and were filtered out, which resulted in that no samplings at all were found in the Gotland basins and the Gulf of Finland, making the results uncertain. Hence, these years has been excluded from the time series.

The results for 2011 are based on data from SMHIs own cruise performed within the national monitoring programme and data from the annual stock assessment, Baltic International Acoustic Survey (BIAS) cruise, with contribution from Latvia, Lithuania, Germany and Poland. Results from 2011 are preliminary, and has been subject to initial quality control only (quality assured laboratory procedures; timing and position checks; range checking). The time series and the values presented for 2011 will be updated when additional data are reported to ICES in 2012.

Data from the BIAS cruises are well suited for concurrent oxygen surveys because of the vast spatial distribution of sampling occasions and since cruises are performed during September and October. Hence, an essential contribution of oxygen data complementing the regular national monitoring performed monthly at fixed stations.

3 Method

To process the dataset and perform calculations 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.

For the annual 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 the depth of 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.

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] to exclude profiles were the hypoxic and anoxic depths were greater than the actual water depth. After filtering of the results, the affected area and volume of hypoxia and anoxia have been calculated for each year.

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 according to the sub-basins commonly used [Fonselius, 1995].

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

4 Result

The areal extent and volumes affected by hypoxia and anoxia during the period 1960 - 2011 are presented in Figures 4 and 5 respectively. Maps presenting bottom areas affected by hypoxia and anoxia during the autumn period can be found in Appendix 2.

In the analysis of the results a distinct regime shift, starting in 1999, has been identified, see Figures 4-6.

From 1960 to the late 1990s anoxic conditions affected, in average, 5% of the bottom areas (corresponding to 2% of the volume) in the Baltic Proper, including the Gulf of Finland and the Gulf of Riga. Hypoxic conditions during this period affected, in average, 22% of the bottom areas (corresponding to a 13% of the volume). Since the beginning of the 2000s both hypoxia and anoxia have increased. Anoxic conditions are found, in average, 15% of the bottom areas (corresponding to 8% of the volume) and hypoxic conditions affect about 28% of the bottom areas, which correspond to 18% of the water volume. See Table 1.

Hence, bottom areas affected by anoxic conditions have increased from 5% to 15%, i.e. by a factor of 3, and hypoxia has increased from 22% to 28%, i.e. by a factor of about 1.3. This increase, leading to the regime shift, is clearly seen in Figure 6a, which shows the ratio between the areal extent of anoxia and hypoxia.

To verify the regime shift a sequential T-test for analysis of regime shifts (change point detection in mean level), [Rodionov, 2004] has been used on the data set, see Figure 6b. Non-zero values of the rsi-index indicate regime shift points and a regime shift can be seen starting in 1999.

Table 1. Mean areal extent and volume of anoxia and hypoxia before and after the regime shift, calculated as part (%) of the area and volume of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga.

in %	1960 – 1998		1999 – 2011	
	Hypoxi	Anoxi	Hypoxi	Anoxi
Mean Areal extent	22	5	28	15
Max Areal extent (Year)	27 (1968)	14 (1969)	32 (2007)	18 (2005)
Mean Volume	13	2	18	8
Max Volume (Year)	19 (1965)	8 (1969)	20 (2010)	10 (2001)

Excluding data from 2011 which are preliminary, the largest areal extent of anoxia, 18%, was recorded in 2005, corresponding to a water volume of 9%, while the largest volume of anoxia, 10%, occurred in 2001, affecting 17% of the area.

Still excluding 2011, the areal extent of hypoxia has since 1993 increased from about 9% to 32% in 2007. The widespread hypoxia during 2007, the largest noted, corresponds to a water volume of one fifth (20%) of the investigated area. The discrepancy between the largest noted areal extent and volume is due to the fact that different areas, with different hypsographic conditions, are affected.

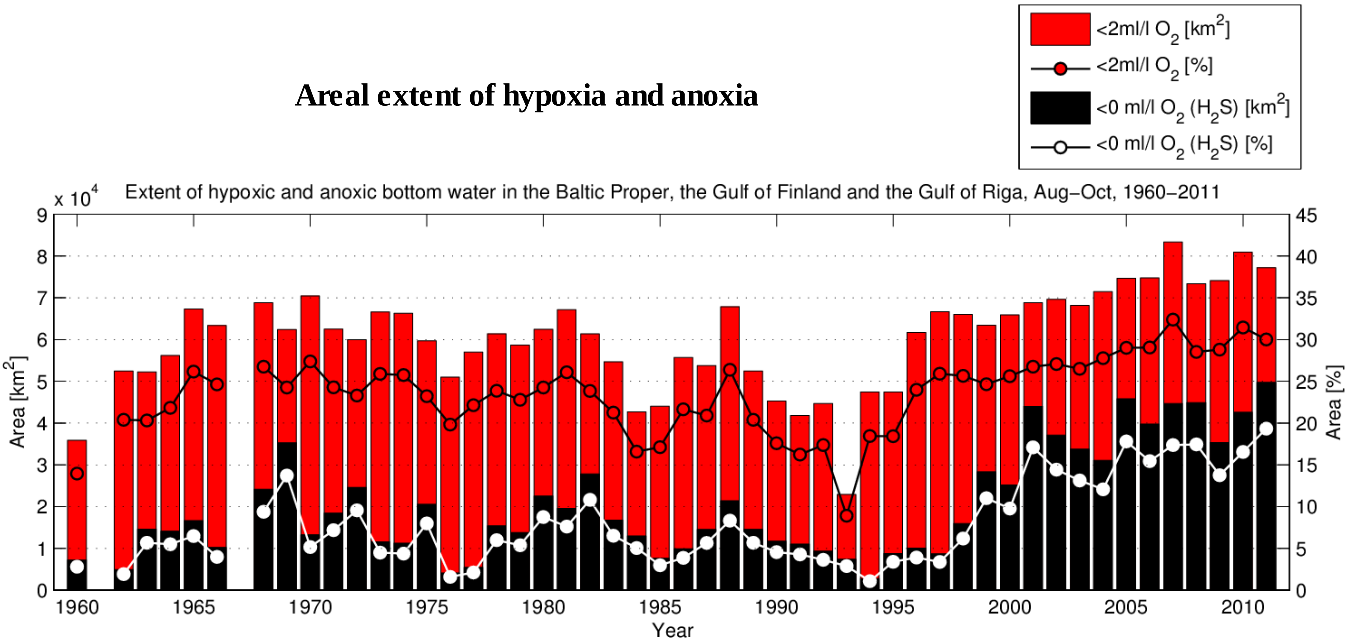


Figure 4. Areal extent of anoxic and hypoxic conditions in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed since sufficient data from the deep basins are missing.

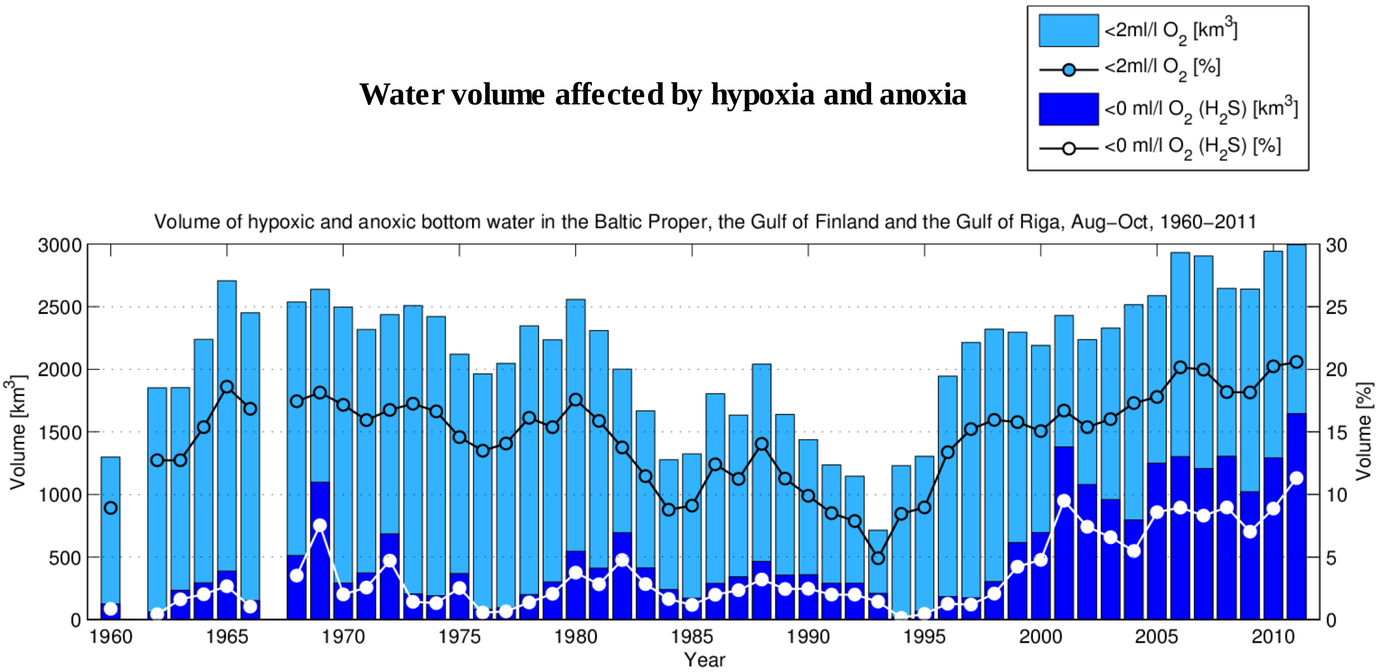


Figure 5. Volume of anoxic and hypoxic deep water in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed since sufficient data from the deep basins are missing.

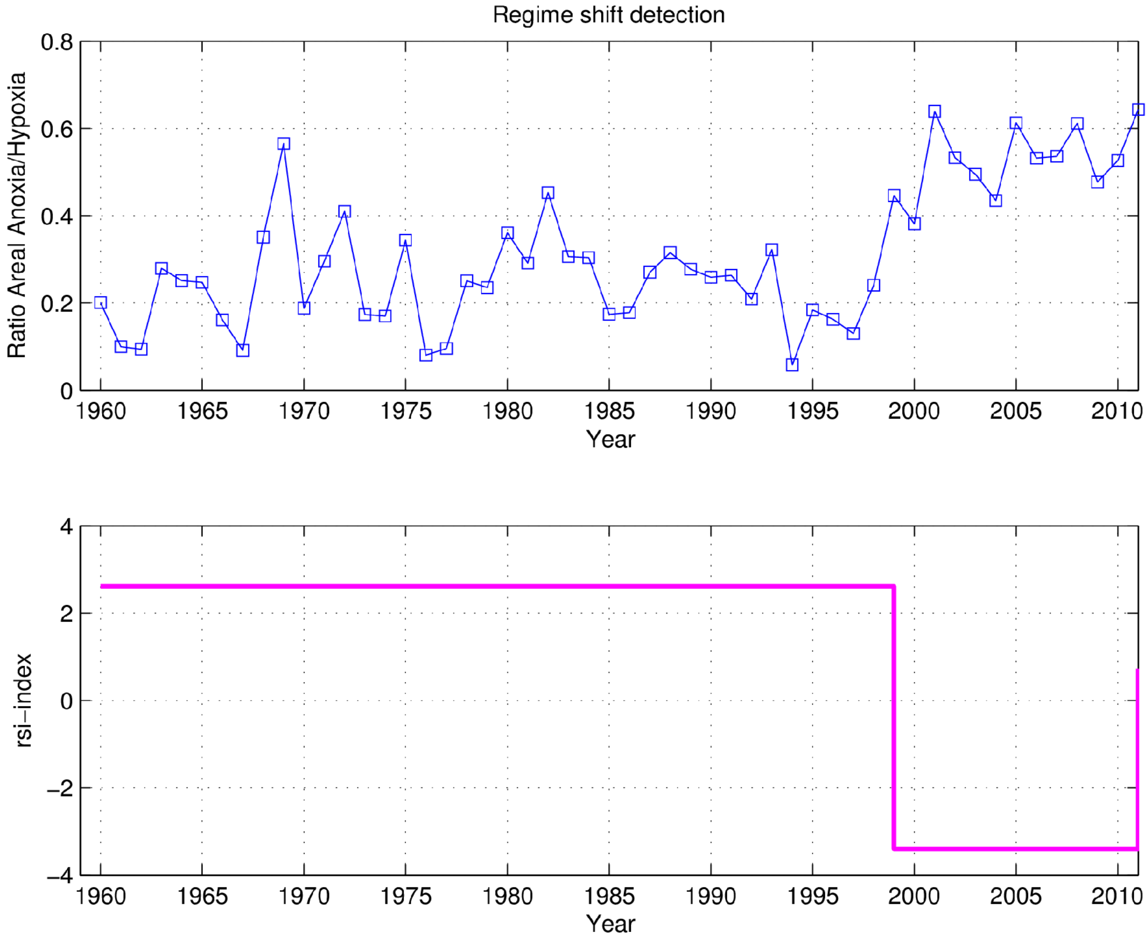


Figure 6. a) Top: Ratio between areal extent of anoxic and hypoxic conditions. b) Bottom: Analysis of regime shifts. Length of analysis window (L)=3, significance (p)=0.10 (90%), Huber weight parameter for outliers (h)=1.0 [Rodionov, 2004]. A regime shift has been identified, starting in 1999.

5 Discussion

Both the intensity and frequency of major Baltic inflows have decreased considerably since the mid 1970s and large inflows have been totally absent during long periods since the 1980s, see Figure 7. This decrease in inflows can most likely be connected to variations in atmospheric conditions and increased zonal circulation, which results in both more precipitation and increased river runoff [Feistel, 2005]. Long periods of easterly winds, which is needed to lower the sea level in the Baltic Sea and to initiate an inflow, have been absent and the prevailing winds have remained westerly during most winters. Steady westerly winds and increased freshwater supply keep the sea level high in the Baltic Sea which prevents inflows. As the outflow of low saline water from the Baltic Sea increases the salinity in the Kattegat decreases. Owing to that, when inflows do occur, the salinity of inflowing water is too low. Hence, the water is not dense enough to renew the bottom water. [Meier & Kauker, 2003]

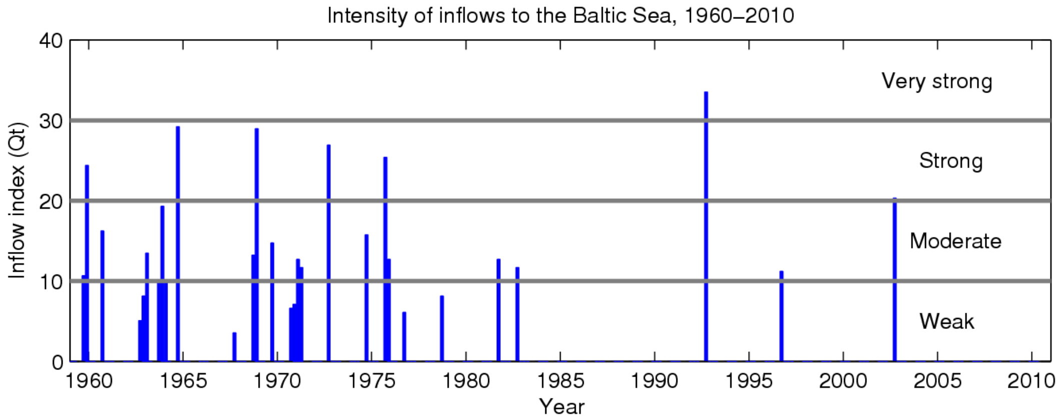


Figure 7. Index of inflows to the Baltic Sea, 1960-2011. From Fischer, H., Matthäus, W. 1996 & Matthäus, W., Franck, H. 1992. Revised and updated.

Before the regime shift in 1999, during the stagnation period in the 1980s and 1990s, oxygen conditions improved as the stratification became weaker. This process, which could be expected in the 2000s, has not been seen since the inflow in 1993. Both anoxic and hypoxic conditions have remained on a steady enhanced level. A hypothesis is that the frequency of small and medium, both barotropic and baroclinic inflows, which generally are found at intermediate depths close to the halocline in the central Baltic Proper keeps the stratification strong, preventing the exchange between the oxygenated surface layer and the oxygen depleted deep water. Warm water inflow (containing less oxygen than cold) during the autumn/summer period as described already for 2002 [Feistel, 2005], seems to be an indication of a new trend in the long term behavior of the Baltic Sea. Baroclinic summer inflows can also contain water with exceptionally high temperature which further enhances microbial oxygen consumption. [Feistel, 2005].

During 2004 and 2005 no noticeable inflows occurred. In 2006 a baroclinic inflow of warm water occurred during the summer which improved oxygen levels in the Eastern Gotland Basin to above 0 ml/l for a short period in 2007. After 2006, several minor inflows have taken place, improving the oxygen situation in the Arkona Basin and parts of the Bornholm Basin. These inflows have settled at intermediate depths in the central Baltic Proper and have not affected the deep water. This is demonstrated in Figure 8, which shows the temperature, salinity and oxygen concentration at 240 meters depth at BY15 situated in the eastern Gotland Basin. A figure of the whole water column at BY15 can be found in Appendix 1.

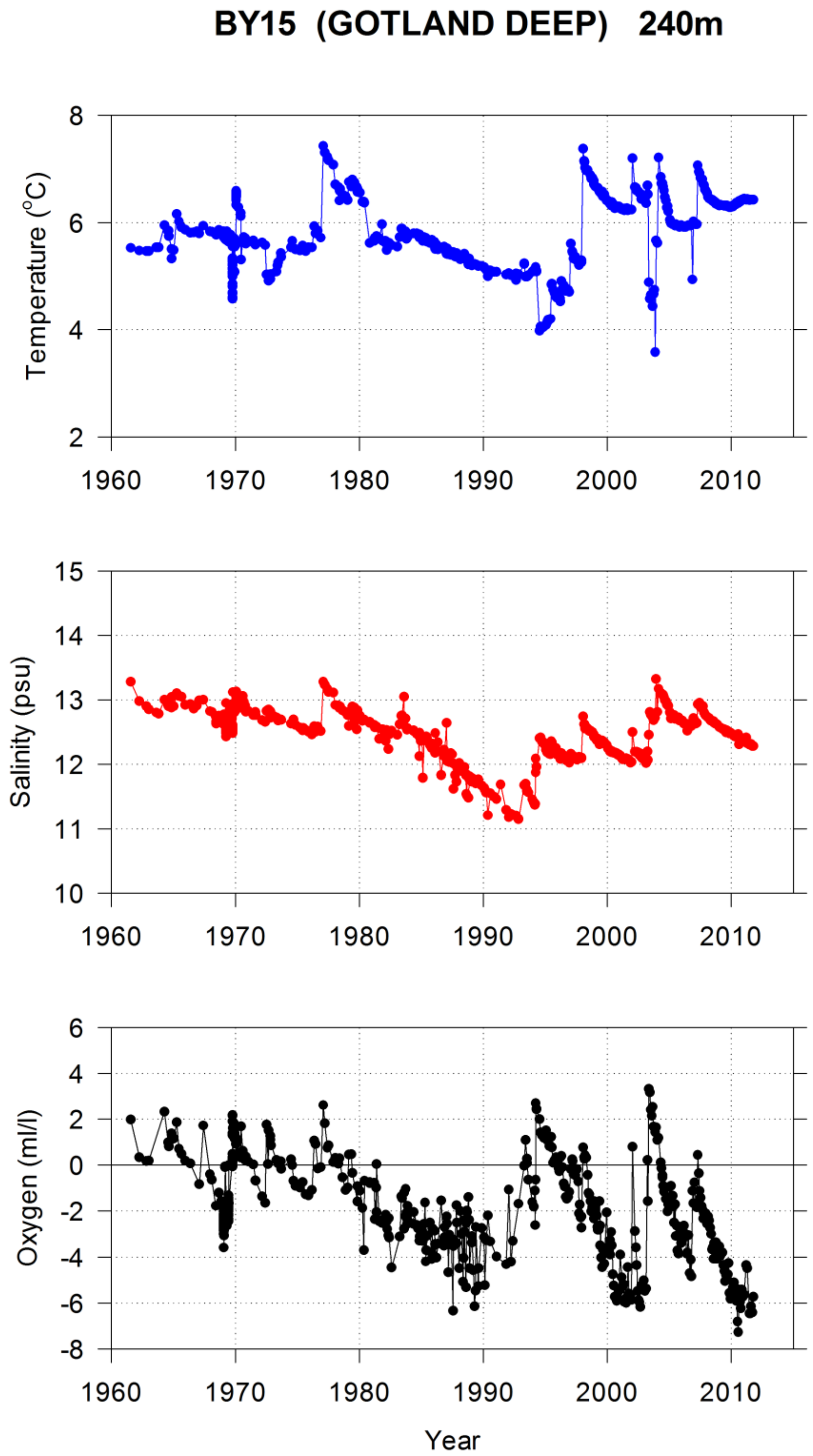


Figure 8. Temperature, salinity and oxygen at BY15, 1960-2011. See also Appendix 1 for the whole water column including phosphate.

From Figure 8 it is also clear that the decrease in oxygen concentration after an inflow has become a faster process. After the major inflow in 1976 the oxygen concentration in the eastern Gotland Basin decreased, during 13 years, from 2.6 ml/l to a minimum of -6.1 ml/l in 1989. In 1993 a major inflow elevated the oxygen concentration to 2.7 ml/l (1994) and it reached a minimum, -6.2 ml/l, after 9 years, in 2002. After the inflow 2003 oxygen concentration decreased from 3.3 ml/l to -4.7 ml/l, after only 3 years, in 2006. Gustafsson & Stigebrant (2007) discussed that the increased oxygen consumption is connected with a larger pool of organic matter in recent years. Earlier, the decomposition could not increase with increasing oxygen concentrations due to lack of organic matter. One possible cause to a larger pool is the increased organic load to the deep water as a result of eutrophication, i.e. increased production in the surface layer.

Historically, the oxygen development in the Baltic Sea has been investigated in detail and most of the processes involved, both physical and chemical, are described. But the recent development during the 2000s is unclear. The areal extent and volume of hypoxia have today probably reached the largest possible extent due to the permanent stratification in the Baltic Proper. However, the extent and volume of anoxic conditions can still increase, see Figure 2 and 6a, which further can enhance the eutrophication of the Baltic Sea due to released phosphorus from sediments that previously have been oxygenated.

6 Conclusions

- A regime shift has been identified during the period 1960-2011:

  - The first regime, 1960s to late 1990s: hypoxia affected large areas and volumes while anoxic conditions affected only minor deeper areas. During the 1990s hypoxia gradually decreased, while anoxic conditions remained more or less unchanged

  - The second regime, 1999 to present: the area and volume of both hypoxia and anoxia are elevated to levels never recorded before. The largest areal extent of anoxia, 18% of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, was observed in 2005 and the largest affected water volume, 10%, was recorded in 2001.

  - The areal extent of hypoxia, 29% after the regime shift in 1999, corresponds to a water volume of 18%. The largest areal extent of hypoxia, 32%, was recorded in 2007 and the largest affected water volume, 20%, was observed in 2010.

  - The oxygen concentration after a major inflow decreases more rapidly in later years.

- The regime shift and a new behaviour of the Baltic Sea with continuously extreme oxygen conditions and its causes and ecosystem effects are still not fully understood.

- There are several likely contributory and concurrent causes to the recent development such as changes in winds, changes in frequency and characteristics of inflows, increased loading of organic matter to the deep water, altered vertical mixing and stratification, and changed freshwater runoff.

- Additional work, including more observations, is needed to fully understand the present oxygen situation and its effects on the ecosystem.

7 Acknowledgement

This work was possible due to the excellent web service at The International Council for the Exploration of the Sea, ICES, making the ICES Dataset on Ocean Hydrography available.

Many thanks to Dr. Georgs Korņilovs, Head of Fish Resources Research Department at the Institute of Food Safety, Animal Health and Environment (BIOR) in Riga, Latvia, Dr. Tycjan Wodzinowski & M.Sc. Lena Szymanek, Department of Fishery Oceanography and Marine Ecology, Sea Fisheries Institute in Gdynia, Poland and Tomas Gröhsler & Matthias Schaber at the Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute of Sea Fisheries, Germany for their cooperation regarding exchange of oxygen data within BIAS during 2010 & 2011. Many thanks also to Nijole Remeikaite at the Lithuania Marine Research Department, Environment Protection Agency, Data Management and Programmes Division for oxygen collected along the Lithuanian coast.

Thanks also to the four reviewers for fruitful comments and suggestions on this report.

8 References

Aertebjerg, G., J. Carstensen, P. Axe, J-N. Druon & A. Stips, 2003: The oxygen Depletion Event in the Kattegat, Belt Sea and Western Baltic. Baltic Sea Environment Proceedings No. 90. Helsinki Commission Baltic Marine Environment Protection Commission. ISSN 0357-2994.

Diaz, R. J. & Rosenberg, R., 1995: Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna, Oceangr. Mar. Bio. Ann. Rev., 33, 245-303.

Feistel, R., Nausch, G. & Wasmund, N., 2008: State and Evolution of the Baltic Sea, 1952-2005: A Detailed 50-Year Survey of Meteorology and Climate, Physics, Chemistry, Biology, and Marine Environment, ISBN: 978-0-471-97968-5.

Fischer, H., Matthäus, W., 1996: The importance of the Drogden Sill in the Sound for major Baltic inflows. J. Mar. Res., 9, 137 - 157.

Fonselius, S., 1969: Fishery Board of Sweden, Ser. Hydrography, Rep. 23, 22.

Fonselius, S., 1995: Västerhavets och Östersjöns Oceanografi. ISBN 91-87996-07-3.

Grasshoff, K., Kremling, K., & Ehrhardt, M., 1999: Methods of Seawater Analysis. ISBN 3-527-29589-5.

Gustafsson, B.G., & Stigebrant, A., 2007: Dynamics of nutrients and oxygen/hydrogen sulphide in the Baltic Sea deep water. J. Geophys. Res. vol. 112, G02023.

HELCOM, 2010: Manual for marine monitoring in the COMBINE Programme of HELCOM, http://www.helcom.fi.

MacKenzie, B., Hinrichsen, H.H., Plikshs, M., Wieland, K., Zezera, A.S., 2000: Quantifying environmental heterogeneity : habitat size necessary for successful development of cod Gadus morhua eggs in the Baltic Sea. Marine Ecology - Progress Series, vol: 193, pages: 143-156.

Matthäus, W. & Franck, H. 1992: Characteristics of major Baltic inflows – a statistical analysis. Cont. Shelf Syst., 12, 1375 – 1400.

Meier, H. E. M. & Kauker, F. 2003: Modeling decadal variability of the Baltic Sea: 2. Role of freshwater inflow and large-scale atmospheric circulation for salinity. J. Geophys. Res. 108:C11, 3368.

Nissling, A., 1994: Survival of eggs and yolk sac larvae of Baltic cod (Gadus morhua) at low oxygen levels in different salinities. ICES Marine Science Symposium 198:626-631.

Plikshs, M., Kalejs, M. & Grauman, G. 1993: The influence of environmental conditions and spawning stock size on the year-class strength of the Eastern Baltic cod. ICES CM 1993/J:22.

Rabalais, N. N. & Eugene, R., Turner (Editors), 2001: Coastal and Estuarine Studies, Coastal Hypoxia, Consequences for living resources and ecosystems. American Geophysical Union. ISBN 0-87590-272-3.

Rodionov, S. N. (2004): A sequential algorithm for testing climate regime shifts, Geophys. Res. Lett., 21, L09204.

SMHI, 2004: Cruise report archive: http://www.smhi.se/en/theme/marine-environment-2-885. Updated: December 6, 2010.

SMHI, 2010: Cruise report from R/V Argos: Oxygen survey in the Baltic Sea, Dnr: Mo 2010-261. URL: http://www.smhi.se.

