SMHI

REPORT OCEANOGRAPHY No. 75, 2023

The Swedish National Marine Monitoring Programme 2022

Hydrography, Nutrients, Phytoplankton

Ann-Turi Skjevik, Karin Wesslander, Lena Viktorsson

Front: TS-plot from CTD-profiles made by SMHI during 2022. Image is produced with ODV (Schlitzer, Reiner, Ocean Data View, odv.awi.de, 2021).

ISSN: 0283-1112

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Classification / Klassificering

Public / Publik

Key words / Nyckelord

Oceanography, marine monitoring, nutrients, Baltic Sea, Gulf of Bothnia, Skagerrak, Kattegat

Oceanografi, marin miljöövervakning, näringsämnen, Östersjön, Bottniska viken, Skagerrak, Kattegatt

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Summary

The temperature in surface layer was above normal in several months during 2022, temperatures below normal were measured only on a few occasions in the summer. These occasions were caused by upwelling events. The minimum temperatures in the surface layer in 2022 were reached in March in Skagerrak, which is a month later than normal. In Kattegat the temperature reached its minimum in January and in March in the Baltic Proper.

Temperatures above normal were measured in the deep and intermediate waters in the Baltic Proper. In the Baltic Proper the temperature in the deep waters show an increasing trend.

The ice season was classified as mild but the duration was longer than normal, with the first ice observations around 25th of October and the last ice seen on 2nd of June.

The nutrient surveys in winter showed that the concentrations of dissolved inorganic nitrogen were below normal, whereas silicate and phosphate were above normal in the Bothnian Bay. The latter is consistent with a trend of increasing phosphate and silicate concentration in the Bothnian Bay. The nutrients decreased in spring as the spring bloom started, in 2022 this happened in March in Kattegat and in April in Skagerrak, which is later than normal. In the Baltic Proper it occurred between the February and March cruises in the southern parts while it started about a month later in the basins around Gotland. In the Bothnian Sea we lack nutrient data for the period when the spring bloom occurred, but phytoplankton data shows that the spring bloom occurred in April. In the Bothnian Bay inorganic nitrogen dropped to levels near the detection limit in July.

The potentially toxic dinoflagellate *Dinophysis acuta* was found in cell numbers above the warning limit during autumn at the stations situated in Skagerrak and Kattegat.

The largest area of cyanobacteria surface accumulations was observed by satellite on the 28th of June when about 83 300 km^2 of the Baltic Proper and Gulf of Finland were affected.

No new inflows occurred that could renew the deep water, and therefore concentrations of nutrients in the deep basins of the Baltic Proper continued to increase during 2022. The deep waters show increasing concentrations of nutrients as well as hydrogen sulphide. The concentrations of both ammonium and hydrogen sulphide are at record high levels in both the Eastern and Western Gotland Basins.

Sammanfattning

Temperaturen i ytvattnet (0-10 m) var över det normala flera månader under 2022, temperaturer under det normala uppmättes endast vid några få tillfällen på sommaren. Dessa köldknäppar orsakades av uppvällning. Årets lägsta temperaturer i ytvattnet nåddes i mars i Skagerrak, vilket är en månad senare än normalt. I Kattegatt uppmättes den lägsta temperaturen i januari och i mars i Egentliga Östersjön.

Temperaturer över det normala uppmättes även i de djupa och intermediära vattnen i Egentliga Östersjön. I Egentliga Östersjön visar temperaturen i djupvattnen en ökande trend.

Issäsongen klassificerades som mild men varaktigheten var längre än normalt. Den första isen observerades runt den 25 oktober och den sista isen den 2 juni.

Närsaltskarteringarna på vintern visade att halterna av löst oorganiskt kväve var under de normala. Kisel och fosfat var över det normala i Bottenviken. Det senare stämmer överens med en trend med ökande fosfat- och silikatkoncentrationer i Bottenviken. Näringsämnena minskar på våren när vårblomningen startar, 2022 skedde detta i mars i Kattegatt och i april i Skagerrak. I Egentliga Östersjön inträffade vårblomningen mellan februari- och marsexpeditionerna i de södra delarna av havsområdet medan den var ungefär en månad senare i bassängerna runt Gotland. I Bottenhavet saknas näringsdata för den period då vårblomningen inträffade. Men artsammansättningen och biomassa ifrån växtplanktonmätningar visar att vårblomningen inträffade i april. I Bottenviken sjönk oorganiskt kväve till nivåer nära detektionsgränsen i juli.

Den potentiellt giftiga dinoflagellaten *Dinophysis acuta* observerades i cellantal över varningsgränsen under hösten stationerna på Västkusten.

Det största området med cyanobakterieansamlingar observerades med satellit den 28 juni då cirka 83 300 km^2 av Egentliga Östersjön och Finska Viken påverkades.

Inga inflöden inträffade under 2022 som var tillräckligt stora för att påverka djupvattnet i centrala Östersjön och därför fortsätter de problematiska syreförhållandena och koncentrationerna av näringsämnen i Egentliga Östersjöns djupa bassänger ökar ytterligare under 2022. Djupvattnet visar ökande halter av såväl näringsämnen som svavelväte. Halterna av både ammonium och svavelväte är rekordhöga i både Östra- och Västra Gotlandsbassängerna.

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1 The monitoring programme

The current Swedish marine monitoring programme of the pelagic has been in place since 1994, with only smaller changes. The focus of the programme has been eutrophication and oxygen deficiency since the end of the 1970's. Historically, the programme focused on fisheries hydrography, while biological parameters were added later. Phytoplankton and chlorophyll were added in the 1980's and extended zooplankton sampling was introduced in 2007. The data from the Swedish marine monitoring are widely used in research and management for e.g. trend analysis, modelling, climate studies and assessments for EU directives such as the Water Framework Directive 2000/60/EC (WFD)[1] and the Marine Strategy Framework Directive 2008/56/EC (MSFD)[2]. The long timeseries with high quality data from fixed positions has been essential for the understanding of the Swedish seas and development of the current models used for both research and management of our open seas.

In 1991 SMHI published an investigation of the Swedish marine monitoring programme, its station network and sampling frequency (Rahm et al 1991[3]). In 1992 an international evaluation panel recommended implementation of the changes suggested by SMHI (SNV Report 4170[4]) and a revised monitoring programme started in 1994. This led to significant changes, mainly in the frequency of cruises. The number of cruises were increased while the number of stations were decreased. This was mainly done to achieve time series with a frequency and length that is suitable for trend analysis. Most stations are now sampled monthly and additional stations are sampled at high frequency (bi-weekly) in all basins. The high frequency stations were introduced to better monitor changes in biological parameters that change rapidly, especially during spring and summer.

In addition to the monthly and high frequency stations, a denser network of stations was set up to map winter nutrient pools to allow estimates of the potential spring phytoplankton production. Winter nutrient mapping is normally done in the Skagerrak and the Kattegat in January, in the Baltic Proper in February, while in the Gulf of Bothnia mapping has usually been performed in December. Nutrient mapping in the Skagerrak is done during the International Bottom Trawl Survey (IBTS Q1, quarter 1) and stations vary from year to year.

In the Kattegat and the Baltic Proper, where oxygen deficiency had been documented during parts of the year, an autumn mapping of oxygen was also started with the revision of the programme 1994. For the oxygen mapping there are no fixed stations, instead stations vary from year to year. The oxygen mapping is performed in combination with fisheries cruises led by Swedish University of Agricultural Sciences (SLU). In the Baltic Sea oxygen is mapped during the Baltic International Acoustic Surveys (BIAS) programme in September-October, while the oxygen mapping in the Kattegat is done during the IBTS Q3 (quarter 3). The oxygen mapping, with focus on the deep water is performed during the autumn because it is the season with the most severe oxygen

[1] Water Framework Directive

[2] Marine Strategy Framework Directive

[3] Rahm L., Sjöberg B., Håkansson B., Andersson L., Fogelqvist E., 1991. *Utredning om Optimering av utsjö-monitoringprogrammet vid SMHI.*

[4] Report / Swedish Environmental Protection Agency, ISSN: 0282-7298 ; 4170, 1993. *Swedish National Marine Monitoring Programme, Report of an Evaluation Panel.* Stored at the library of SwAM.

deficiency. Since many countries around the Baltic Sea also perform BIAS-cruises in their national waters and take oxygen samples during these cruises, the coverage of autumn oxygen data is generally good and the combined results from all countries are presented in a separate annual SMHI report on the oxygen situation[5]. The good spatial resolution of oxygen data during the most severe period of the year is essential for the calculations of the maximum extent of anoxic and hypoxic bottoms in the Baltic Sea.

In recent years coastal stations have been added to the programme. In 2007 two coastal stations were added to support the work associated with the EU Water Frame Work Directory; N14 Falkenberg (Kattegat) and Ref M1V1 (Baltic Proper). The latter station will be excluded from the program in 2023 and replaced by the station BY39 Ölands södra udde. The replacement station is part of the winter monitoring and represent the transition area between the Western Gotland Basin and the Hanö Bay/Bornholm Basin. Recently two stations have been added on the west coast to monitor the gradient from the Gullmar fjord to the open sea. The two new stations are Alsbäck (in the fjord) and BroA (outside the sill). Together with the station Släggö they represent the gradient from fjord to archipelago. Also, in the Baltic Proper, stations have been added to represent a gradient from coast to open sea. The station H4 in Himmerfjärden together with B1 and BY31 represent the gradient in the area. In the Bothnian Sea two coastal stations have been added, U19 Norra Randen (NR) north of Stockholm and Gavik-1 in the northern part of the Bothnian Sea. In the Bothnian Bay two stations have been added, Råneå-1 and Råneå-2. A full description of the current national monitoring programme of the pelagic, is published by the Swedish Agency for Marine and Water Management[6], in Swedish.

In addition to the national pelagic programme, municipalities and counties perform monitoring in coastal waters. In the open sea there are also several fixed platforms mainly run by SMHI, including wave buoys, coastal buoys and one offshore buoy. One cabled platform is operational in the Sound between Denmark and Sweden. SMHI and the Swedish maritime administration are also responsible for a network of stations measuring sea water level. Many of these stations also measure surface water temperature.

The first oceanographic measurements in Swedish waters were performed on the initiative of Gustav Ekman who in 1877 initiated a mapping of all Swedish seas with the warships HMS Alfhild and HMS Gustav af Klint. The data from this first mapping were not analysed until 1901 by Otto Petterson. Otto Petterson was the permanent secretary of the Hydrographic-biologic commission 1901-1930 and the initiator of the formation of the International Council for the Exploration of the Sea (ICES). In 1948 the Hydrographic-biologic commission became the National board of fisheries (Fiskeristyrelsen) with the main aim to explain what oceanographic conditions controlled the variations in herring stocks. The first Swedish research vessel R/V Skagerrak I was used and the measurements were mainly salinity, temperature and oxygen. Stations were sampled at 1-2 cruises per year and after a few years alkalinity and pH were added to the measurements. In the 1950’s, the frequency of cruises increased and from 1958 the Swedish monitoring became part of an internationally coordinated sampling effort. During the 1960’s nutrients entered the picture; first phosphorus, then nitrogen and

[5] Hansson M., Viktorsson L., Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia, 1960-2022, REPORT OCEANOGRAPHY No. 74, 2022

[6] Beskrivning av delprogrammet Fria vattenmassan version 3:1 2019-02-04, Havs- och vattenmyndigheten

finally silica. However, the frequency was still variable between years. During some periods the measurements were only performed during summer and in others only in spring. This makes it difficult to create continuous time series and trend analyses with data from this period. Furthermore, conditions are relatively more stable in the deep basins of the Baltic Sea than in surface waters and for these areas data from the deep basins are better fitted for long trend analysis. Although the frequency still varied between one and three visits per year, the network of stations was roughly the same as today. At the end of the 1960's monitoring became more structured; the Skagerrak and the fjords were visited 4 times per year, the Kattegat and the Sound five times per year, the Baltic Proper four times per year and the Bothnian Bay two times per year. Sampling was made of both physical and chemical parameters as well as biological, including bottom fauna.

1969-1970 was the International Baltic Year and this is why many of the station still have names starting with BY. In 1978 the Programme for Environmental Control (Programmet för Miljökontroll, PMK) was started and the following year HELCOM started its Baltic Monitoring Programme (BMP). The Swedish commitment in BMP 1979 included nutrients, oxygen, salinity and temperature and all countries around the Baltic Sea started sharing data. The programme continued until 1993 when it was revised as described above. The current programme is part of the commitment within HELCOM and OSPAR.

2 Performance in 2022 and description of the current programme

The marine monitoring programme of the pelagic in Sweden currently consists of about 40 standard stations distributed in the seas surrounding Sweden, deep blue and red dots in Figure 1. The visiting frequency is monthly at most standard stations (blue) but bi-weekly at six stations (red). Concentrations of winter nutrients in the surface layer (light blue) and oxygen during autumn (white) are mapped once per year at additional stations.

The number of visits at the standard stations during 2022 is presented in Figure 2. In Skagerrak the stations Å14 and Å16 profiles from the ship-board CTD are in the process of being replaced by profiles from the Moving Vessel Profiler on R/V Svea and profiles from this instrument are not included in the count in Figure 2. From most cruises there are complementary profiles every 5th minute from Å13-Å17. There were 18 visits instead of the planned 24 to the station Anholt E in Kattegat, since the station is only sampled twice monthly when the SMHI cruise with R/V Svea start and stops in Lysekil on the west coast. Data from the coastal station Ref M1V1 was only reported by SMHI and not from the coastal monitoring ordered by Kalmar läns kustvattenkommitté (Coastal water committee of Kalmar county administration board) and was visited 10 times during 2022. From 2023 the station will be replaced by BY39 Ölands södra udde. In January there was a case of Covid on board Svea and this together with a bad weather forecast led to the decision to cancellation of the sampling in the rest of Baltic Proper and to return to the harbour in Lysekil. Therefore, no stations east of the station BY4 Christiansö was sampled in January. In December the weather was rough with storm winds and high waves and BY20 and BY15 could not be sampled.

During 2022 Stockholm university was not able to sample at the stations BY29 in the Northern Baltic Proper. SMHI could cover a few of the missing visits to BY29 (March and June) and BY31 (March) in conjunction with service of the ocean buoy at Huvudskär.

After the test in December 2021 to perform a joint cruise with SMHI and Umeå Marine Sciences Centre (UMSC) on board R/V Svea, this was continued 2022. This cruise cover both the stations in the nutrient survey of the Gulf of Bothnia as well as the regular monthly sampling from the UMSC part of the national programme.

