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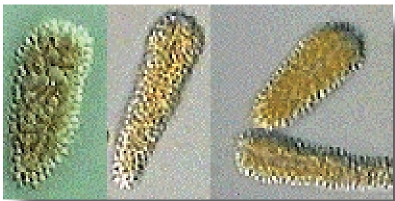

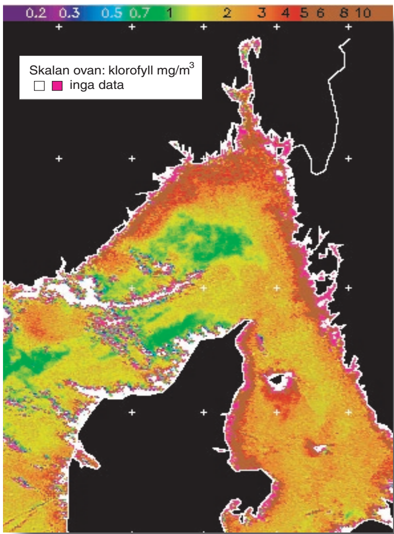

The Chattonella-bloom in year 2001 and effects of high freshwater input from river Göta Älv to the Kattegat-Skagerrak area

Bengt Karlson & Lars Andersson

Cover pictures:
Chattonella sp., photo by Mats Kuylenstierna.
Research vessel Sensor, photo by anonymous..
Satellite image indicating the extension of the *Chattonella*-bloom on March 26th 2001. Copyright NASA SeaWiFS project Team / Orbital Imaging Corp. by courtesy of the Remote Sensing Group, Plymouth Marine Laboratory, UK and Nansen Environmental and Remote Sensing Center, Norway.

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Abstract/sammandrag

In autumn year 2000 and winter-spring 2001 the precipitation in the catchment area of Lake Vänern was higher than normal. During spring 2001, the flow in river Göta älv was around 1200 m^3/s, nearly three times higher than the average indicating extreme conditions. The flow in the smaller rivers entering the Bohus coast is minor compared to river Göta Älv. To investigate possible effects on the marine environment in the area close to the river mouth an investigation with weekly sampling at four locations was initated by SMHI. Physical and chemical variables in the water was measured as well as phytoplankton composition and abundance. The Swedish Environmental Protection Agency and the Water Quality Association of the Bohus Coast co-funded the investigation together with SMHI. Effects on the water quality such as low surface salinities, high concentrations of dissolved inorganic nitrogen and dissolved phosphate and silicate compared to monthly averages 1990-99 was observed close to the river mouth but not off shore. Effects on the Secchi depth were not observed. On a few occassion high phytoplankton biomass, measured as chlorophyll *a,* was observed. At other locations along the Bohus coast effects where absent or small. Primary productivity measurements at the mouth of the Gullmar Fjord, showed no effects from the river outflow. During the investigation a bloom of the harmful alga *Chattonella* sp. occurred in the Kattetat and the Skagerrak.. The bloom of this small flagellate, which is described in the report, is probably not connected to the river input. A unique or unusual feature of the *Chattonella*-bloom is that it occured in cold water right after the diatom spring bloom in early March. In conclusion the effects of the extreme flooding were less than expected, the fresh water from the river were quickly mixed with the water in the sea and only small effects were seen. No connection between the flooding and the *Chattonella* bloom was detected.

Key words/sök-, nyckelord

Chattonella, Harmful algal bloom, Göta Älv, Kattegat, Skagerrak, freshwater, marine, nutrients, flow

Supplementary notes/Tillägg	Number of pages/Antal sidor	Language/Språk
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Contents

Summary in Swedish/Svensk sammanfattning

Under hösten år 2000 och vinter-vår 2001 var nederbörden i Vänerns avrinningsområde högre än normalt. Flödet i Göta älv var under våren 2001 extremt högt, ca 1200 m^3/s, d.v.s. tre gånger högre än medelflödet. Flödet i mindre vattendrag som mynnar vid Bohuskusten är litet jämfört med Göta älv. För att undersöka eventuella effekter på den marina miljön i området nära Göta älvs mynning genomfördes en studie med provtagning veckovis vid fyra stationer. Fysiska och kemiska variabler mättes liksom växtplanktonsammansättning och abundans. Naturvårdsverket och Bohuskustens vattenvårdsförbund bidrog till finansieringen av provtagningarna tillsammans med SMHI. Effekter på vattenkvaliteten i Göta älvs mynningsområde noterades i form av låga salthalter i ytvatnet och som höga halter av löst oorganiskt kväve, fosfat-fosfor och silikat jämfört med månadsmedelvärden för peioden 1990-99. I utsjön noterades inga sådana effekter. Några effekter på siktdjupet (Secchidjupet) observerades ej. Vid några tillfällen observerades hög växtplanktonbiomassa, mätt som klorofyll *a*. Vid andra platser längs Bohuskusten uppmättes inga eller små effekter. Primärproduktionsmätningar vid Gullmarfjordens mynning visade inte på några effekter av höga flöden från land. Under undersökningen inträffade en skadlig algblomning då flagellaten *Chattonella* sp. blommade i Kattegat och Skagerrak. Blomningen, som beskrivs i rapporten, är sannolikt inte knuten till de höga flödena från land. En unik eller ovanlig egenskap hos denna *Chattonella*-blomning var att den pågick i kallt vatten direkt efter vårblomningen av kiselalger i början av mars. Slutsasen av undersökningarna är att effekten av höga flöden från land var mindre än väntad, sötvattnet från älven blandades snabbt med havsvatten och endast små effekter observerades. Ingen koppling mellan höga flöden och *Chattonella*-blomningen detekterades.

Summary

In autumn year 2000 and winter-spring 2001 the precipitation in the catchment area of Lake Vänern was higher than normal. During spring 2001, the flow in river Göta älv was around 1200 m^3/s, nearly three timess higher than the average indicating extreme conditions. The flow in the smaller rivers entering the Bohus coast is minor compared to river Göta Älv. To investigate possible effects on the marine environment in the area close to the river mouth an investigation with weekly sampling at four locations was initated by SMHI. Physical and chemical variables in the water was measured as well as phytoplankton composition and abundance. The Swedish Environmental Protection Agency and the Water Quality Association of the Bohus Coast co-funded the investigation together with SMHI. Effects on the water quality such as low surface salinities, high concentrations of dissolved inorganic nitrogen and dissolved phosphate and silicate compared to monthly averages 1990-99 was observed close to the river mouth but not off shore. Effects on the Secchi depth were not observed. On a few occassion high phytoplankton biomass, measured as chlorophyll *a*, was observed. At other locations along the Bohus coast effects where absent or small. Primary productivity measurements at the mouth of the Gullmar Fjord, showed no effects from the river outflow. During the investigation a bloom of the harmful alga *Chattonella* sp. occurred in the Kattetat and the Skagerrak.. The bloom of this small flagellate, which is described in the report, is probably not connected to the river input. A unique or unusual feature of the *Chattonella*-bloom is that it occured in cold water right after the diatom spring bloom in early March. In conclusion the effects of the extreme flooding were less than expected, the fresh water from the river were quickly mixed with the water in the sea and only small effects were seen. No connection between the flooding and the *Chattonella* bloom was detected.

Preface

In January 2001 the Swedish Meteorological and Hydrological Institute realised that the high water flow in the river Göta Älv during autumn year 2000 and expected high flow in spring year 2001 may exert an influence on the sea, i.e. the Kattegat and the Skagerrak. SMHI, The Swedish Environmental Protection Agency (Naturvårdsverket) and the Water Quality Association of the Bohus Coast (Bohuskustens Vattenvårdsförbund) co-funded an investigation of possible effects in the area relatively close to the river mouth. The investigation started in February and ended in the beginning of June. The work by the crew of the research vessel Sensor, Bo Juhlin and Björn Becker and others, is much appreciated. Personnel at the SMHI laboratory at Nya Varvet performed the analyses of nutrients, chlorophyll *a* etc. and Dr. Mats Kuylenstierna (Marine botany, Göteborg University) made the quantitative phytoplankton analyses at Kristineberg Marine Research Station. Their contribution to the project has been invaluable. Other personnel at SMHI has contributed data on water flow, solar radiation etc. and helped with data processing and the production of graphs, their help is much appreciated. Odd Lindahl at Kristineberg Marine Research Station is thanked for making primary productivity data available. Data on nutrient concentrations in rivers was made available from the Swedish University of Agricultural Sciences (Sveriges lantbruksuniversitet). Discussions with Bertil Håkansson at SMHI regarding the results have been fruitful.