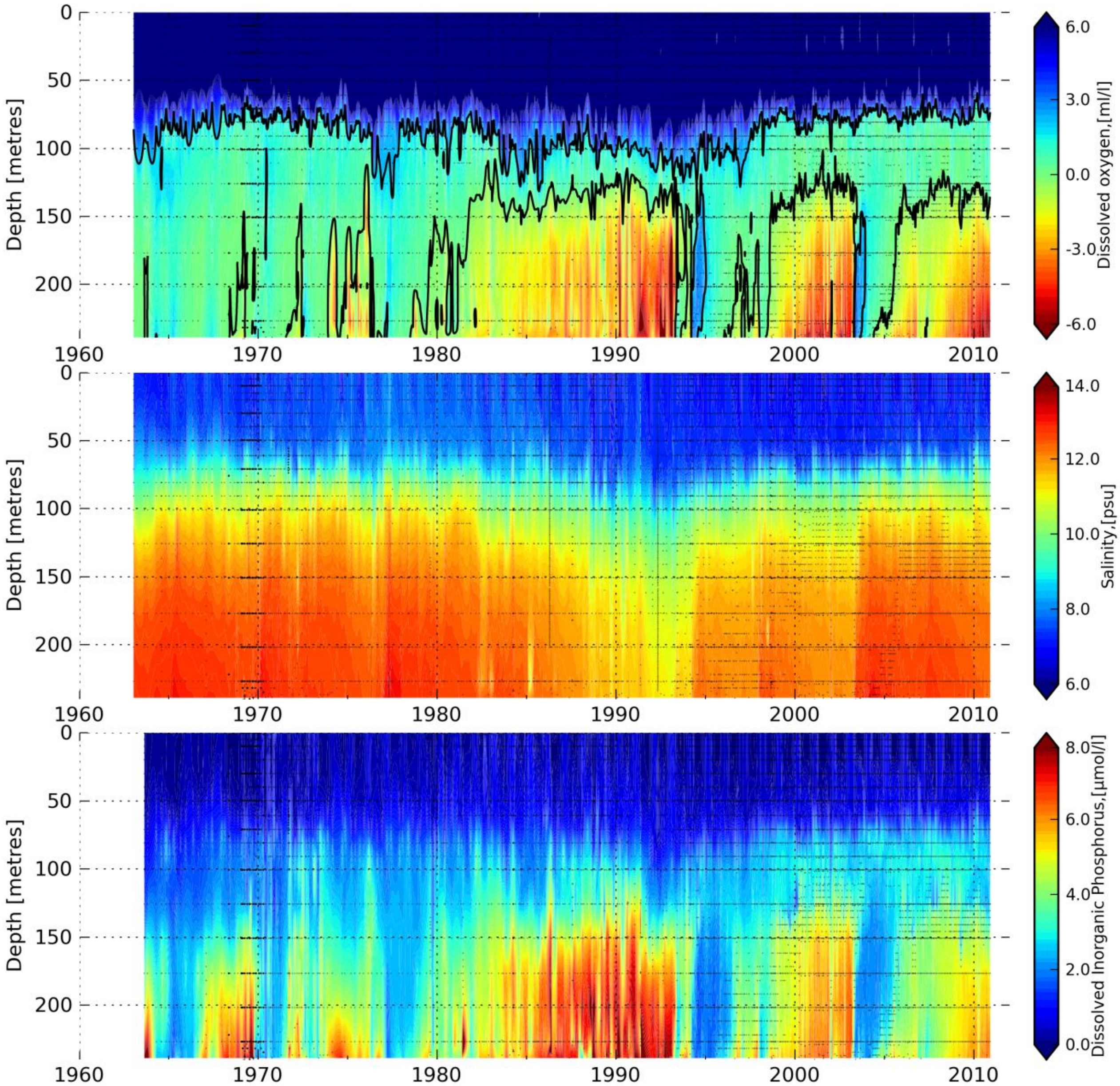
Swedish EPA, 2007: Bedömningsgrunder för kustvatten och vatten i övergångszonen, Bilaga B till handboken 2007:4, Naturvårdsverket, ISBN 978-91-620-0149-0.

T. Seifert, F. Tauber, B. Kayser: 2001: A high resolution spherical grid topography of the Baltic Sea – 2nd edition, Baltic Sea Science Congress, Stockholm 25-29. November 2001, Poster #147.

U.S. EPA, 2003: Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries, U.S. Environmental Protection Agency.

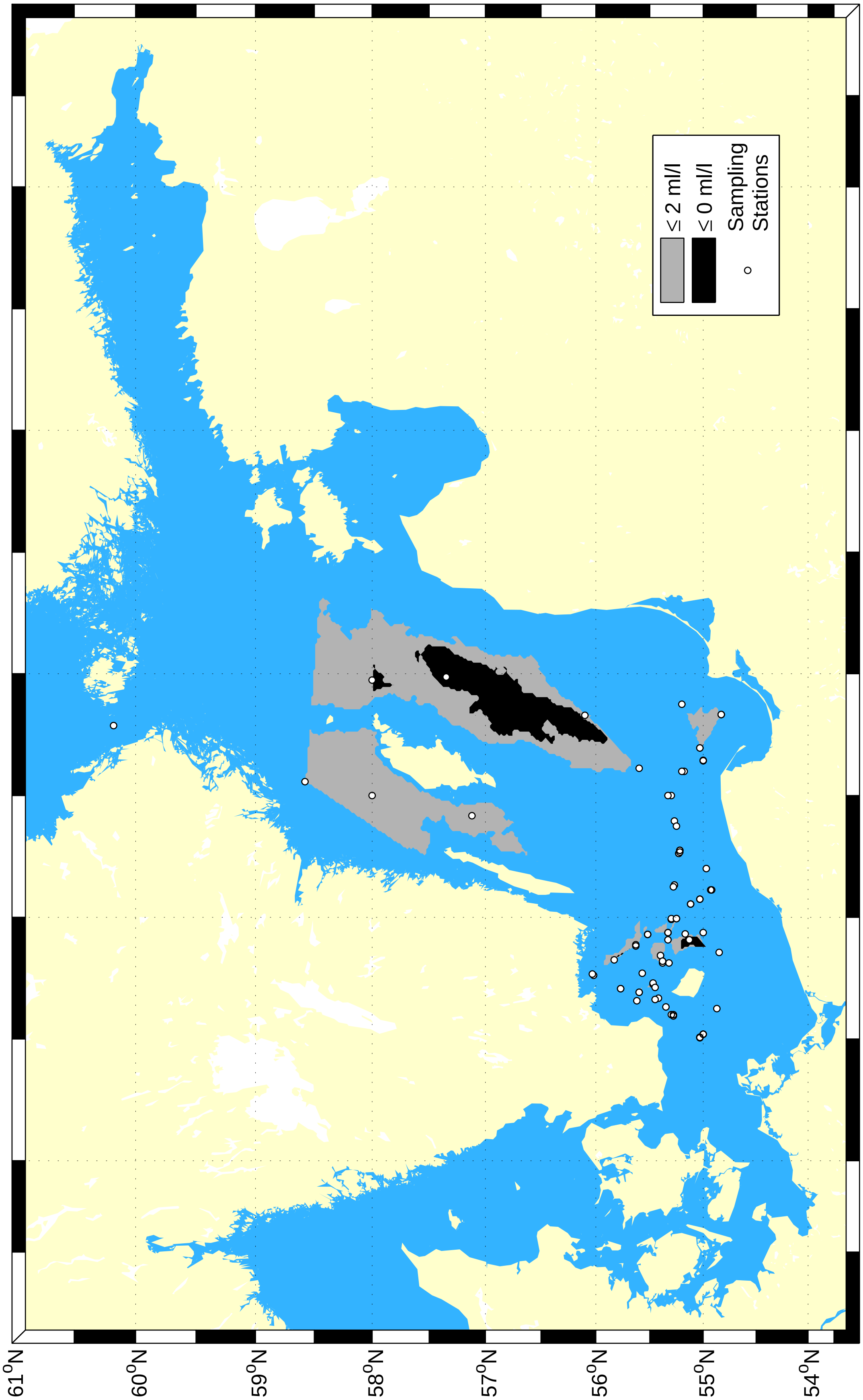
U.S. EPA, 2000: Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen(Saltwater): Cape Cod to Cape Hatteras, U.S. Environmental Protection Agency, EPA-822-R-00-012.

Appendix 1 – Dissolved oxygen, salinity and dissolved inorganic phosphorous in the Eastern Gotland Basin, station BY15, 1960-2011

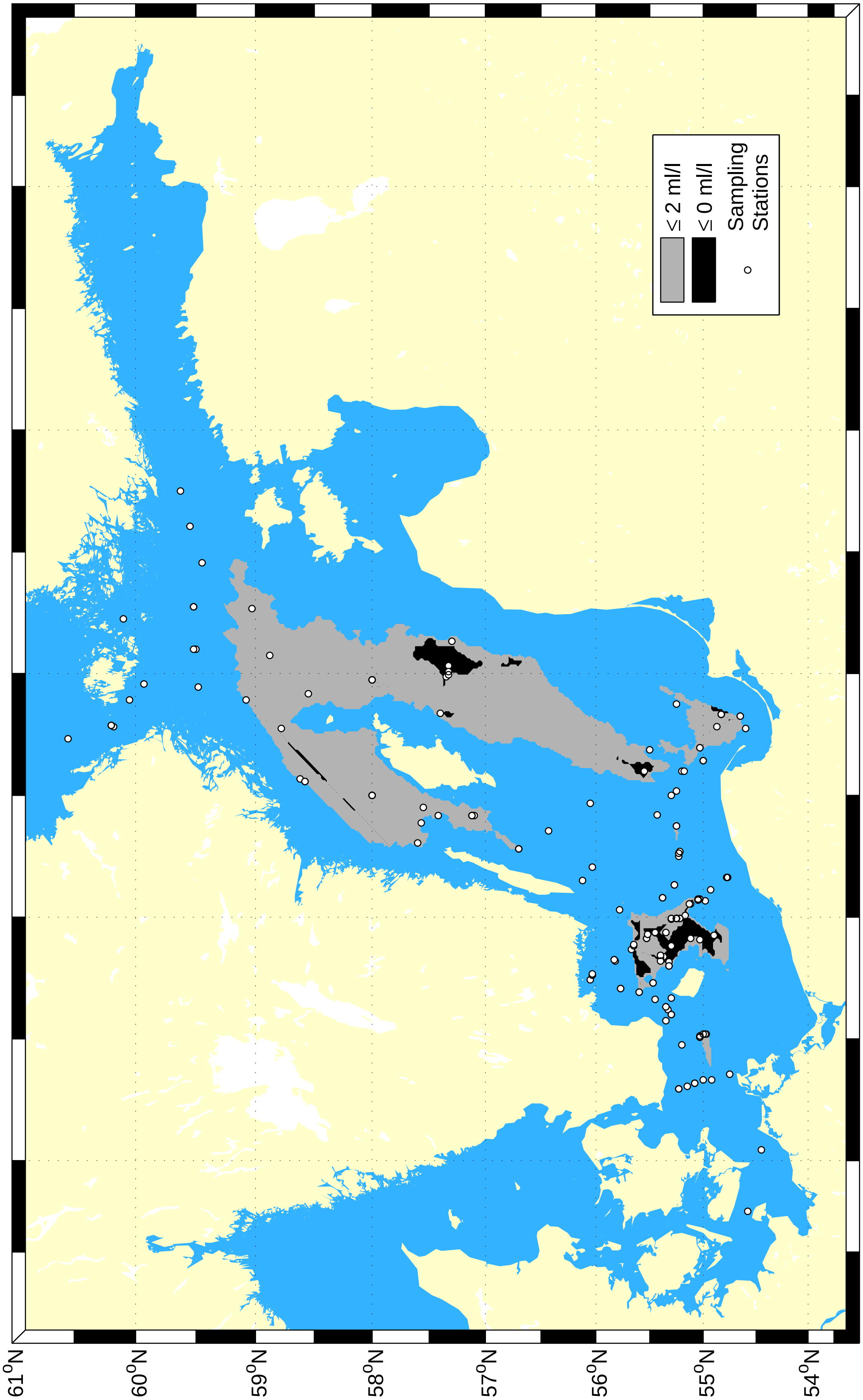


Appendix 2 – Climatological atlas of anoxic and hypoxic areas in the Baltic Sea, 1960-2011.

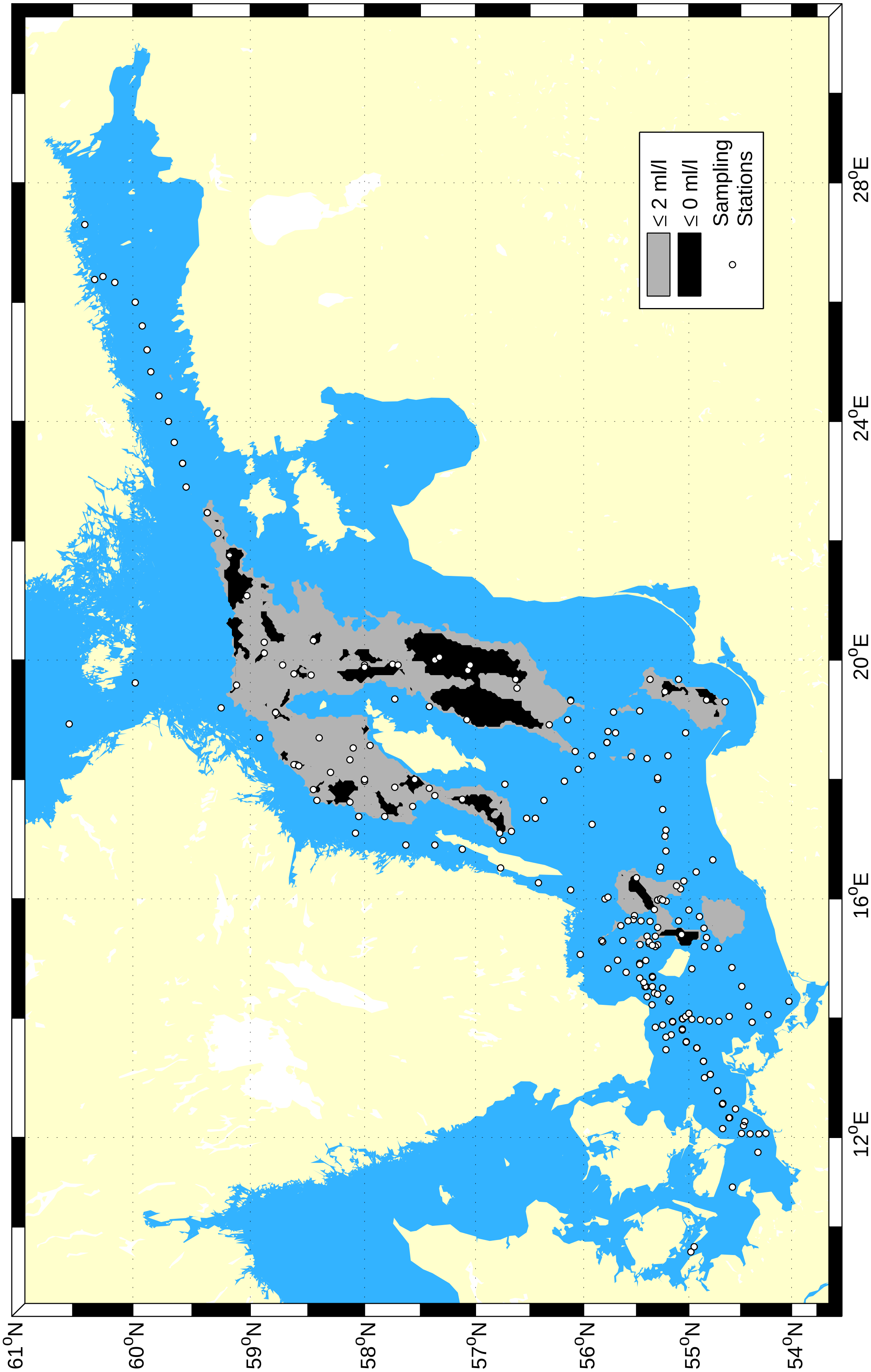
Extent of hypoxic & anoxic bottom water, Autumn 1960



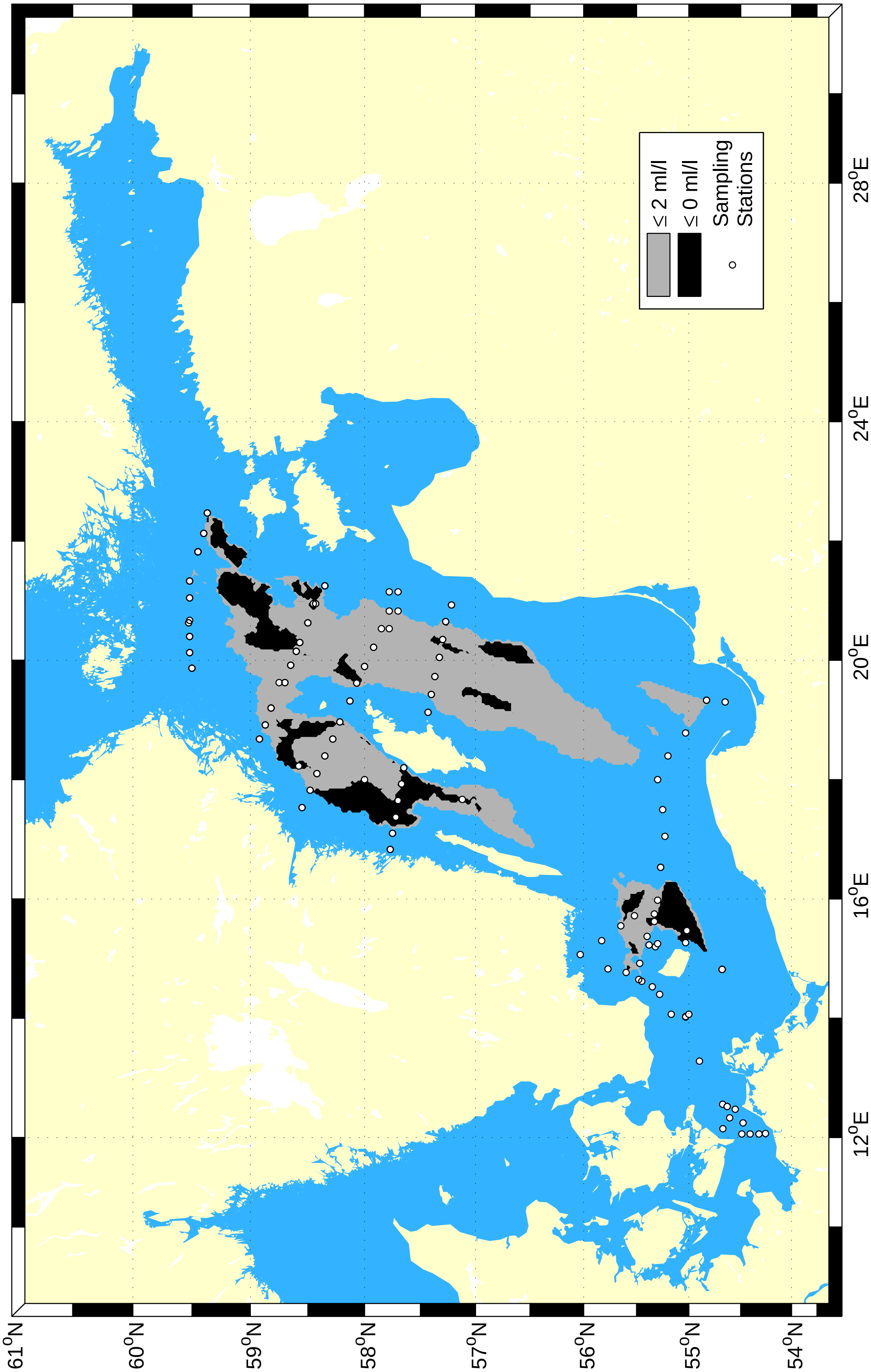
Extent of hypoxic & anoxic bottom water, Autumn 1962



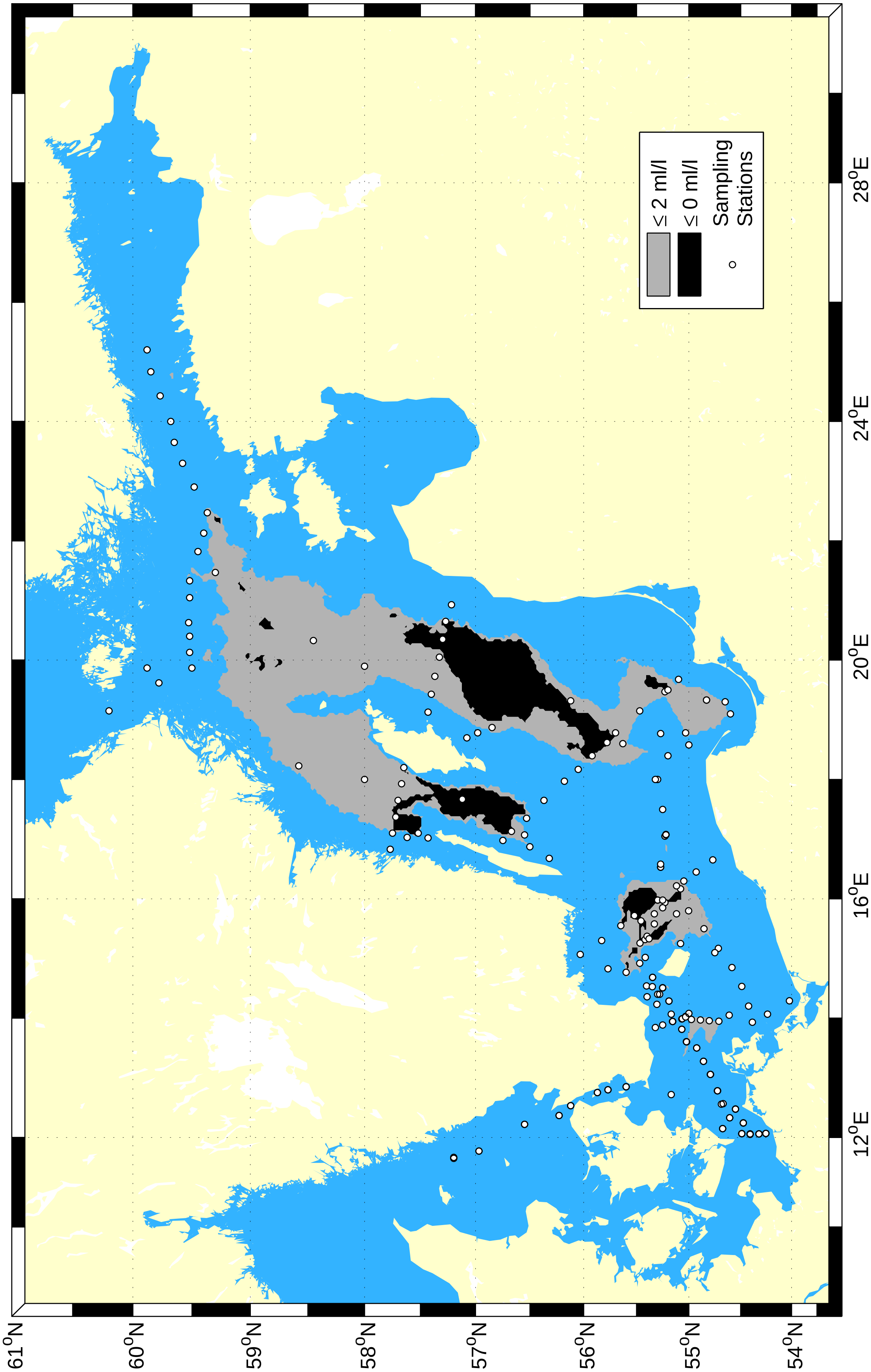
Extent of hypoxic & anoxic bottom water, Autumn 1963

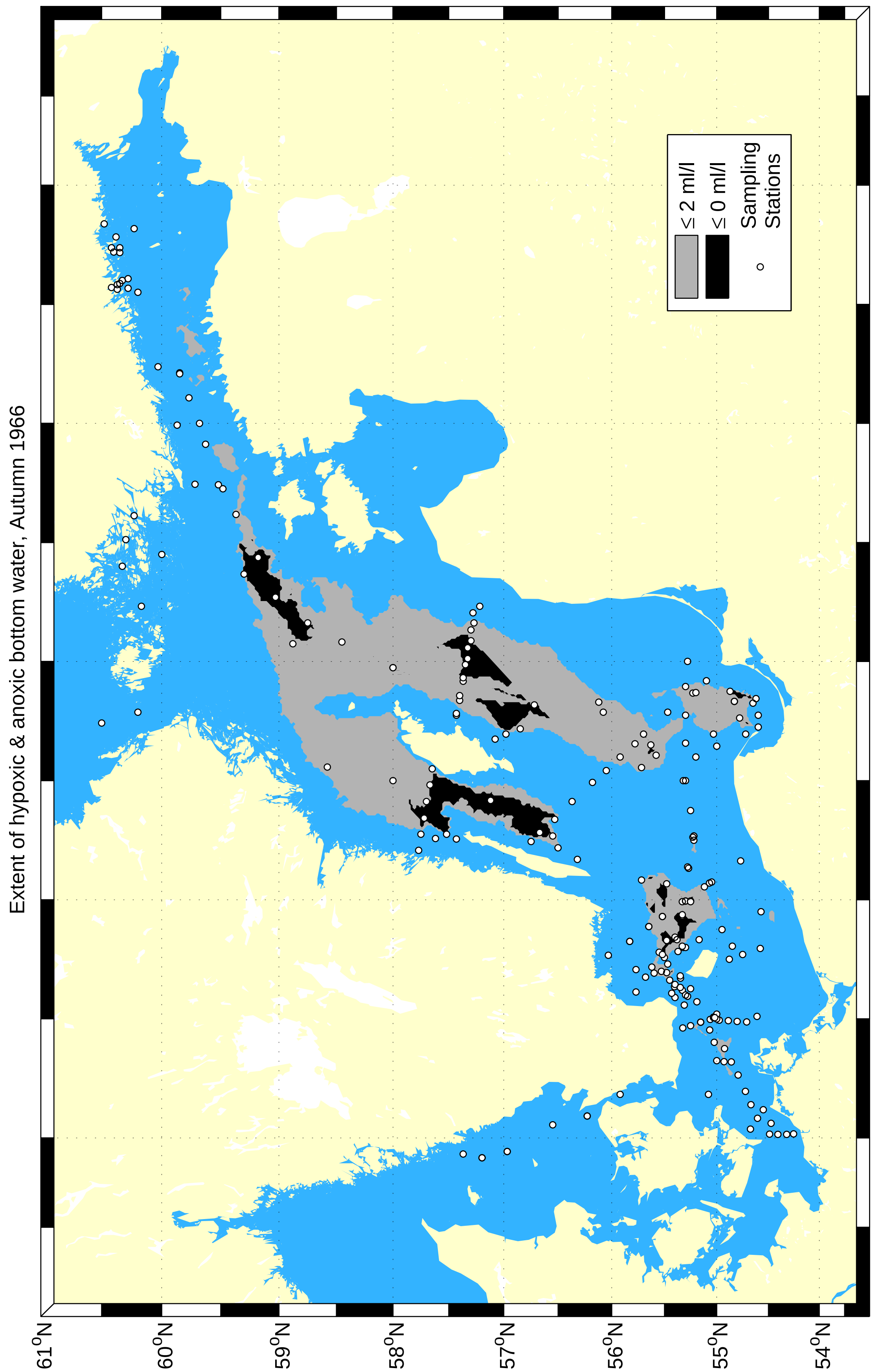


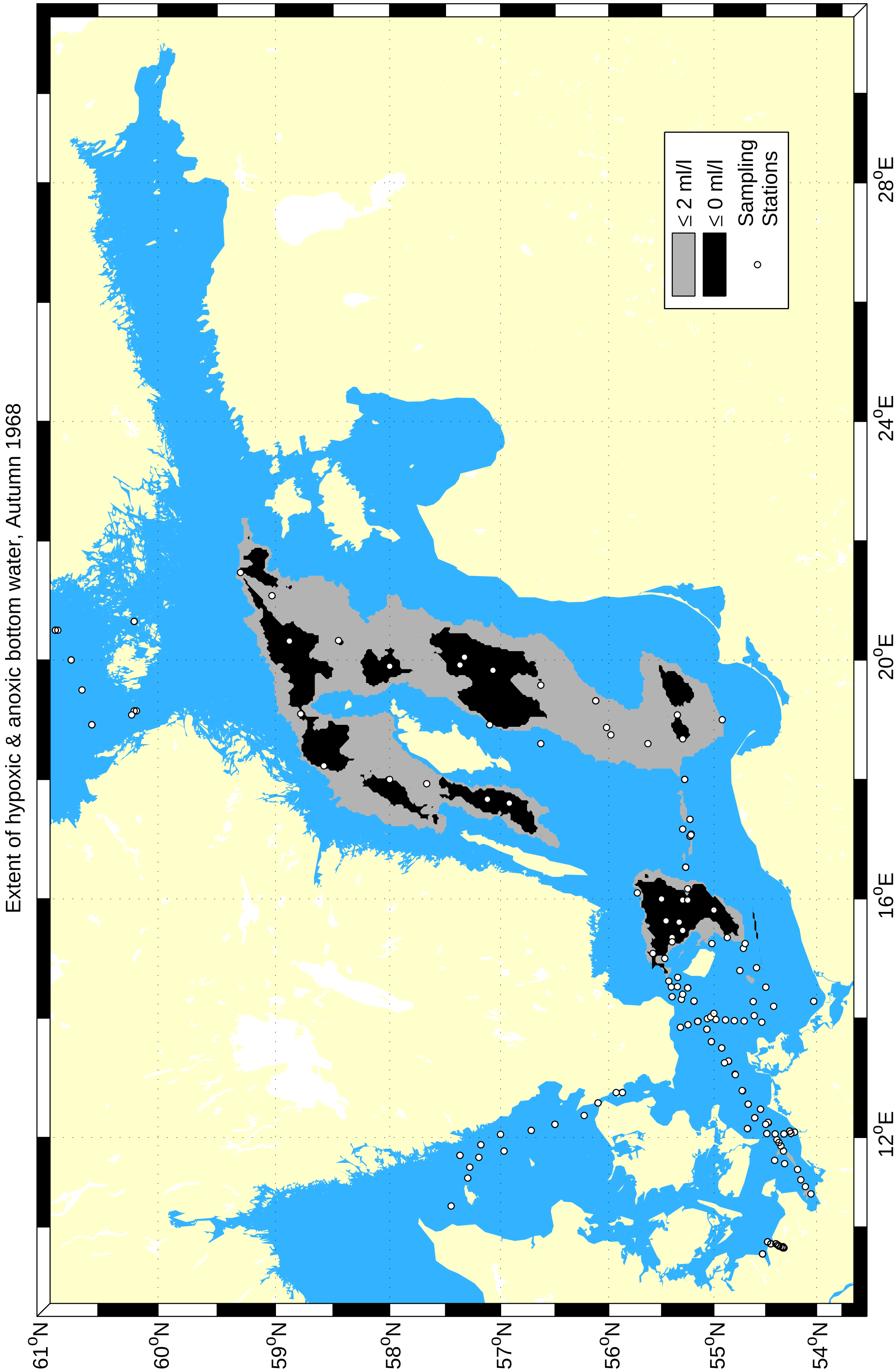
Extent of hypoxic & anoxic bottom water, Autumn 1964