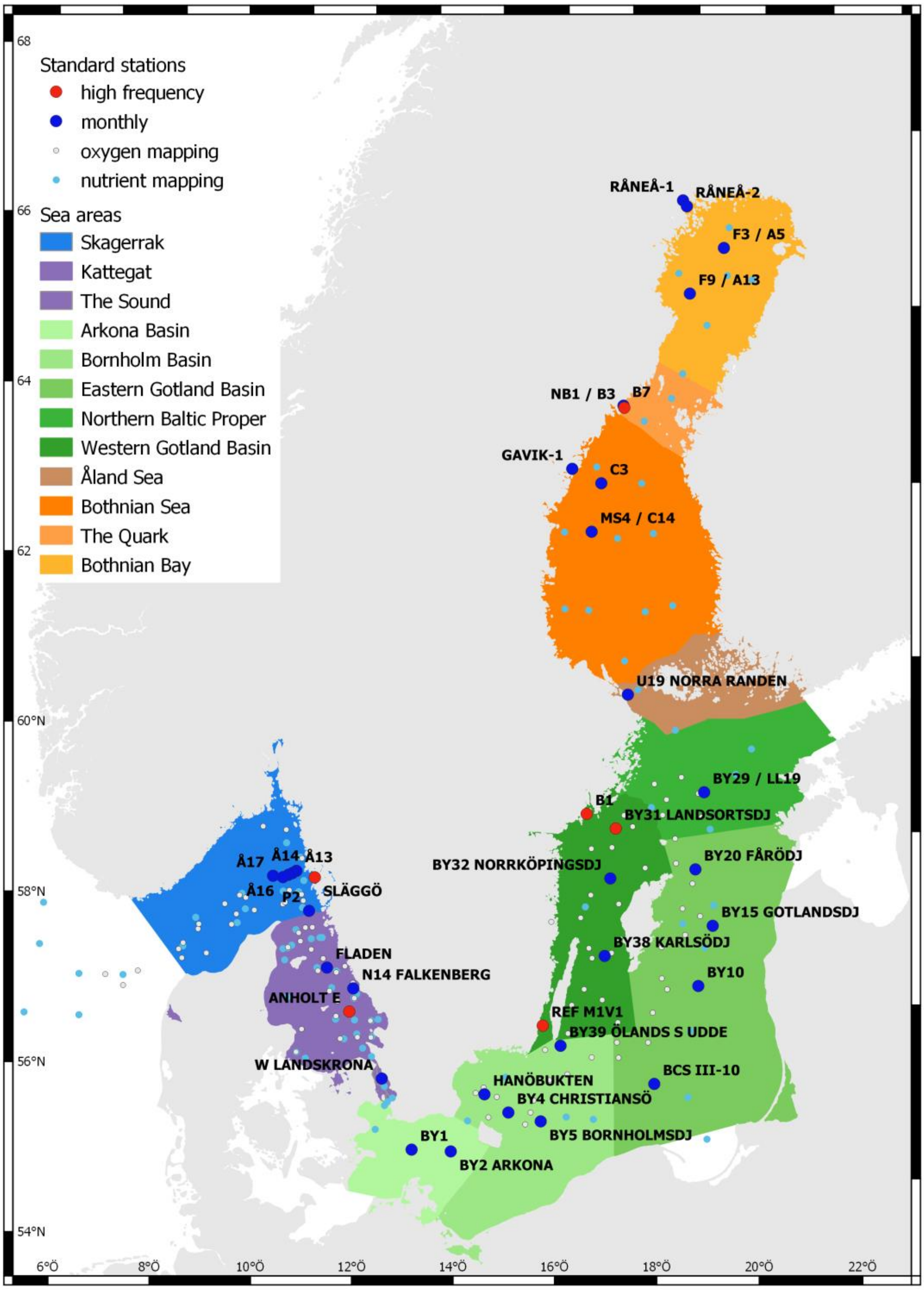

Figure 1. Map of the visited stations in the national monitoring programme during 2022. Blue: stations visited monthly, red: stations visited two times per month or more frequently, white: stations visited for oxygen mapping, light blue: stations visited for nutrient mapping.

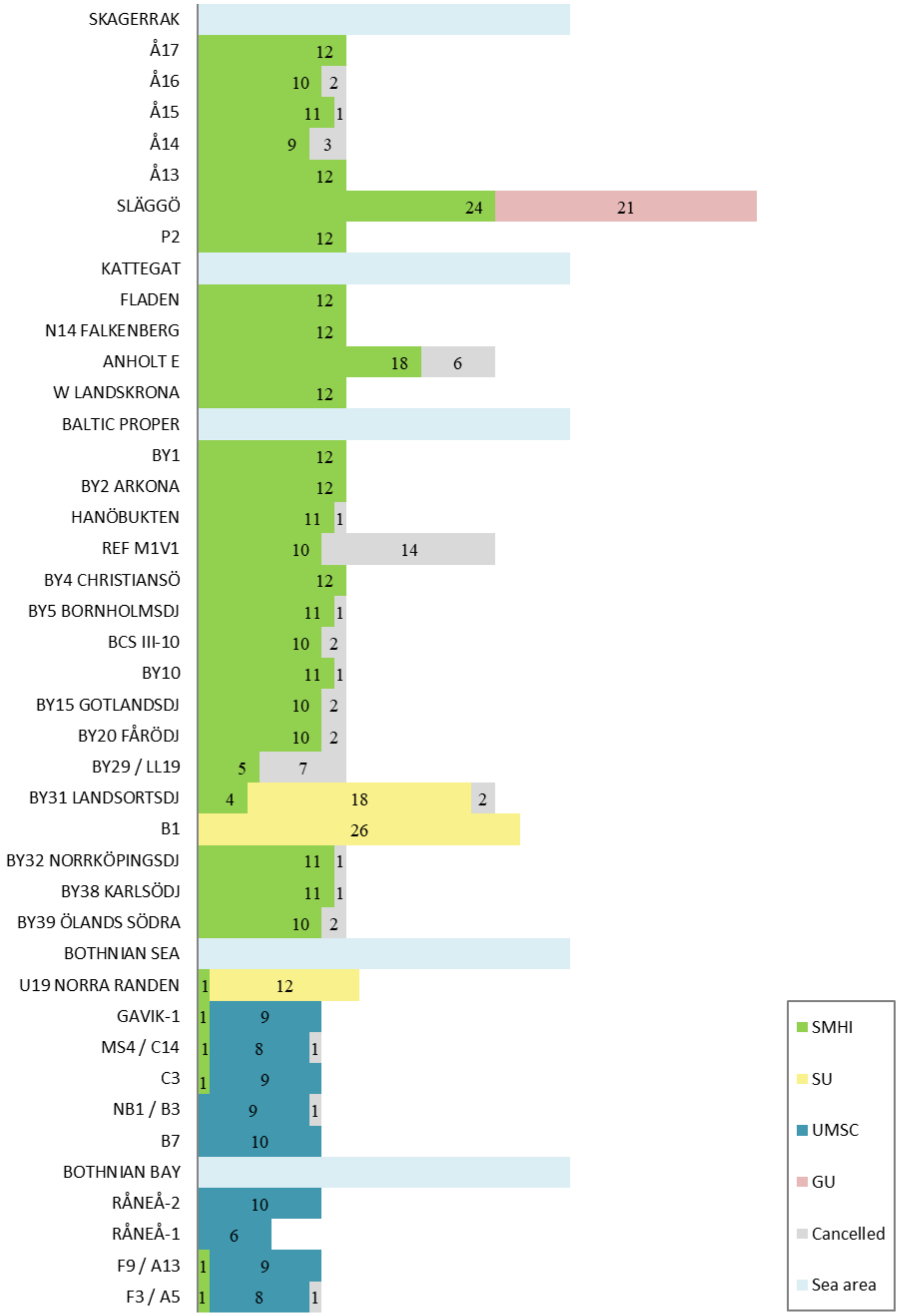

Figure 2. Number of visits at each standard monitoring station during 2022.The stations with one visit from SMHI in the Bothnian Sea and Bothnian Bay was performed during the joint December cruise where both SMHI and UMF participated.

3 Weather 2022

The year 2022 was warmer than normal throughout Sweden. It was also warmer than 2021, but colder than the record year of 2020. There were two storms during 2022, Malik in January and Nora in February.

The maximal ice extent was reached the 4th of February 2022 with 93 000 km^2. At this time the entire Bothnian Bay, the Quark, north and eastern parts of the Bothnian Sea, parts of the Gulf of Finland and the Gulf of Riga were ice covered. The ice season was classified as mild but the duration was longer than normal, with the first ice recorded around 25 October and the last ice on 2 June.

It was a mild spring in the north with temperatures up to 1-2 degrees above normal and more normal in the south.

The summer was also warmer than normal. Midsummer was record hot and one day in July, the 21st, was extremely hot. It was a dry summer in some places, especially in the southern parts of the country. In July it was windier than normal and at the end of August it was rainy in places.

The autumn had temperatures around 1.5 degrees above normal. A little less rain than normal and no autumn storms. The year ended with varying weather in December, it was at its coldest in the middle of the month and Christmas was green in the southern parts and rather cold in the north.

4 Oceanographic conditions

Annual cycles of the surface water (0-10m), vertical sections from the Skagerrak to the Western Gotland Basin and time series from 1960-2022 are presented in Appendices I-IV. In the text, reference to normal condition or normal values means the average +/- one standard deviation for the period 1991-2020. There is also extra material, as vertical profiles for each station from the stations sampled by SMHI, in the cruise reports available at the SMHI webpage[7].

The Swedish seas have large variations, especially in salinity, which gives the seas their different characteristics, Figure 3. The Skagerrak on the West Coast has almost open ocean salinities >30 psu, with lower salinities closer to the coast due to river runoff and the Baltic current bringing the outflowing Baltic water northward along the Swedish West Coast. The Baltic Proper has typical fjord-like hydrography with a strong stratification separating the deep water from the surface water. This makes the Baltic Proper naturally sensitive to increases in nutrient input leading to a eutrophic state and oxygen deficiency in the deep basins. The Gulf of Bothnia in the north is the less saline sea in Swedish waters with salinities <7 psu. It is an oligotrophic sea with other levels of and ratios between nutrients than the Baltic Proper.

[7] Cruise reports from SMHI

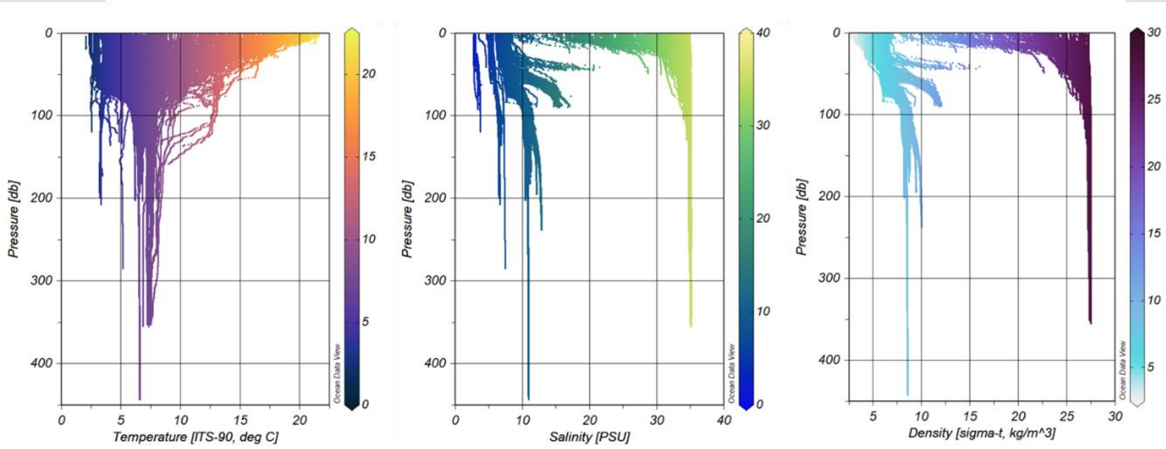

Figure 3. All temperature, salinity and density profiles from the SMHI monitoring cruises during 2022

To illustrate the highly variable seas around Sweden, a selection of parameters at stations from the different sea areas are presented in Figure 4 with mean values in the surface water (0-10 m) at each sampling occasion during 2022. Besides the difference in salinity mentioned above, other parameters also show differences between the areas. For example, the concentration of phosphate is much lower in the Bothnian Bay while the concentration of dissolved inorganic nitrogen is higher. It is also visible from the chlorophyll concentrations and the inorganic nutrients that the spring bloom occurs at different times.

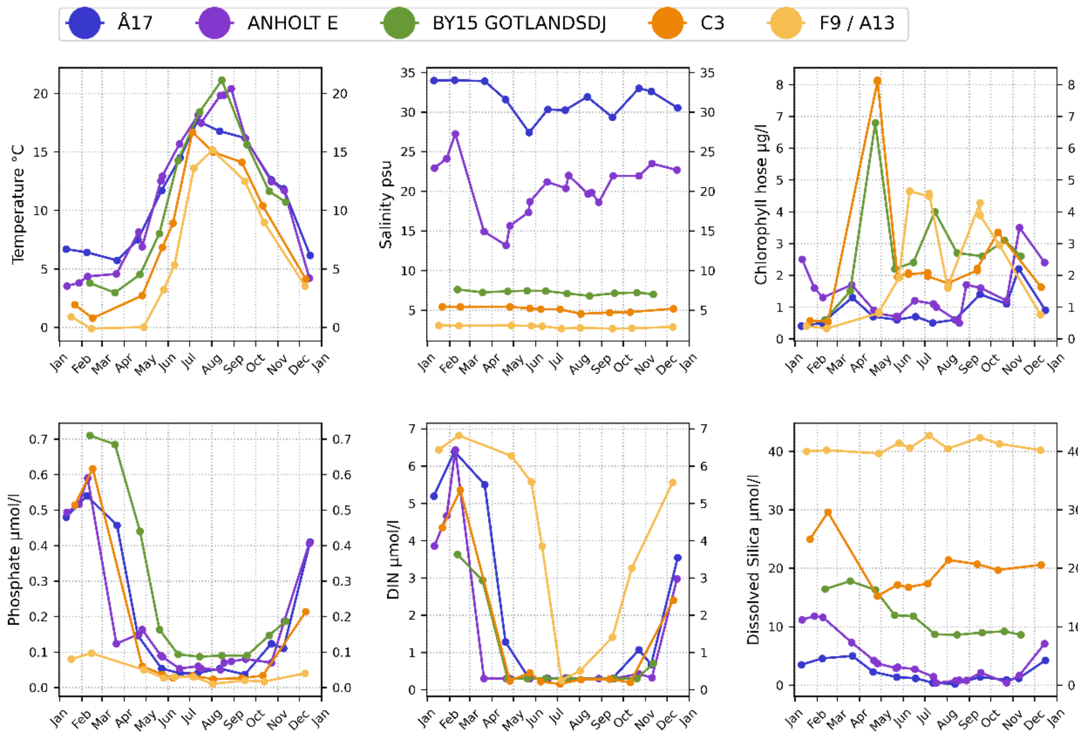

Figure 4. Temperature, salinity, chlorophyll, phosphate, dissolved inorganic nitrogen and dissolved silica from the different sea areas around Sweden: the Skagerrak (Å17), the Kattegat (Anholt E), the Baltic Proper (BY15), the Bothnian Sea (C3) and the Bothnian Bay (F9/A13). All parameters are mean values of surface water (0-10 m) during 2022.