Göteborg, December 2003

Bengt Karlson & Lars Andersson

1 Introduction

The autumn year 2000 was extremely rainy, especially over the drainage area of lake Vänern were the water level rose to extreme levels. During spring 2001, the flow in Göta River, which drains Lake Vänern, was around 1200 m^3/s, nearly three times as high as normal. Also other rivers, e.g. Örekilsälven and Enningsdalsälven, had higher then normal run-off values.

During the first six months of year 2001, SMHI carried out an extended monitoring programme in the coastal area outside Göteborg with the aim to observe possible effects of extreme outflow from the river. During the study a harmful algal bloom of *Chatonella* sp. took place. The purpose of this report is to describe the development in the area during the extreme flooding and to compare the results with historical data. The extra measurements that were carried out once a week, consisted of salinity, temperature, nutrients, chlorophyll and phytoplankton in the coastal zone outside the Göta River mouth. Also data from other monitoring programmes is used to give a more complete picture of the situation.

1.1 Description of the area

The area at the Swedish west coast, outside Göteborg, can be characterised as a transition zone between the Kattegat and the Skagerrak, with a high variability in salinity. Kattegat surface water, which is a mixture of Kattegat deep water and Baltic water, enters from the south. Surface water from the Skagerrak normally reaches the coast north of the area under consideration, but can occasionally reach the Göteborg archipelago and there mix with the Kattegat surface water. This water is normally transported northwards along the Swedish west coast following the main anticlockwise circulation in the Skagerrak. Into this area the Göta River have its outlets. The Göta River is the largest river in Sweden with a mean flow over the year of ca. 500 m^3/s. The variations are however large, from 150 to 800 m^3/s. Since the flow is regulated the between year variations are normally small. Some years, however, there have been peaks in the flow of more than 1000 m^3/s. During spring 2001, there was an extreme flooding, and the flow was around 1200 m^3/s, for the first six months of the year. (Fig. 8). The Göta River separates into two branches at Kungälv, a few km before it reaches the sea, one part still called the Göta River continues trough Göteborg and the other part called Nordre Älv has its outlet north of the island Hisingen. The main part of the transport goes trough Nordre Älv (about 2/3). (see map fig 2)

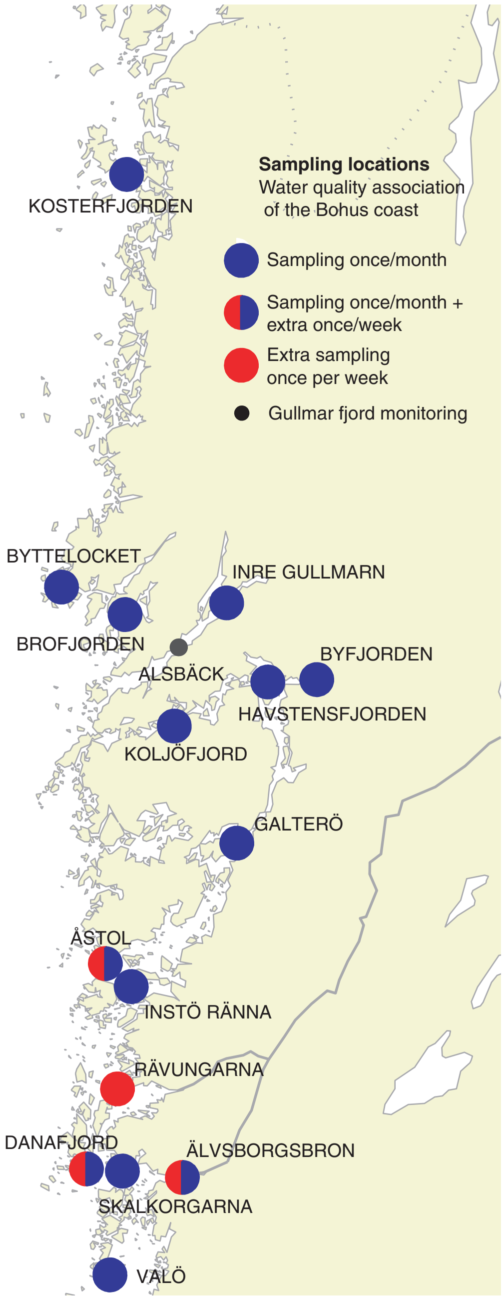

Figure 1. Coastal sampling locations (Släggö shown on other map).

1.2 Chemical and biological conditions

During winter, when the biological production is low, due to low insolation and high mixing, the nutrient concentrations increases. When the water gets stratified and the insolation increases the normal spring bloom of diatoms starts. This normally occurs during the period mid February to late March and lasts for a few weeks. Crucial for the start of the bloom is the weather, weak winds and high insolation speed up the process while strong winds delays it. Normally, spring blooms at the west coast of Sweden, starts earlier than in the North Sea due to stronger stratification.

Figure 2. Map showing off shore sampling locations (red dots) as well as locations from which hydrographic data is presented (green dots).

The bloom ends when the nutrients in the surface water have been depleted. The main part of the phytoplankton then sinks down to the bottom where they become food for bottom living animals, which in turn constitute food for fish. The reason that such a large amount of the spring bloom ends up at the bottom is that the few zooplankton that overwinter can not grow as fast as the phytoplankton. After the spring bloom, high biomass blooms are seldom observed, until autumn when the water masses are mixed again due to stronger winds. The fact that blooms are not observed does not mean that the growth of phytoplankton is low. Zooplankton quickly graze the phytoplankton and because of that the biomass do not get high. The solar energy taken up by the phytoplankton is quickly transported into the marine food web.

The nutrient concentrations in the Kattegat surface water as well as in the southeastern Skagerrak shows very clear annual cycles. During summer there are only small amounts of phosphorus and silicate left while the concentration of nitrogen is below detection limit most of the time. There are also clear annual cycles in nutrient concentrations within the river (fresh) water, but at least for nitrogen and silicate, the variations are around a rather high level. The amounts of nutrients entering the coastal zone and the sea are more depending on the volume transports of water than on the concentrations. The fresh water in the river has much higher concentrations of nitrogen and silicate than the sea water, while the concentration of phosphorus on the other hand are slightly lower.

1.3 Harmful algal blooms – short description and history

Algal blooms are mostly natural phenomena but the frequency of harmful algal blooms has increased due to human activity, e.g. eutrophication.

Recent information on harmful algal blooms and algal toxins in shellfish is found in (Karlson 2003, Karlson & Rehnstam Holm 2003).

1.3.1 The main types of harmful algal blooms:

1. Algae toxic to fish and other organisms, e.g. *Chrysochromulina polylepis*
2. Algae that clog the gills of fish, e.g. *Chattonella* spp.
3. Algae that mechanically damage gills of fish, *Chaetoceros* spp.
4. Algae that make shellfish toxic to humans, e.g. species from the dinoflagellate genera *Alexandrium*, *Dinophysis* and the diatom genus *Pseudo-nitzschia*.
5. High biomass of algae that cause anoxic conditions on the sea floor after sedimenting, e.g. *Ceratium* spp.
6. Surface accumulations of algae which are a nuisance to outdoor life, e.g. *Noctiluca scintillans* which is a heterotrophic dinoflagellate mainly known as one of the organisms causing sea-fire bioluminescence.
7. Nitrogen fixing cyanobacteria that sunny and calm summers occur in large surface accumulations in the Baltic Sea (mainly the Baltic proper and the Gulf of Finland) do not grow in the Kattegat-Skagerrak. This is due to the fact that nitrogen fixing only works well in brackish and fresh water. Thus, the toxic species *Nodularia spumigena*, casuses no harm on the Swedish west coast. However, remnants of the blooms in the Baltic are sometimes transported into the Kattegat where growth ceases. This happened e.g. in 1997 and in 2003.