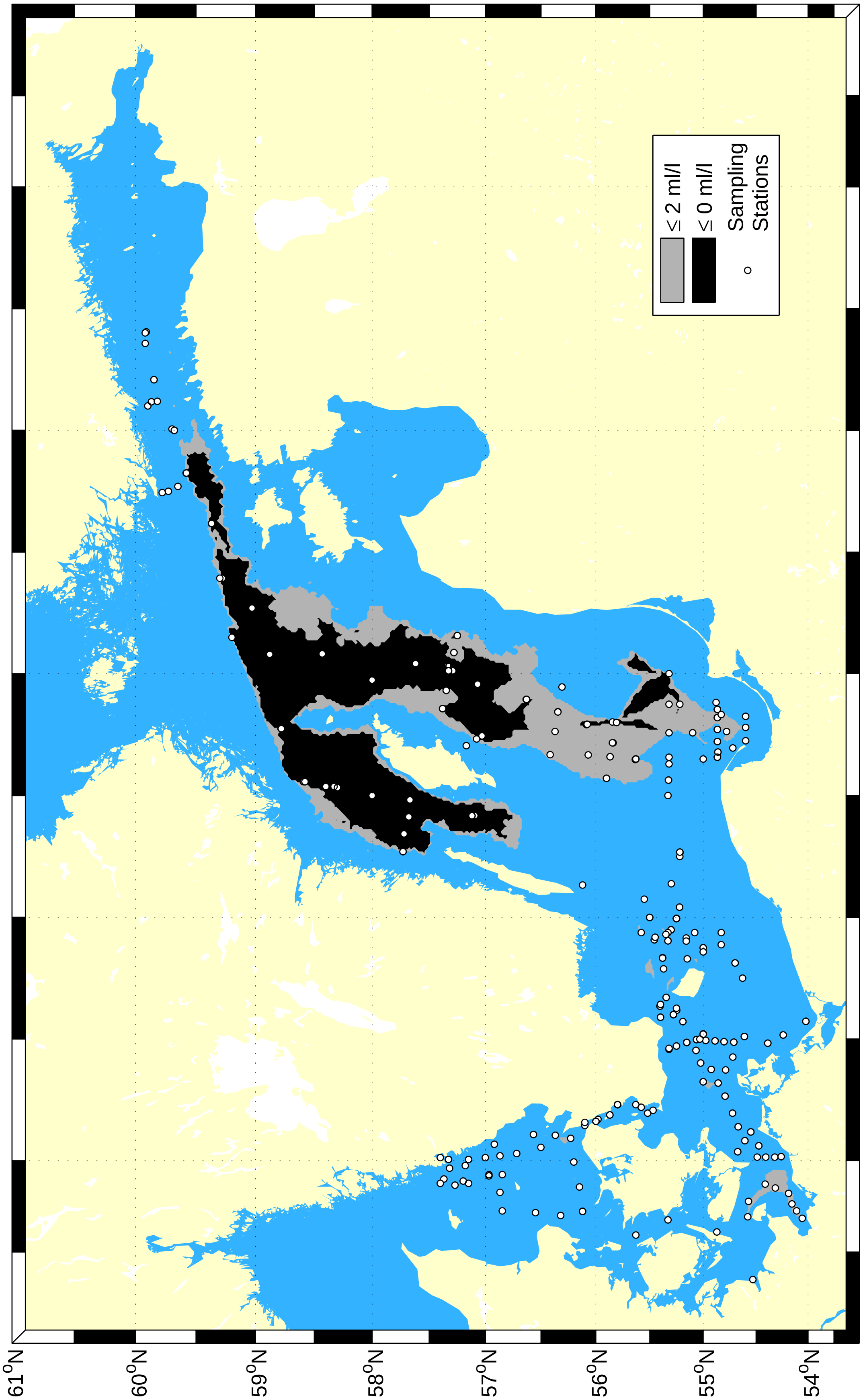
Extent of hypoxic & anoxic bottom water, Autumn 1965

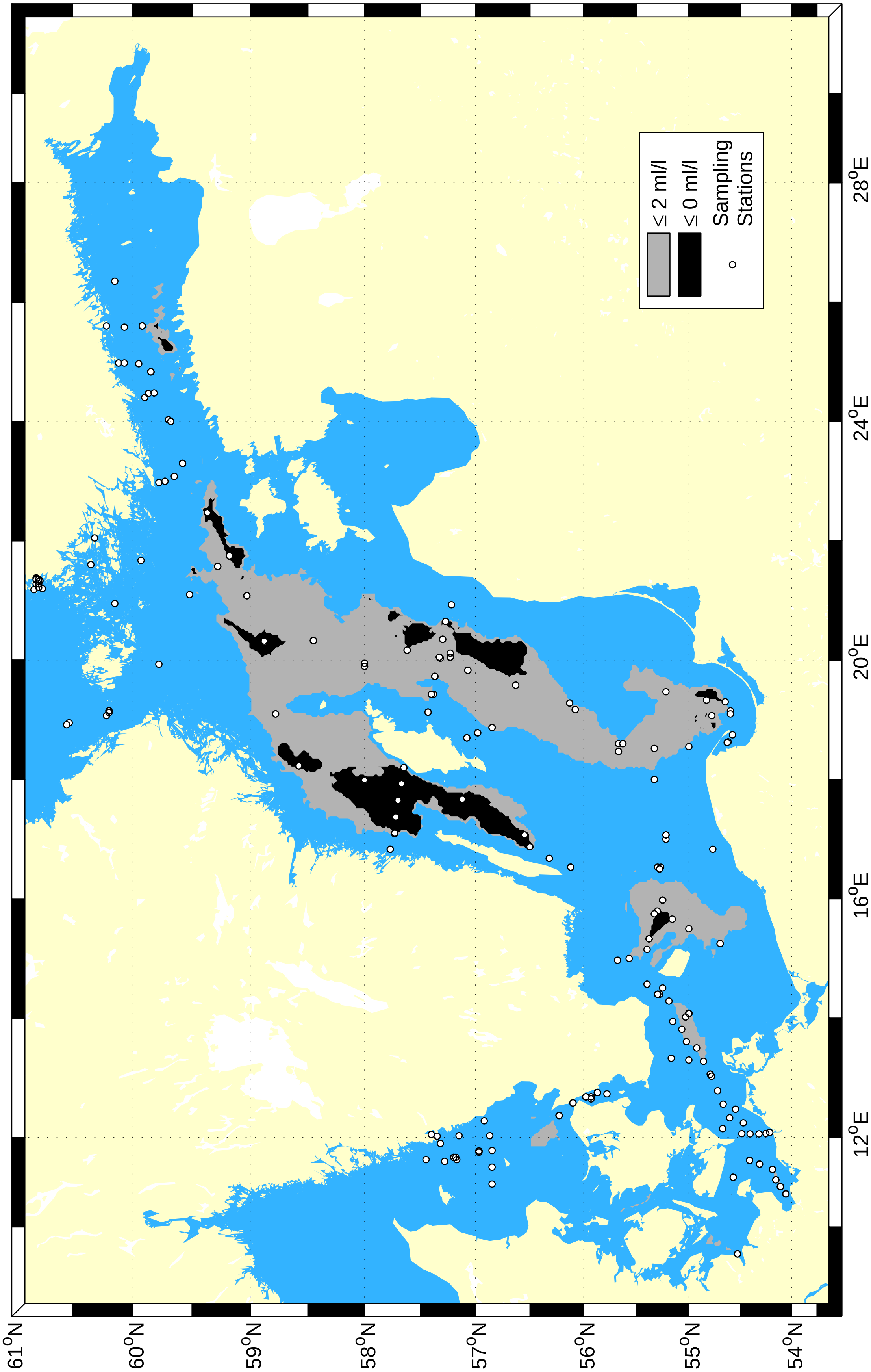



Extent of hypoxic & anoxic bottom water, Autumn 1966
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N

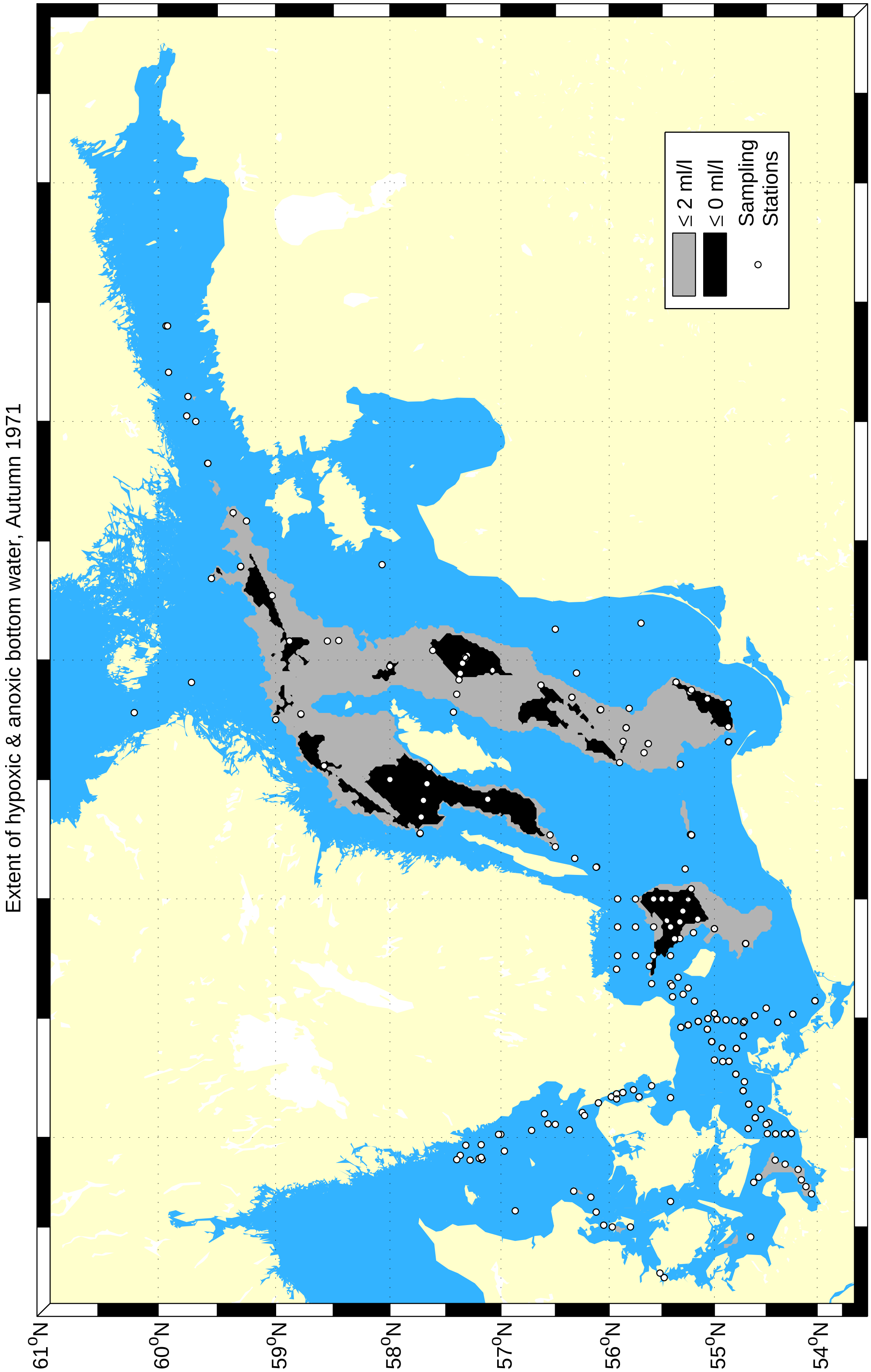

Extent of hypoxic & anoxic bottom water, Autumn 1968
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E

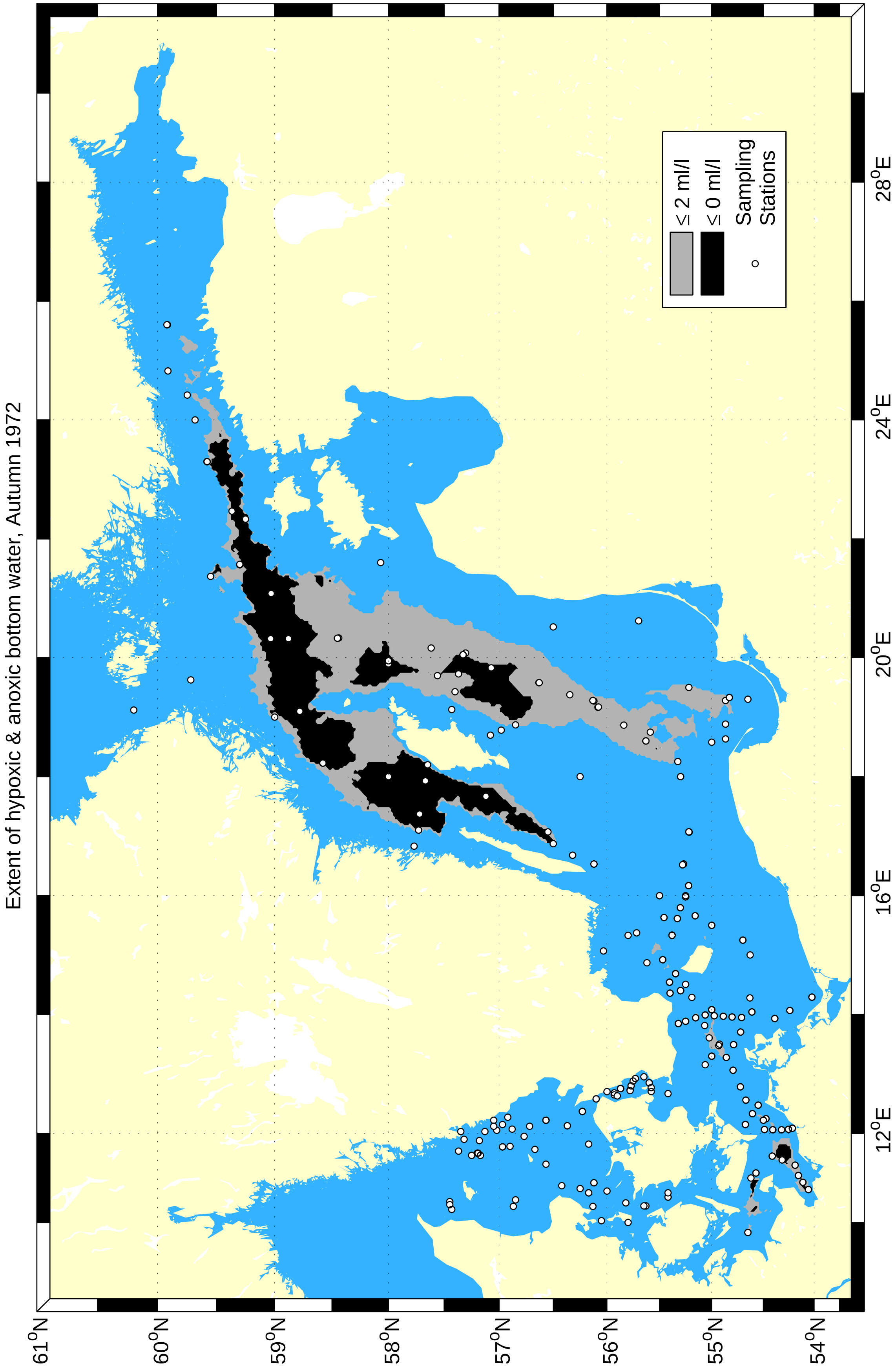
Extent of hypoxic & anoxic bottom water, Autumn 1969



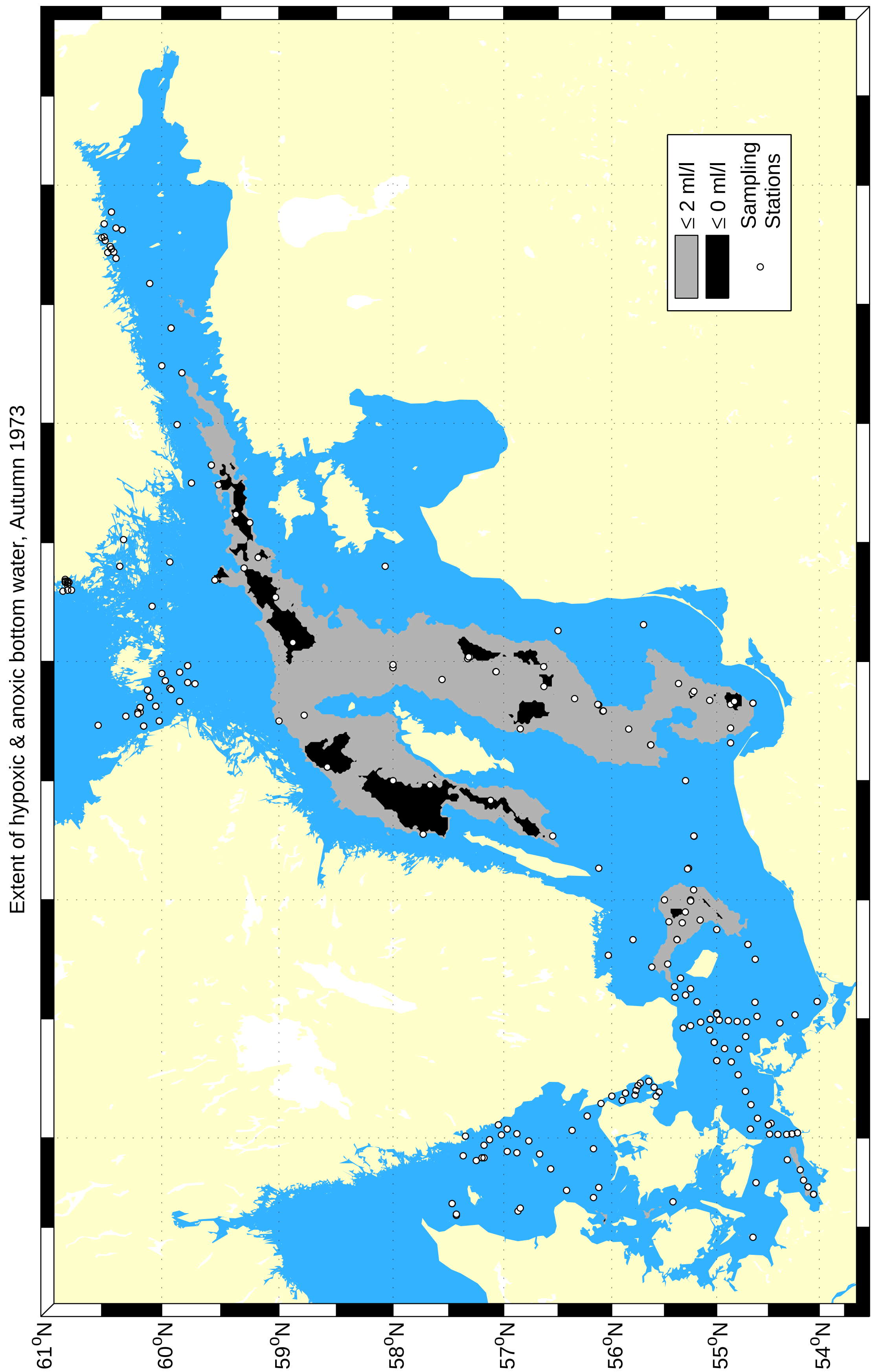


Extent of hypoxic & anoxic bottom water, Autumn 1970

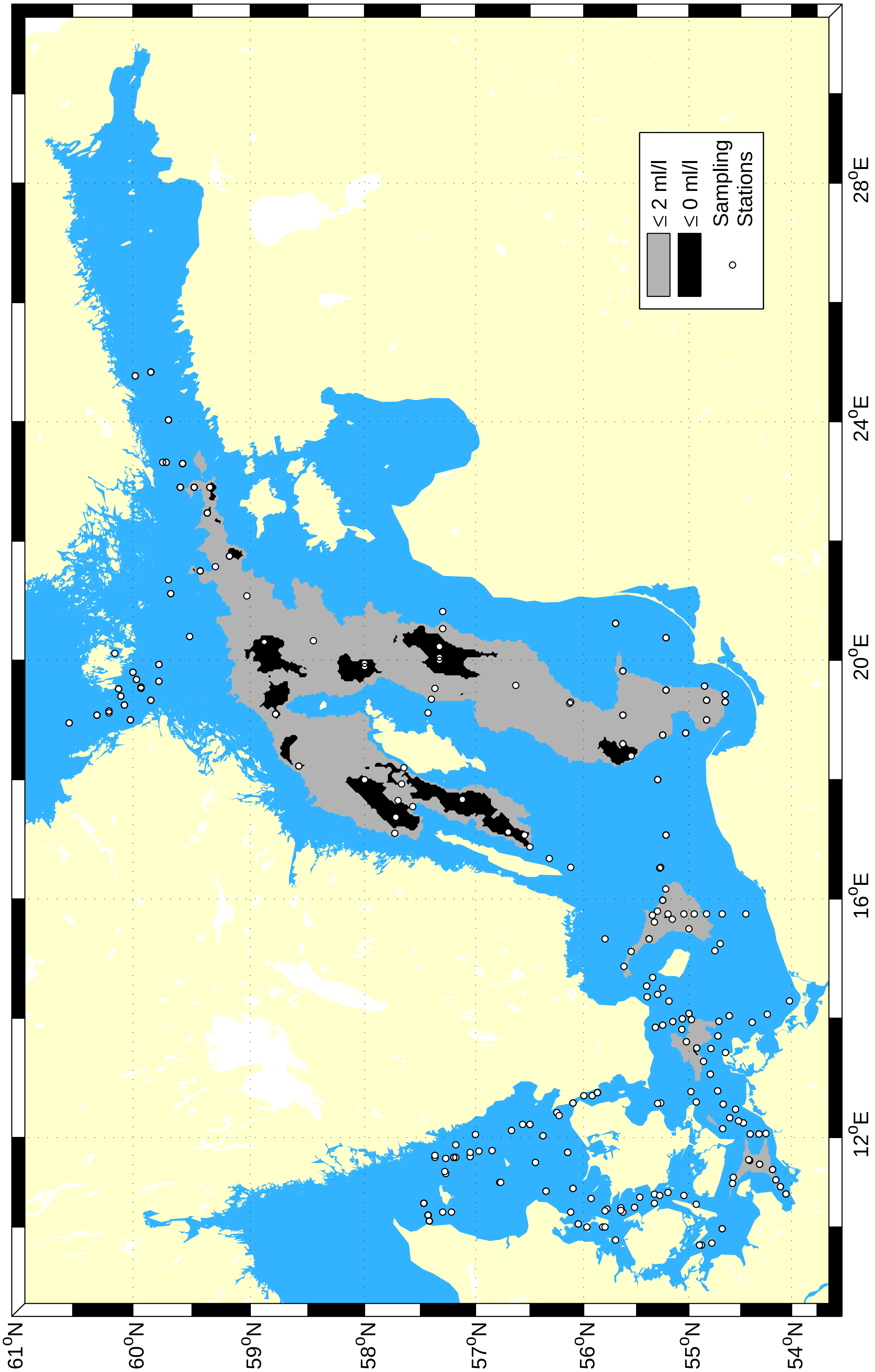

Extent of hypoxic & anoxic bottom water, Autumn 1971
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N



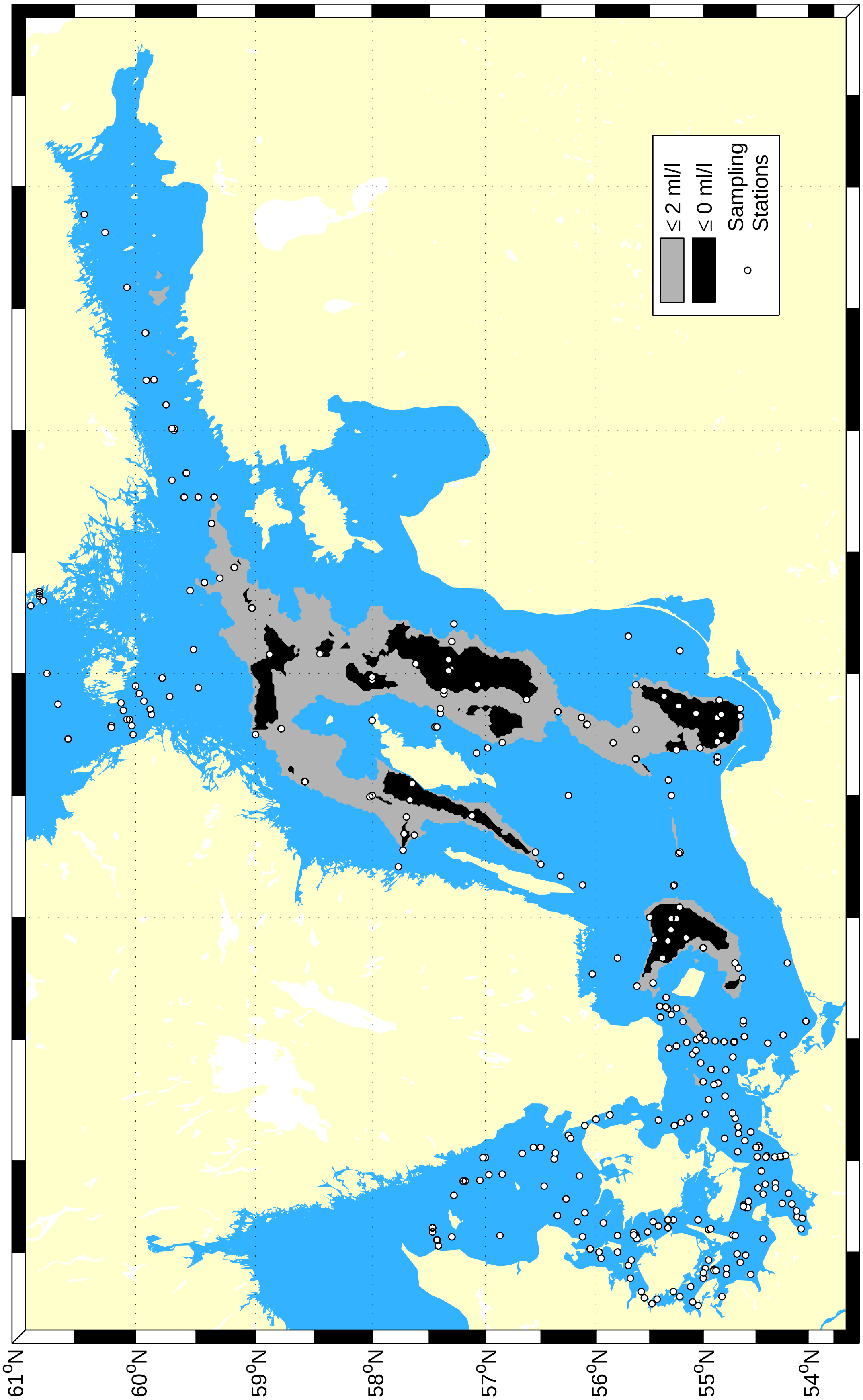
Extent of hypoxic & anoxic bottom water, Autumn 1972
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N


Extent of hypoxic & anoxic bottom water, Autumn 1973
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N