4.1 Skagerrak, Kattegat and the Sound

4.1.1 Temperature and salinity

Usually the coldest winter month along the west coast is February, but the surface temperatures in February 2022 were all above normal. The surface layer in the beginning of the year was instead coldest in March in Skagerrak and in January in Kattegat, Figure 5. The warming of the surface layer had begun in April and continued until July in Skagerrak and until August in Kattegat. Summer temperatures were normal and Kattegat had the highest surface temperature where it was about 20 degrees. After summer the temperature decreased along with the autumn until November when the cooling of the surface layer slowed down. November was warmer than normal but then the cooling process started up again and December became colder than normal.

Surface temperature in the Skagerrak and the Kattegat

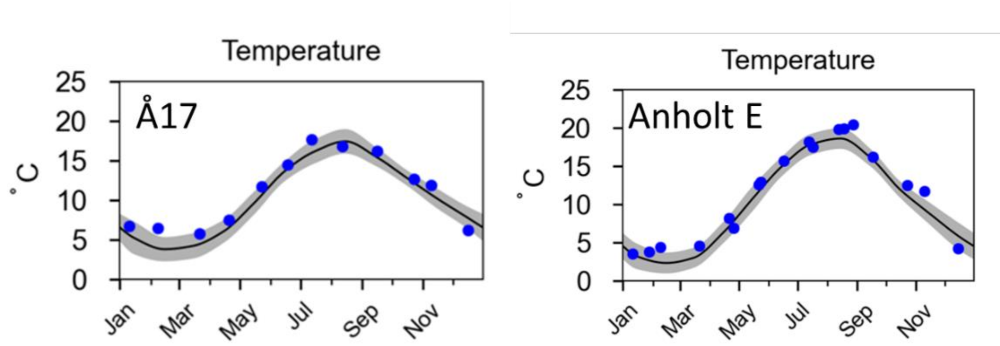

Figure 5. Surface temperature (0-10 m) at Å17 in the Skagerrak (left) and at Anholt E in the Kattegat (right). Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

To show seasonal variation in stratification, profiles of temperature and salinity from one station per sea area are presented in the figures below: station Å17 in Skagerrak, Figure 6, station Anholt E in Kattegat, Figure 7, and station W Landskrona in the Sound, Figure 8.

Seasonal variations in temperature and salinity varies more in the surface layer than at deeper depths. This is because the effects of air temperature and wind mixing does not reach far below the surface layer. In winter, the surface layer was well mixed down to 50 m in Skagerrak. In April there was a stratification near the surface, at 10 meters, caused by a lower salinity layer. This low salinity layer was observed at many stations along the West Coast. In Kattegat the salinity was lowest in March and further north this layer was observed in April. The well mixed layer during winter in Kattegat reached to 20 m. During the summer a thermocline developed in the warmer surface layer and this was at 5-10 meters when it was at its warmest. The deep water that is not affected by what happens at the surface but more reliant from advective processes was separated from the surface layer by a halocline at about 20 meters depth, except from during winter when it was deeper. The off-shore Skagerrak is deep and the deep-water properties does not change much during the year. Below 20 m the salinity increased in the deep part of Skagerrak until 100 m from where the salinity stabilises at around 35 psu and temperature around 7-8°C, Figure 6. Kattegat however is shallower and its bottom water are of similar properties as the Skagerrak intermediate water, Figure 7. The annual variations of both temperature and salinity are larger in the Kattegat bottom water compared with Skagerrak where it has less variations. The Kattegat surface layer is influenced by the surface water from the Baltic Sea and its salinity is lower than in Skagerrak. The salinity in the Kattegat surface water therefore vary a lot but was mostly within normal ranges in 2022. In October, there was a layer of rather warm water in the outer parts of Skagerrak between 20 and 130 m, this was however only temporary since it was back to normal in November at that depth.

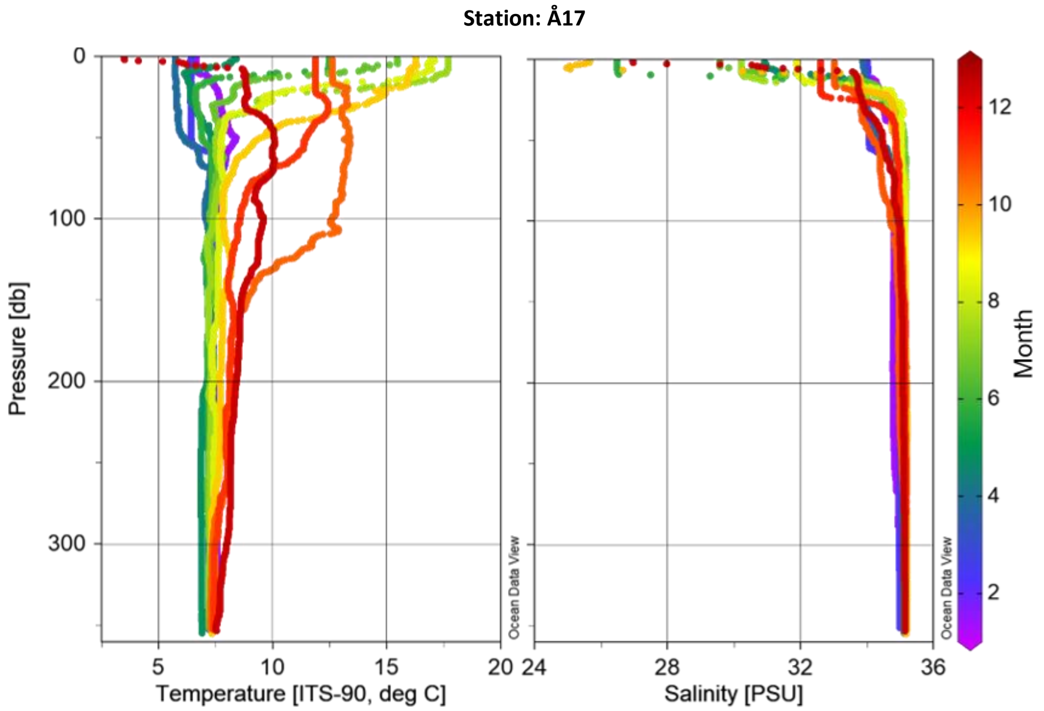

Figure 6. CTD-profiles at station Å17 in Skagerrak during 2022: temperature and salinity. Colours indicate the sampling month.

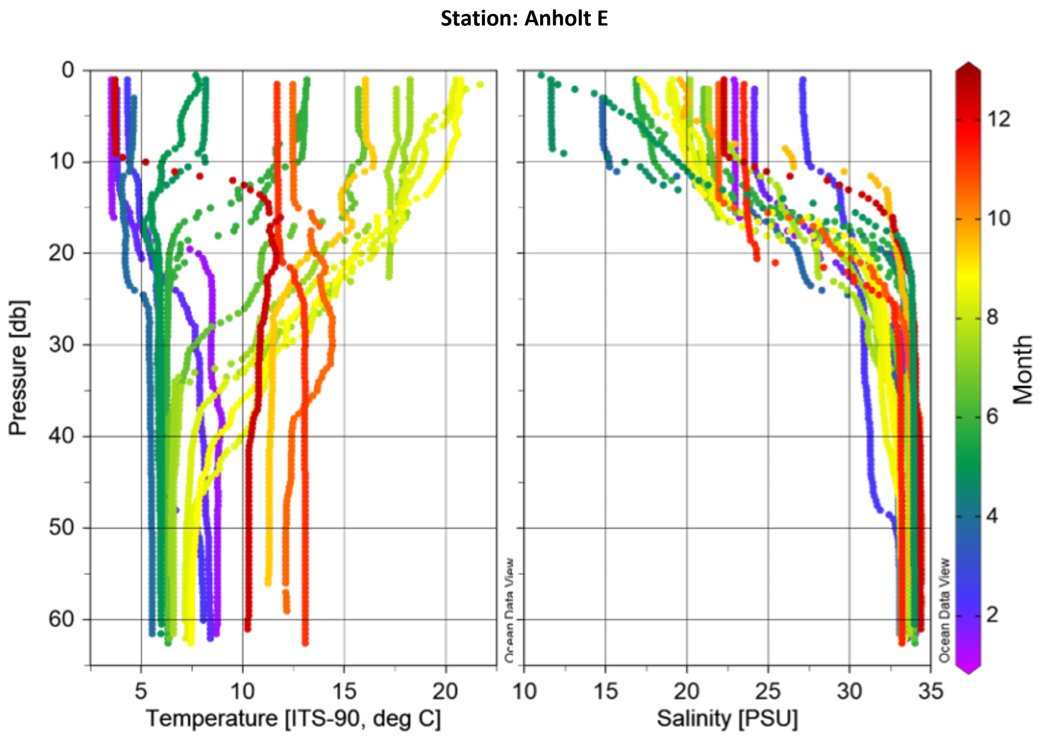

Figure 7. CTD-profiles at station Anholt E in Kattegat during 2022: temperature and salinity. Colours indicate the sampling month.

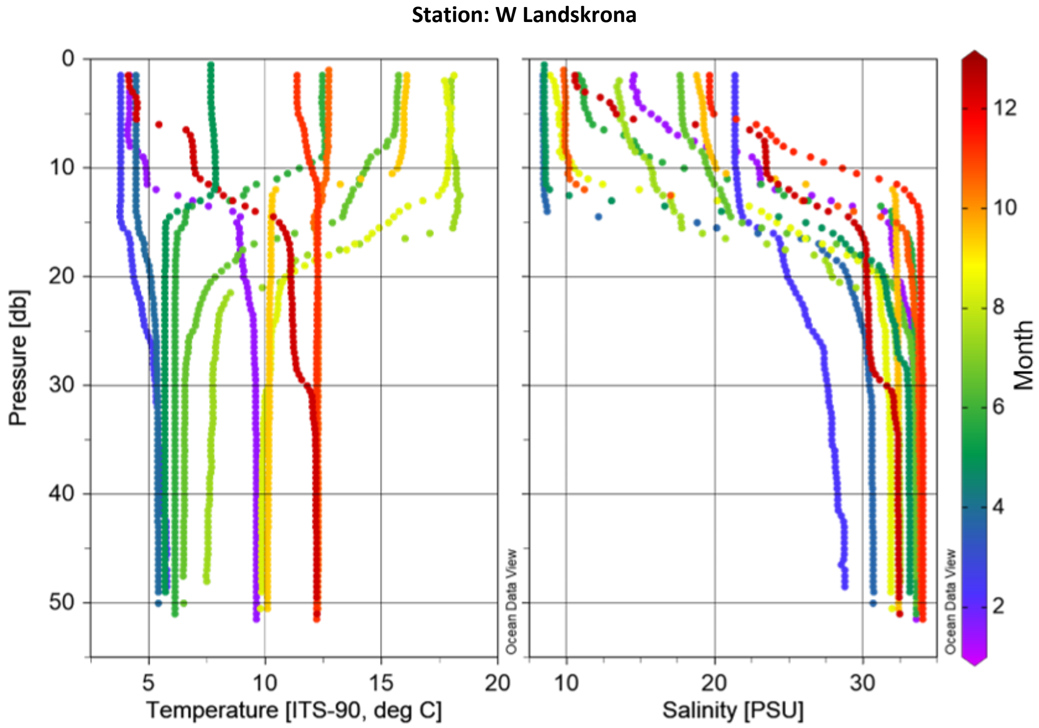

Figure 8. CTD-profiles at station W Landskrona in the Sound during 2022: temperature and salinity. Colours indicate the sampling month.

4.1.2 Oxygen conditions in the bottom water

In the Skagerrak open water, the bottom water is normally well oxygenated and at the station Å17 the concentration of oxygen was about 6 ml/l with small seasonal variation. Closer to the coast where the water depth is shallower the bottom concentration of oxygen varies more during the year. The lowest oxygen concentration in 2022 was found at the coastal station Släggö with 2.9 ml/l in both October and November which is within the lower range of what is normal, see Figure 9.

In Kattegat, which is shallower than Skagerrak, the oxygen concentration near the bottom normally gets lower. In 2022, the lowest concentration was observed at station Anholt E with 2.5 ml/l in late August. There were unusually low oxygen levels in the beginning of the year at Anholt E, but not critical levels, see Figure 9. This was probably due to the water temperature at the time. The lowest oxygen concentration in the Sound was 2.4 ml/l in mid-September.

Oxygen concentration in the bottom water in Skagerrak and Kattegat

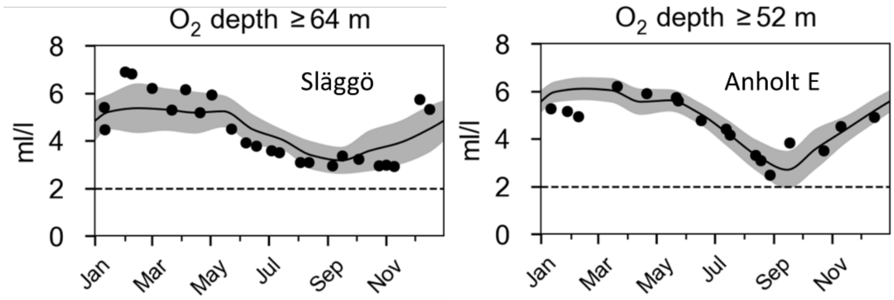

Figure 9. Concentration of oxygen in the bottom water ≥64 m at the coastal station Släggö in Skagerrak (left) and ≥52 m at station Anholt E in Kattegat (right). Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

4.1.3 Nutrients

The concentration of inorganic nutrients along the West Coast was mostly within the normal variations and between normal ranges. The winter concentrations of dissolved inorganic nitrogen and phosphate were highest in February. At many stations there was a peak in silicate concentration in March which could be a consequence of the lower salinity layer at this time. Water with lower salinity comes from the Baltic Sea that has higher concentrations in silicate. The growth of phytoplankton consumes nutrients and the onset of the spring bloom is indicated by a large drop in inorganic nutrients. This happened in March in Kattegat and in April in Skagerrak. Both dissolved inorganic nitrogen and phosphate were more or less depleted in the surface layer until the end of the summer. Silicate also reached very low concentrations. The levels of inorganic nutrients increased as normal during the autumn.