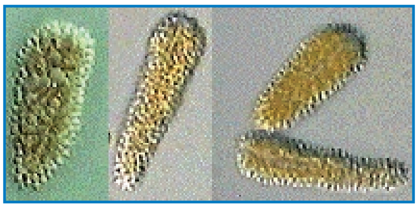

Figure 3. *Chattonella* sp. from the Skagerrak. The cells are from the bloom in 1998. Cellshape is variable and length varies from ca 10-50 µm. Photo by Mats Kuylenstierna.

1.3.2 Examples of harmful algal blooms in the Kattegat-Skagerrak area:

1988
Bloom of *Chrysochromulina polylepis,* mortality of fish,, macroalgae and other organsims.
1998
First large bloom of C*hattonella* sp., mortality of wild and farmed fish.
2000
Bloom of *Chattonella* sp. in the North Sea. The bloom did not reach the Swedish coast.
2001
Bloom of *Chattonella* sp. in the Kattegat, the Skagerrak and in the North Sea, 1100 tons of salmon died in Norwegian fish farms.
Every year, at least since 1988-2003
Dinophysis spp. causes diarrhetic shellfish toxicity in blue mussels.
Several years during the period 1988-2003
Alexandrium spp. cause paralytic shellfish toxicity in blue mussels.
Yearly since the 1980:s
High plankton growth due to eutrophication causing e.g. anoxic conditions on th sea floor.

1.3.3 What is Chattonella?

The phytoplankton genus *Chattonella* belongs to the class Raphidophyceae that is part of the division Heterokontophyta. Several potentially harmful species belong to the genus. The species blooming in Scandinavian waters have been termed *Chattonella* sp., *C.* aff. *verruculosa* and *C. marina*. The correct name of the species that occurred in the 2002-bloom is still unclear. It is quite possible that it will be described as a new species within the genus *Chattonella*. *Chattonella* sp. has a variable shape from spherical to elongate or cone-shaped. It is a flagellate with two flagella used for motility.

Primary effect	Secondary effects
Lowered salinity in surface water	Changes in species composition - species with a wide salinity tolerance favoured
Stronger stratification	Increase in primary productivity due to smaller mixing depth of phytoplankton Lowered primary productivity due to lowered transport of nutrients from deep water Changes is species composition - flagellates (some harmful aglae) favoured
Increased concentrations of nutrients	Increase in primary productivity Changes is species composition
Changed ratio between dissolved inorganic nitrogen, silicate and phosphate	Changes is species composition - some harmful algae may be favoured
Increase in particle content of water	Lowered primary production if light is limiting production Change in species composition - shade adapted species favoured

Table 1. Some possible effects of high fresh water flow to the Kattegat-Skagerrak area.

1.4 Possible effects of high freshwater flow

1.4.1 Biological effects

River plumes exert an influence on phytoplankton production in several ways, which are compiled in table 1. Effects on biota other than phytoplankton is not considered in this report but of course biological effects may also appear in the deep water and at the sea floor, i.e. oxygen depletion.

2 Material & methods

Positions for sampling locations and dates for sampling is found in appendices 1 and 2. SMHI: s research vessel Sensor was used for sampling at the stations close to Göteborg. A mini CTD (SAIV SD 204) fitted with a chlorophyll *in situ* fluorometer (Dr. Haardt mini backscat) was used to obtained depth profiles of temperature, salinity and chlorophyll *a* fluorescence. Water samples were collected using Nansen-type reversing water bottles (volume 2 L) fitted with digital thermometers “Sea Turtle” manufactured by OceanOrigo AB. Water bottles were mounted on a hydrography wire. Sampling depths were fixed at 2, 5, 10, 15, 20, 30, 40, 50 and 60 m or to the bottom. A sample was also collected ca 0.5 m from the sea floor. Chemical analysis of dissolved inorganic nutrients was made within 24 hours of sampling. Samples were kept at 4°C in darkness until analysis according to the “Manual for Marine Monitoring in the COMBINE Programme of HELCOM” (Anonymous 2001). For determination chlorophyll *a* concentrations 100 ml of seawater was filtered onto Whatman GF/F filters (nominal pore size 0.7 µm). Extraction was in ethanol (96%) for 6-24 hours and a Sequoia Turner fluorometer was used for determining concentration of chlorophyll *a* (Anonymous 2001). Chlorophyll *a* analysis was made from samples from fixed depths between 2 and 30 m and from tube sampling (see below).

Samples for quantitative phytoplankton analysis was collected using a flexible tube with an inner diameter of ca 20 mm. The end of the tube was lowered to 20 m when the upper end was closed. A valve at 10 m made it possible to split the sample in two parts: 0-10 m and 10-20 m. Also a sample from the depth of the maximum chlorophyll *a* fluorescence was collected. Acid Lugols iodine was used for preservation (Throndsen 1978). Mats Kuylenstierna performed quantitative analysis of phytoplankton abundance using an inverted

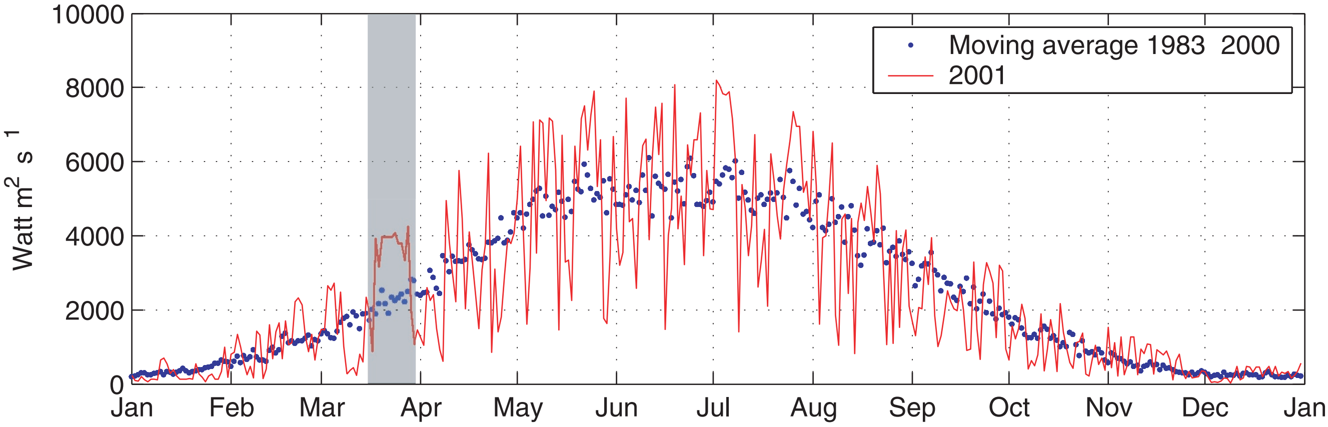

Figure 4. Irradiance measured in the city of Göteborgs. The moving average was calculated for three day periods. During the second half of March the Chattonella bloom reached its maxium.