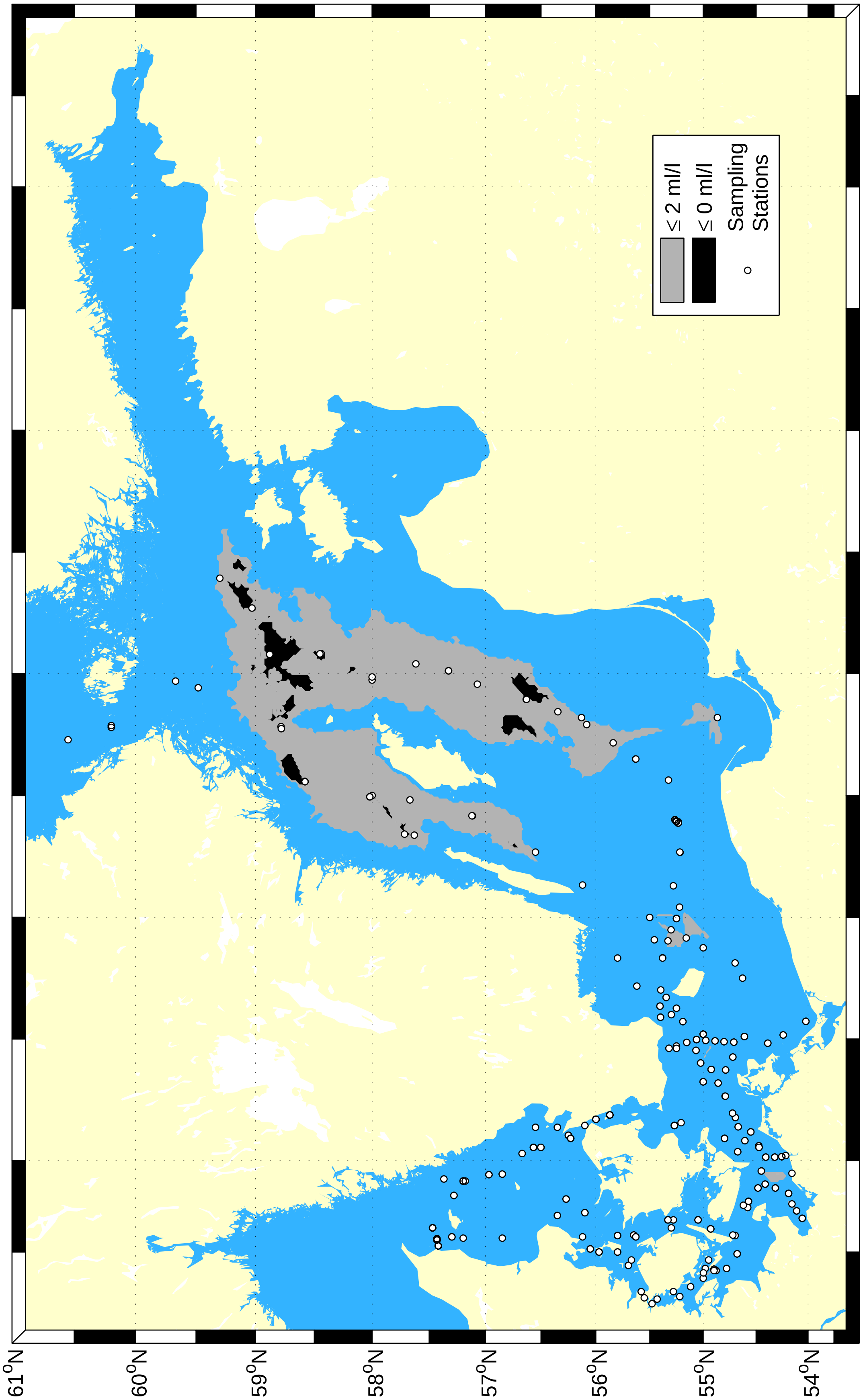
Extent of hypoxic & anoxic bottom water, Autumn 1974

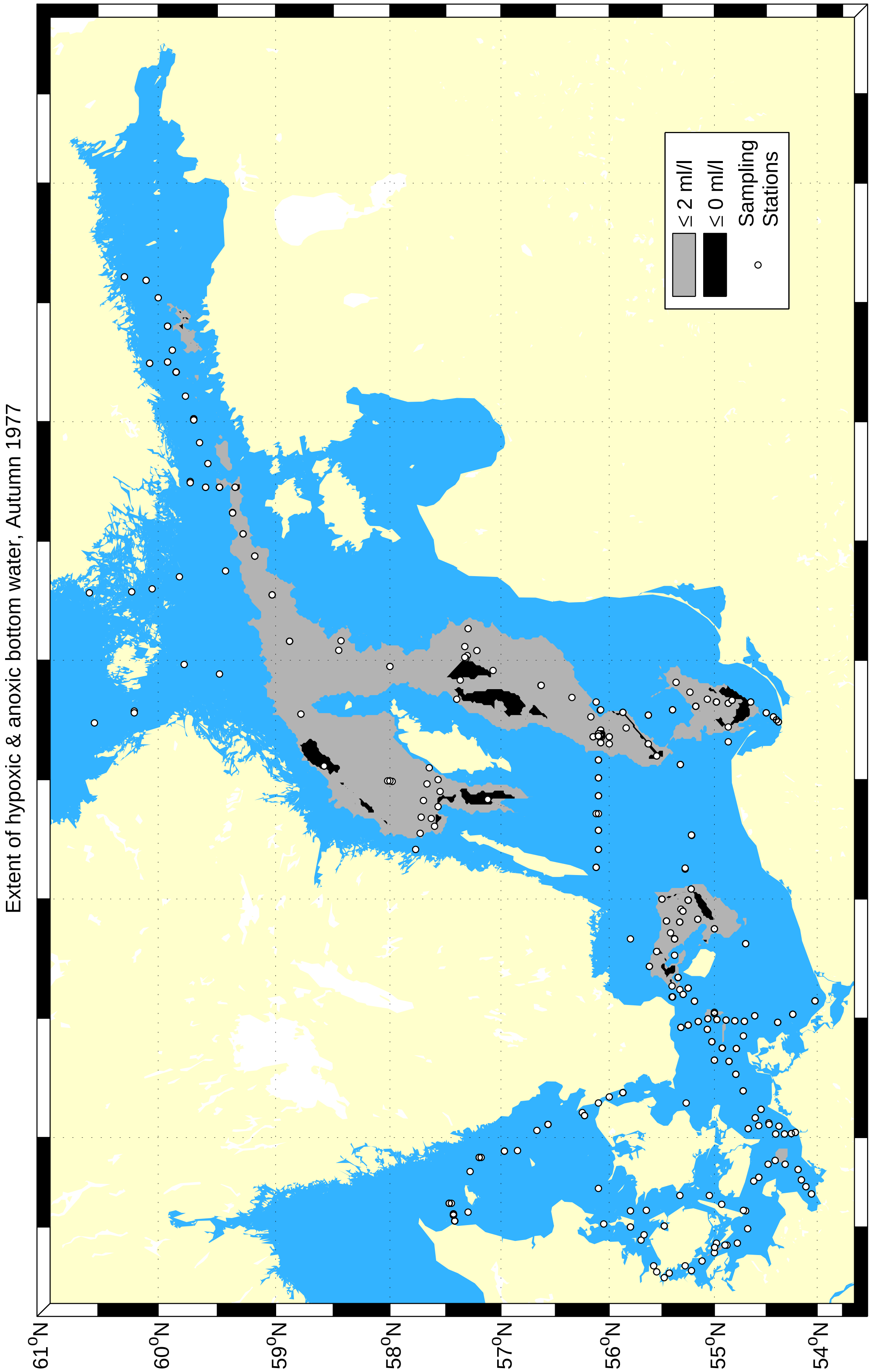


Extent of hypoxic & anoxic bottom water, Autumn 1975



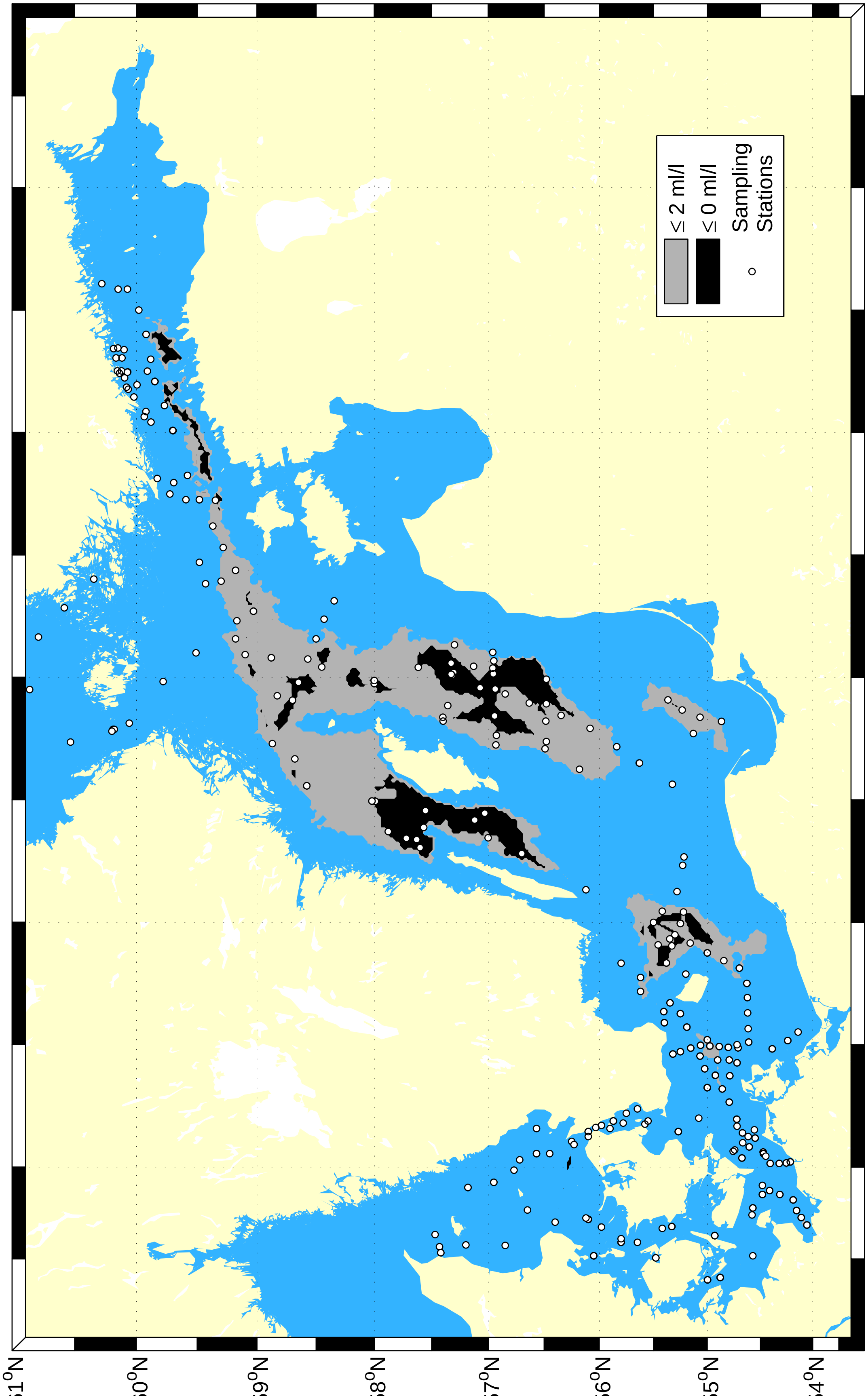
Extent of hypoxic & anoxic bottom water, Autumn 1976



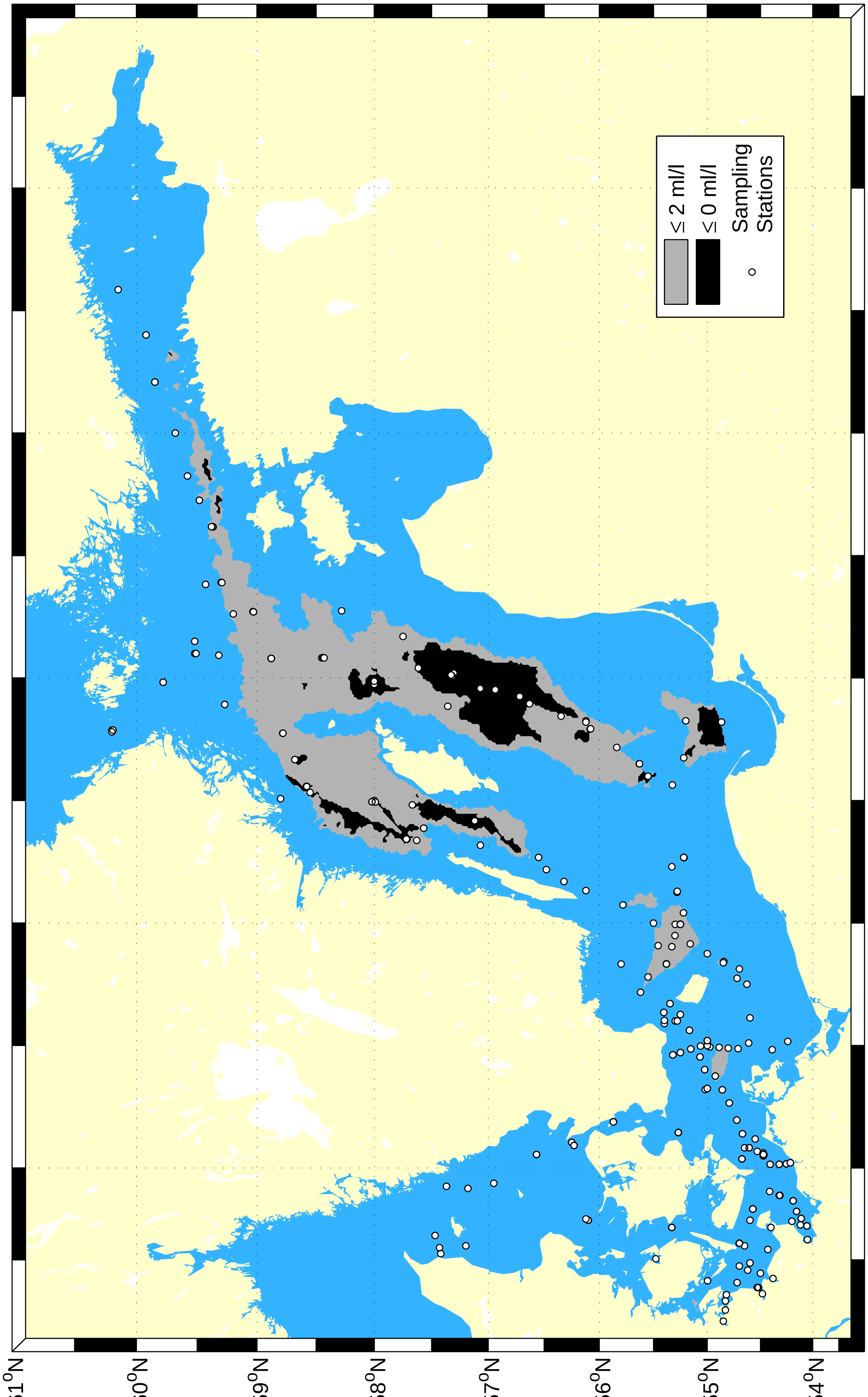


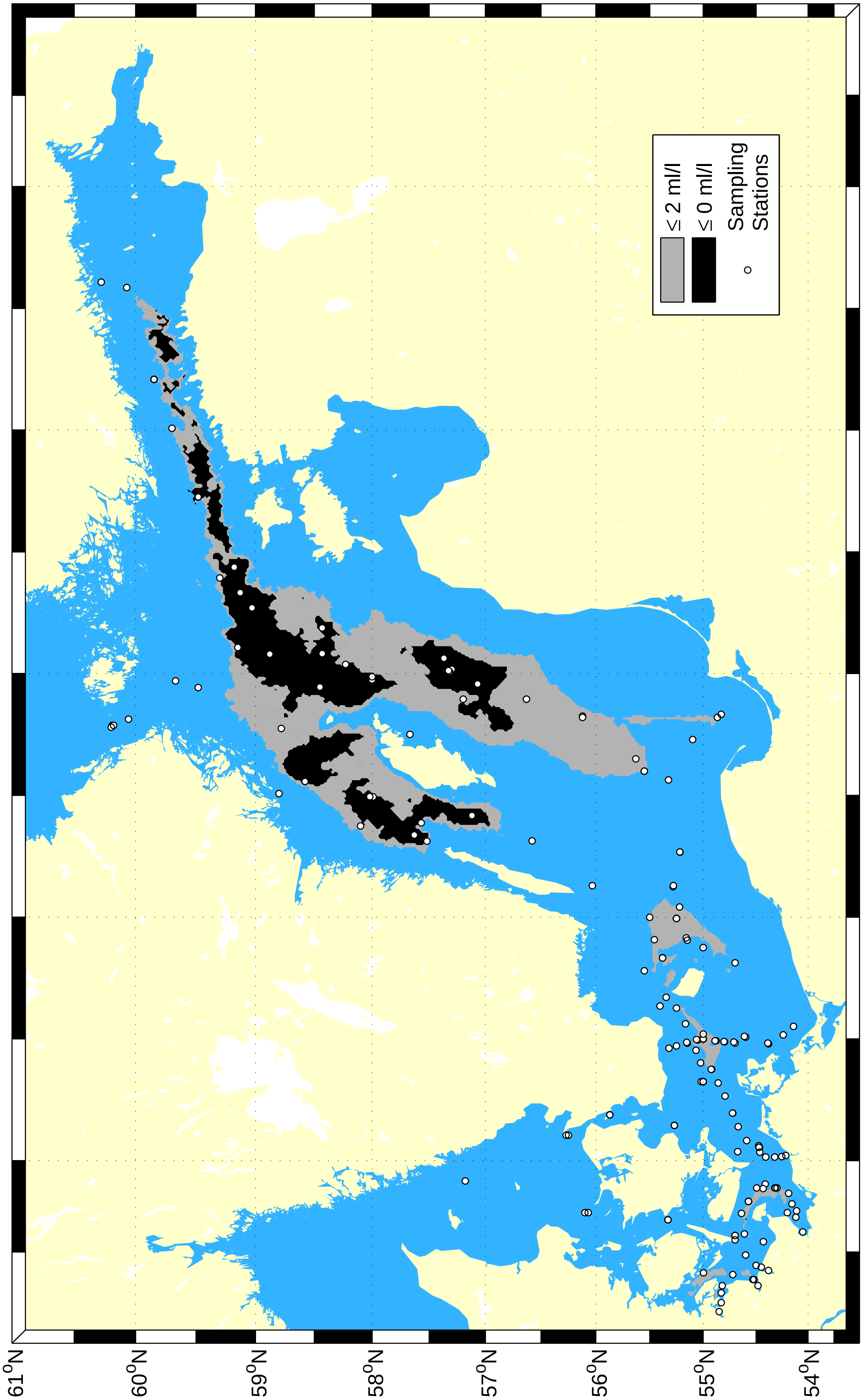
Extent of hypoxic & anoxic bottom water, Autumn 1977
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
$12^{o}E$
$16^{o}E$
$20^{o}E$
$24^{o}E$
$28^{o}E$
$61^{o}N$
$60^{o}N$
$59^{o}N$
$58^{o}N$
$57^{o}N$
$56^{o}N$
$55^{o}N$
$54^{o}N$

Extent of hypoxic & anoxic bottom water, Autumn 1978



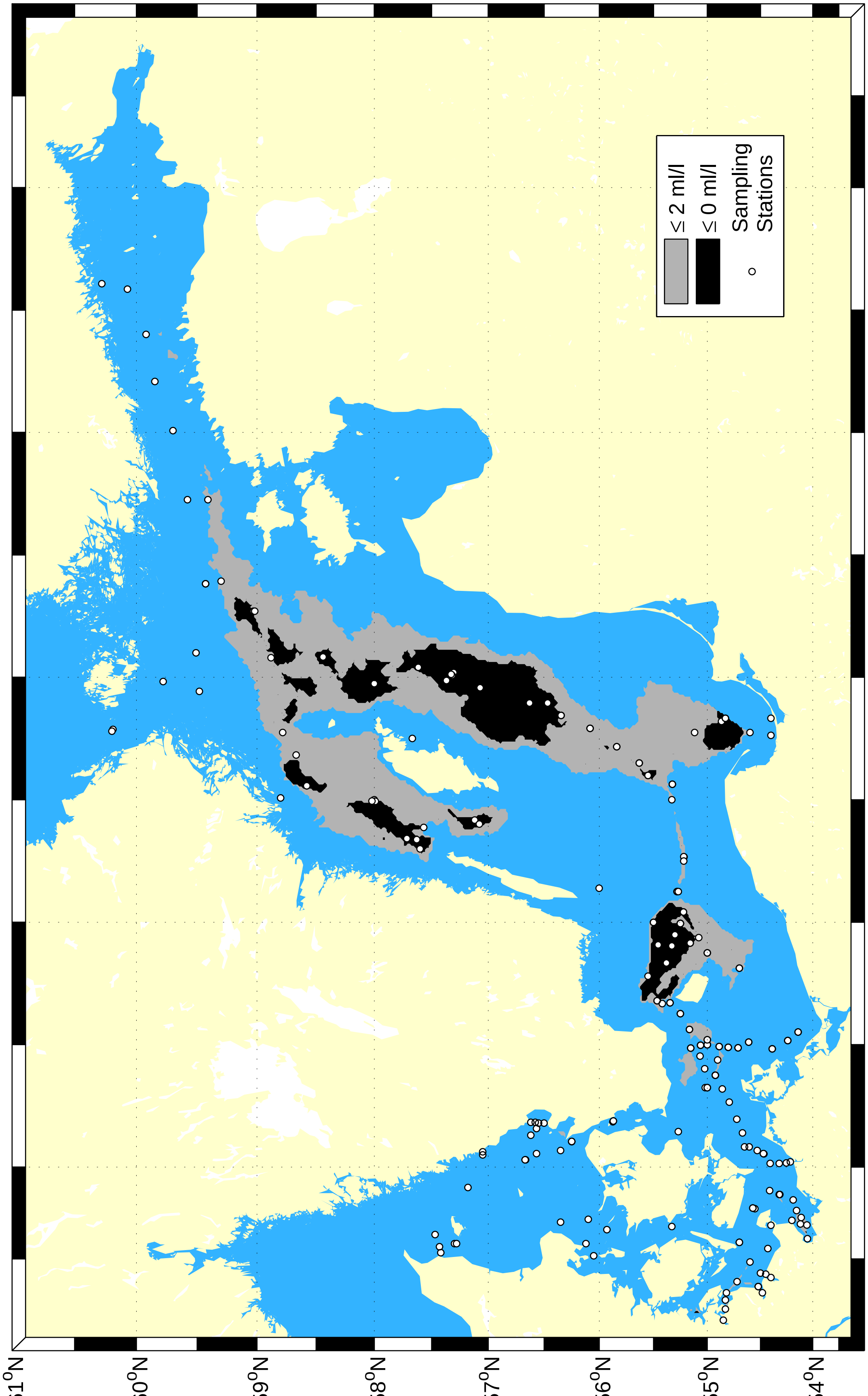
Extent of hypoxic & anoxic bottom water, Autumn 1979

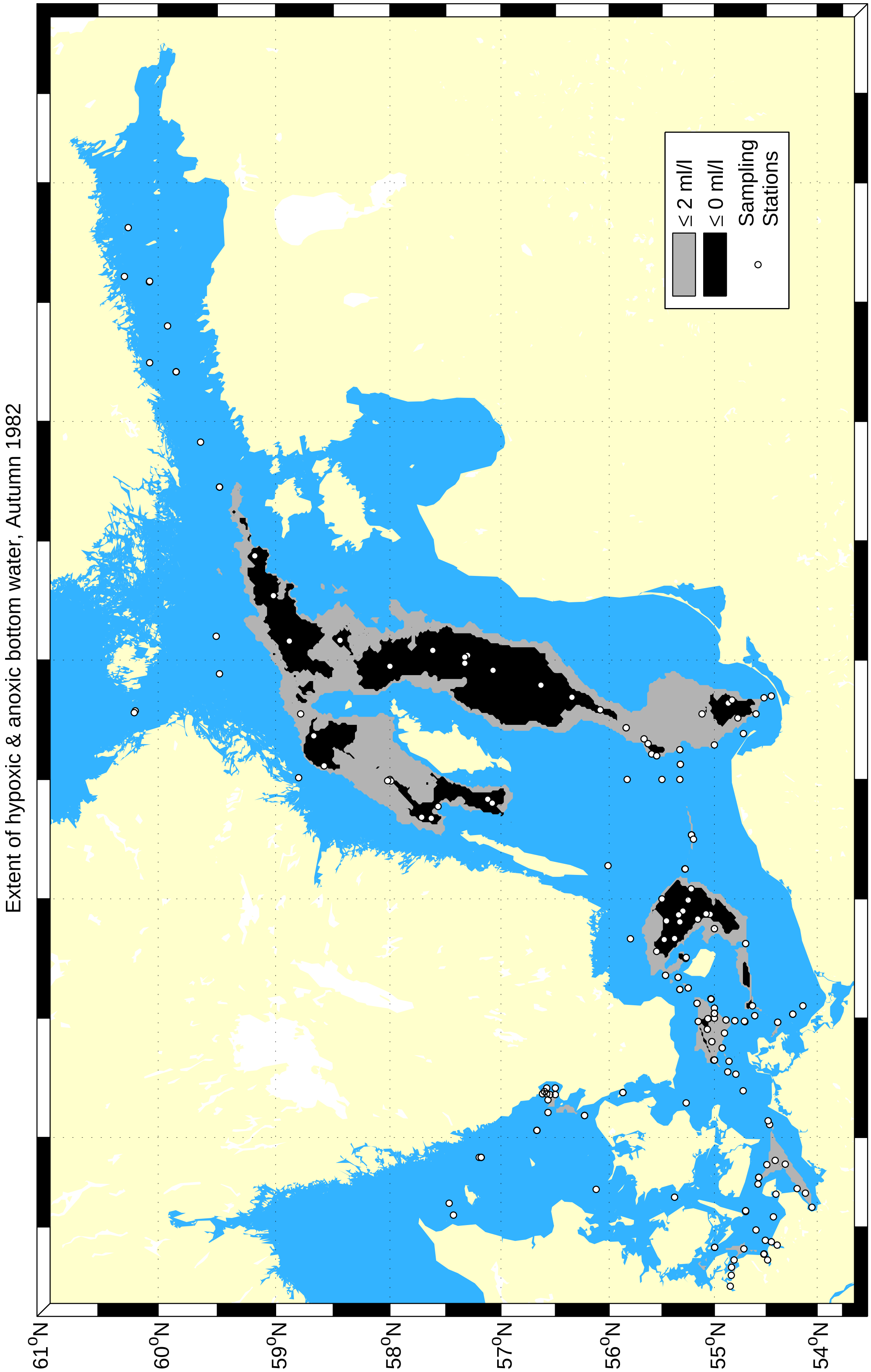




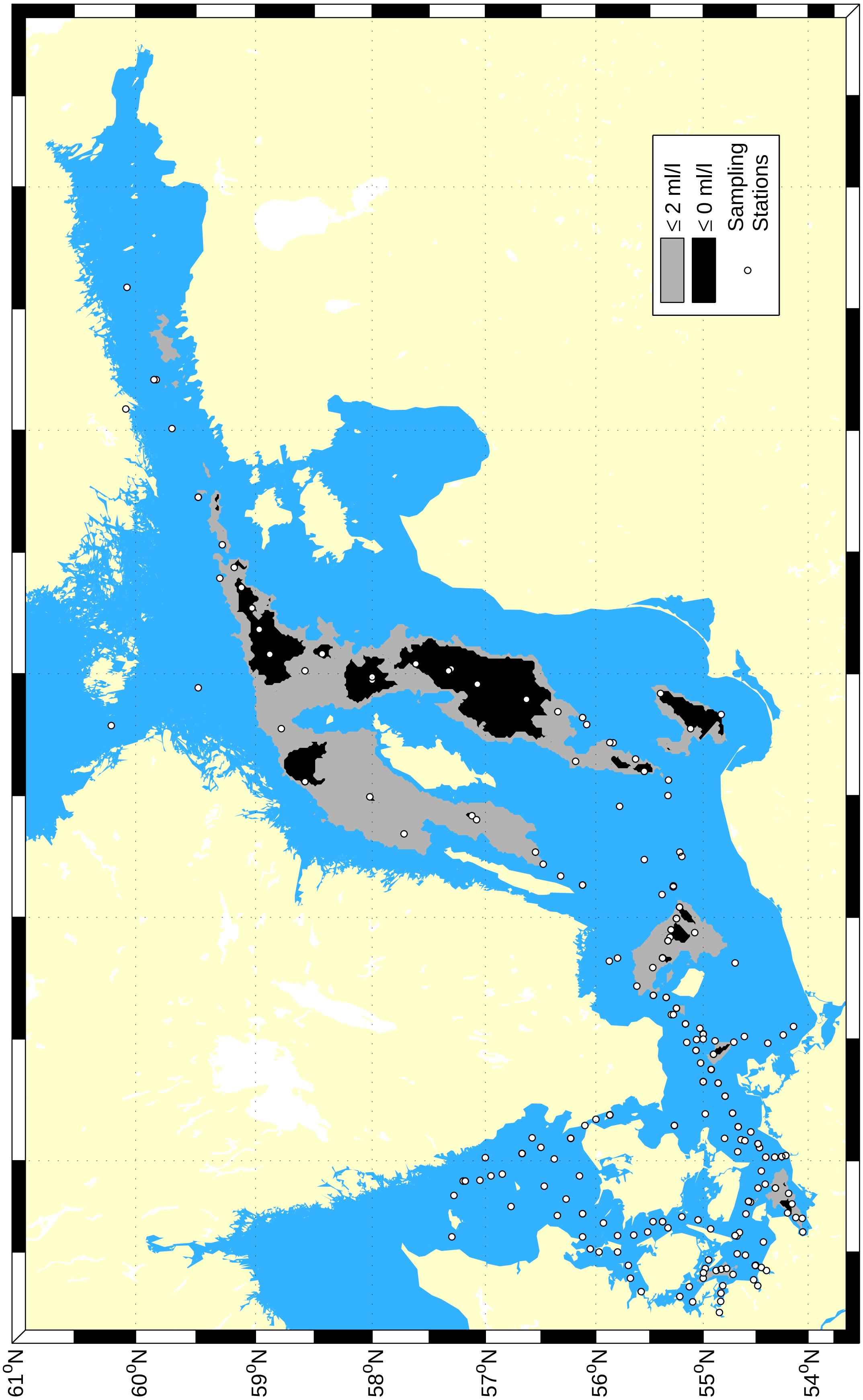
Extent of hypoxic & anoxic bottom water, Autumn 1980