The seasonal variability of total nutrients is much smaller and they never get depleted. The total phosphorus had normal concentrations at most stations and visits but the total nitrogen was lower than normal at many stations, see an example in Figure 10.

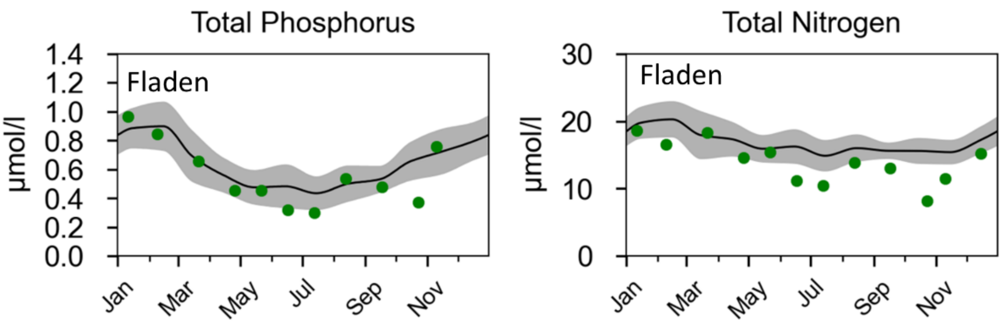

Figure 10. Concentrations of total phosphorus and total nitrogen in the surface layer, 0-10 m, at station Fladen in Kattegat in 2022. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

4.1.4 Phytoplankton

Unlike 2021, there were no signs of spring bloom in the Skagerrak and Kattegat in February. Chlorophyll concentrations (Figure 11), species diversity and total cell counts were low and nutrients were high (Figure 12) at the measurements in February. Unfortunately, the spring bloom started between the sampling occasions and was thus not seen in the measurements. In the Kattegat it occurred between the February and March cruises and in the Skagerrak between the March and April cruises as indicated by the nutrients (Figure 12). In the phytoplankton samples from March, the end of the spring bloom was noted through high diatom diversity and the high numbers of the typical spring species *Skeletonema marinoi*. At Å17, outer Skagerrak, a minor bloom of the coccolithophorid *Emiliania huxleyi* was observed at the same time.

In April there were still signs of the spring bloom, mainly as diatoms (*S. marinoi*) that were found, at Släggö at the Skagerrak coast

In April the station Anholt E was visited with merely five days in between and two very different situations were noted. At the first visit, the water was stratified down to 10 meters whereas at the second visit the halocline was eroded, see Figure 13. The stratification caused chlorophyll concentrations above normal at the first visit with high diversity and dominance of diatoms while the second occasion had ciliates and small species.

A diatom peak in June at Anholt E was dominated by typical summer species like *Dactyliosolen fragilissimus* and *Proboscia alata*.

In the autumn the potentially toxic dinoflagellate *Dinophysis acuta* was found in cell numbers above the warning limit (200 cells per liter, determined by the Swedish Food Agency (SLV)) at the west coast stations. *D. acuta* is the most potent of the *Dinophysis* species and can cause diarrhea toxins in mussels that have filtered water with enhanced levels of it.

The coccolithophorid *E. huxleyi* was numerous in November in the Kattegat and Skagerrak areas. Due to its size this small species is hardly noticeable in the biomass. In the opposite way, the naked form of *Dictyocha* species was found in rather low numbers, but the large cells cause high biomass values.

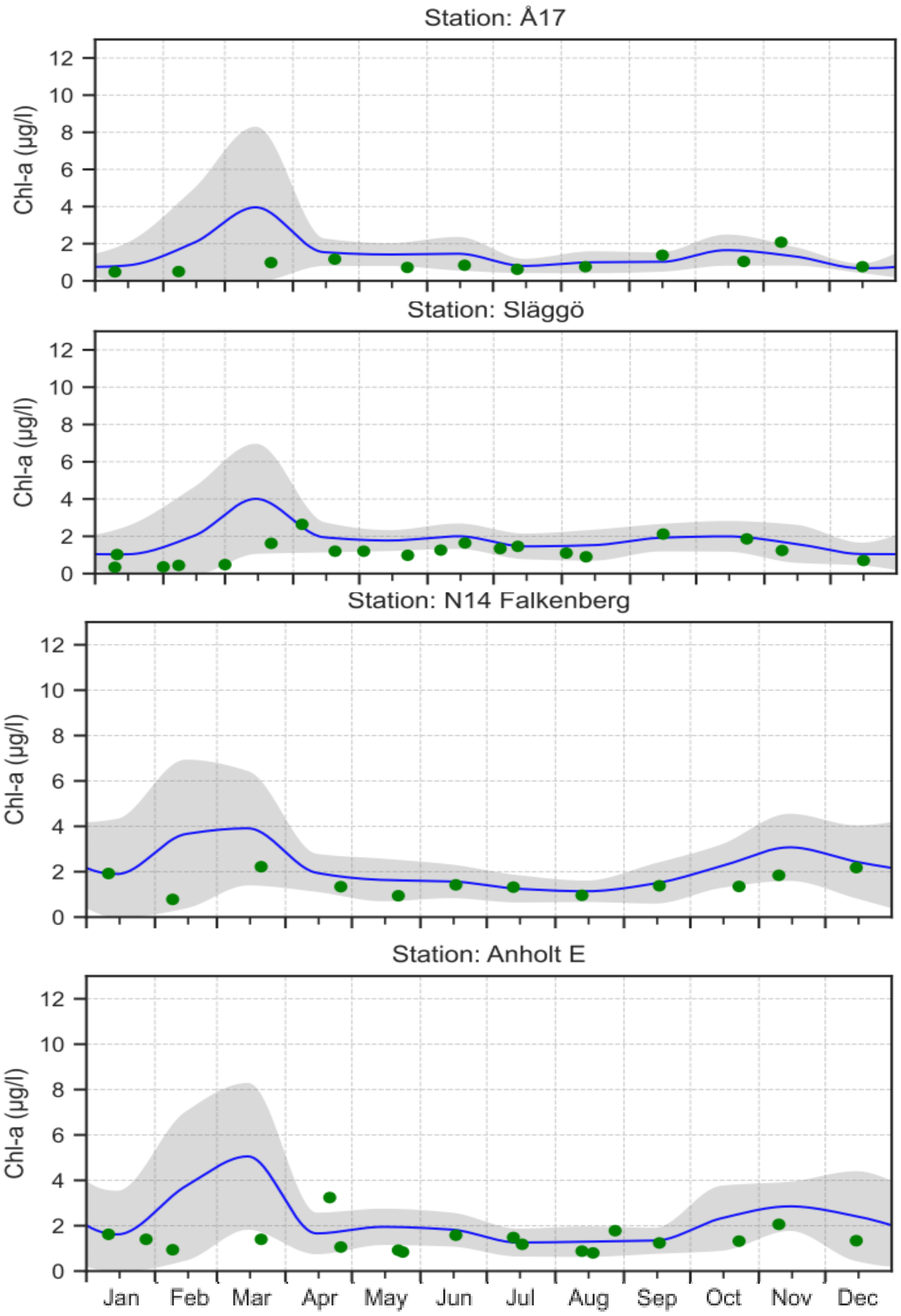

Figure 11. Integrated (0-20 m) chlorophyll a (µg/l) from Å17 and Släggö in the Skagerrak and N14 Falkenberg and Anholt E in the Kattegat. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (blue line) and +/- 1 standard deviation (grey area).

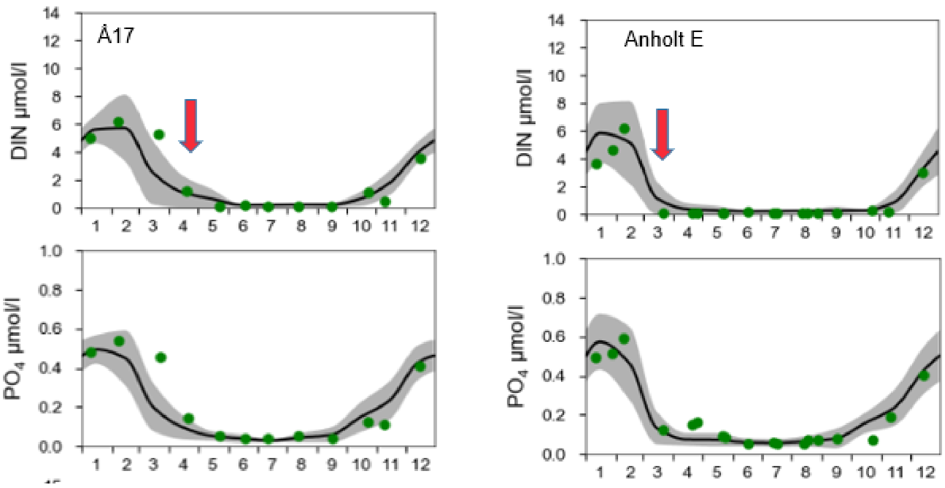

Figure 12. Concentrations of DIN (dissolved inorganic nitrogen), top panel, and phosphate, lower panel, in the surface layer, 0-10 m, at station Å17 in the Skagerrak and at station Anholt E in the Kattegat in 2022. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area). Red arrows indicate the spring bloom.

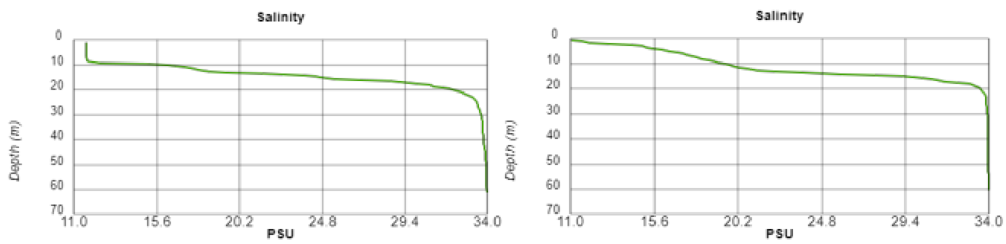

Figure 13. The salinity at station Anholt E in Kattegat. Left 2022-04-21, right 2022-04-26.

4.2 Baltic Proper

4.2.1 Temperature and salinity

The surface water temperature in the Baltic Proper was mostly normal at the time of the winter mapping expedition in February.

In the Baltic Proper the water becomes mixed by the wind down to the halocline (ca 60 m, see Figure 17) during winter and the coldest surface temperature is often recorded later here compared to the Skagerrak and Kattegat. In 2022 the coldest surface water temperature was observed in March, similar to 2021. The surface water began to warm up in May. The surface water was above normal at most stations in June and August, but normal in July. The warmest temperature was recorded during the August cruise at station BY15 Gotland deep, 21.5°C. At this time a shallow thermocline had formed at ca 5 m depths and below this the temperature quickly decreased. In September, a month after the maximum temperature was measured in August, the surface water had cooled down by ca 7°C and the water was well-mixed down to a thermocline at 15 m depth. The water continued to cool down and the thermocline deepened to ca 30 m in December. In July and August there were several events of upwelling along the Swedish south-eastern coast and this is seen as temperatures in the surface water well below normal, see Figure 14.

Surface temperature in the Baltic Proper

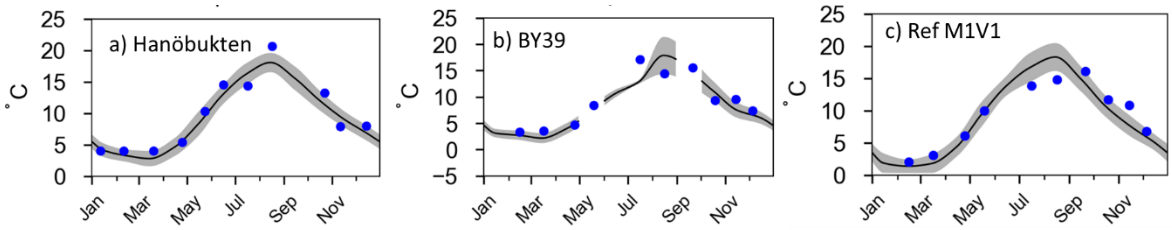

Figure 14. Surface temperature (0-10 m) at; a) Hanö Bay, b) BY39 Ölands södra udde, c) Ref M1V1. Temperatures below normal during summer months due to up-welling events. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area). Missing black line and grey area indicates that there are too few data in the period 1991-2020 to calculate statistics.

The temporal development of temperature and salinity from the surface to the 150 m in the Baltic Proper during 2022 are presented in more detail in Figure 16 and Figure 17. This shows the seasonal variation of thermocline and halocline depths above the permanent halocline and also the difference in variability of the permanent halocline between the eastern and western Gotland basins.

During 2022 the salinity in the surface water was mostly normal in all basins in the Baltic Proper, at some visits slightly above but never under normal, Figure 15 a-c. From the longer timeseries (1960-2022) we can see that the surface salinity was highest at the end of the 1970's and then decreased until the end of the 1990's, Figure 15 d.