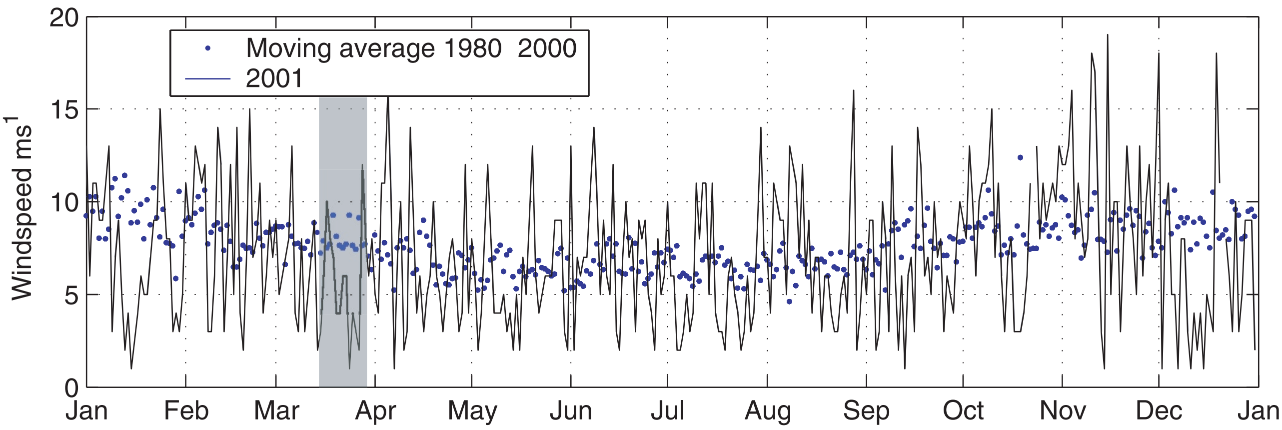

Figure 5. Wind speed measured at noon on the island of Måseskär. The moving average was calculated for three day periods.

microscope (Leitz DMIRB) at magnifications 40-1000x according to (Utermöhl 1931, 1958). Differential interference contrast enhancement was used. The standard monitoring samples were analysed by Lars Edler using a Nikon inverted microscope with a similar configuration as the Leitz.

Net samples for qualitative analysis of phytoplankton were collected using a plankton net with mesh size 10 µm. A vertical tow 20-0 m was made and the samples were stored live in Nunc cell culture bottles (125 ml) kept at 4°C in darkness until analysis. A Leitz microscope with phase contrast enhancement at 40-400 x magnification was used for analysis by Bengt Karlson.

The presented wind data is from the SMHI meteorological observations at the island of Måseskär. Irradiance was measured in the city of Göteborg.

3 Results & discussion

3.1 Wind & insolation

During spring of year 2001 a period of low winds and strong irradiance induced the diatom spring bloom in the beginning of March. From mid March to the end of March an unusually long period with low wind speeds and strong irradiance prevailed (Figs. 4 & 5). This period coincided with the maximum of the *Chattonella* bloom.

3.2 Run-off to the Kattegat-Skagerrak area

A long-term dataset for flow in the river Göta älv is shown in figure 7. A distinct change in flow pattern is observed after the start of regulating control in 1938. In figure 8 the last 15 years of flow data is found. The interannual variability is large, in 1996 a year with little precipitation resulted in low flow and in 1999 a wet year was recorded. During spring 2001, the flow in river Göta älv was around 1200 m^3/s, nearly three times as higher than the average indicating extreme conditions. The flow in the smaller rivers entering the Bohus coast is minor compared to river Göta Älv. (Lindström 2002) describes river flow in Sweden 1900-2000.

3.3 Nutrient concentrations in Göta river

Time series of the nutrient concentrations in Göta River, at Trollhättan, from 1965 till 2001 are shown in figures 9-13. It is clear that the concentrations of nitrogen increased from the mid 60-ties up till the beginning of the 80-ties and has thereafter stayed at a rather constant level with a small decrease during the later years. Phosphate on the other hand shows a decrease from the late 60-ties to the mid 80-ties, and have thereafter stayed at a low level with the exception of a few peaks in the late 80-ties. Silicate shows a decrease from 1965 to 1975 and has stayed at a constant level with the exception of a few peaks some years. Typical winter concentrations in the river and the coastal zone are shown in table 2.

3.4 Transports of nutrients in Göta river

The annual transports of nutrients, calculated by SMHI from nutrient data from Swedish University of Agricultural Sciences and flow data from SMHI, based on measurements at Trollhättan are shown in figure 11-13.

3.5 Nutrient concentrations in the coastal zone and in the open sea

Annual cycles of temperature, salinity and nutrients as well as oxygen saturation in the surface water at three different stations in the coastal area are shown in figures 14-17. At the station E Älvsborgsbron in the river mouth the salinity during 2001 is clearly below normal during the whole year 2001. Nutrient concentrations show normal values with the exception of silicate that shows some extreme peaks in January and March. At the station Danafjord the salinity in January was extremely low, during February normal and during the main part of spring and summer clearly below normal. Phosphate in January was below mean while it during the rest of the year showed normal values. Nitrogen (DIN) as well as silicate had an extremely high value in January and showed during the rest

Figure 6. The sluicegates at Trollhättan were fully open in spring 2001 to avoid flooding of the land surrounding lake Vänern.

of the year a larger than normal scatter. The station Rävungarna is located close to the mouth of Nordre Älv, and shows the same tendency as the other stations.

The signal from the extreme flow in the river is also seen at station Åstol in the outer part of the archipelago in January in both salinity and nutrients. During the rest of the period of interest, the effect is mainly seen in salinity, which is below normal, while the effect on nutrients is less clear (pronounced).

Nutrient concentrations versus salinity in January at the surface and at a depth of 2 metres are shown in figure 24. There is a clear linear relationship between nutrient concentrations and salinity. Concentrations of nitrogen and silicate are high within the river water, represented by the station E Älvsborgsbron compared to the stations Fladen and P2 in the open sea, while phosphate shows the opposite behaviour. The stations in the archipelago are located on the mixing-line, indicating that the concentrations of nutrients at these stations are determined by mixing of river water and open sea water. Already at a depth of two metres the stations in the archipelago are closer related to the conditions in the open sea, indicating a very shallow surface layer. The different nutrients also shows skewed ratios compared to the Redfield-ratio.

3.6 Stratification and residence time

When the fresh water leaves the river mouth it spreads out in a thin layer and is then mixed with

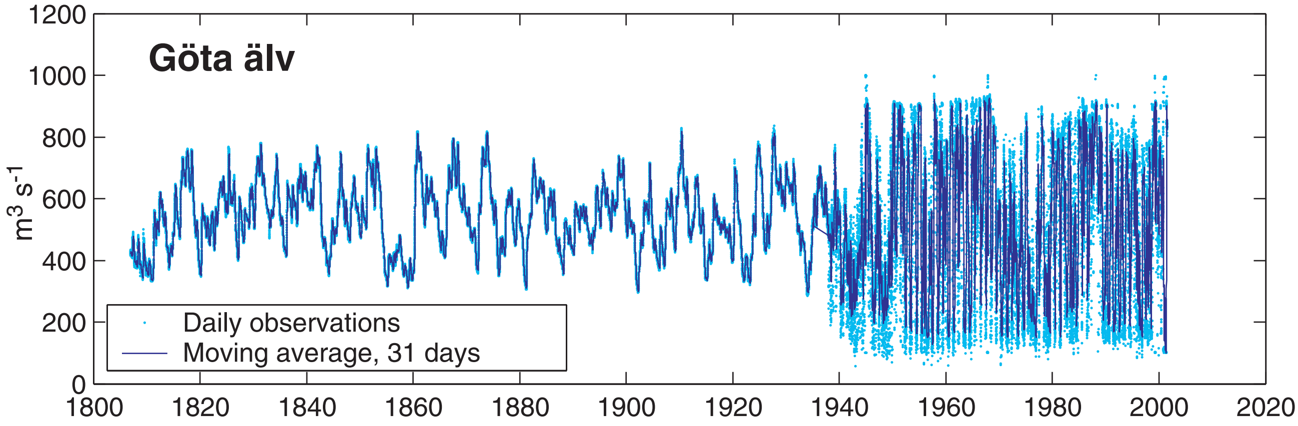

Figure 7. Water flow in river Göta älv from 1807 to 2001. Data from the period 1807-1954 is based on water level mesurements at Sjötorp in lake Vänern. From 1954 onwards data from the power plant at Vargön close to the towns of Trollhättan and Vänersborg are shown. Regulating control of the river started ca 1938 and resulted in a different pattern of variations in flow.