Extent of hypoxic & anoxic bottom water, Autumn 1981

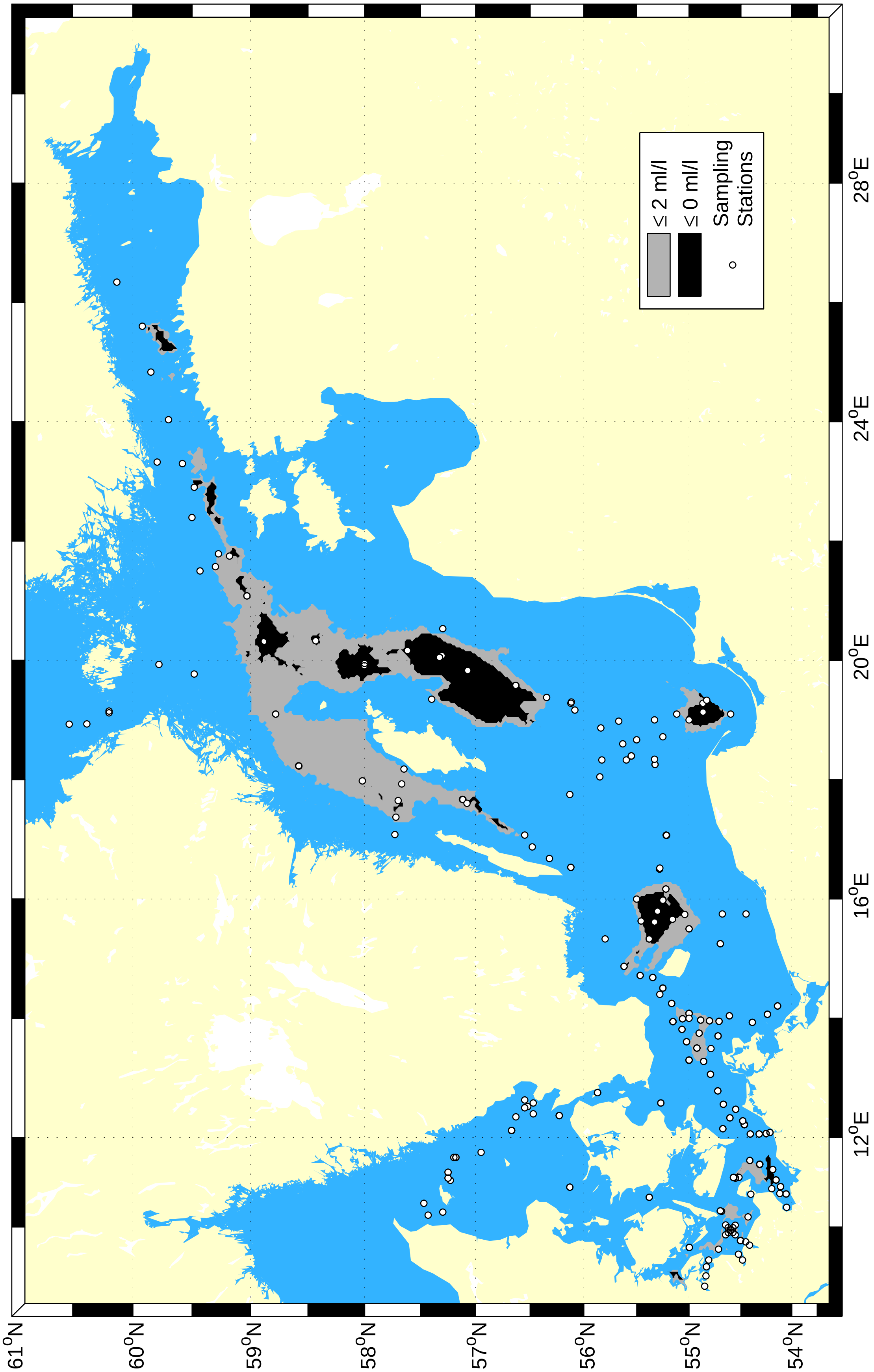


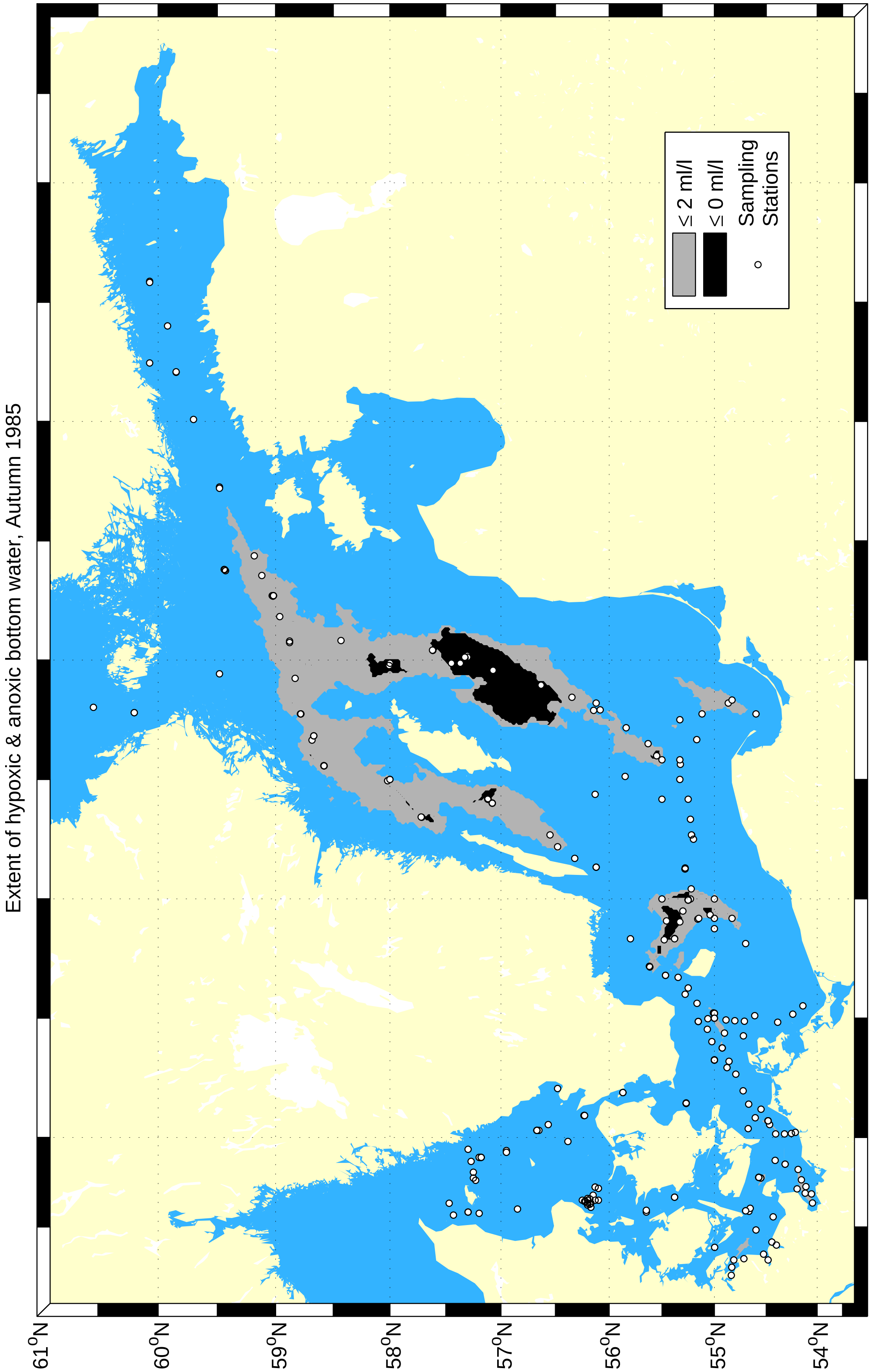

Extent of hypoxic & anoxic bottom water, Autumn 1982
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E

Extent of hypoxic & anoxic bottom water, Autumn 1983

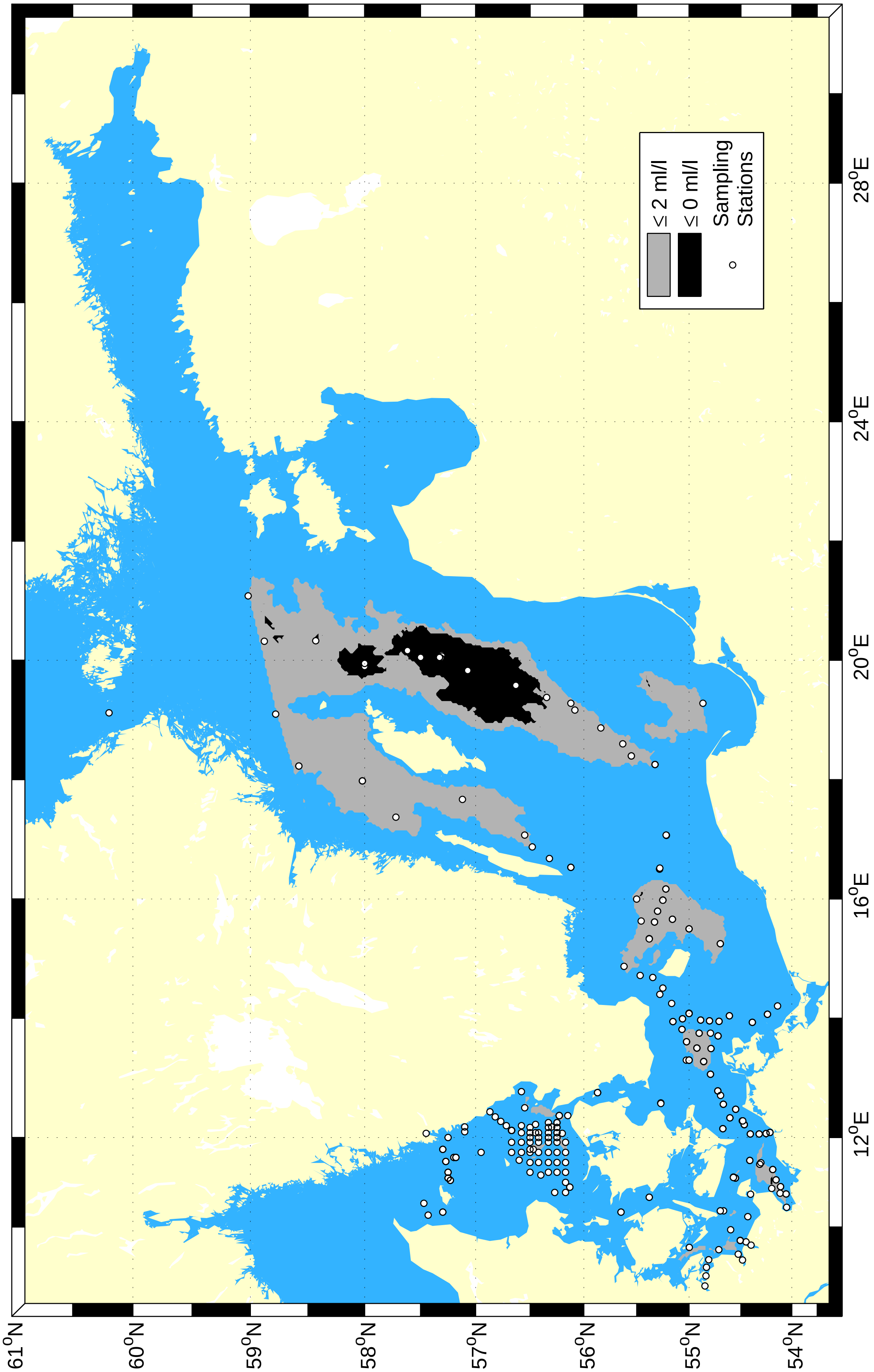


Extent of hypoxic & anoxic bottom water, Autumn 1984

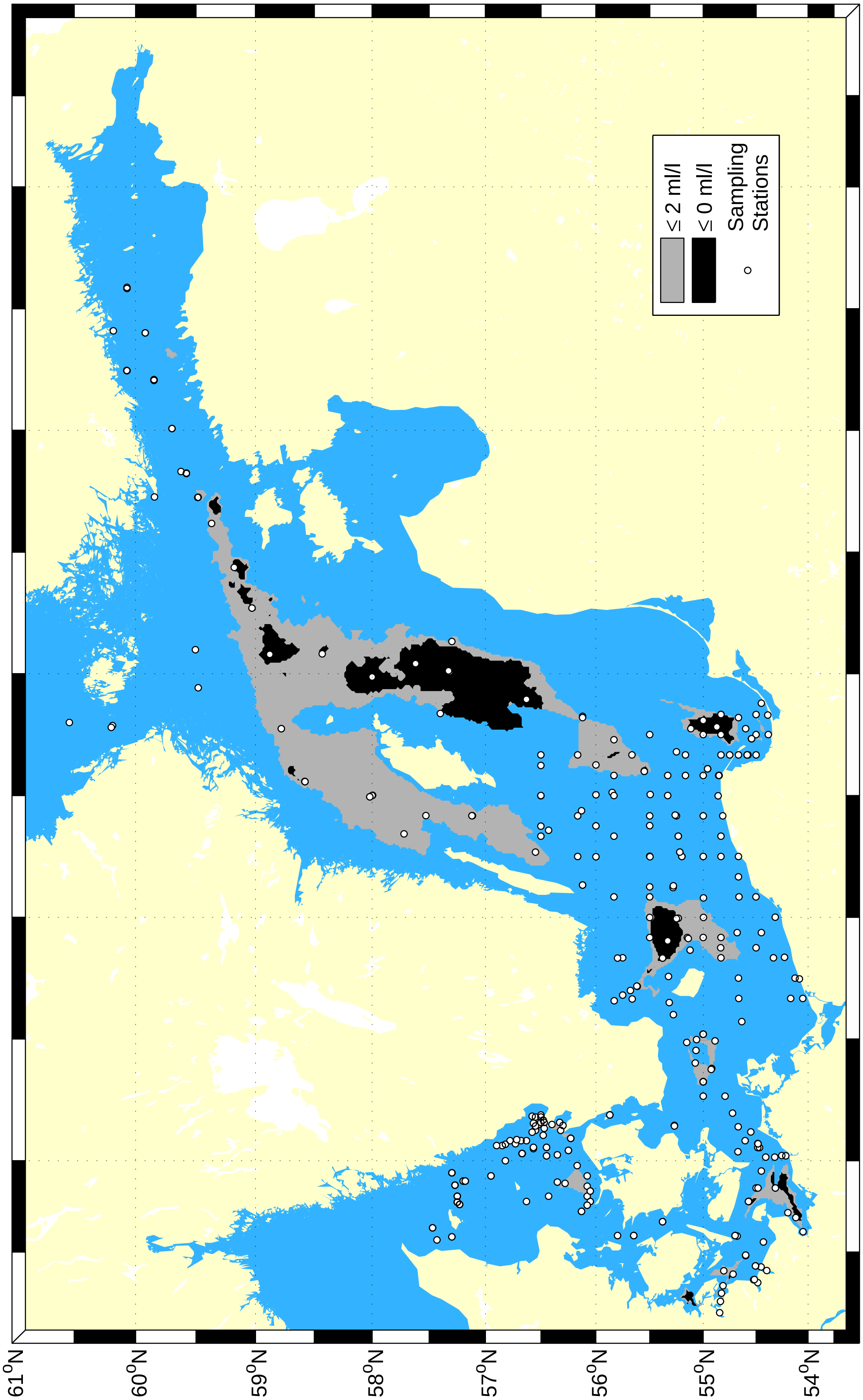


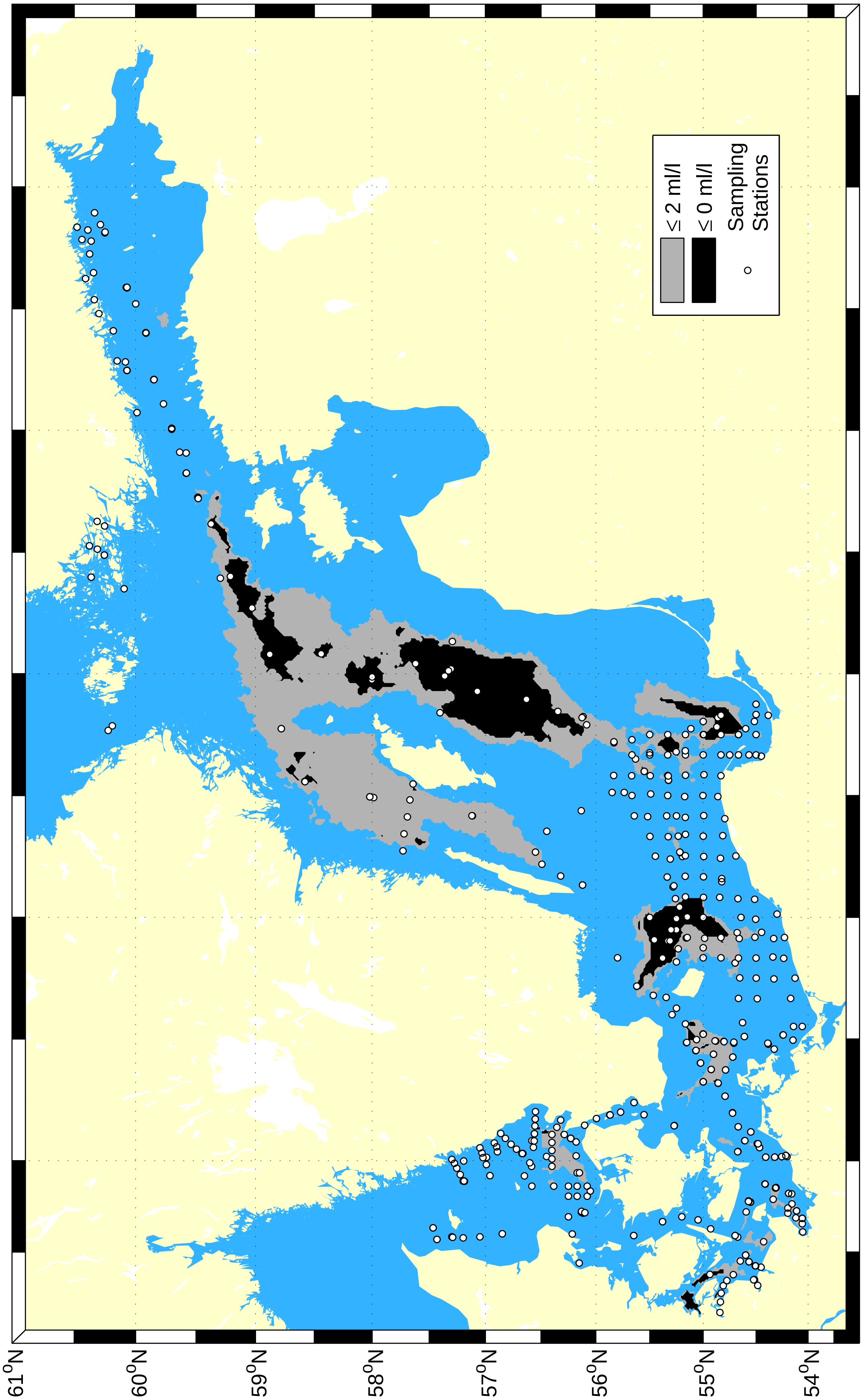

Extent of hypoxic & anoxic bottom water, Autumn 1985
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E