Surface salinity in the Baltic Proper

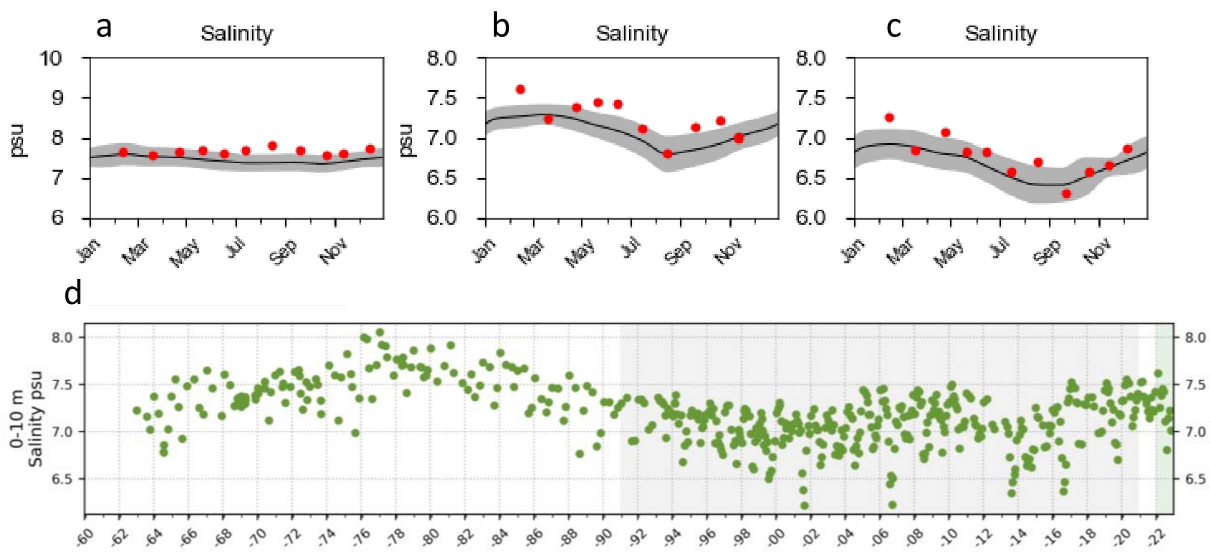

Figure 15. Salinity in surface water (0-10 m) during 2021 at the stations: a) BY5 in the Bornholm Basin, b) BY15 in the Eastern Gotland Basin, c) BY32 in the Western Gotland Basin, d) a timeseries from 1960-2022 from BY15. Monthly measurements (red dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

After the inflow in the winter 2014-2015 the surface salinity increased and was mostly above normal for the time period 1991-2020 until it decreased during 2021-2022. In the deep water, below the permanent halocline the salinity was above normal, as it has been since the large inflow in the winter 2014-2015. The halocline in the Baltic Proper is around 60 m but with seasonal fluctuations and also geographic variations. In the

Arkona and Bornholm Basin, which are shallower, the halocline is at about 40-50 m. The halocline in the Eastern Gotland Basin is sharper and less dynamic compared to the Western Gotland Basin, Figure 16. In the Western Gotland Basin, the halocline position fluctuated more than in the Eastern Gotland Basin, Figure 16.

Stratification in the Baltic Proper

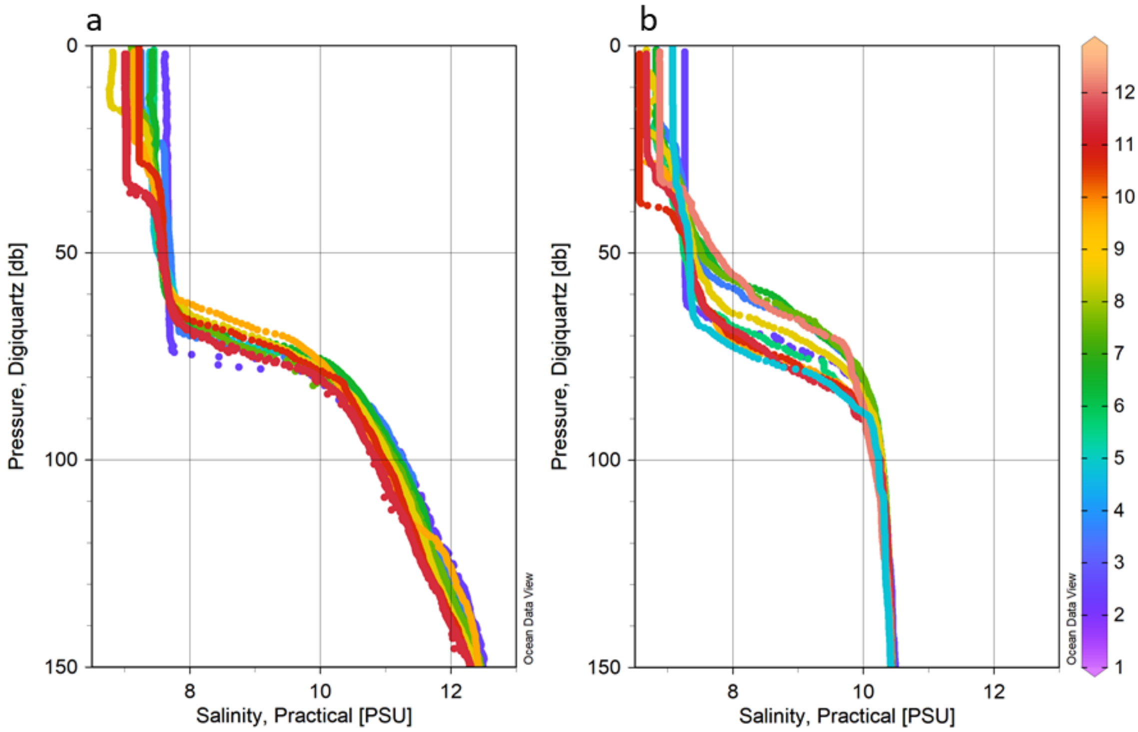

Figure 16 Profiles of salinity at a) BY15 Gotland deep and b) BY32 Norrköping deep from 2022. The figure shows the more variable halocline depth in the Westerns Gotland Basin (b) compared to the Eastern Gotland Basin (a).

Station: BY15

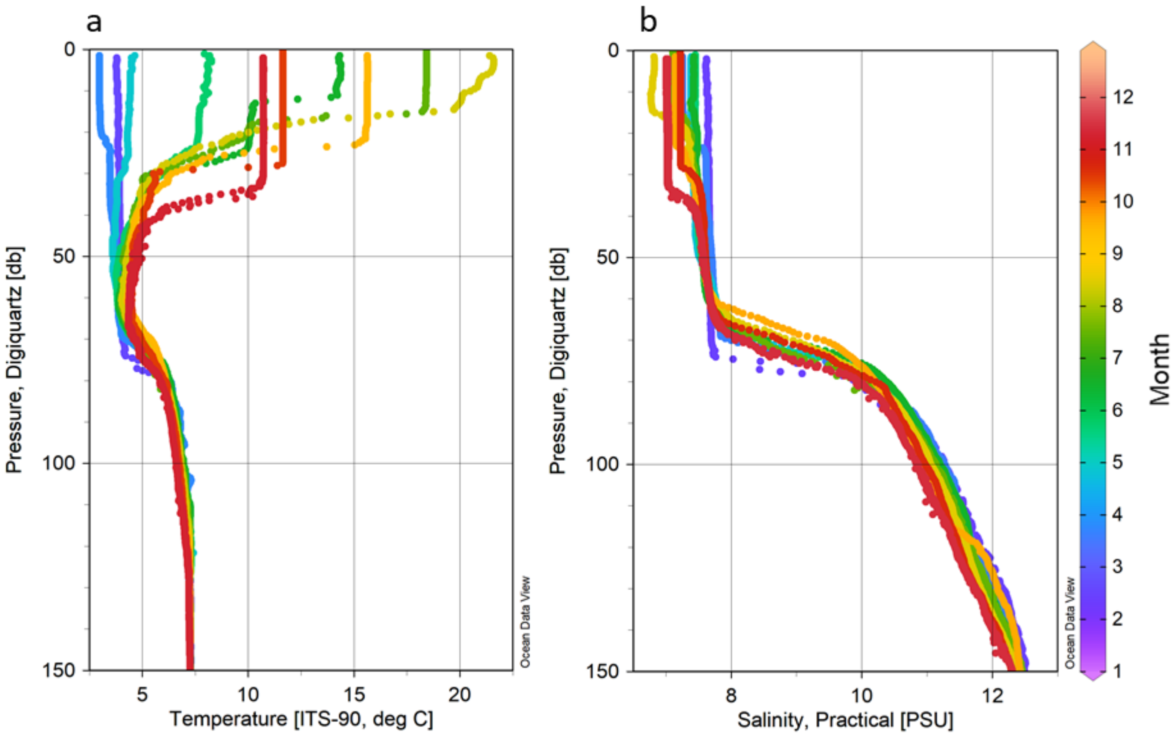

Figure 17. CTD-profiles at station BY15 in Baltic Proper during 2022: temperature and salinity. Colours indicate the sampling month.

Salinity and temperature are less variable below the halocline. In the Arkona and Bornholm basins, the variability in the deep water is somewhat larger because of the influence from salt water inflows from Kattegat. After the inflow event in 2014 both salinity and temperature increased in the bottom water of the basins in the Baltic Proper (Figure 18b and c). During 2022 both temperature and salinity was above normal in the deep basins in the Baltic Proper. The salinity is steadily decreasing in the stagnant water below the halocline but the temperature has not decreased significantly since the last Major Baltic Inflow (MBI) and in the Western Gotland Basin it has even increased after the last MBI. In the eastern and western Gotland basins salinity and temperature are above normal not only in the bottom water but at all depths below the halocline (profiles can be found in expedition reports[7]).

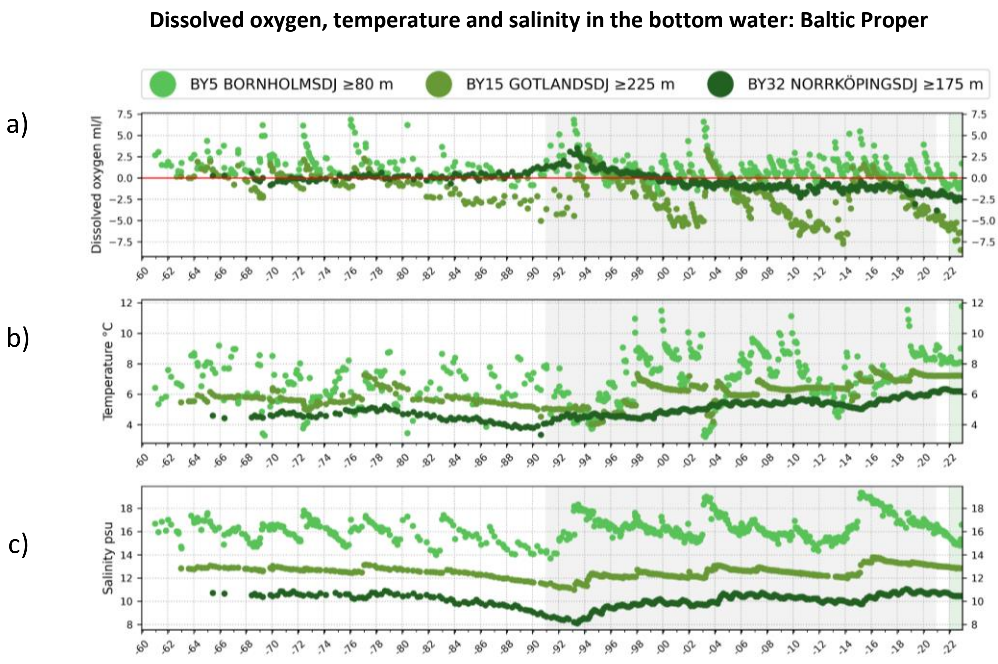

Figure 18. a) Dissolved oxygen, b) temperature and c) salinity in the bottom water at three stations in the Baltic Proper representing the basins Bornholm Basin (BY5), Eastern Gotland Basin (BY15), Western Gotland Basin (BY32). The shadowed grey area highlights the time period that statistics is based on in this report, 1991-2020. The shadowed green area highlights the year 2022.

4.2.2 Oxygen conditions in the bottom water

During 2022 there were no major inflows to the Baltic Proper that could improve the oxygen conditions in the bottom water to any larger extent. Three smaller inflows of around 20 km^3 occurred that could be detected in the Arkona Basin, Hanö Bay and Bornholm Basin. The latest annual report on the oxygen situation in the Baltic Sea 2022 published by SMHI[5], the severe oxygen conditions continues in the Baltic Proper. The concentration of hydrogen sulphide continued to increase in the Eastern and Western Gotland Basins, shown as negative oxygen in Figure 18a above. In both basins the hydrogen sulphide concentration reached record high levels during 2022. However, the increase is faster and the concentration is more than twice as high in the Eastern Gotland Basin compared to the Western Gotland Basin. In the Bornholm Basin hypoxia is regularly found in the autumn and more seldom anoxia and hydrogen sulphide. In 2022 however, hydrogen sulphide was measured from June to October, Figure 19. In November a small inflow reached the Bornholm deep and the oxygen concentration rose to just below 2 ml/l.

Oxygen concentration in the bottom water at BY5

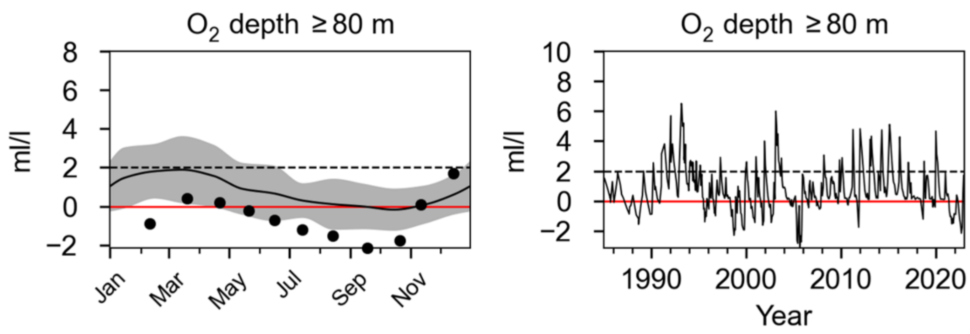

Figure 19. Oxygen and hydrogen sulphide (shown as negative oxygen) at station BY5 in the Bornholm Basin. To the left monthly measurements (black dots) during 2022 in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area). To the right the while timeseries from 1985-2022.

4.2.3 Nutrients

The winter pool of inorganic nutrients in the Baltic Proper was mostly within normal ranges, Figure 20. Dissolved inorganic nitrogen deviated towards lower than normal concentrations, especially in the Western Gotland Basin. Silicate was higher than normal in the Eastern Gotland Basin.

Nutrient concentration in the surface water, February

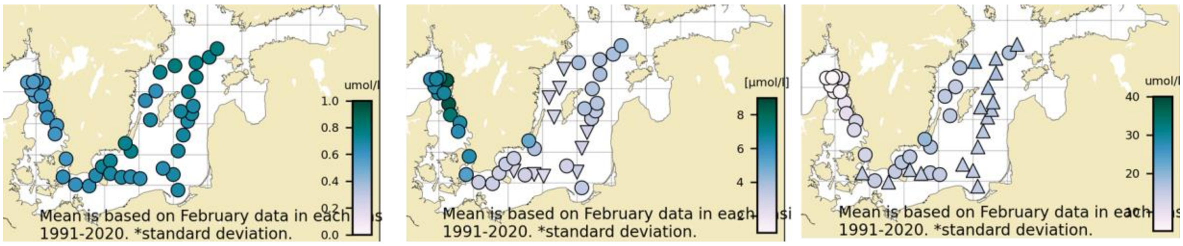

Figure 20. Maps showing the concentration of phosphate (a), dissolved inorganic nitrogen (b) and silicate (c) in February 2022. Circles represent values within +/- 1 standard deviation, upwards and downwards pointing triangles represent values that are above/below +/- 1 standard deviation.