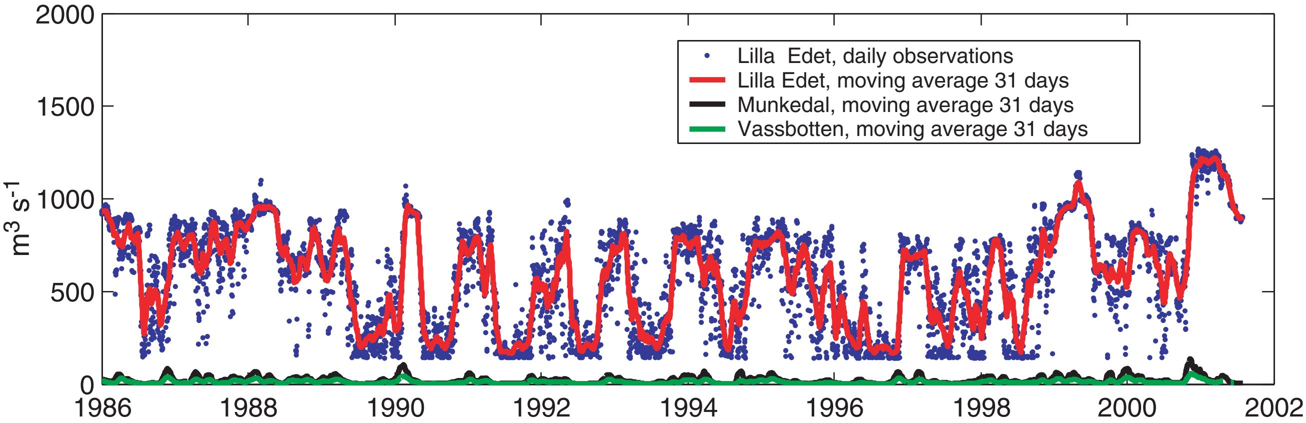

Figure 8. Water flow in the larger rivers entering the Bohus coast during the period 1986-2001. River Göta älv is represented with the measurements made at Lilla Edet. The flow at the river mouth is slightly higher but the estimates from the mouth are less reliable. River Örekilsälven, which enters the fjord Gullmarsfjorden, are represented by measurements at Munkedal and Enningdalsälven, which enters the fjord Idefjorden, by measurements at Vassbotten.

the underlying sea water. This means that it only can be traced in a restricted area.

Just after the river enters the coastal area and the velocity is reduced, the low saline water spreads out on top of the more saline water. This surface layer is normally, at least if the wind speed is low (weak mixing), very thin.

The water from the Göta river and Nordre Älv normally turns northward when entering the sea, following the main circulation on the west coast. This leaves the area south of Göteborg rather unaffected. Only at rare occasions the water leaving the river turns southwards.

The length scales are very different in the north-south direction compared to the east-west direction. In east-west direction the river water can be traced approximately 20 km while it in the north-south direction can be traced ca. 40 km. This would give a coastal area affected by the river water of approximately 800 km^3. However 50% of this area is land so the water occupies some 400 km^3. The mean depth of this area is 10 metres giving a total volume of roughly 4 km^3. If we assume that the surface layer is only 1 metre thick it would occupy 0.4 km^3. The mean flow of freshwater in the river is 500 m^3/s, giving a residence time of approximately one week. However, the river water is not spread out even over the whole area, but is

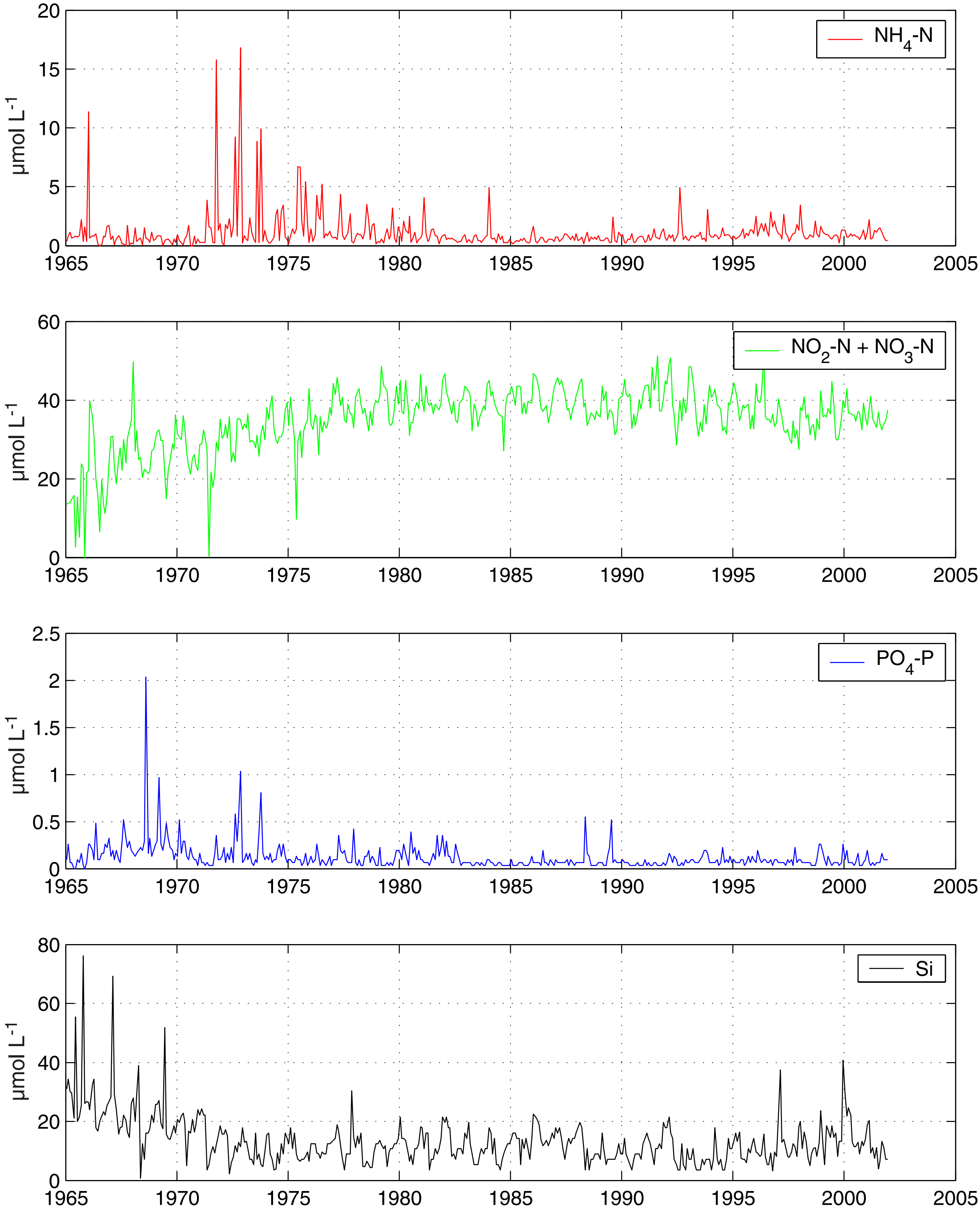

Figure 9. Nutrient concentrations in river Göta älv at Trollhättan.
Data from Swedish University of Agricultural Sciences.