Extent of hypoxic & anoxic bottom water, Autumn 1986

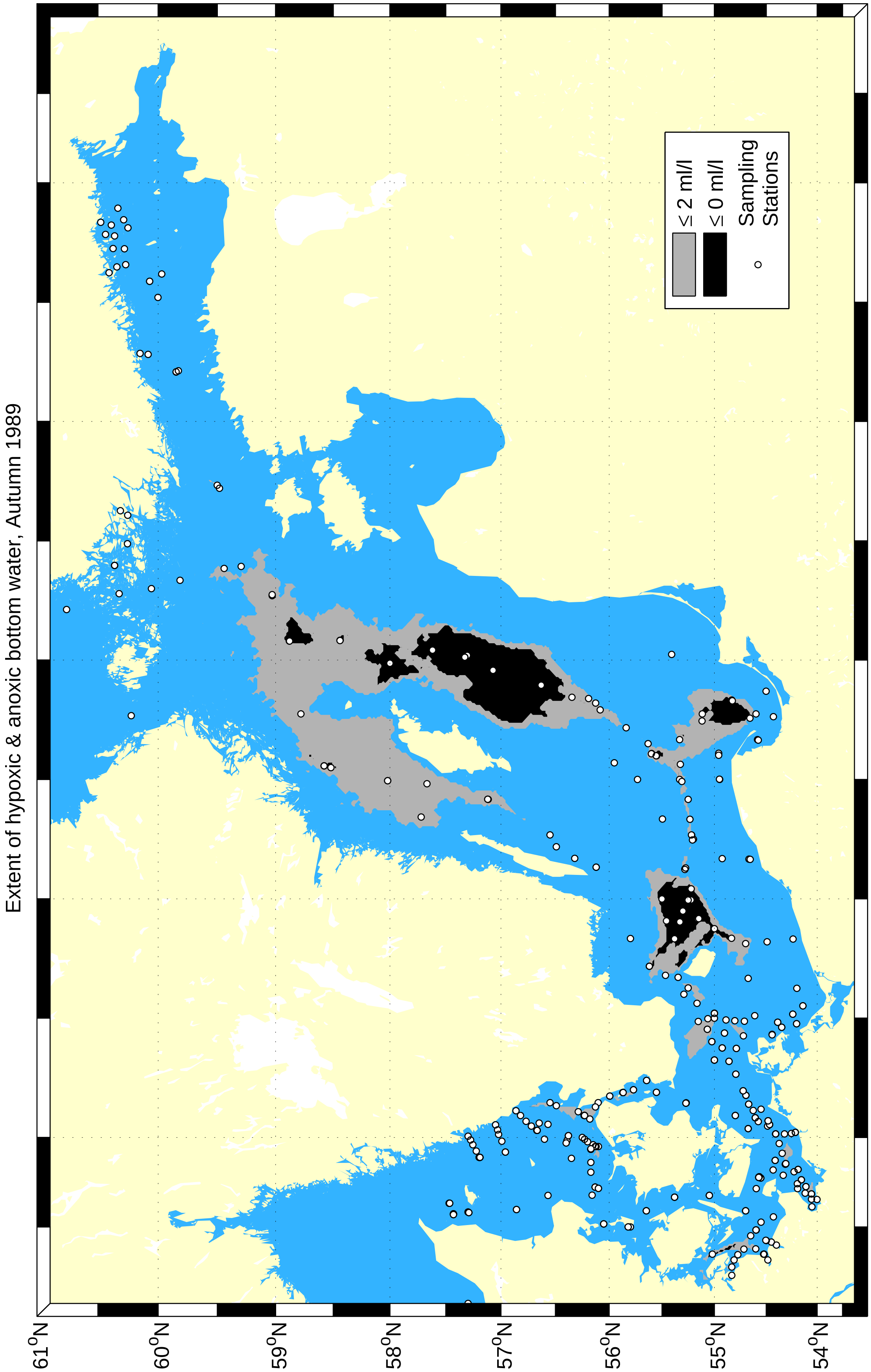


Extent of hypoxic & anoxic bottom water, Autumn 1987



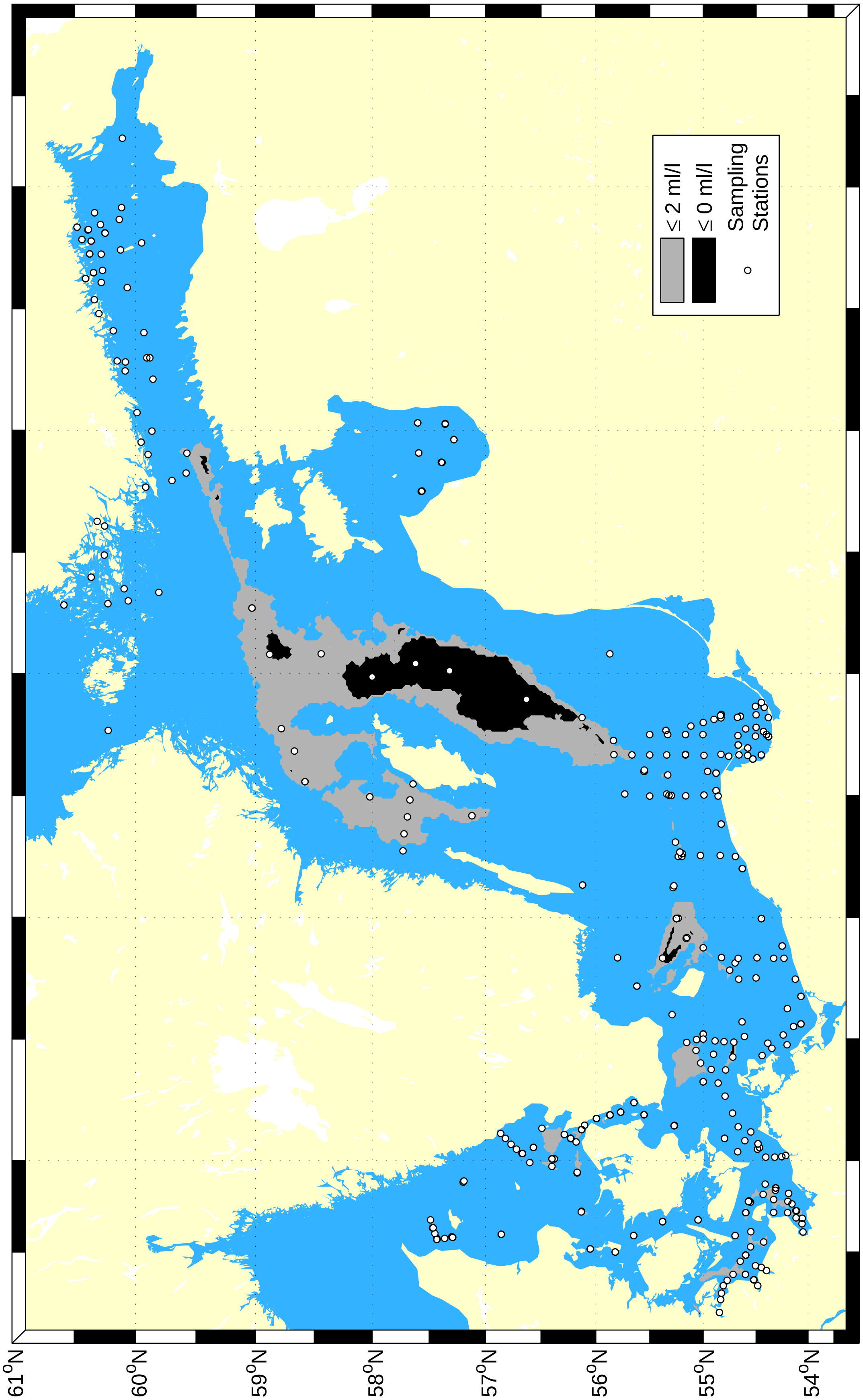


Extent of hypoxic & anoxic bottom water, Autumn 1988

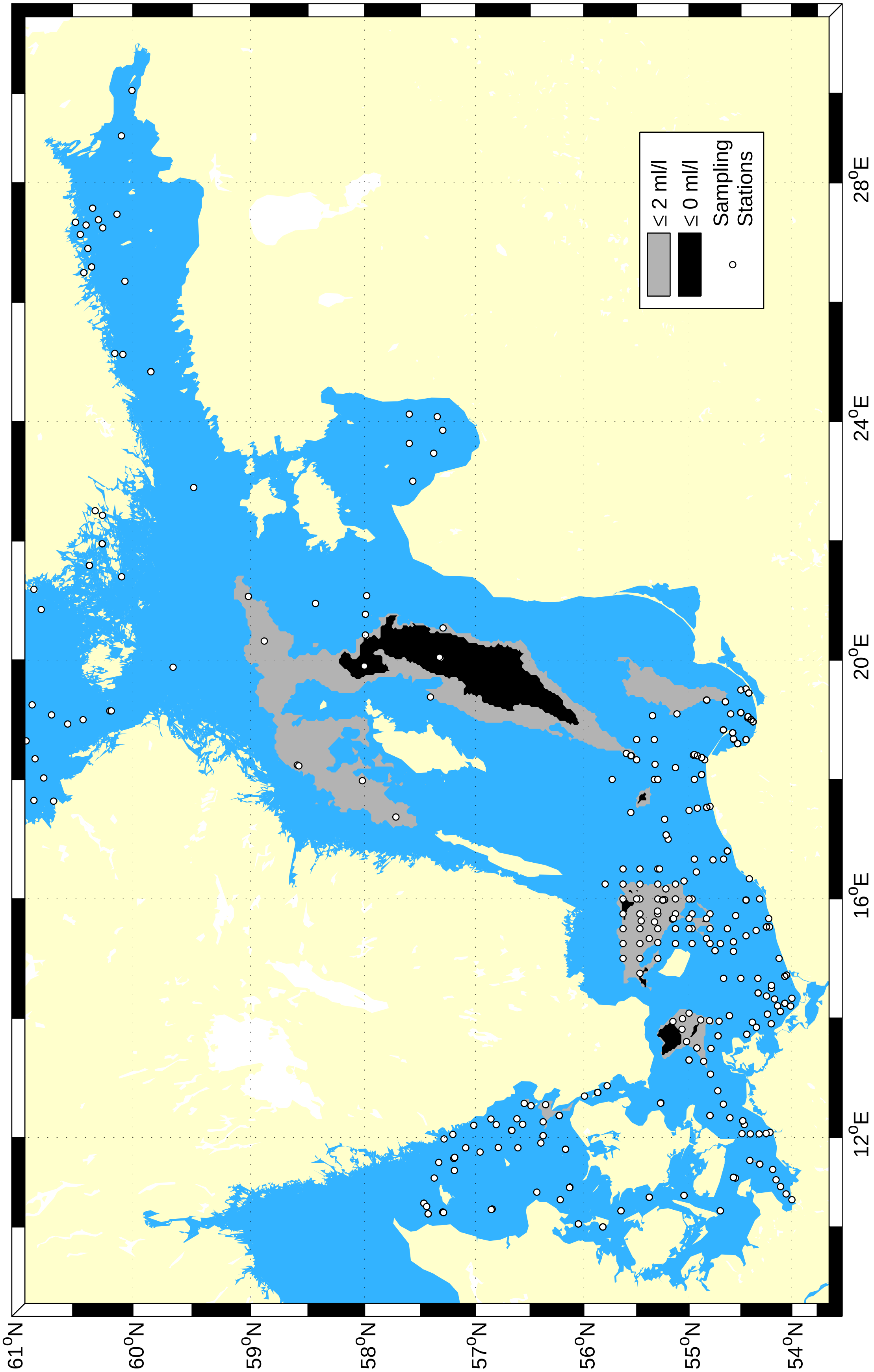


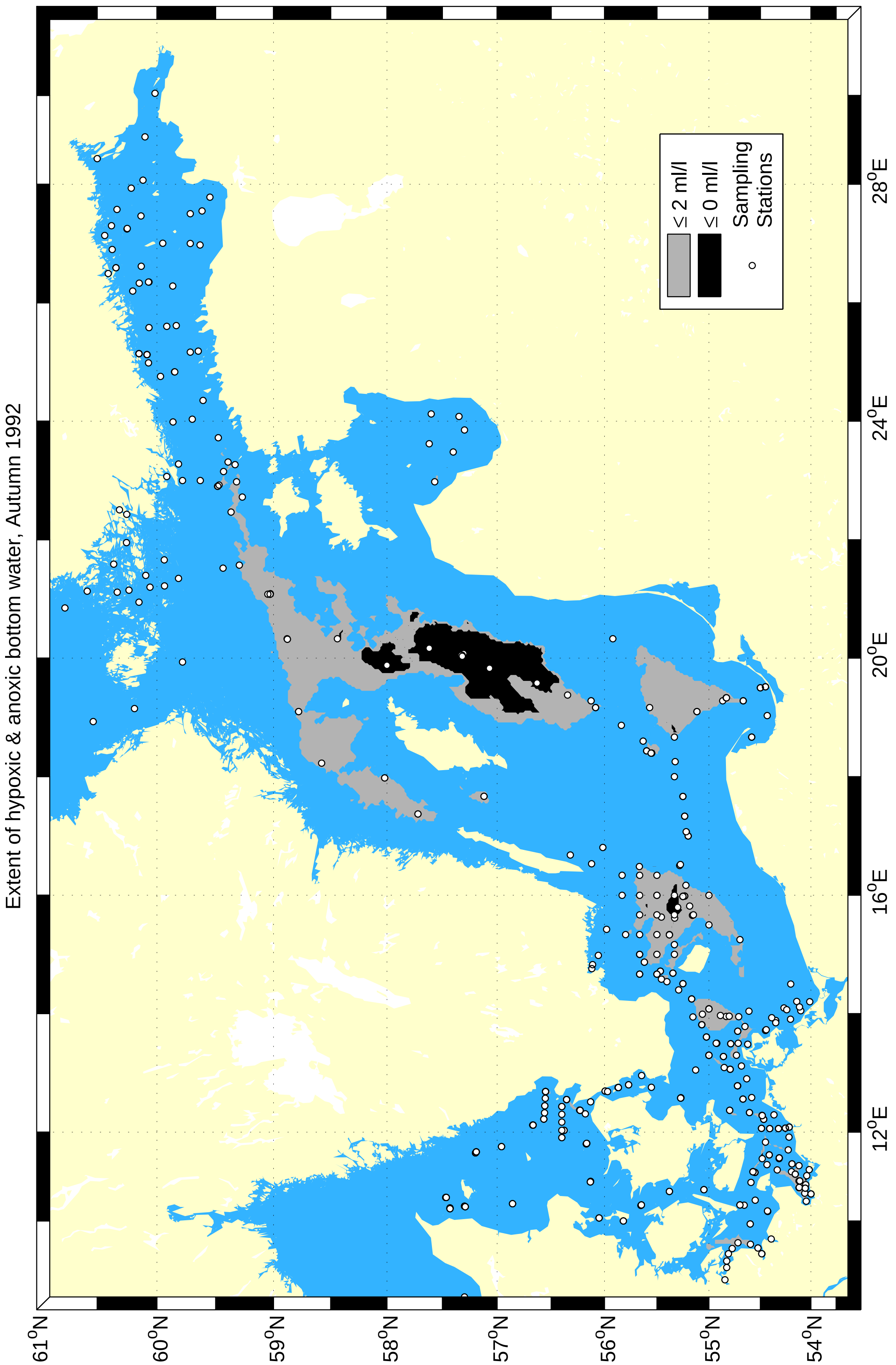
Extent of hypoxic & anoxic bottom water, Autumn 1989
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
54°N
55°N
56°N
57°N
58°N
59°N
60°N
61°N

Extent of hypoxic & anoxic bottom water, Autumn 1990

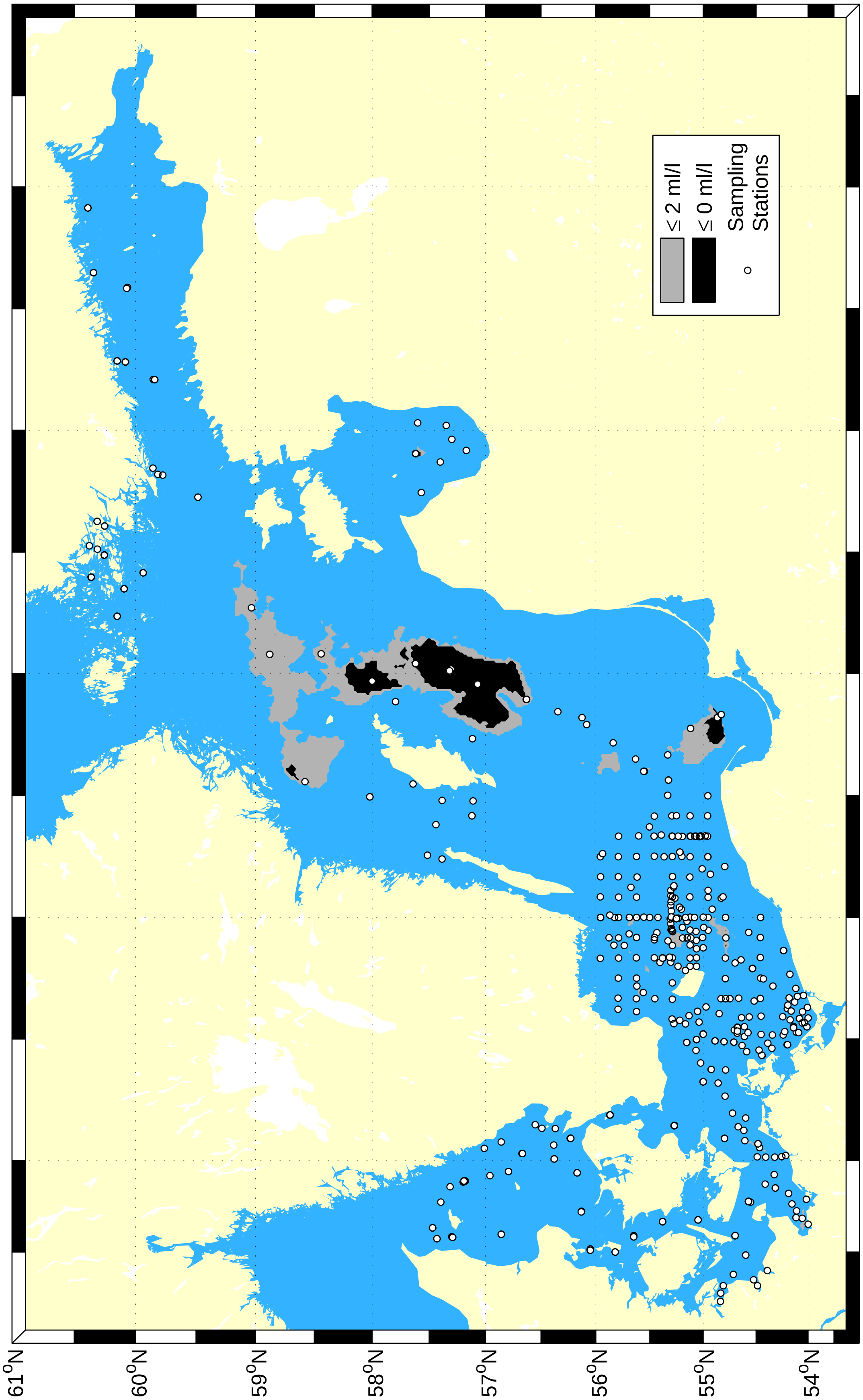


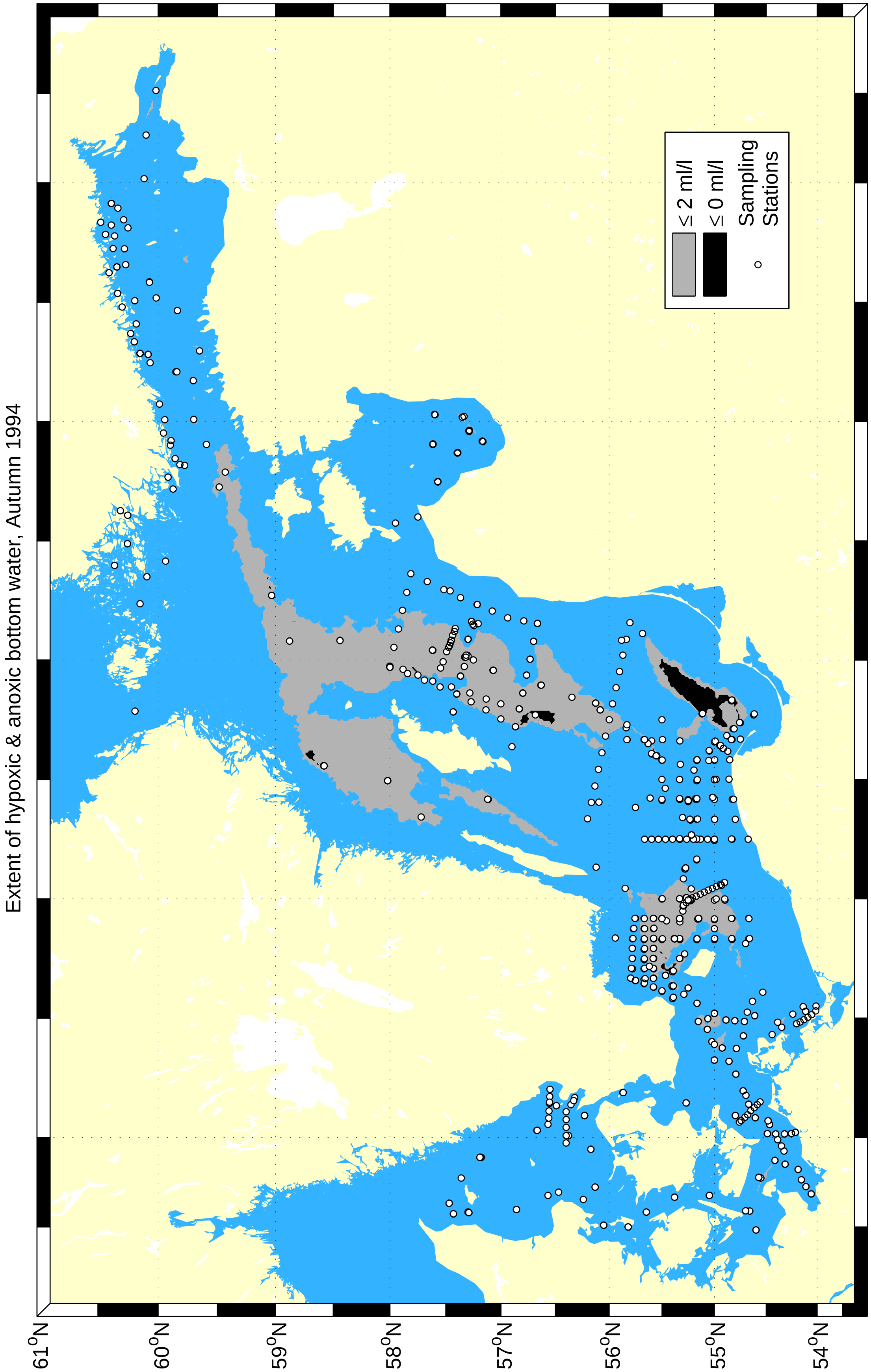
Extent of hypoxic & anoxic bottom water, Autumn 1991

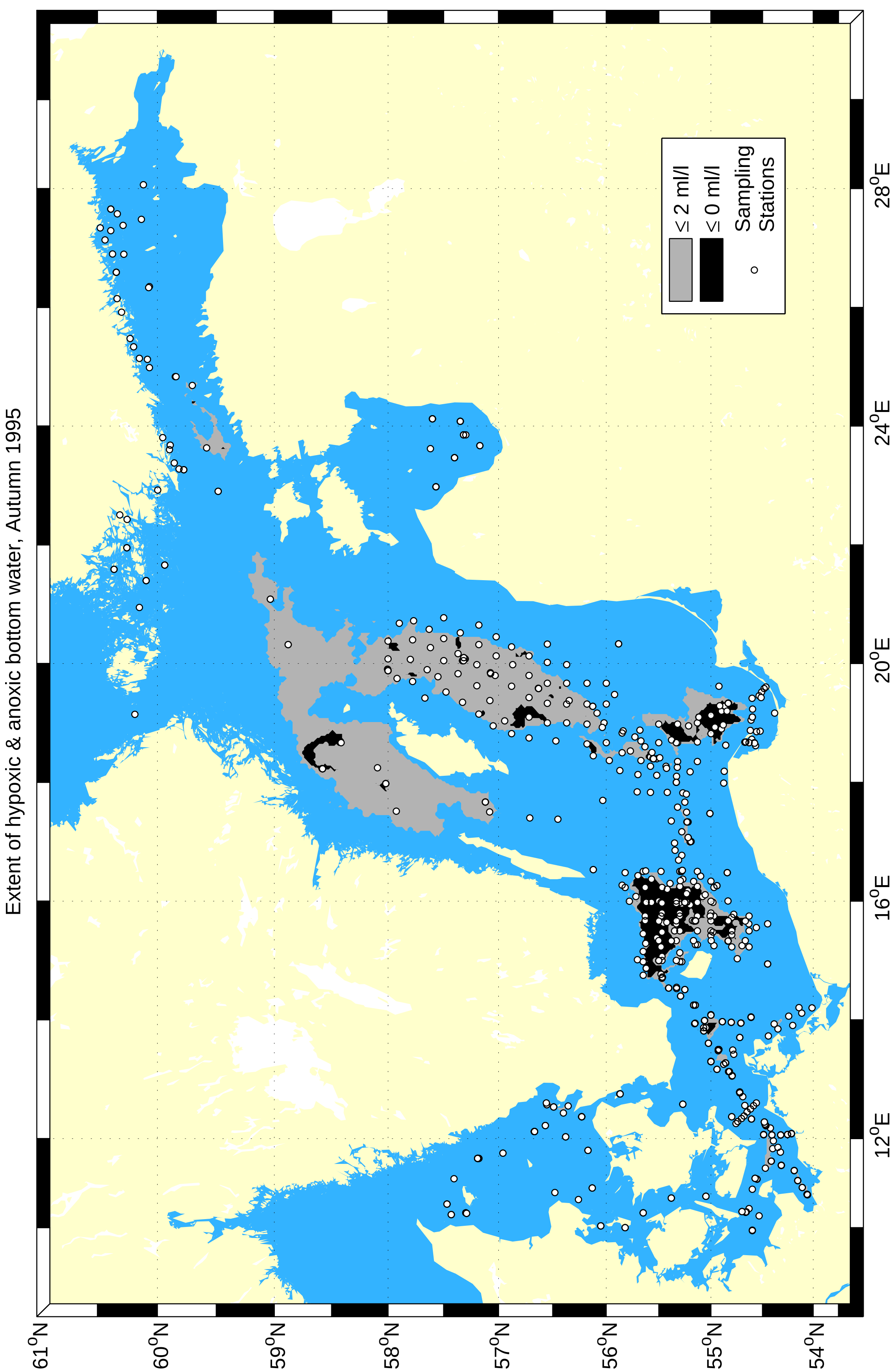



Extent of hypoxic & anoxic bottom water, Autumn 1992
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E

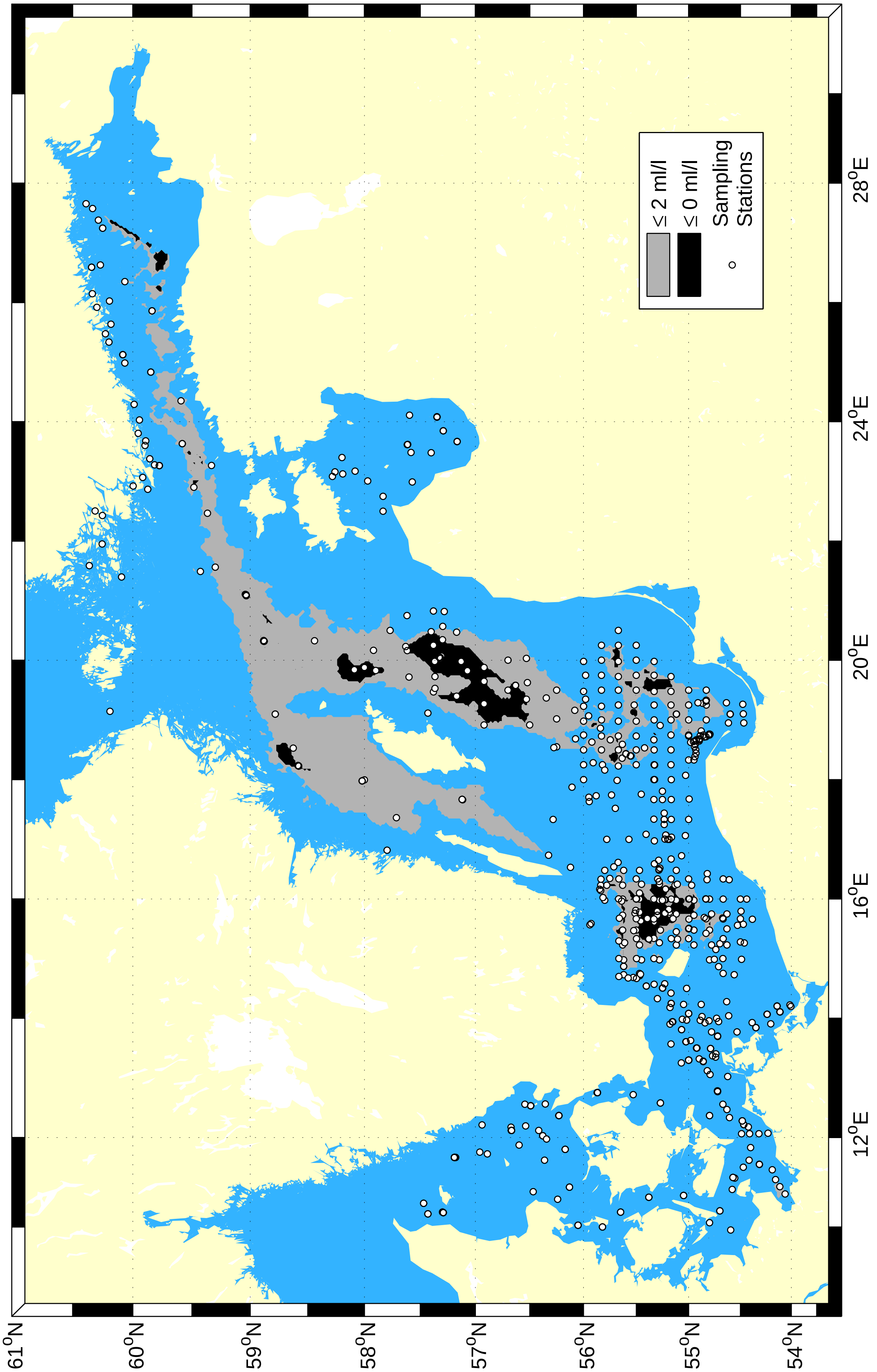
Extent of hypoxic & anoxic bottom water, Autumn 1993

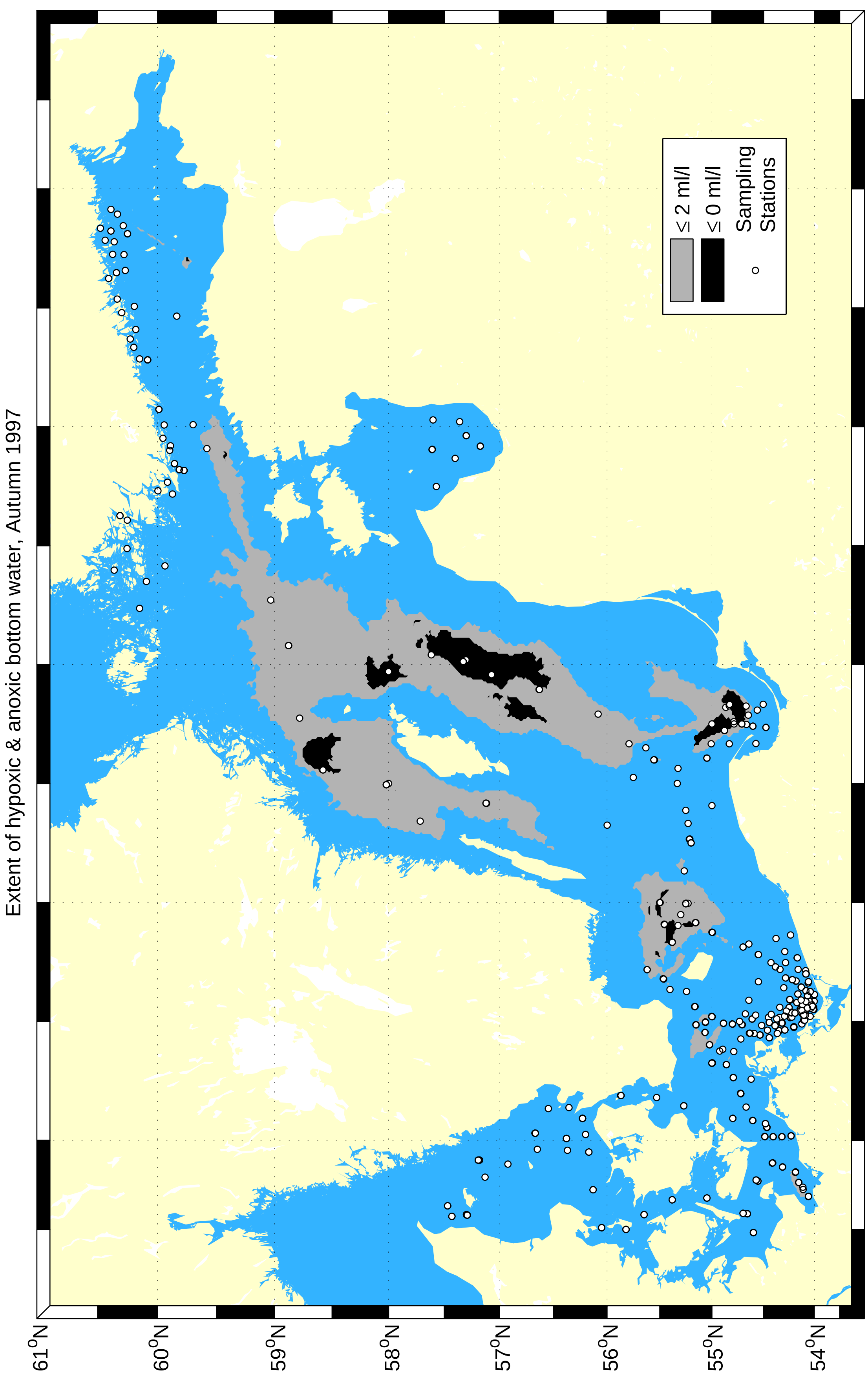



Extent of hypoxic & anoxic bottom water, Autumn 1994
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E

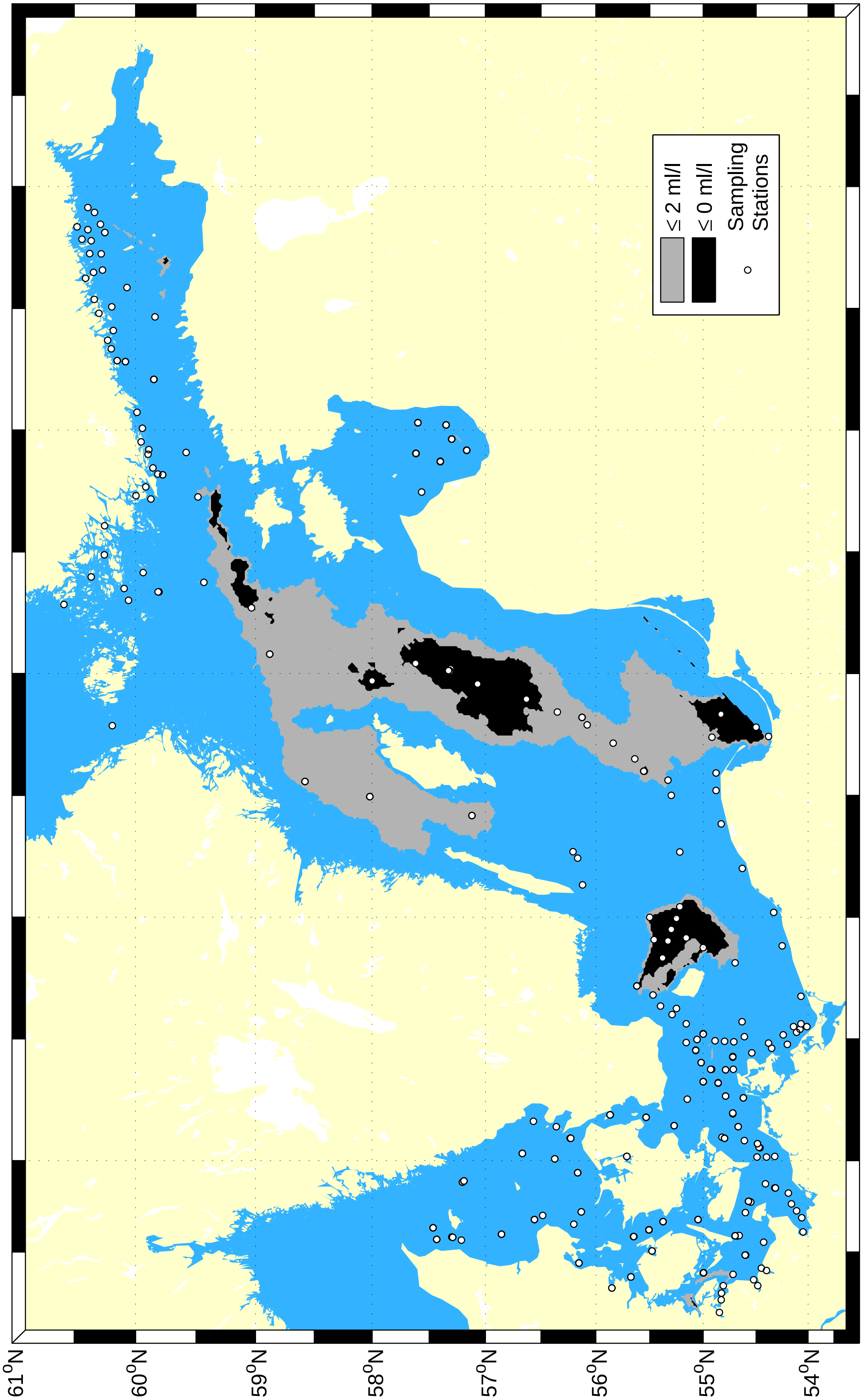

Extent of hypoxic & anoxic bottom water, Autumn 1995
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
54°N
55°N
56°N
57°N
58°N
59°N
60°N
61°N