In the Baltic Proper a sharp drop in the concentration of dissolved inorganic nitrogen indicates the time of the spring bloom. In 2022 the spring bloom occurred between the February and March cruises in the southern parts (Arkona Basin, Hanö Bay and Bornholm Basin) while it was later in the basins around Gotland where it occurred between the March and April cruises, Figure 21. Phosphate drops much slower during the spring bloom in the Baltic Proper and phosphate continued to decrease until June in the Eastern Gotland Basin and in the Arkona Basin phosphate stayed at relatively high concentrations (0.2 µmol/l throughout the summer. The concentrations of dissolved inorganic nitrogen stayed at low levels through the autumn and did not start to increase again until November.

Station: BY2 Arkona and BY15 Gotland deep

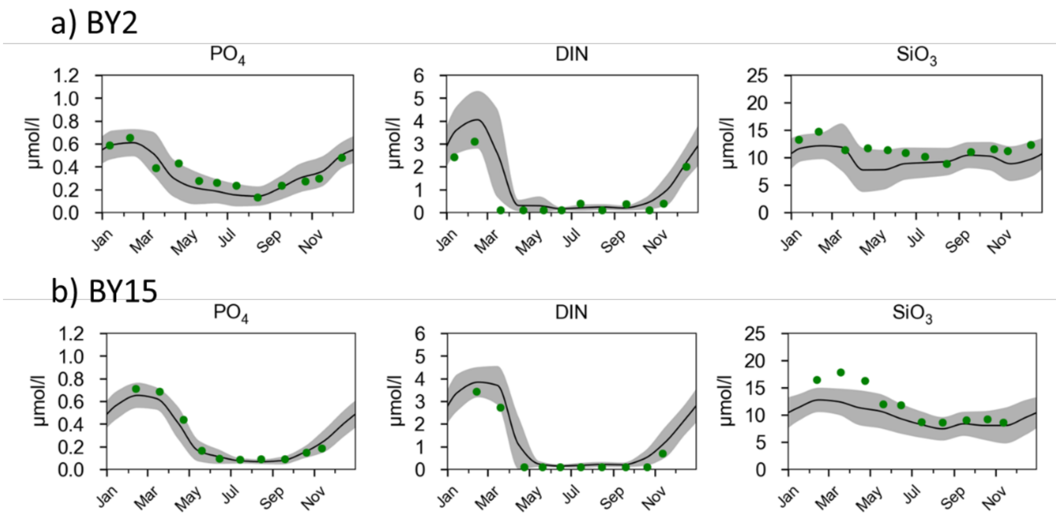

Figure 21. Concentrations of nutrients in the surface water (0-10 m) at stations BY2 in the Arkona Basin (a) and BY15 in the Eastern Gotland Basin (b). To the left: phosphate, middle: dissolved inorganic nitrogen (DIN) and to the right: silicate. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

No inflows large enough to renew the deep water, occurred and therefore concentrations of nutrients in the deep basins of the Baltic Proper continued to increase during 2022. In the Western Gotland Basin dissolved inorganic nitrogen was present in the form of nitrate until the year 2000 when the basin shifted to anoxia. After 2000 ammonium has been building up in the basin and the concentrations measured during 2022 are almost twice as high as the mean value for the normal period (Figure 22). In the Eastern Gotland Basin ammonium and DIN follow the same pattern because DIN consists mainly of ammonium through the time series (1960-2022). Also, here the DIN concentration is increasing but there are clear signals from inflows that cause a temporary decrease in the DIN concentration. The differences in how the DIN and ammonium concentration looks in the two basins is caused by the difference in stratification, oxygen and hydrogen sulphide concentrations. As for hydrogen sulphide the ammonium concentration increases faster and the concentration is more than twice as high in the Eastern Gotland Basin compared to the Western Gotland Basin.

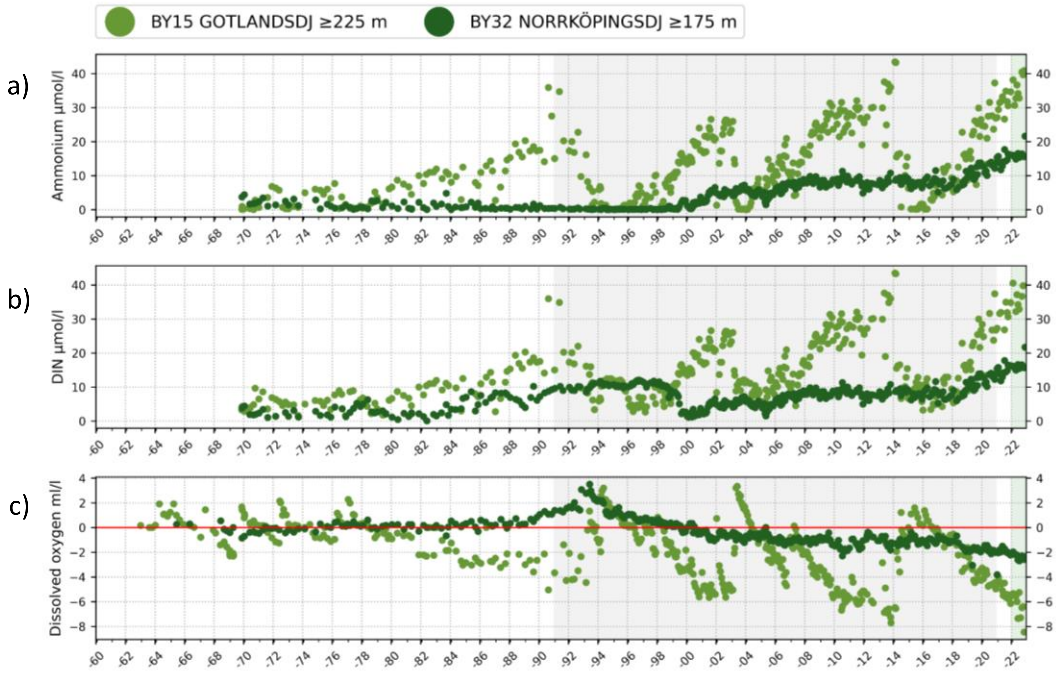

Figure 22. Concentration of a) ammonium, b) dissolved inorganic nitrogen (DIN) and c) dissolved oxygen, where hydrogen sulphide is expressed as negative oxygen in the bottom water, at two stations in the Baltic Proper representing the basins Eastern Gotland Basin (BY15) and Western Gotland Basin (BY32). The shadowed grey area highlights the time period that statistics is based on in this report, 1991-2020. The shadowed green area highlights the year 2021. The concentrations are increasing over time at stations BY15 and BY32 and the highest concentrations are found at stations BY15.

Profiles of dissolved inorganic nitrogen and oxygen/hydrogen sulphide can give some insight to the differences in DIN concentrations in the two basins. In the Western Gotland Basin, the increase in nutrients and decrease in oxygen happens over a relatively thin layer (ca 10-20 m thick), Figure 23. In the Eastern Gotland Basin, on the contrary, there is a thick layer (ca 40-50 m thick, from ca 80-120 m depth) where oxygen is close to zero, there is no or little hydrogen sulphide and DIN concentrations are also very low, almost at detection limit. The low DIN concentrations in this layer are likely an effect of the oxygen concentrations that are just around zero creating an environment where denitrification can occur and remove bio-available nitrogen. This situation with an anoxic but not sulphidic layer in the Eastern Gotland Basin is similar to the conditions in the Western Gotland Basin bottom water during the first part of the 2000’s when oxygen concentrations were close to zero and there was no hydrogen sulphide.

As shown in Figure 22 the DIN concentration in the bottom water is higher in the Eastern Gotland Basin than in the Western Gotland Basin. This means that in the Western Gotland basin there are concentrations of DIN around 12-15 µmol/l from around 100 m to the bottom while in the Eastern Gotland Basin the layer with high DIN concentrations (here 15-30 µmol/l) starts at 150 m.

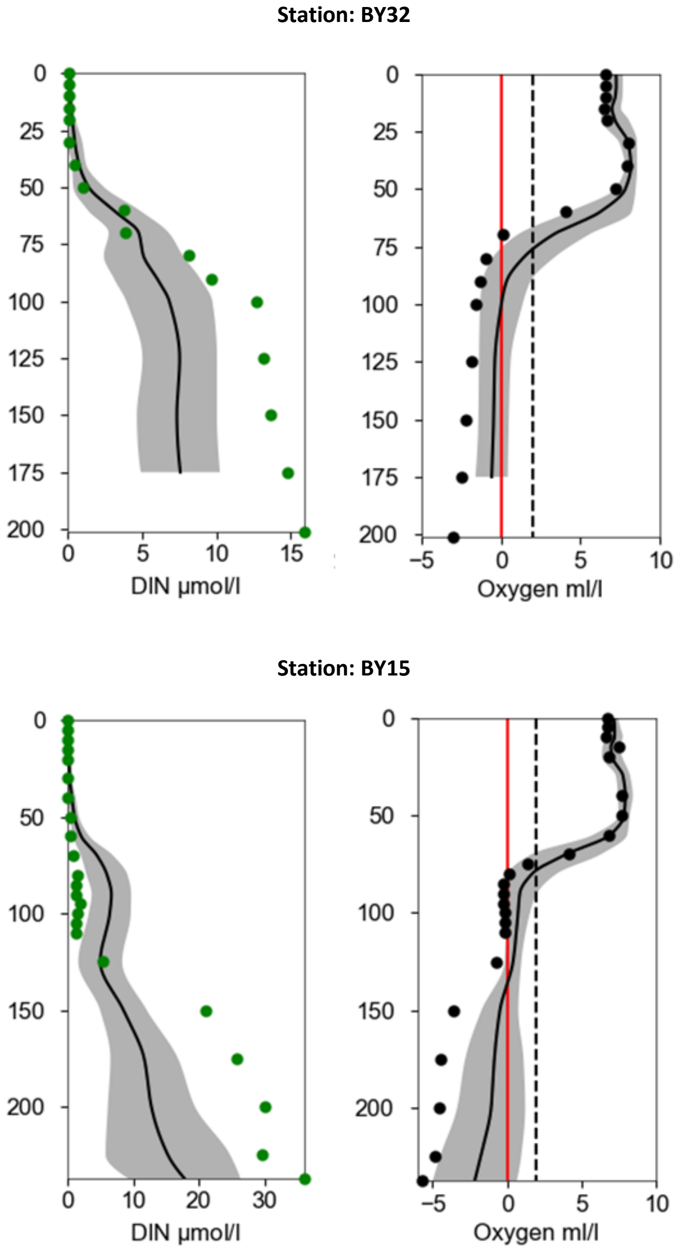

Figure 23. Profiles of oxygen (left, black) and dissolved inorganic nitrogen (right, green) from July 2022. Station BY32 in the Western Gotland Basin (top) and station BY15 in the Eastern Gotland Basin (bottom). Measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

4.2.4 Content of nutrients in the Baltic Proper basins

Appendix III contains time series of calculated content of nutrient concentrations in each basin in the Baltic Sea for the winter season. The content of nutrients in each basin was calculated from the monthly sampling station, i.e. the same data set that was used for the time series 1960-2021 presented in Appendix II. The resulting time series of nutrient content shows large scale changes of the nutrient pools as well as differences between the basins.

Starting in the south with the Arkona Basin and the Bornholm Basins, an increase in the content of both inorganic and total phosphorus is seen between the period 1994-2004 and the period from 2005-2022. In the Bornholm Basin in the period between 1994-2004 the total phosphorus content varied between 20-50 kilotonnes while the content from 2005-2022 varies between 50-70 kilotonnes (Figure 24). This could be a consequence of the inflow in the winter 2003-2004 that lifted phosphorus rich water from the deep basins in the Baltic Proper to surface waters. However, it should be noted that the total phosphorus method at the SMHI laboratory was changed at the same time which makes the changes in total phosphorus more difficult to connect to changes due to the inflow.

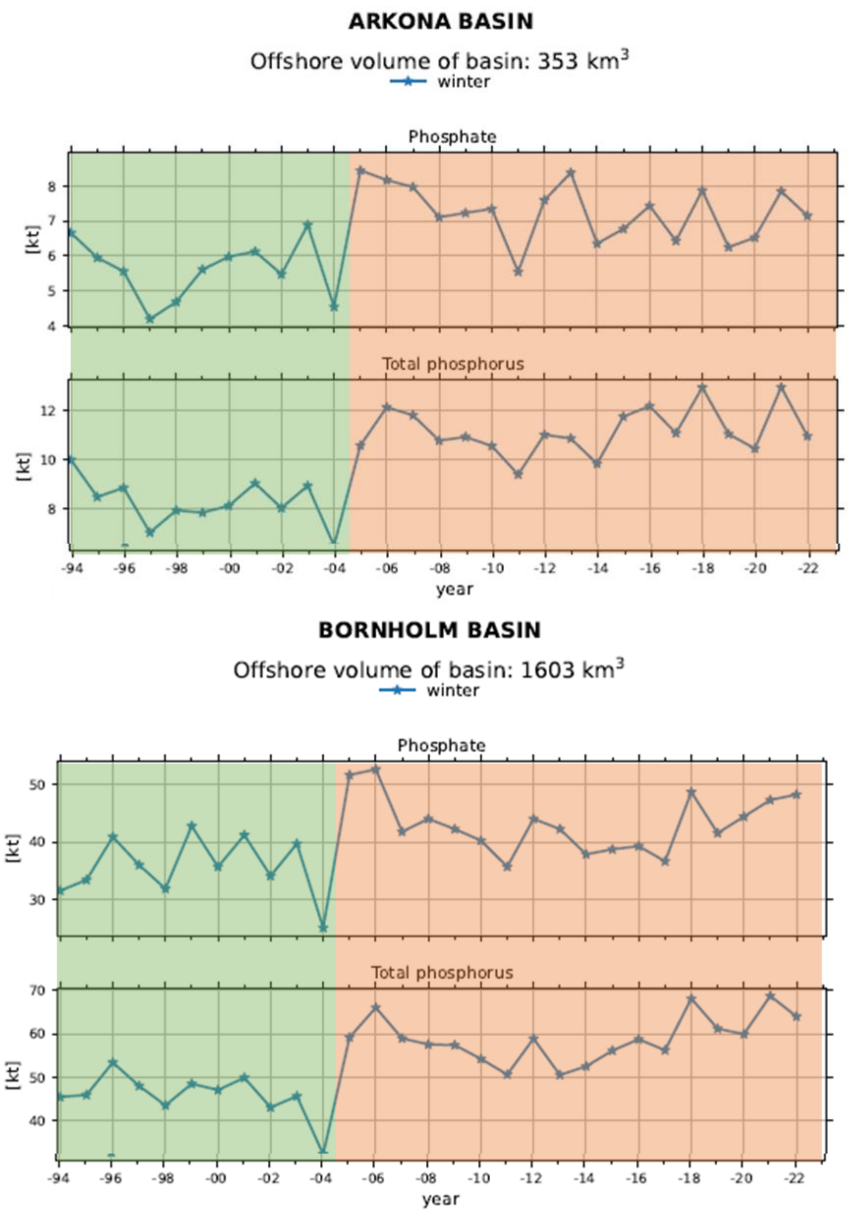

Figure 24. Content of phosphate (top) and total phosphorus (bottom) in Arkona basin and Bornholm basin from 1994-2022. The content is higher in the period from 2005-2022 (orange) than 1994-2004 (green).