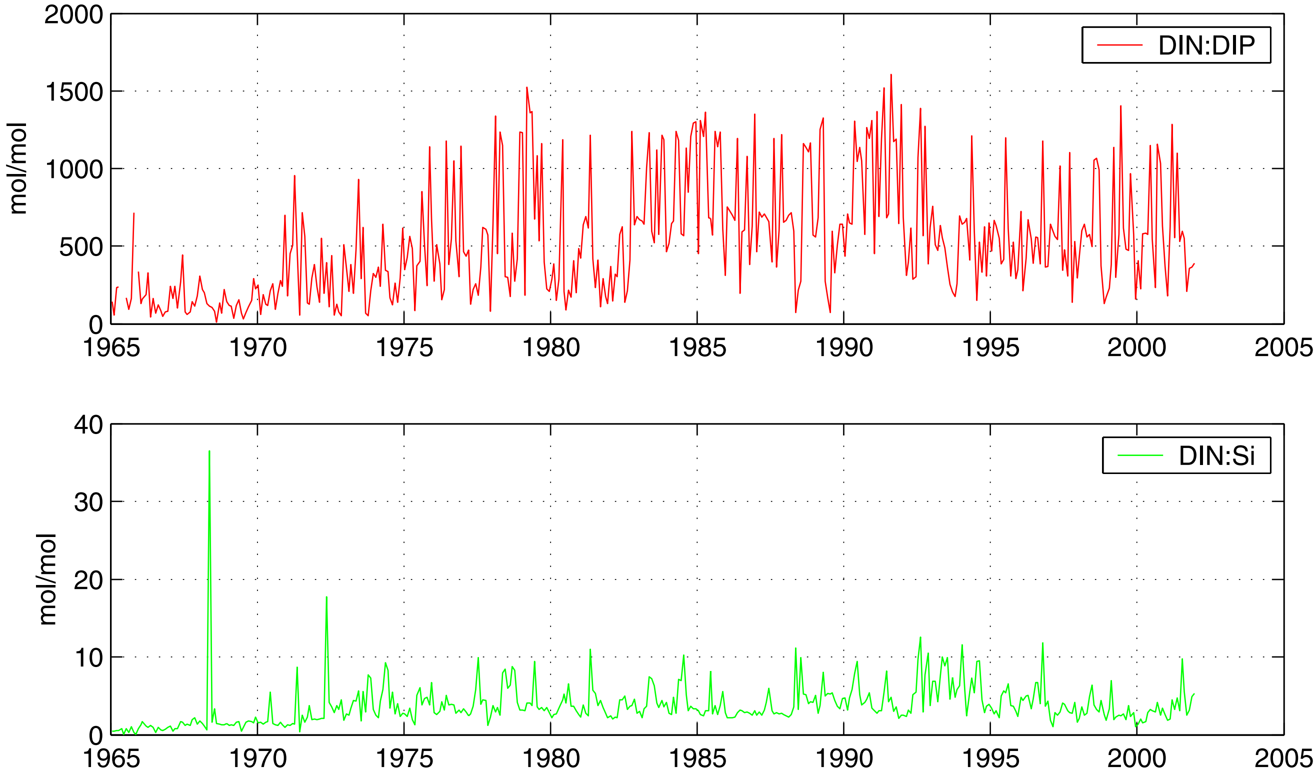

Figure 10. Ratios of nutrient concentrations in river Göta älv at Trollhättan.
Data from Swedish University of Agricultural Sciences.

mainly transported in a plume, and the residence time is thereby probably much shorter, about a couple of days.

3.7 Secchi depth

The Secchi depth is a visual measure of the clarity of a water column. Empirical studies indicate a good relation between Secchi depth and the depth of the euphotic zone, although the relationship varies from region to region. The data on Secchi depth is presented in figures 29-30. The data from spring 2001 does not deviate from the rest of the dataset.

3.8 Chlorophyll

Phytoplankton biomass, measured as chlorophyll *a*, showed a very similar development in time at the three stations, Åstol, Rävungarna and Danafjord (Figs. 23, 25 & 27), with a peak in mid March and a second peak in late April. Two different sampling methods were used for chlorophyll *a*. Samples were obtained from water samples as well as from tubes. The highest concentration from a tube sample, 16.1 µg l^{-1}, was from Danafjord, 0-10 m, on 13 March whereas the highest concentration from discrete samples was19.1 µg l^{-1} at 2 m on 10 April at Åstol. A reason for the discrepancy may be patchy distribution of phytoplankton. The overall pattern of chlorophyll concentration is the same for both methods.

In Figs. 23 and 28 an overview of chlorophyll *a* concentrations from the Kattegat and the Skagerrak is presented. The stations in the Kattegat and the coastal Skgaerrak show a similar pattern with two peaks of chlorophyll occurring partly as subsurface maxima. Station Å17 in the central Skagerrak, has a different pattern with a strong suburface maxima observed in the end of March.

Comparing chlorophyll *a* concentrations for year 2001 with long term data the sampling occasion on 13 March stand out as exceptional. Our interpretation is that the peak of the spring bloom that

Table 2. Typical winter nutrient concentrations in µmol/l.

	PO_4	DIN	SiO
Göta River	0.3	40	20
Coastal zone	0.6	9	8

coincided with the start of the *Chattonella* bloom was sampled thanks to the weekly sampling during this study. Normally, sampling is made only once a month.

The chlorophyll was also distributed according the salinity. Not surprisingly it is seen that high phytoplankton biomass is found in the surface water of the area, i.e. at ca 20 psu (Fig. 27). The more offshore station, Åstol, have a few occurrences with high chlorophyll *a* at high salinities corresponding to subsurface chlorophyll *a* maxima. Chlorophyll *a* at salinities <15 psu was below 10µg l^{-1} except for one sample. We interpret this in such a way that the phytoplankton species being brought to the area with low saline water from rivers do not survive at salinities found in the surface water of the coastal area. Although low saline surface water sometimes occur together with high nutrient concentrations favourable for phytoplankton growth these niches are very short lived and no phytoplankton species have been able to exploit them. The "nice water" is simply transported away and mixed with the coastal surface water.

3.9 Plankton

In this study phytoplankton samples were only analysed for species composition and cell numbers. The biomass of different species was not measured. This should be kept in mind when graphs are interpreted. All phytoplankton data is stored in the phytoplankton database at SMHI.

3.9.1 Diatoms

The temporal development of diatom cell numbers is presented in Fig. 33. Cell numbers are generally higher at the two more marine stations, Danafjord and Åstol, compared to Rävungarna. A distinctive peak in the beginning of March represents the spring bloom. Several peaks later in the spring were observed, e.g. at Åstol in the end of May.

3.9.2 Dinoflagellates

Cell numbers of dinoflagellates (Fig. 34) are generally one order of magnitude smaller than that of the diatoms. It is unknown if this is the case for biomass also. A distinctive peak was observed in early April.

3.9.3 Other phytoplankton

The majority of phytoplankton does not belong to the diatoms or the dinoflagellates. Together they comprise about one order of magnitude more cells per litre than the diatoms and dinoflagellates combined (Fig. 35). Most cells are small and thus efficient in regard of e.g. nutrient uptake. In mid March a bloom of *Chattonella* sp. started. The highest cell numbers close to Göta älv were observed 25-26th of March Fig. 36). In the Gullmar fjord the maximum was observed a few days earlier (Fig. 42). During the later stages of the bloom very small *Chattonella* cells were abundant (Fig. 37). *Chattonella* belong to the class Raphidophyceae. Another organism from the same group, *Heterosigma* sp., occurred in high cell numbers during the decline of the *Chattonella* bloom (Fig. 38.). Satellites were used to follow the development of the *Chattonella* bloom (Figs. 39-40). Although only the uppermost part of the water column is observed these images are quite useful.

3.10 Primary production

A time series of primary productivity measurements in the mouth of the Gullmar fjord from 1985 and onwards is maintained by Odd Lindahl, Kristineberg Marine Research Station. Incubations are made i*n situ* and on average 19 incubations per year have been carried out. Data is presented in Fig. 31. The primary production in year 2001 is in no way exceptional in this location. No long-term primary production measurement series is available where the physical effects of high river runoff was observed.

3.8 About the *Chattonella* bloom

The harmful algal bloom of *Chattonella* sp. that occurred in 2001 is probably not connected directly to high freshwater input. During the increased freshwater flow in Göta River during spring of year 2001 imminent effects on the phytoplankton was not detectable. Primary production was only measured far away from the river mouth and no effects were detected. Higher biomass, measured as chlorophyll-a, than normal was only occassionally detected. However, one has to keep in mind that phytoplankton blooms take about a week to develop and then last at most a few weeks, thus the measurements made monthly are difficult to compare with. The residence time is probably not long enough for a bloom to develop fully in the coastal zone before the water has left the area. There is also a clear imbalance between different nutrients, compared to the Redfield ratio, which can affect the plankton bloom.

4 Conclusion

The effects of the extreme flooding were less than expected, the fresh water from the river were quickly mixed with the water in the sea and only small effects were seen. No connection between the flooding and the *Chattonella* bloom has been detected.