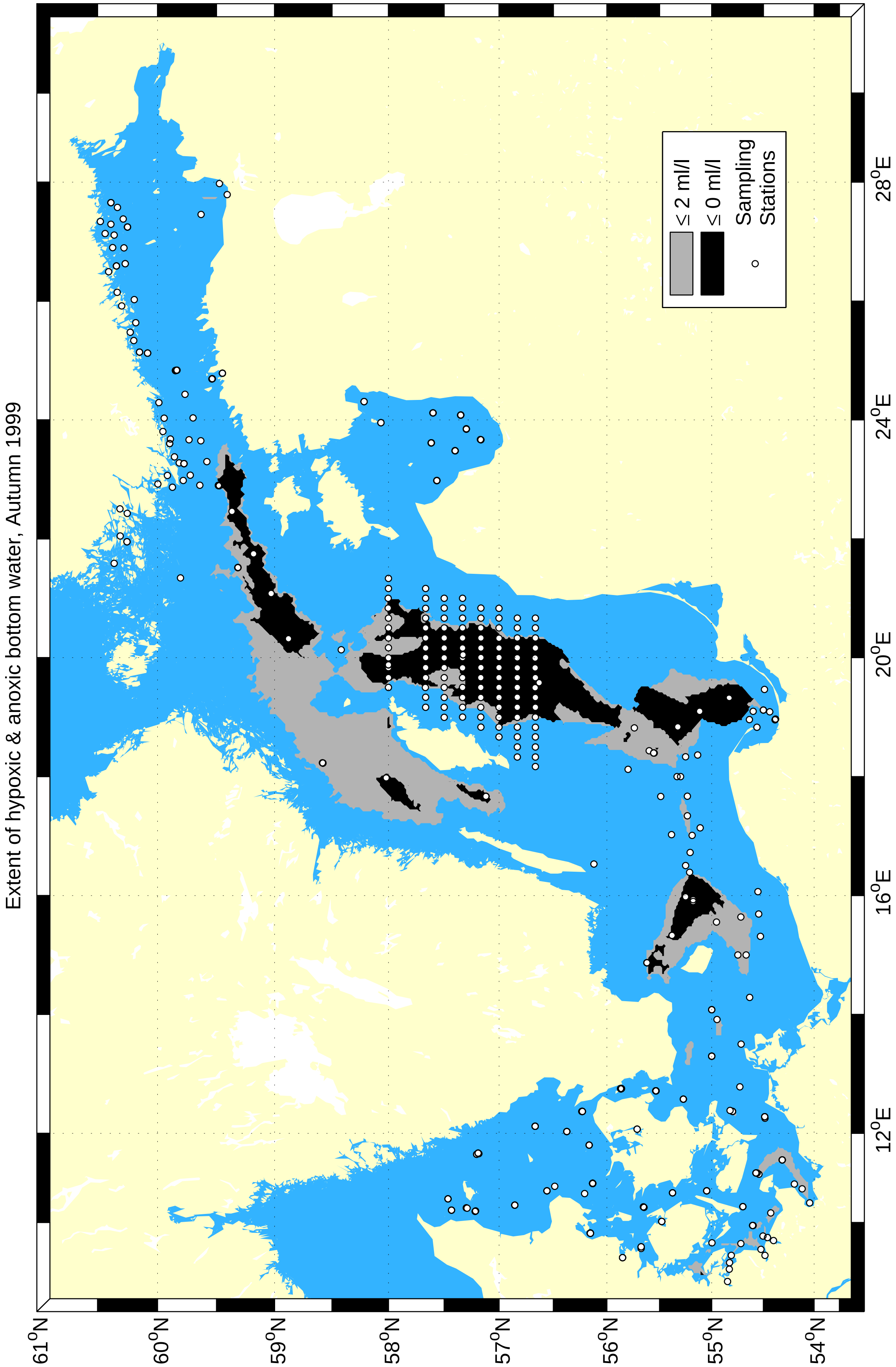
Extent of hypoxic & anoxic bottom water, Autumn 1996

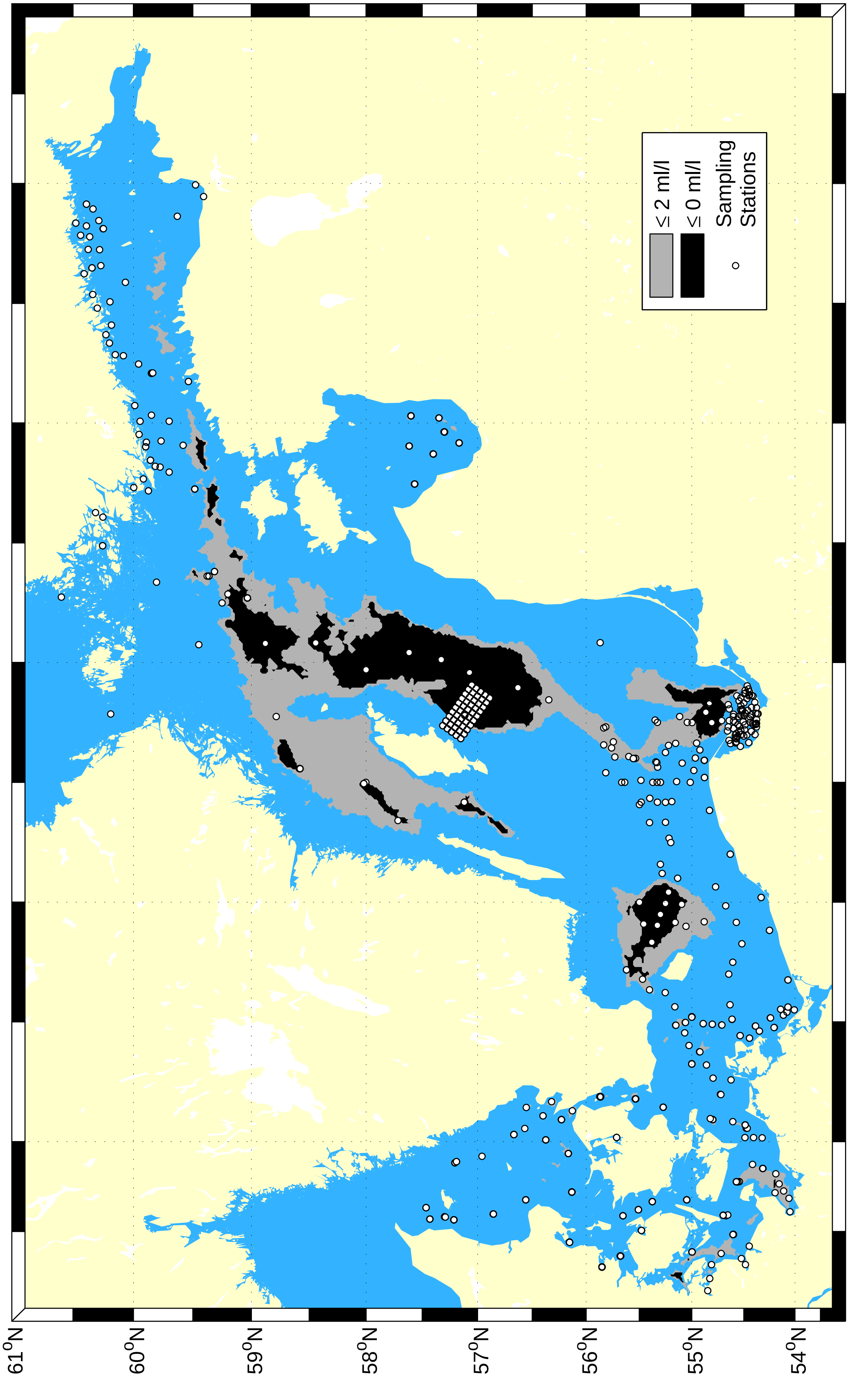



Extent of hypoxic & anoxic bottom water, Autumn 1997
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N

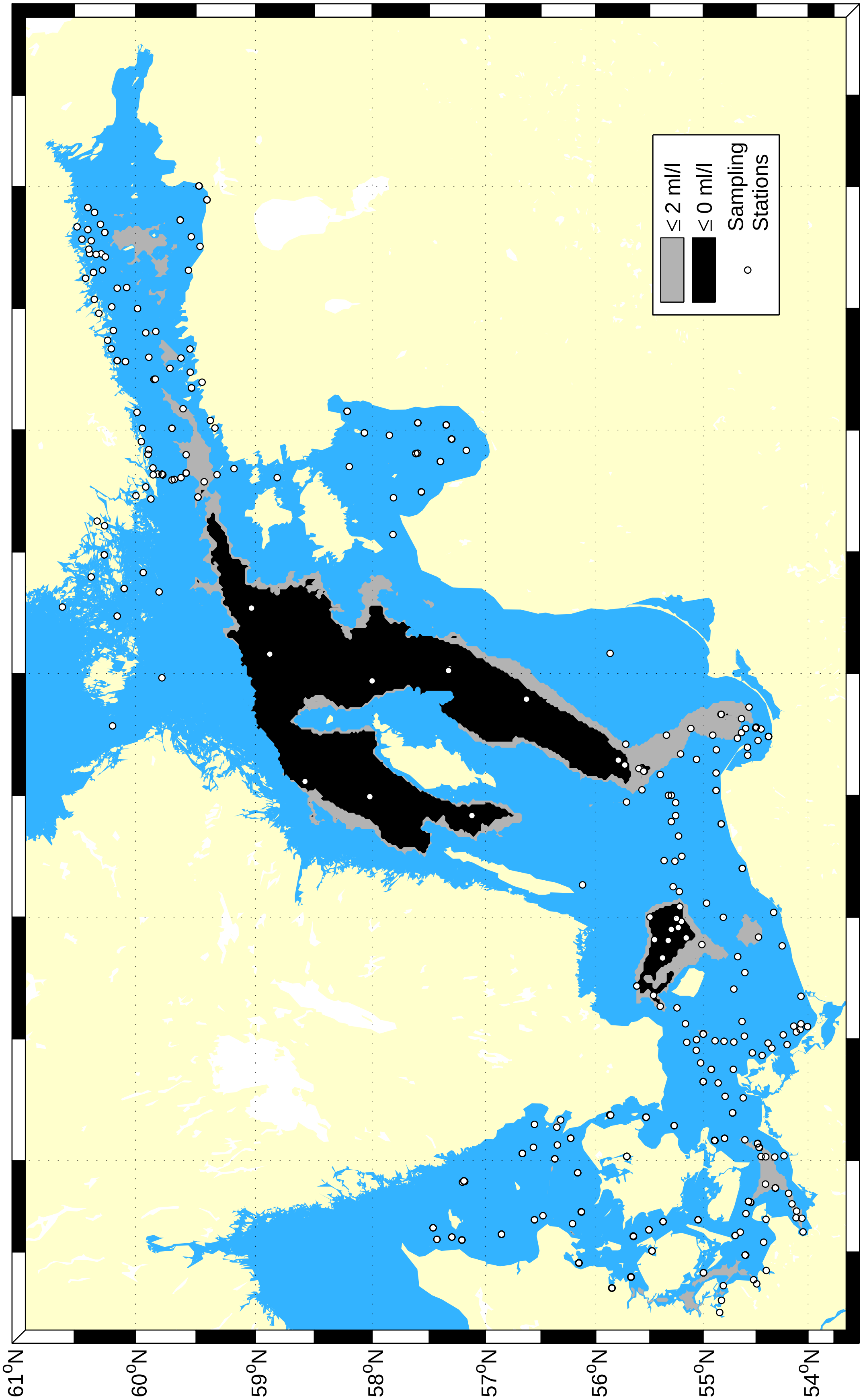
Extent of hypoxic & anoxic bottom water, Autumn 1998



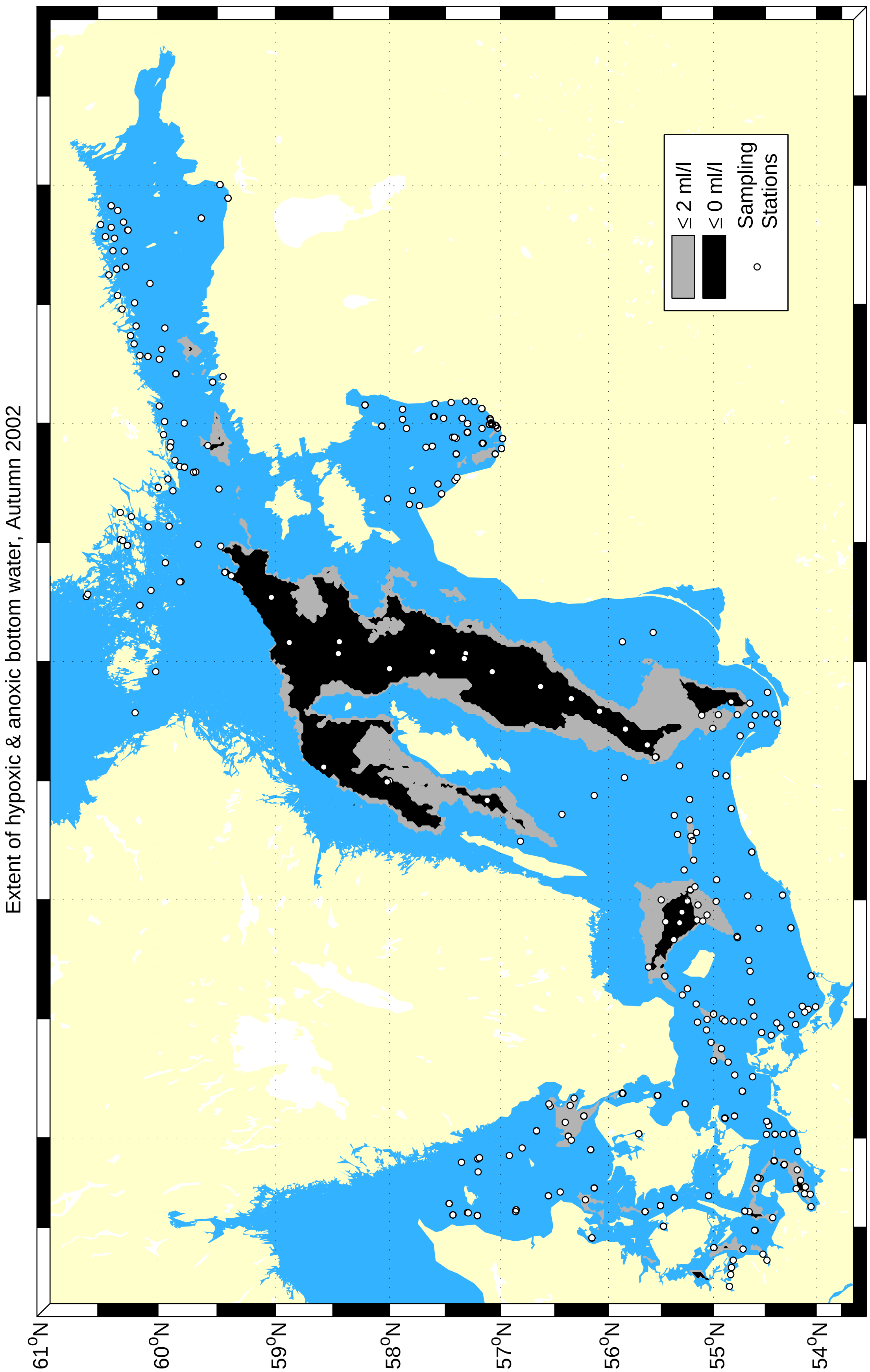

Extent of hypoxic & anoxic bottom water, Autumn 1999
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N

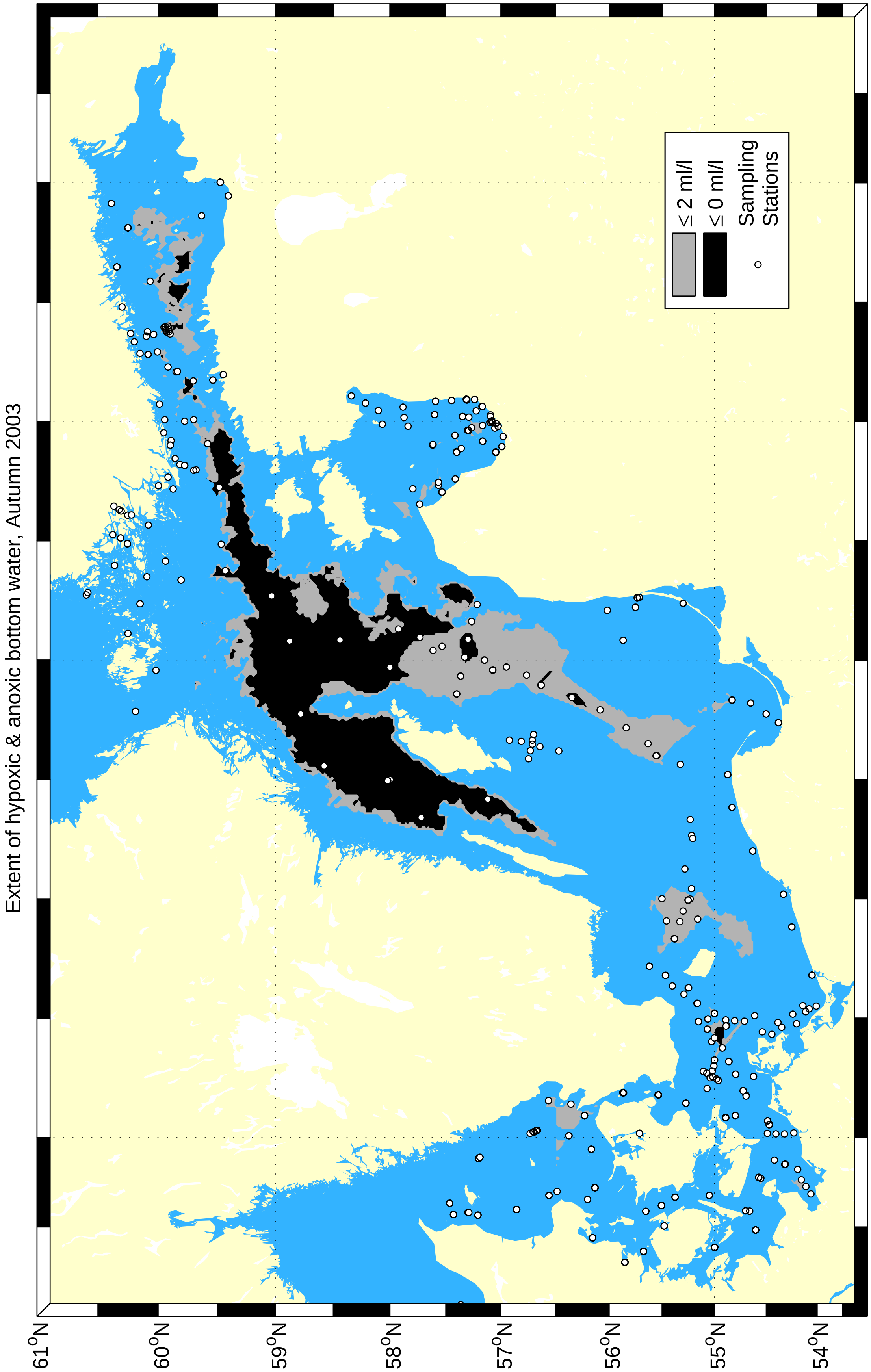


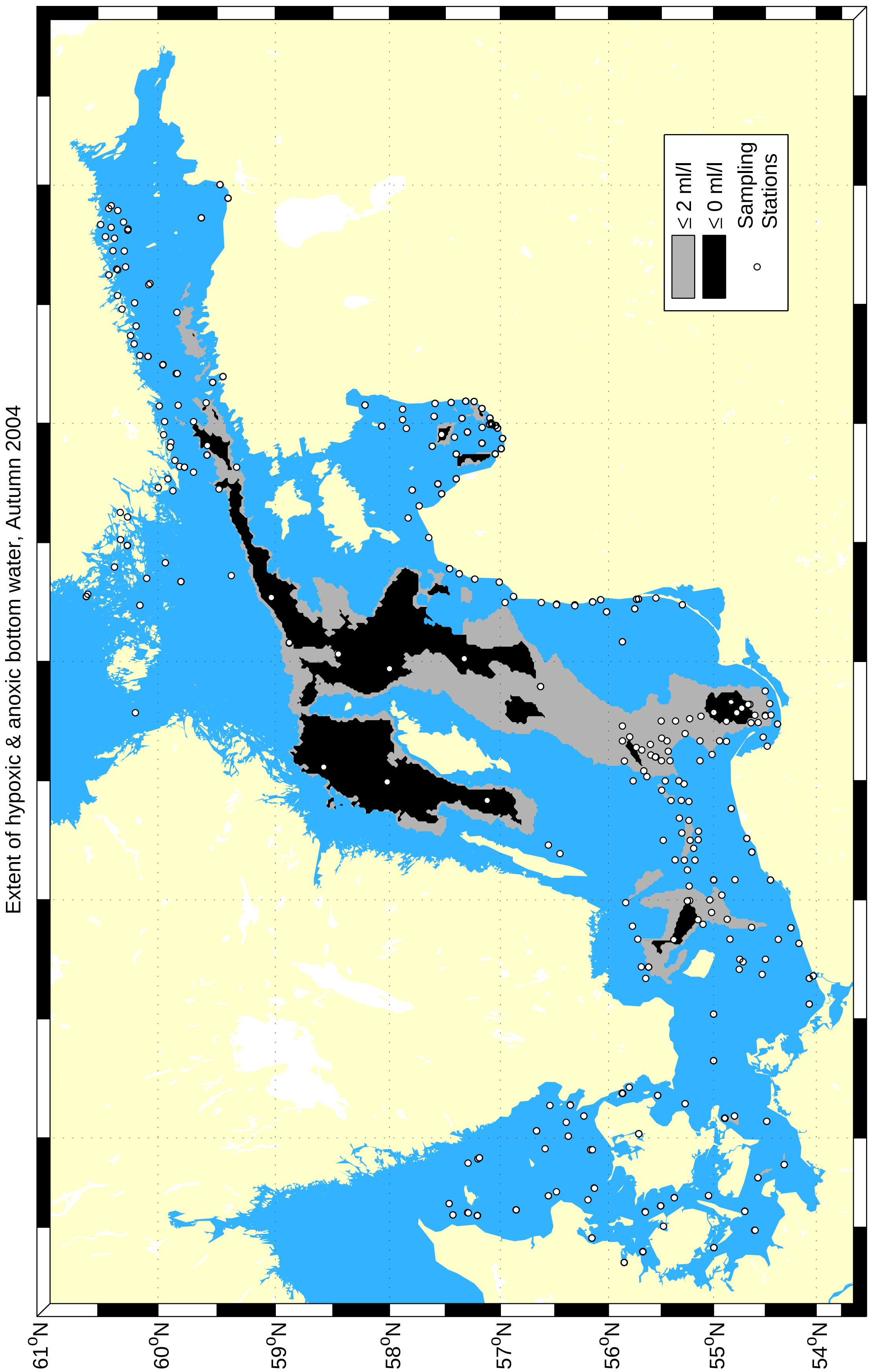
Extent of hypoxic & anoxic bottom water, Autumn 2000

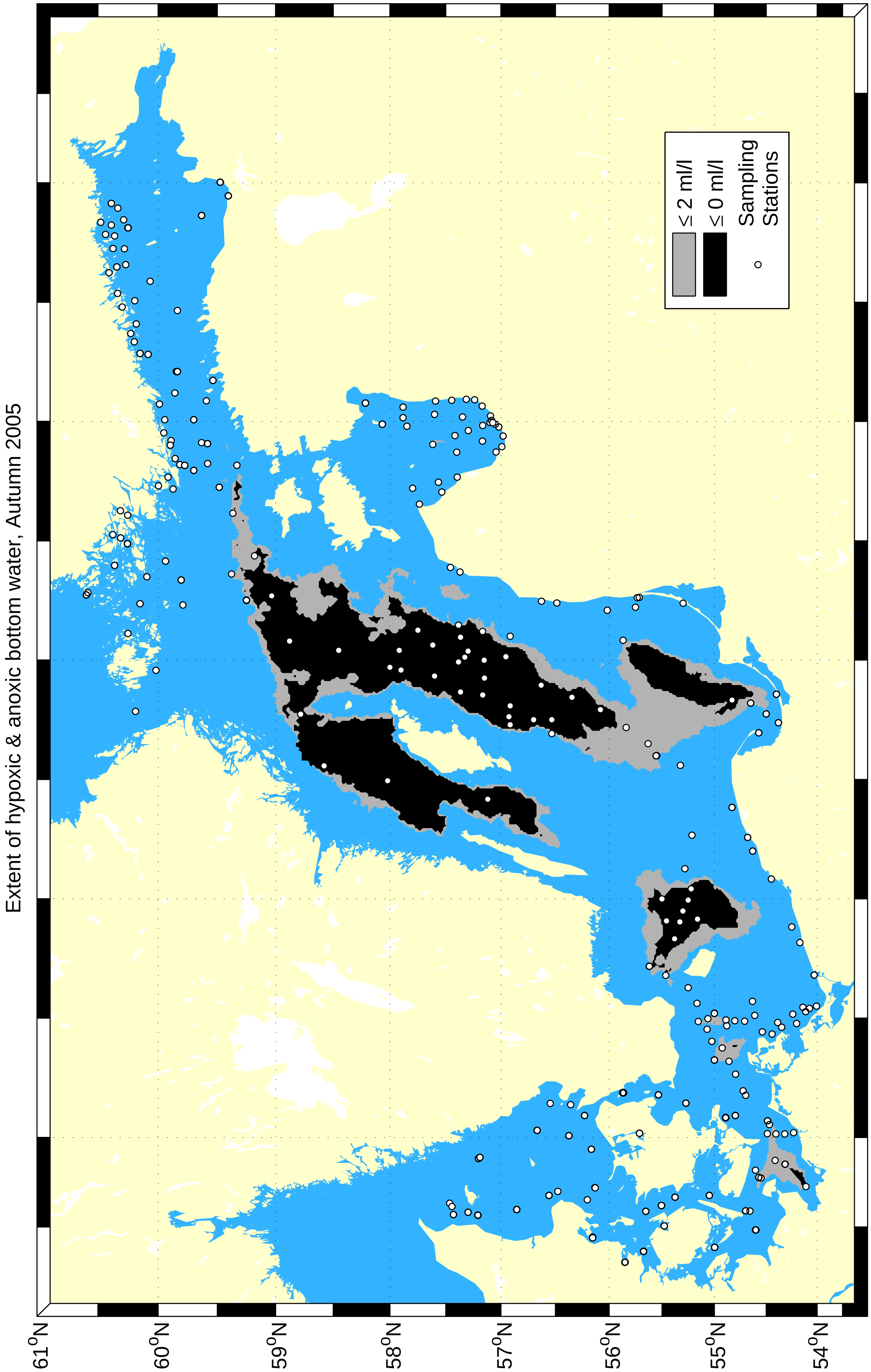


Extent of hypoxic & anoxic bottom water, Autumn 2001

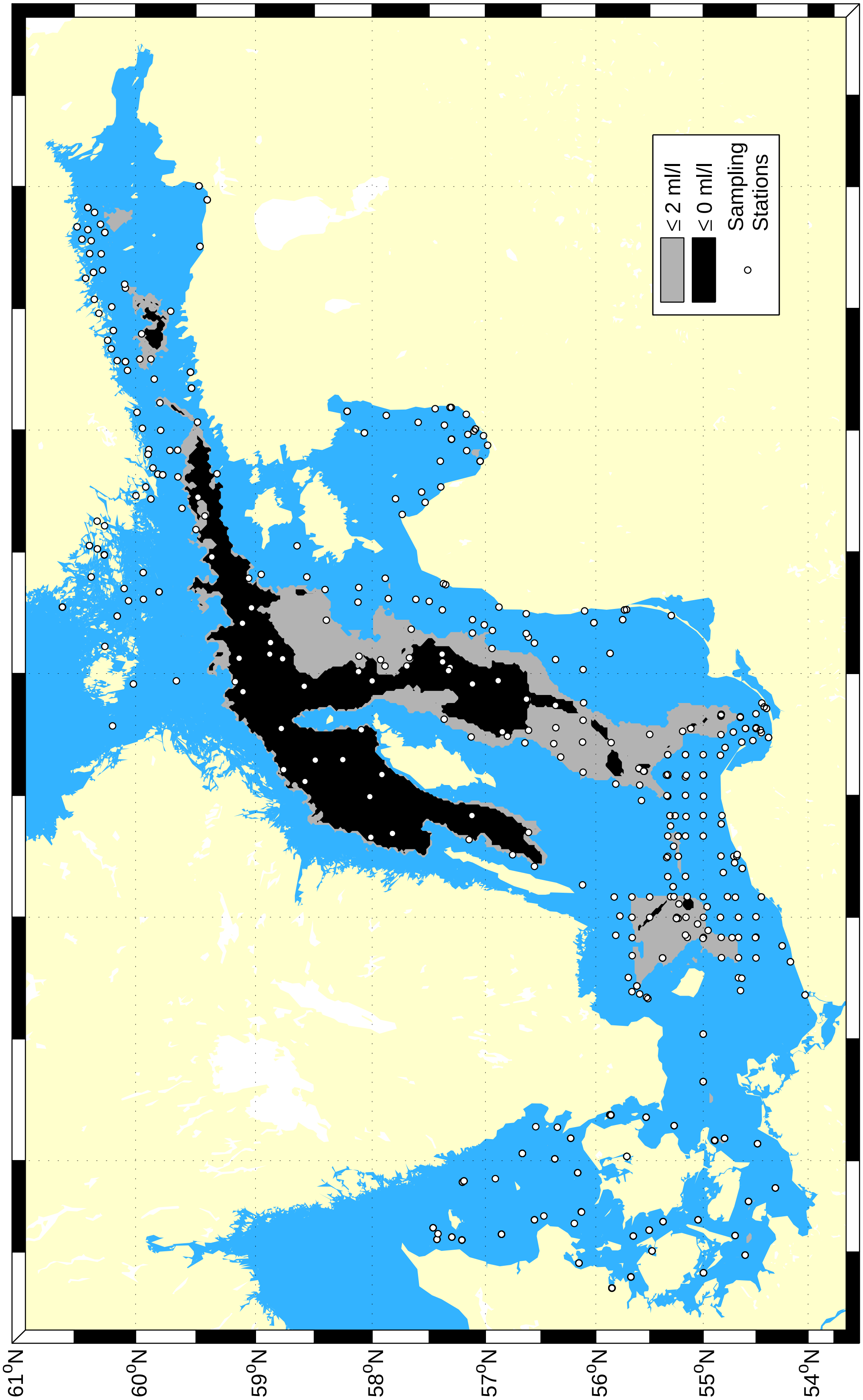

Extent of hypoxic & anoxic bottom water, Autumn 2002
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N