In the rest of the Baltic Proper the phosphorus content increased in a more linear way from 1994 until around 2000 when it starts to level out. Since 2018 the phosphate content has increased each year. The nitrogen content in all basins around Gotland decreased from 1994 to the beginning of the 21st century (Appendix III). The drop in DIN is most drastic in the Western Gotland Basin for the sub-basins around stations BY31 and BY32 (Appendix III). To some extent this can also be seen in the DIN concentration in the bottom water shown in Figure 22b.

In the Bothnian Sea the increasing phosphorus and silicate concentrations are clearly reflected in an increase in phosphorus and silicate content since year 2000. In the Bothnian Bay the silicate and phosphorus content is also increasing and here the nitrogen content is clearly decreasing over the same period (Appendix III).

4.2.5 Phytoplankton

The spring bloom was ongoing in the southern Baltic Proper already in March. In the Central and Northern Baltic Proper, the spring bloom occurred one month later which is normal. A high diversity and high cell numbers of diatoms were noted, as well as the typical spring species the dinoflagellate *Peridiniella catenata* and the ciliate *Mesodinium rubrum*.

In May, a bloom of the potentially toxic group Prymnesiales was noted with a maximum of 61 million cells per liter at BY2 in the Southern Baltic Proper. The bloom continued throughout the summer.

The filamentous cyanobacterium *Aphanizomenon flosaquae* was found at BY15 and BY38 in May and by June the amounts of all cyanobacteria had increased at all of the Baltic stations. In June and July, *A. flosaquae* dominated among the three most typical summer species of the filamentous cyanobacteria, but the amounts of *Dolichospermum* sp. and *Nodularia spumigena* were also high. During June to August, small colony forming cyanobacteria were found in extremely high cell numbers especially at BY15 and BY31 in the northern Baltic Proper, which is normal during summer as it is also for picoplankton.

Chlorophyll peaks at BY2 and BY38 in September were mainly caused by a variety of small species, but also by *A. flosaquae*. Through the autumn and winter months, small amounts of filamentous cyanobacteria were still present, but the highest biomass was caused by the large diatom *Coscinodiscus granii*. Small species from various phytoplankton groups dominated the cell counts during the same period.

Figure 25 shows the chlorophyll concentrations in the Arkona, Bornholm and Eastern Gotland basins.

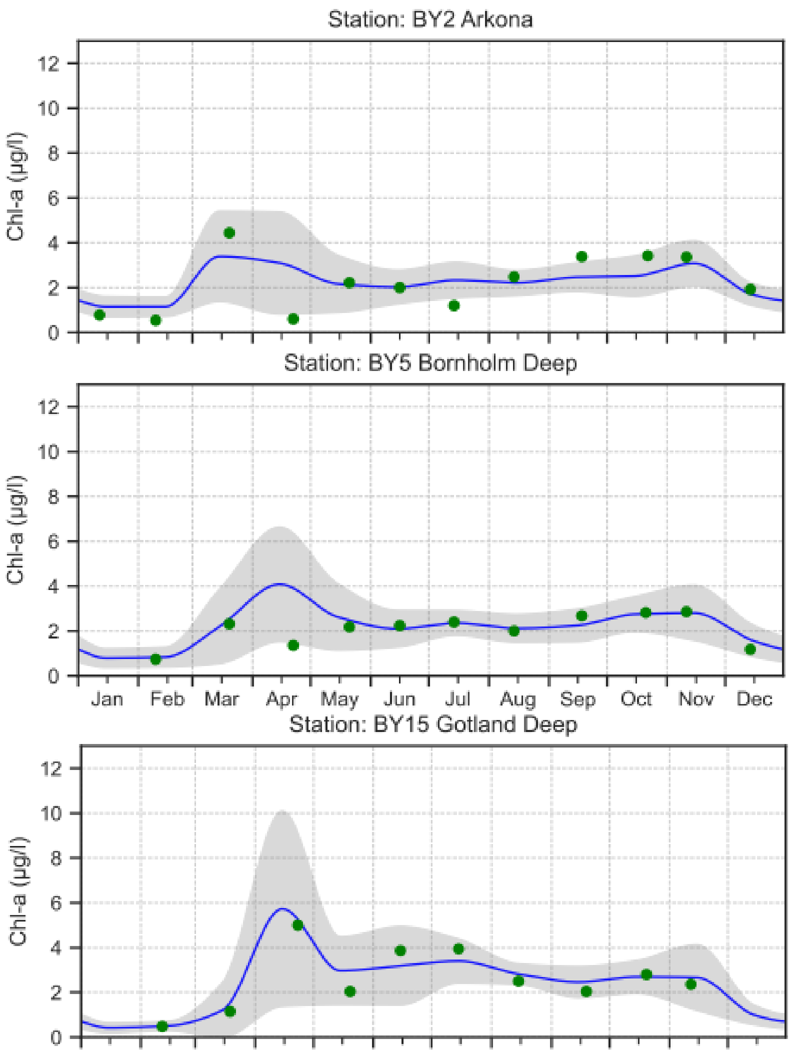

Figure 25. Integrated (0-20 m) chlorophyll a (µg/l) from the stations BY2 Arkona and BY5 Bornholm in the southwestern Baltic Proper and BY15 in the Eastern Gotland Basin. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (blue line) and +/- 1 standard deviation (grey area).

4.2.5.1 Satellite observations of the summer cyanobacteria accumulations

The largest area of cyanobacteria surface accumulations was observed by satellite on the 28th of June when about 83 300 km^2 of the Baltic Proper and Gulf of Finland were affected, Figure 26. The first satellite observations were made on the 17th of June so one week was all that was needed to get to the maximum extent for 2022. The accumulations were first detected in the Northern Baltic Proper where the sea surface temperature reached the critical level earlier. Usually the accumulations start in the southeastern parts of the Baltic. Peaks in surface area of cyanobacteria were noted in the end of June and beginning of July. After that the weather changed with colder temperatures and winds and waves that mixed the cyanobacteria downwards in the water column. Some small peaks were observed in August and then the cyanobacteria accumulations declined. During the summer, most observations were made from the Northern Baltic Proper and the outer parts of the Gulf of Finland, Figure 27.

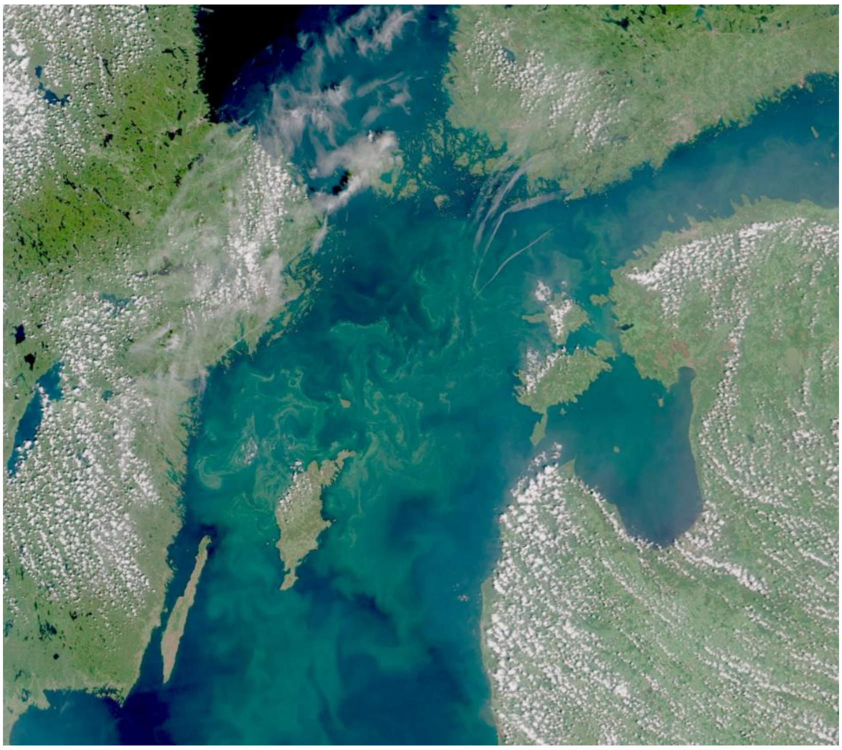

Figure 26. The largest area of cyanobacteria surface accumulations was observed by satellite on the 28th of June when about 83 300 km² of the Baltic Proper and Gulf of Finland were affected.

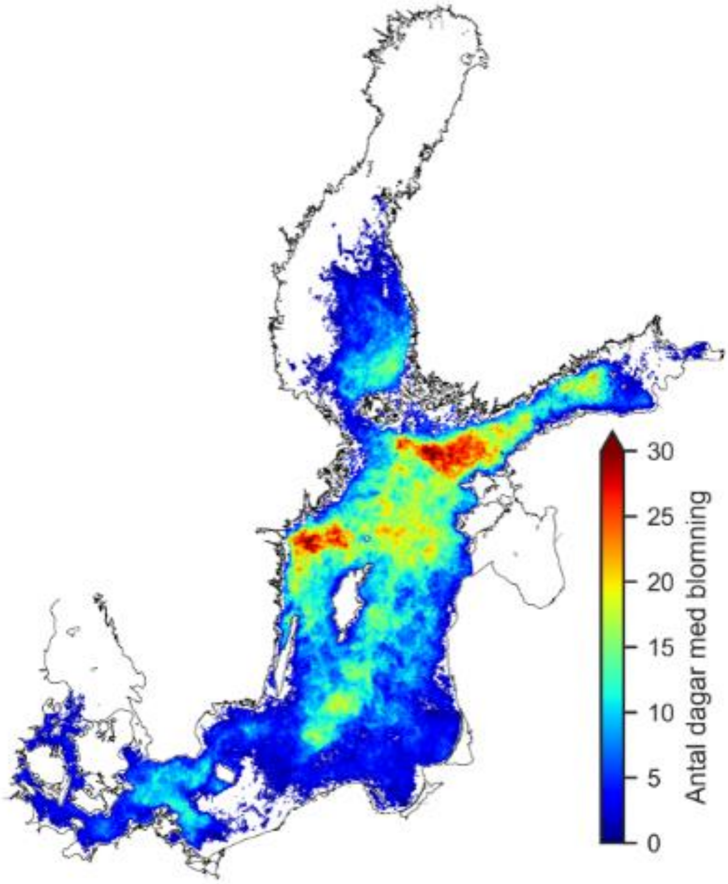

Figure 27. Number of days in 2022 with observed cyanobacteria bloom from satellite images.

4.3 The Gulf of Bothnia (Bothnian Sea and Bothnian Bay)

4.3.1 Temperature and salinity

In both the Bothnian Sea and the Bothnian Bay the lowest winter temperature was measured during the cruise in February, close to 0°C, see Figure 28. The surface water started to warm up in April and the highest temperatures (15-17°C) were measured during the July and August cruises. In the Bothnian Sea the temperature at station C3 the temperature in July was above normal. In October the surface temperature had started to decrease again.

The difference in salinity between the surface and bottom water is even smaller in the Bothnian Bay than in the Bothnian Sea but there is a weak stratification at 75 m.

Surface temperature at C3 and F9/A13

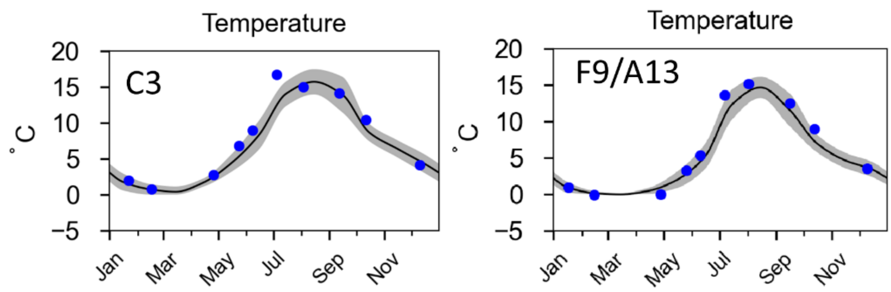

Figure 28. The temperature in the sea surface, 0-10 m, during 2022 at the stations C3 (left) in the Bothnian Sea and F9/A13 (right) in the Bothnian Bay. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area).

In the Bothnian Bay the surface salinity was below normal from July to December and in the Bothnian Sea it was above normal at the beginning of the year and below normal in August to October, Figure 29. This is consistent with the long-term development that shows decreasing salinity in the Bothnian Bay since 1990.

Surface salinity at C3 and F9/A13

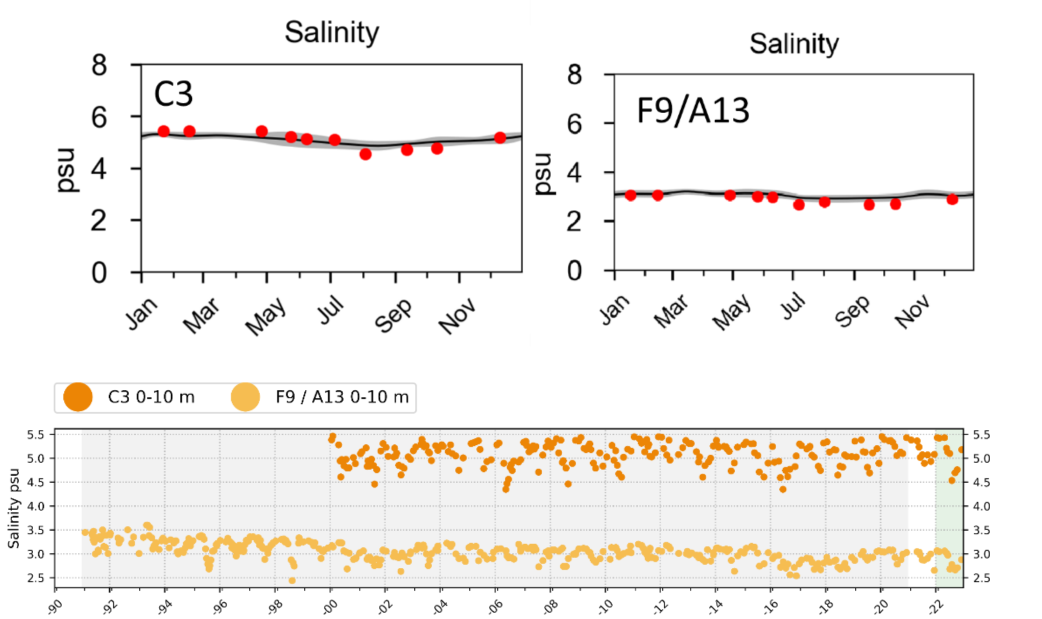

Figure 29. Top panel: The salinity in the sea surface, 0-10 m, during 2022 at the stations C3 (left) in the Bothnian Sea and F9/A13 (right) in the Bothnian Bay. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area). Lower panel: Surface water salinity in the Bothnian Bay (yellow) and the Bothnian Sea (orange) from 1990-2022. There is a decreasing trend in salinity in the Bothnian Bay.