5 References

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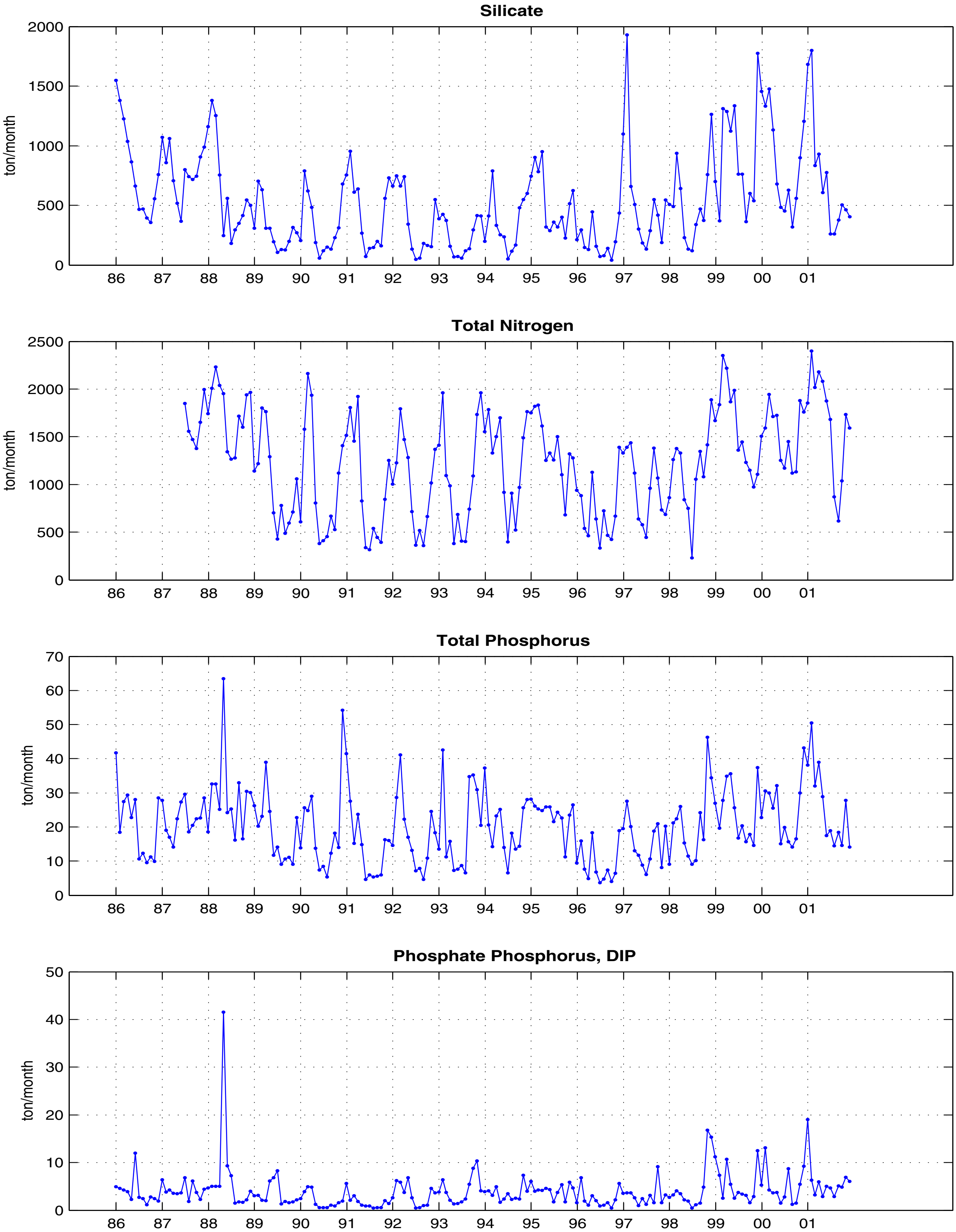

Figure 11. Transport of nutrients in river Göta älv calculated from monthly nutrients measurements (Swedish University of Agricultural Sciences) and daily measurements of water transport (SMHI). Unit is tonnes per month.

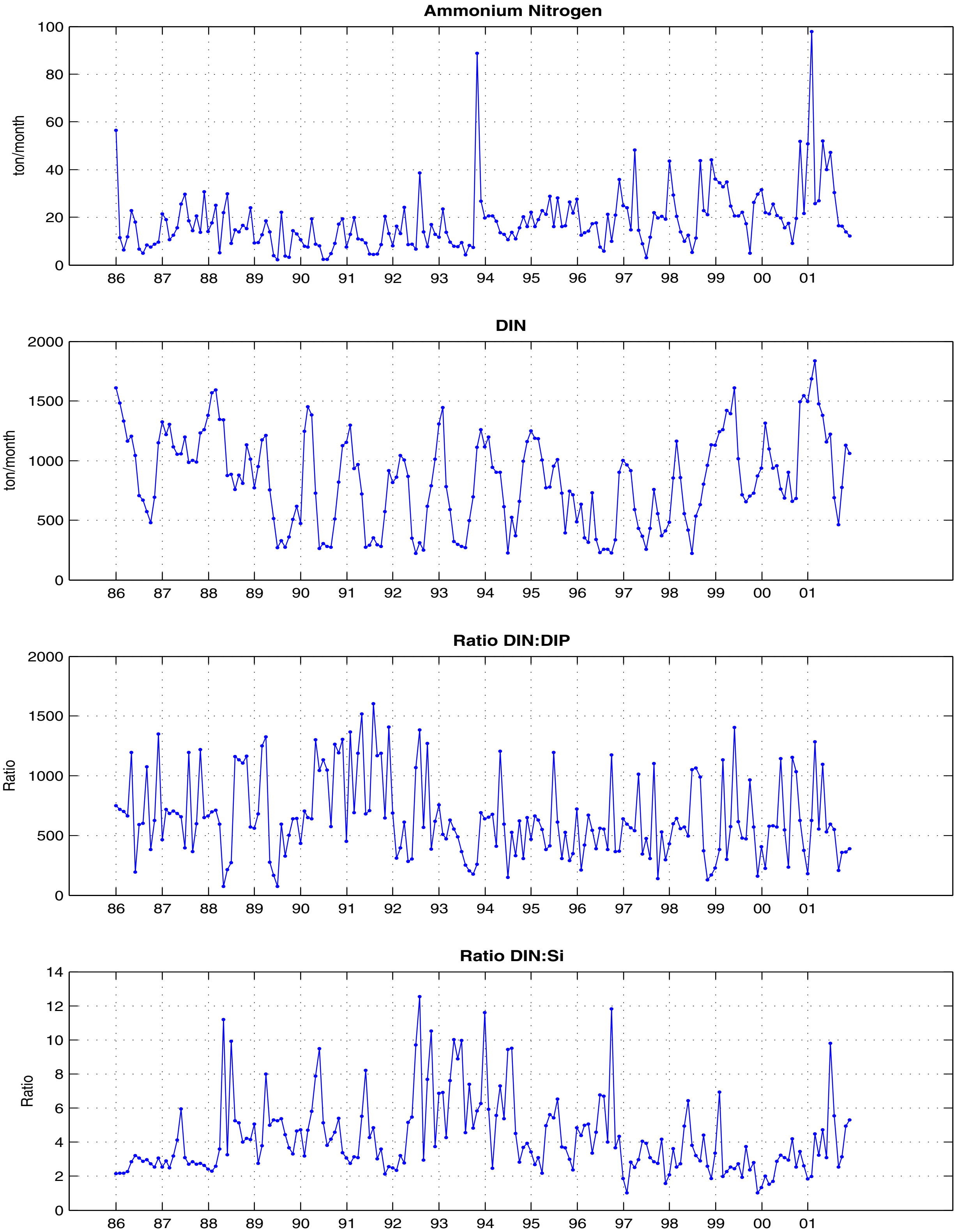

Figure 12. Transport of nutrients in river Göta älv calculated from monthly nutrients measurements (Swedish University of Agricultural Sciences) and daily measurements of water transport (SMHI). Unit is tonnes per month. Ratios are molar.