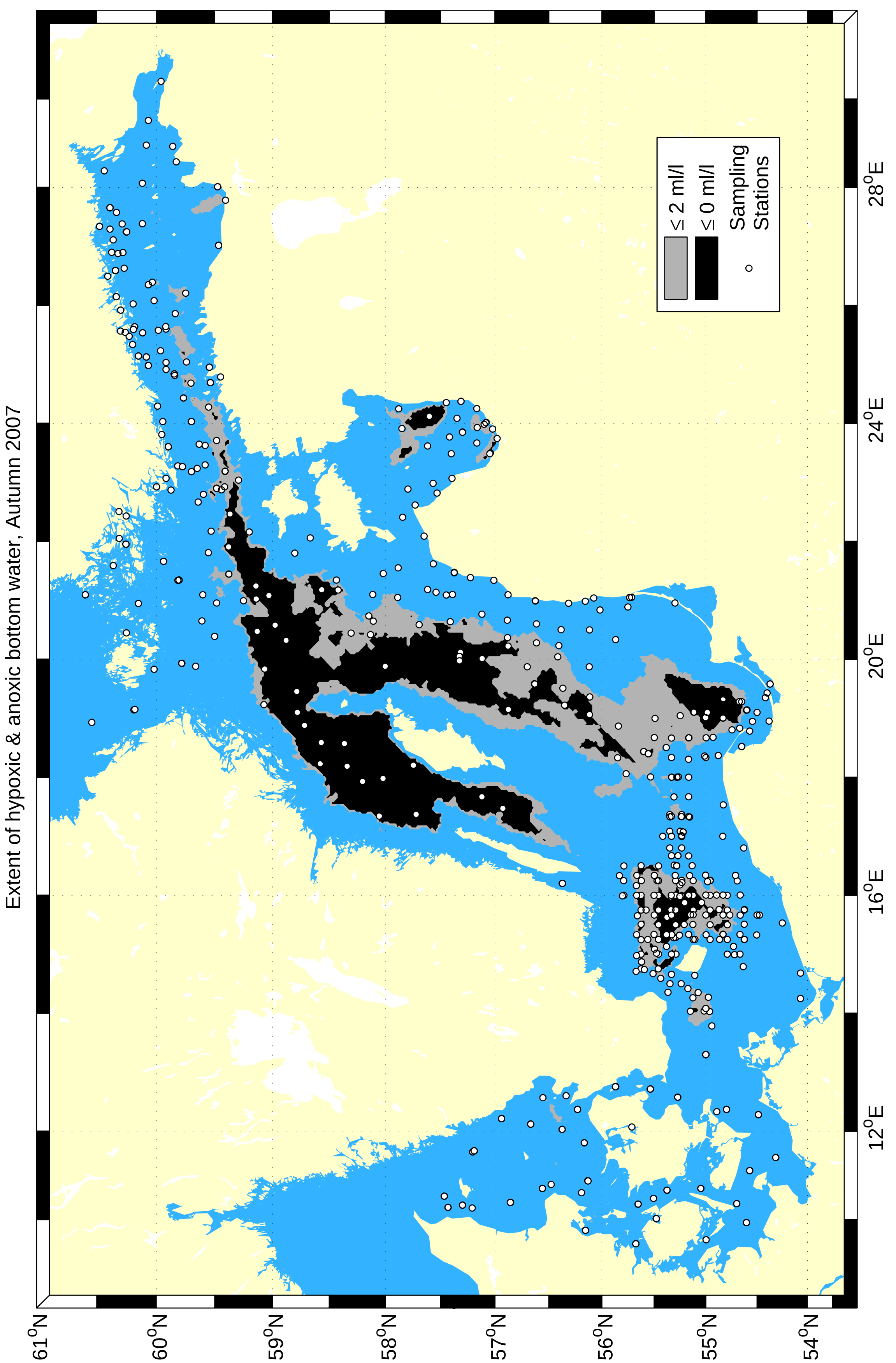

Extent of hypoxic & anoxic bottom water, Autumn 2003
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N


Extent of hypoxic & anoxic bottom water, Autumn 2004
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
54°N
55°N
56°N
57°N
58°N
59°N
60°N
61°N

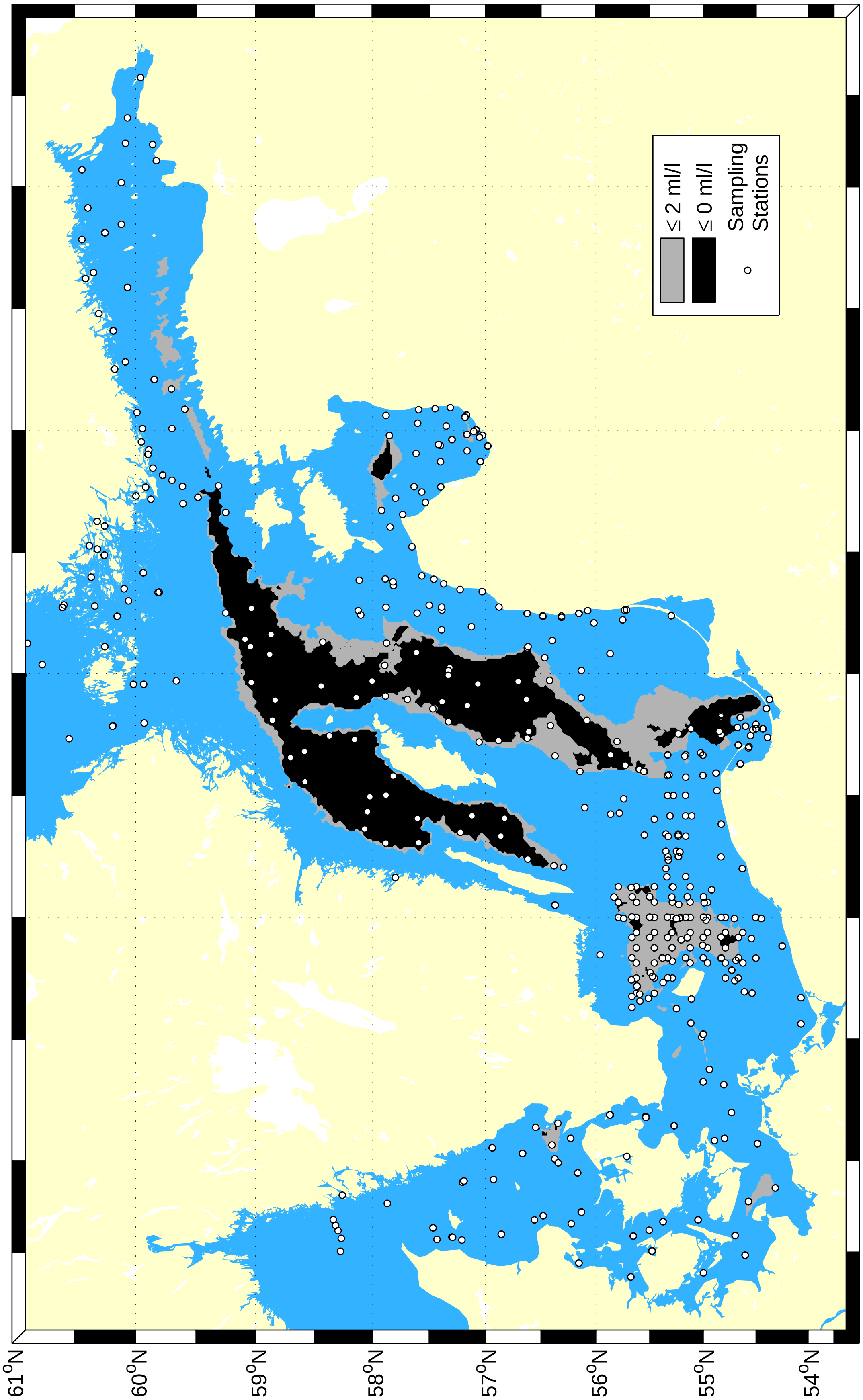

Extent of hypoxic & anoxic bottom water, Autumn 2005
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
54°N
55°N
56°N
57°N
58°N
59°N
60°N
61°N

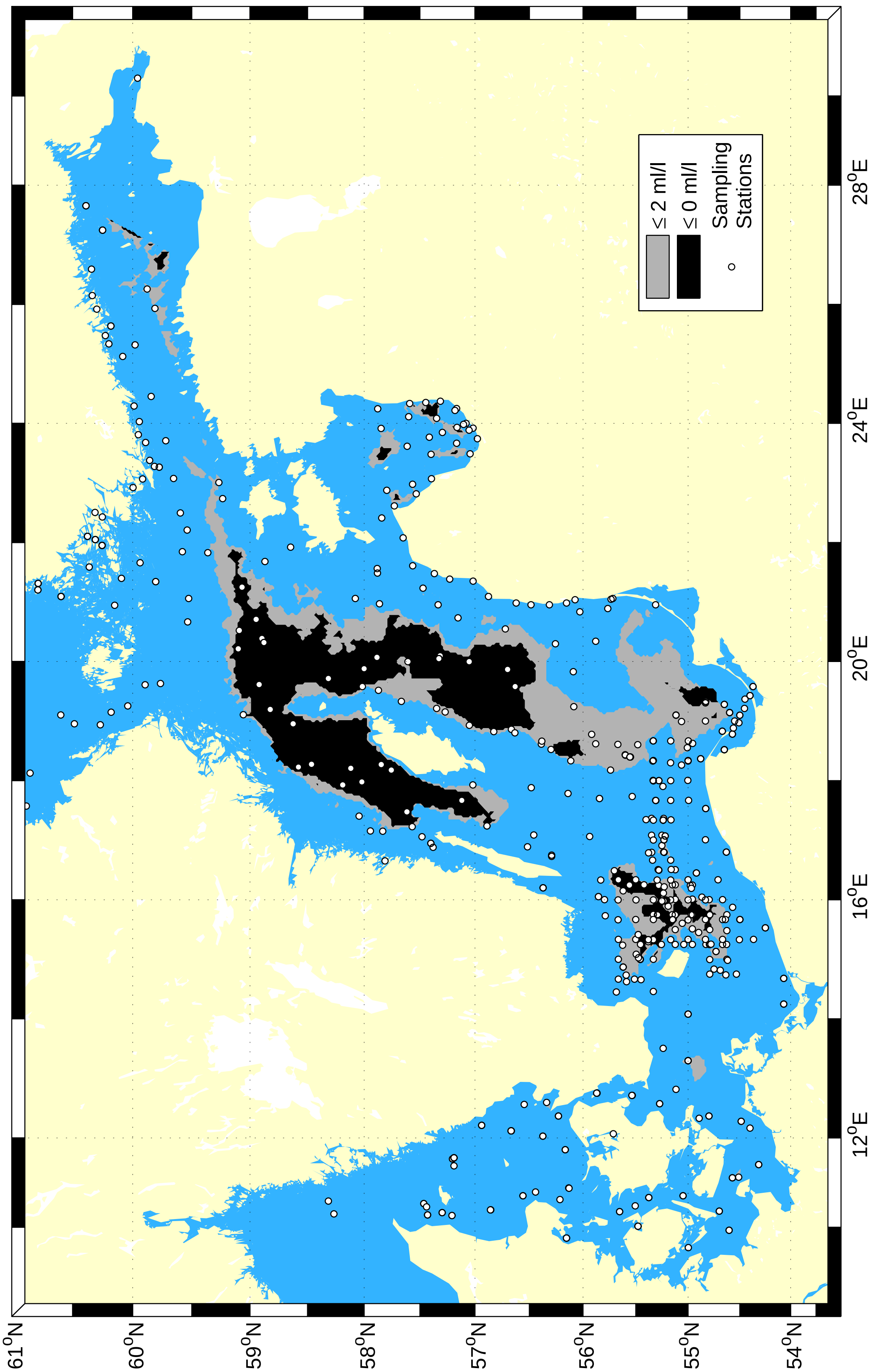
Extent of hypoxic & anoxic bottom water, Autumn 2006




Extent of hypoxic & anoxic bottom water, Autumn 2007
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
12°E
16°E
20°E
24°E
28°E
54°N
55°N
56°N
57°N
58°N
59°N
60°N
61°N

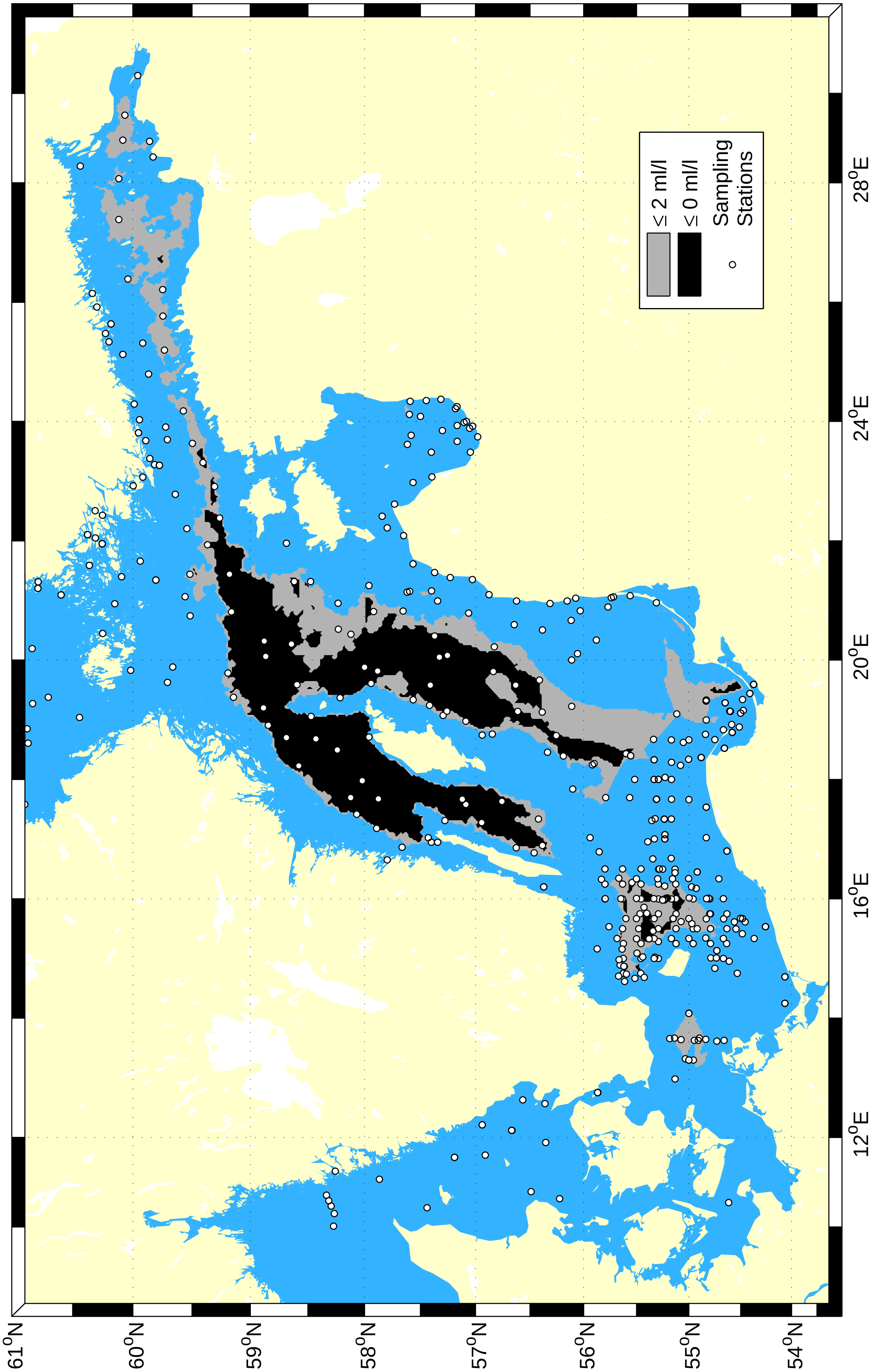
Extent of hypoxic & anoxic bottom water, Autumn 2008

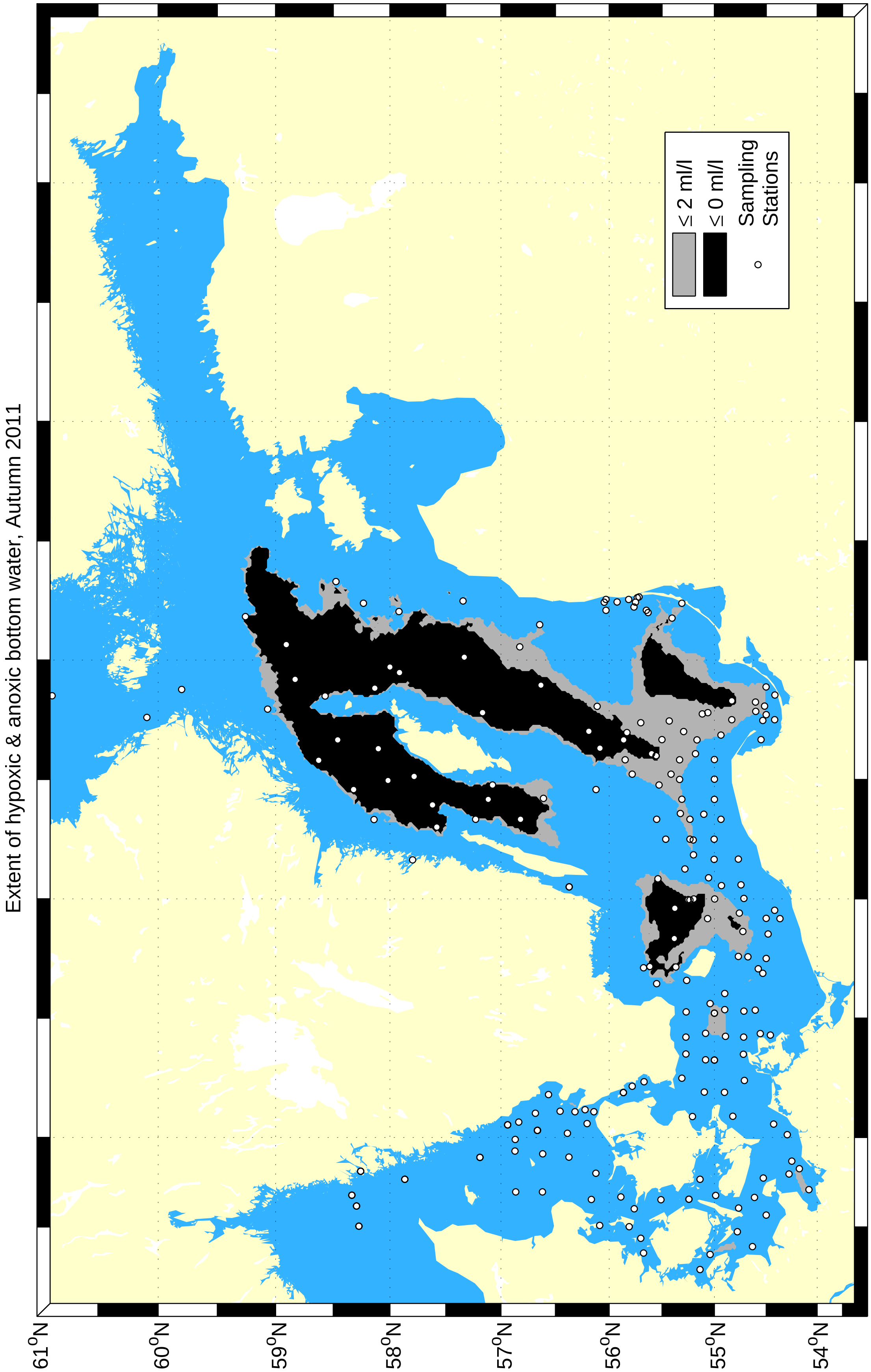




Extent of hypoxic & anoxic bottom water, Autumn 2009

Extent of hypoxic & anoxic bottom water, Autumn 2010




Extent of hypoxic & anoxic bottom water, Autumn 2011
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
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

9 SMHI Publications

SMHI publish seven reportseries. Three of these, the R-series, are intended for international readers and are in most cases written in English. For the others the Swedish language is used.

Name of the series	**Published since**
RMK (Report Meteorology and Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985
KLIMATOLOGI	2009

Earlier issues published in RO

1 Lars Gidhagen, Lennart Funkquist and Ray Murthy (1986)
Calculations of horizontal exchange coefficients using Eulerian time series current meter data from the Baltic Sea.

2 Thomas Thompson (1986)
Ymer-80, satellites, arctic sea ice and weather.

3 Stig Carlberg et al (1986)
Program för miljökvalitetsövervakning - PMK.

4 Jan-Erik Lundqvist och Anders Omstedt (1987)
Isförhållandena i Sveriges södra och västra farvatten.

5 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg och Bengt Yhlen (1987)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1986.

6 Jorge C. Valderama (1987)
Results of a five year survey of the distribution of UREA in the Baltic sea.

7 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlen och Danuta Zagradkin (1988).
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1987

8 Bertil Håkansson (1988)
Ice reconnaissance and forecasts in Storfjorden, Svalbard.

9 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlen, Danuta Zagradkin, Bo Juhlin och Jan Szaron (1989)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1988.

10 L. Fransson, B. Håkansson, A. Omstedt och L. Stehn (1989)
Sea ice properties studied from the ice-breaker Tor during BEPERS-88.

11 Stig Carlberg, Sven Engström, Stig Fonselius, Håkan Palmén, Lotta Fyrberg, Bengt Yhlen, Bo Juhlin och Jan Szaron (1990)
Program för miljökvalitetsövervakning - PMK. Utsjöprogram under 1989.

12 Anders Omstedt (1990)
Real-time modelling and forecasting of temperatures in the Baltic Sea.

13 Lars Andersson, Stig Carlberg, Elisabet Fogelqvist, Stig Fonselius, Håkan Palmén, Eva-Gun Thelén, Lotta Fyrberg, Bengt Yhlen och Danuta Zagradkin (1991)

Program för miljökvalitetsövervakning – PMK. Utsjöprogram under 1989.

14 Lars Andersson, Stig Carlberg, Lars Edler, Elisabet Fogelqvist, Stig Fonselius, Lotta Fyrberg, Marie Larsson, Håkan Palmén, Björn Sjöberg, Danuta Zagradkin, och Bengt Yhlen (1992)
Haven runt Sverige 1991. Rapport från SMHI, Oceanografiska Laboratoriet, inklusive PMK - utsjöprogrammet. (The conditions of the seas around Sweden. Report from the activities in 1991, including PMK - The National Swedish Programme for Monitoring of Environmental Quality Open Sea Programme.)

15 Ray Murthy, Bertil Håkansson and Pekka Alenius (ed.) (1993)
The Gulf of Bothnia Year-1991 - Physical transport experiments.

16 Lars Andersson, Lars Edler and Björn Sjöberg (1993)
The conditions of the seas around Sweden. Report from activities in 1992.

17 Anders Omstedt, Leif Nyberg and Matti Leppäranta (1994)
A coupled ice-ocean model supporting winter navigation in the Baltic Sea.
Part 1. Ice dynamics and water levels.

18 Lennart Funkquist (1993)
An operational Baltic Sea circulation model.
Part 1. Barotropic version.

19 Eleonor Marmefelt (1994)
Currents in the Gulf of Bothnia. During the Field Year of 1991.

20 Lars Andersson, Björn Sjöberg and Mikaell Krysell (1994)
The conditions of the seas around Sweden. Report from the activities in 1993.

21 Anders Omstedt and Leif Nyberg (1995)
A coupled ice-ocean model supporting winter navigation in the Baltic Sea.
Part 2. Thermodynamics and meteorological coupling.

22 Lennart Funkquist and Eckhard Kleine (1995)
Application of the BSH model to Kattegat and Skagerrak.

23 Tarmo Köuts and Bertil Håkansson (1995)
Observations of water exchange, currents, sea levels and nutrients in the Gulf of Riga.

24 Urban Svensson (1998)
PROBE An Instruction Manual.

25 Maria Lundin (1999)
Time Series Analysis of SAR Sea Ice Backscatter Variability and its Dependence on Weather Conditions.

26 Markus Meier[1], Ralf Döscher[1], Andrew, C. Coward[2], Jonas Nycander[3] and Kristofer Döös[3] (1999). RCO – Rossby Centre regional Ocean climate model: model description (version 1.0) and first results from the hindcast period 1992/93.

[1] Rossby Centre, SMHI [2] James Rennell Division, Southampton Oceanography Centre, [3] Department of Meteorology, Stockholm University

27 H. E. Markus Meier (1999)
First results of multi-year simulations using a 3D Baltic Sea model.

28 H. E. Markus Meier (2000)
The use of the $k - \varepsilon$ turbulence model within the Rossby Centre regional ocean climate model: parameterization development and results.

29 Eleonor Marmefelt, Bertil Håkansson, Anders Christian Erichsen and Ian Sehested Hansen (2000)
Development of an Ecological Model System for the Kattegat and the Southern Baltic. Final Report to the Nordic Councils of Ministers.

30 H.E Markus Meier and Frank Kauker (2002).
Simulating Baltic Sea climate for the period 1902-1998 with the Rossby Centre coupled ice-ocean model.

31 Bertil Håkansson (2003)
Swedish National Report on Eutrophication Status in the Kattegat and the Skagerrak
OSPAR ASSESSMENT 2002

32 Bengt Karlson & Lars Andersson (2003)
The Chattonella-bloom in year 2001 and effects of high freshwater input from river Göta Älv to the Kattegat-Skagerrak area

33 Philip Axe and Helma Lindow (2005)
Hydrographic Conditions Around Offshore Banks

34 Pia M Andersson, Lars S Andersson (2006)
Long term trends in the seas surrounding Sweden. Part one - Nutrients

35 Bengt Karlson, Ann-Sofi Rehnstam-Holm & Lars-Ove Loo (2007)
Temporal and spatial distribution of diarrhetic shellfish toxins in blue mussels, Mytilus edulis (L.), at the Swedish West Coast, NE Atlantic, years 1988-2005

36 Bertil Håkansson
Co-authors: Odd Lindahl, Rutger Rosenberg, Pilip Axe, Kari Eilola, Bengt Karlson (2007)
Swedish National Report on Eutrophication Status in the Kattegat and the Skagerrak
OSPAR ASSESSMENT 2007

37 Lennart Funkquist and Eckhard Kleine (2007)
An introduction to HIROMB, an operational baroclinic model for the Baltic Sea

38 Philip Axe (2008)
Temporal and spatial monitoring of eutrophication variables in CEMP

39 Bengt Karlson, Philip Axe, Lennart Funkquist, Seppo Kaitala, Kai Sørensen (2009)
Infrastructure for marine monitoring and operational oceanography

40 Marie Johansen, Pia Andersson (2010)
Long term trends in the seas surrounding Sweden
Part two – Pelagic biology

41 Philip Axe, (2010)
Oceanographic Applications of Coastal Radar

42 Martin Hansson, Lars Andersson, Philip Axe (2011)
Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011

Swedish Meteorological and Hydrological Institute
SE 601 76 NORRKÖPING
Phone +46 11-495 80 00 Telefax +46 11-495 80 01

ISSN 0283-1112