4.3.2 Oxygen conditions in the bottom water

The bottom water in the Gulf of Bothnia is generally well oxygenated since the stratification is week and the sea area is mainly oligotrophic. At the coastal stations Råneå-1, Råneå-2 and B7 the bottom water oxygen becomes lower during summer months but there is no oxygen deficiency. There is a trend with decreasing oxygen concentrations in the Bothnian Sea deep water[8]. In 2022 the deep water was unusually well oxygenated from June to November, with some points above 6 ml/l, Figure 30.

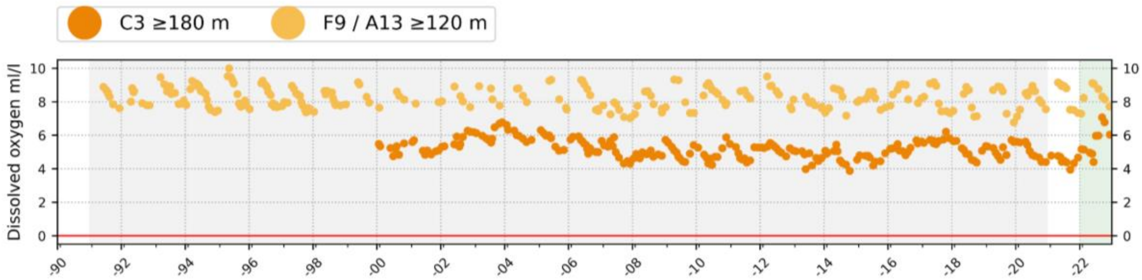

Figure 30. Dissolved oxygen in the bottom water at two stations in the Gulf of Bothnia; F9/A13 Bothnian Bay, C3 Bothnian Sea. The shadowed grey area highlights the time period that statistics is based on in this report, 1991-2020. The shadowed green area highlights the year 2022.

4.3.3 Nutrients

In the Gulf of Bothnia phosphate was above normal in the winter (December 2021 to February 2022). Silicate concentrations were above normal in February, but in December when the winter mapping of nutrients was performed, it was above normal only at four of 13 visited stations in the Bothnian Sea but at seven of ten visited stations in the Bothnian Bay. DIN was normal or below in the winter in the both sea areas, both in December and in February.

The Bothnian Bay has the lowest phosphate levels and the highest silicate levels of all Swedish open sea areas and DIN concentrations are just a little lower than in the Skagerrak and Kattegat, Figure 4. We do not have a mean value for the normal period 1991-2020) to compare with for all months so we cannot see deviations from the normal period as easily as in the other sea areas. But the data from 2022 (Figure 31) show that both phosphate and DIN are depleted or close to depleted during summer. In the Bothnian Bay DIN did not decrease to very low levels until July and was at its lowest in July and August to increase again in September. In the Bothnian Sea there is a clear decrease in DIN and phosphate in the end of April. Here, the production season is markedly longer with low concentrations of phosphate and DIN from the end of April until October. In a longer perspective phosphate and silicate is increasing in the surface waters in the Gulf of Bothnia while DIN is decreasing, see Figure 32.

[8] Ahlgren J., Grimvall A., Omstedt A., Rolff C., Wikner J., 2017, Temperature, DOC level and basin interactions explain the declining oxygen concentrations in the Bothnian Sea. Journal of Marine Systems 170 (2017) 22–30.

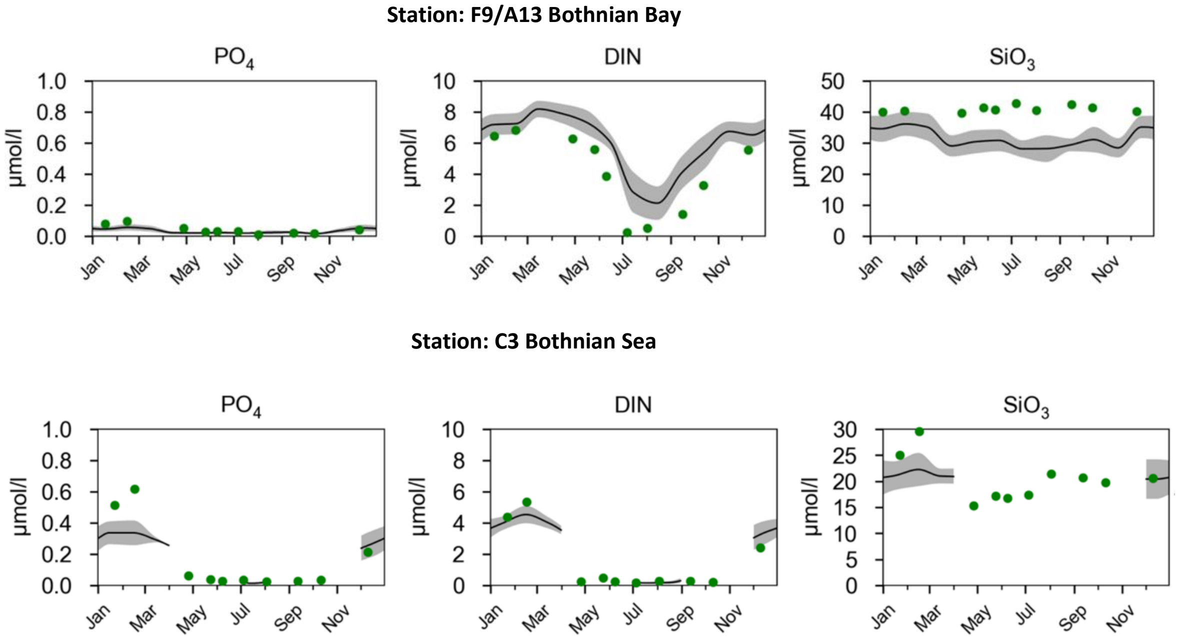

Figure 31. Concentrations of inorganic nutrients in the surface water (0-10 m) in the Gulf of Bothnia. Top row station F9/A13, Bothnian Bay, bottom row station C3 Bothnian Sea. Monthly measurements (dots) during 2022 are shown in relation to average value for the period 1991-2020 (black line) and +/- 1 standard deviation (grey area). Missing black line and grey area indicates that there are too few data in the period 1991-2020 to calculate statistics.

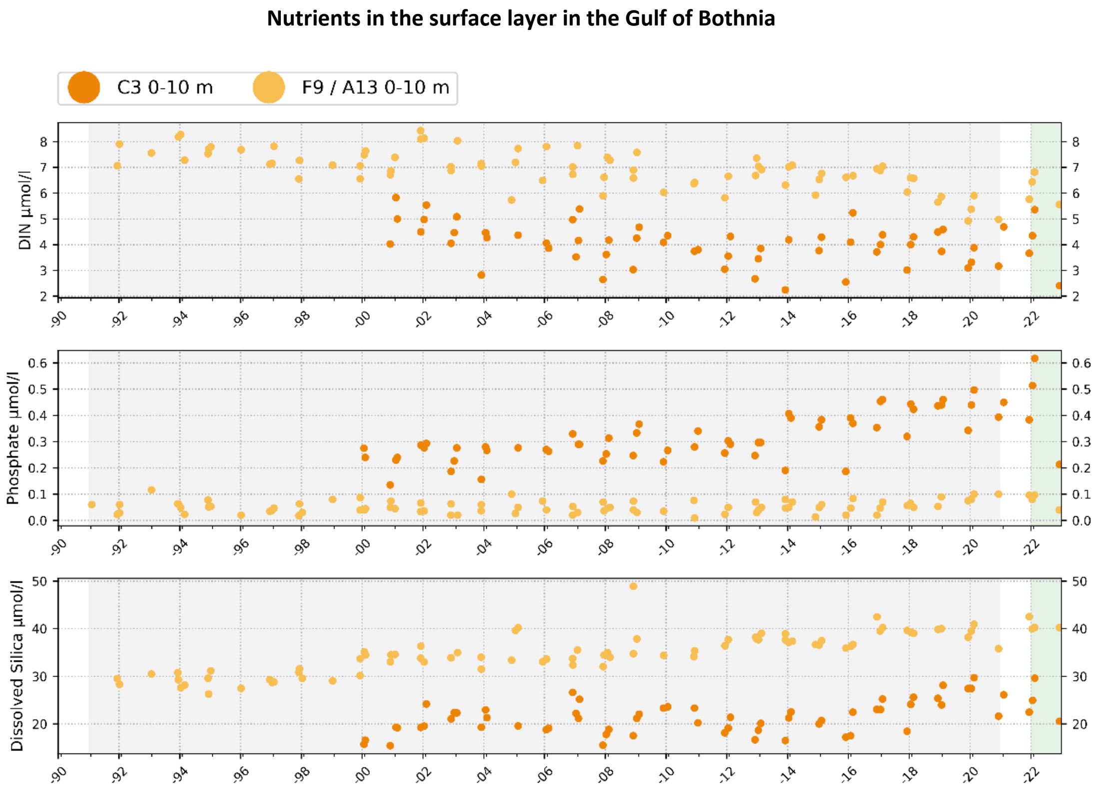

Figure 32. Timeseries of winter (Dec-Feb) inorganic nutrients in the surface water (0-10 m) at two stations in the Gulf of Bothnia (F9/A13 Bothnian Bay andC3 Bothnian Sea. The shadowed grey area highlights the time period that statistics is based on in this report, 1991-2020. The shadowed green area highlights the year 2022.

4.3.4 Phytoplankton

Spring bloom was found the earliest, as expected, at the Bothnian Sea stations B3, B7, GA1 and C3, in April, with various species of diatoms dominating the phytoplankton samples. At C3, the highest biomass value since 2015 was recorded during the April spring bloom, see Figure 33. At B3 and B7, the biomass declined during summer and rose again during autumn when a bloom of the filamentous cyanobacterium *Aphanizomenon* spp. and elevated cell numbers of the potentially toxic dinoflagellate *Dinophysis acuminata* were included. At station C3, filamentous cyanobacteria took over in late summer and autumn, of which *Aphanizomenon* dominated. In the end of the year, diatoms dominated in the phytoplankton samples.

The southernmost Bothnian Bay station C24, was sampled twice, in August and December. The August sample was dominated by cyanobacteria, mostly by *Aphanizomenon* spp., but rather high amounts of *Nodularia spumigena* was also found. Furthermore, the summer sample contained high numbers of the potentially harmful flagellate *Chrysochromulina* spp., cryptomonadales and *D. acuminata.* The December sample was dominated by diatoms.

At the station A13 in the Bothnian Bay, the diatom *Fragilariopsis cylindricus* dominated in early spring. The biomass maximum value was noted in July and was caused by diatoms, the mixotrophic ciliate *Mesodinium rubrum* and the potentially harmful genus *Chrysochromulina* spp. During the autumn, the phytoplankton composition altered and had a dominance of *M. rubrum* and rather high numbers of the diatom *Chaetoceros wighamii.*

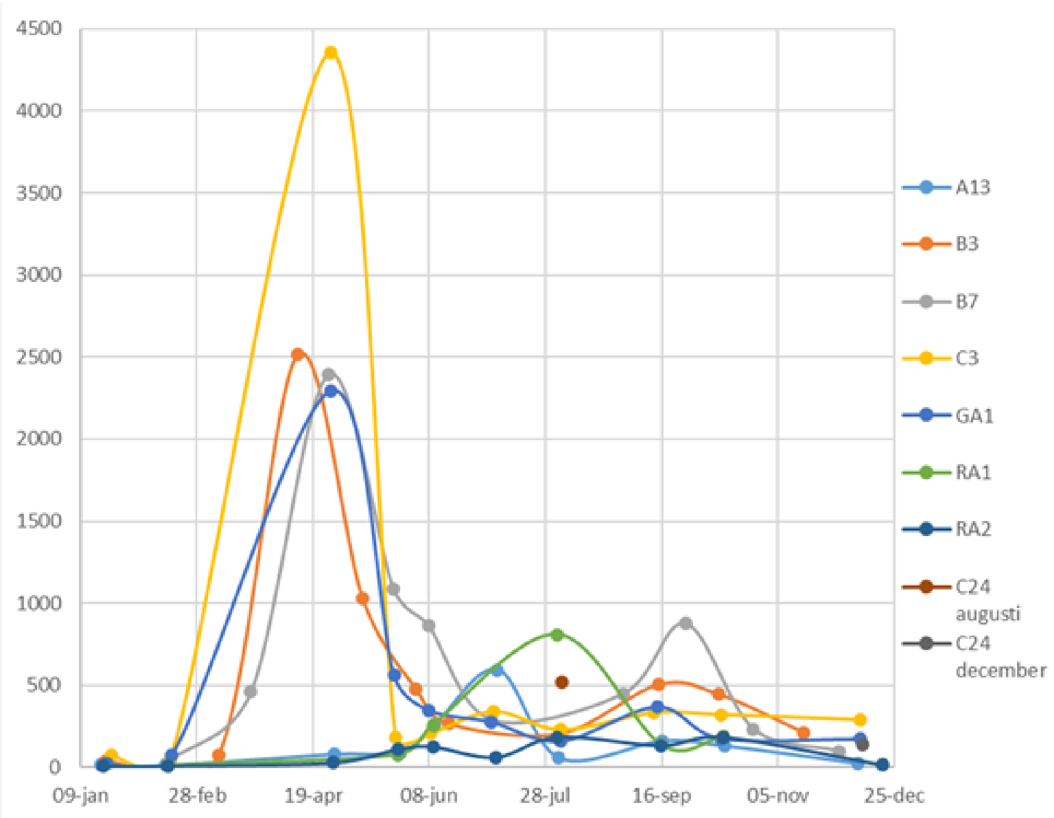

Figure 33. Phytoplankton biomass (µg C/l) at the Bothnian Sea and the Bothnian Bay stations.

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ISSN 0283-1112