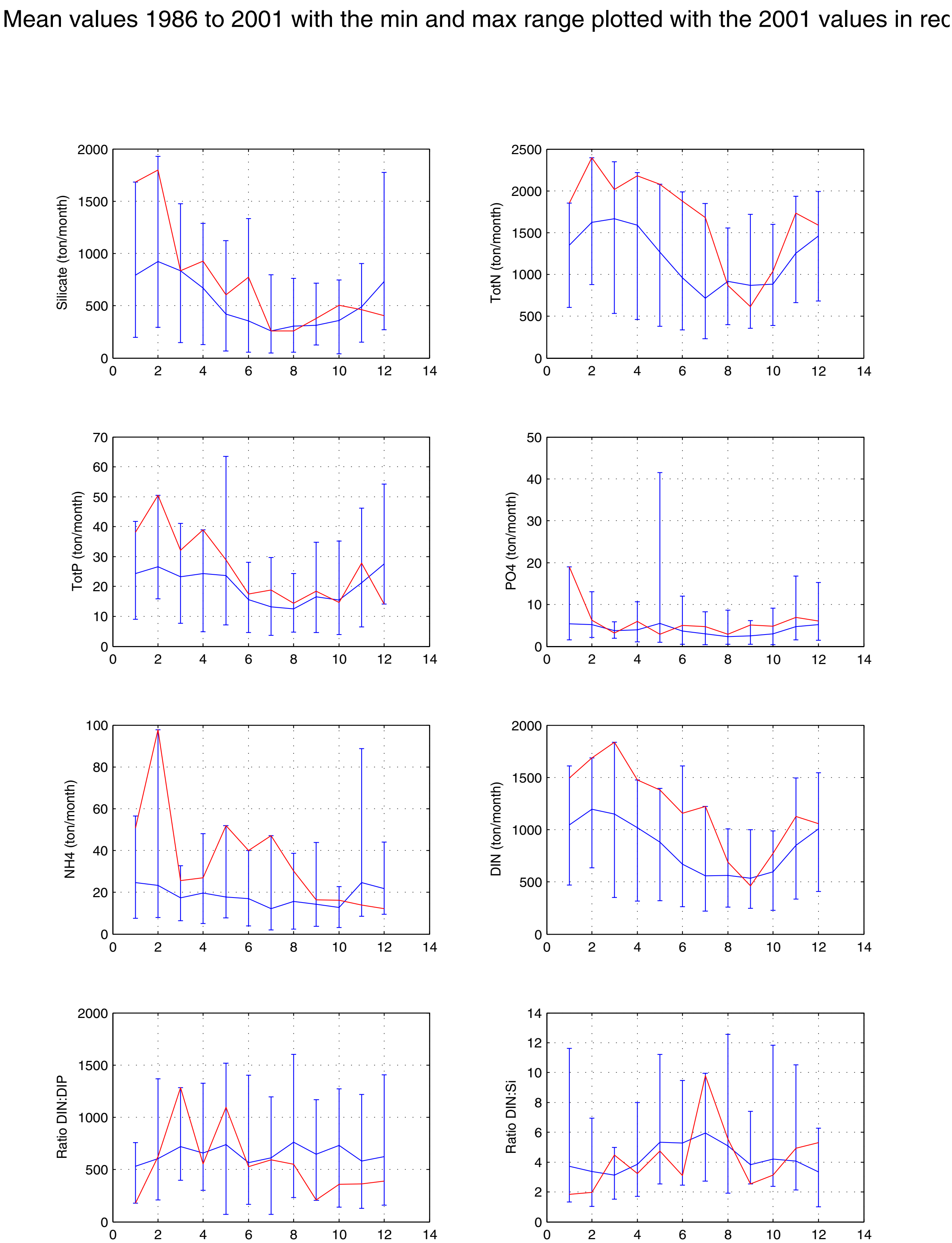

Figure 13. Transport of nutrients in river Göta älv and molar ratios. Blue line shows monthly means (1986-2002) with range. Red line shows data for year 2001. Source: monthly nutrients measurements (Swedish University of Agricultural Sciences) and daily measurements of water transport (SMHI).

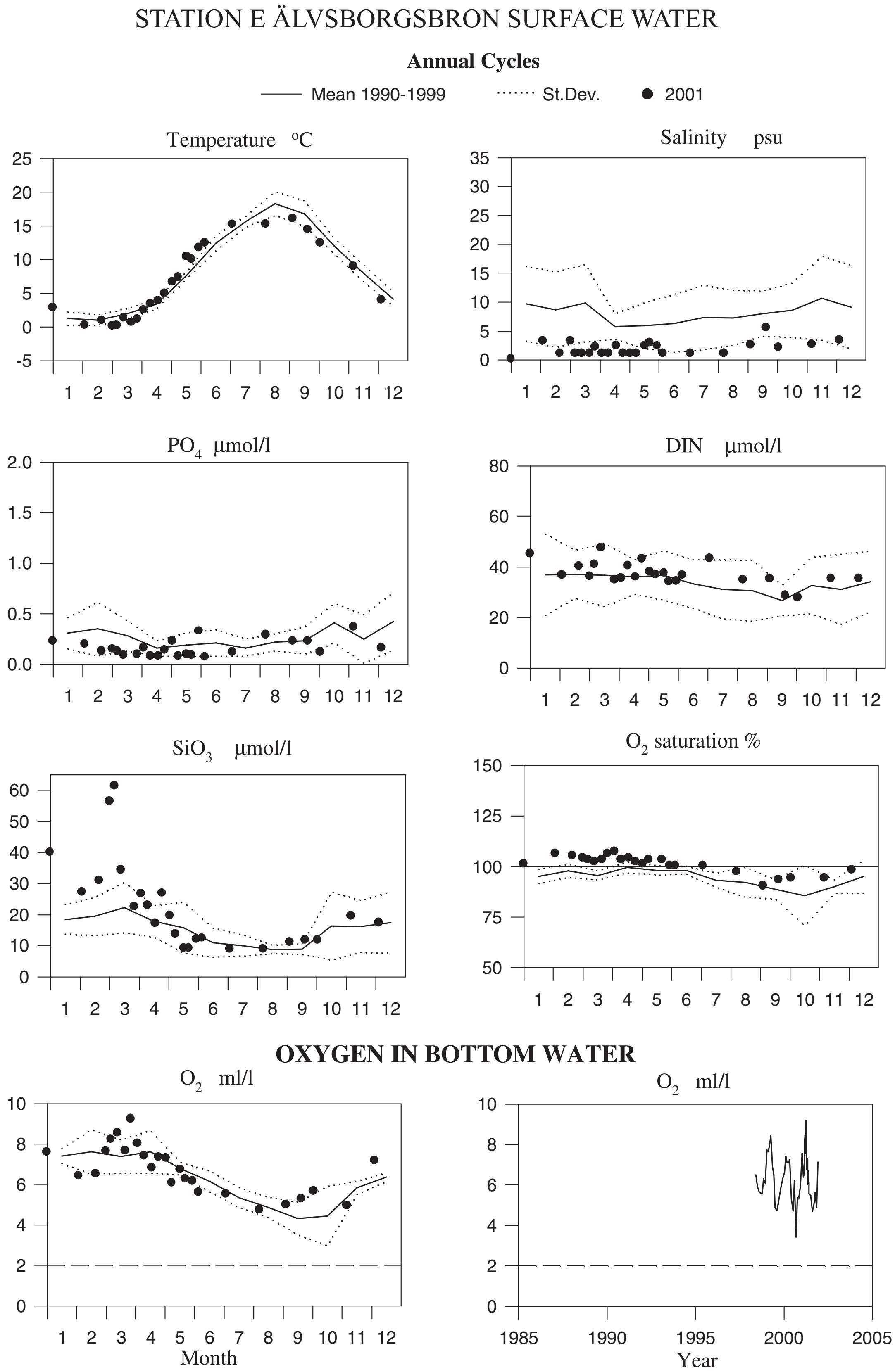
STATION E ÄLVSBORGSBRON SURFACE WATER
Annual Cycles
Mean 1990-1999
St.Dev.
2001
Temperature °C
Salinity psu
PO4 µmol/l
DIN µmol/l
SiO3 µmol/l
O2 saturation %
OXYGEN IN BOTTOM WATER
O2 ml/l
O2 ml/l
Month
Year

Figure 14.

STATION DANAFJORD SURFACE WATER

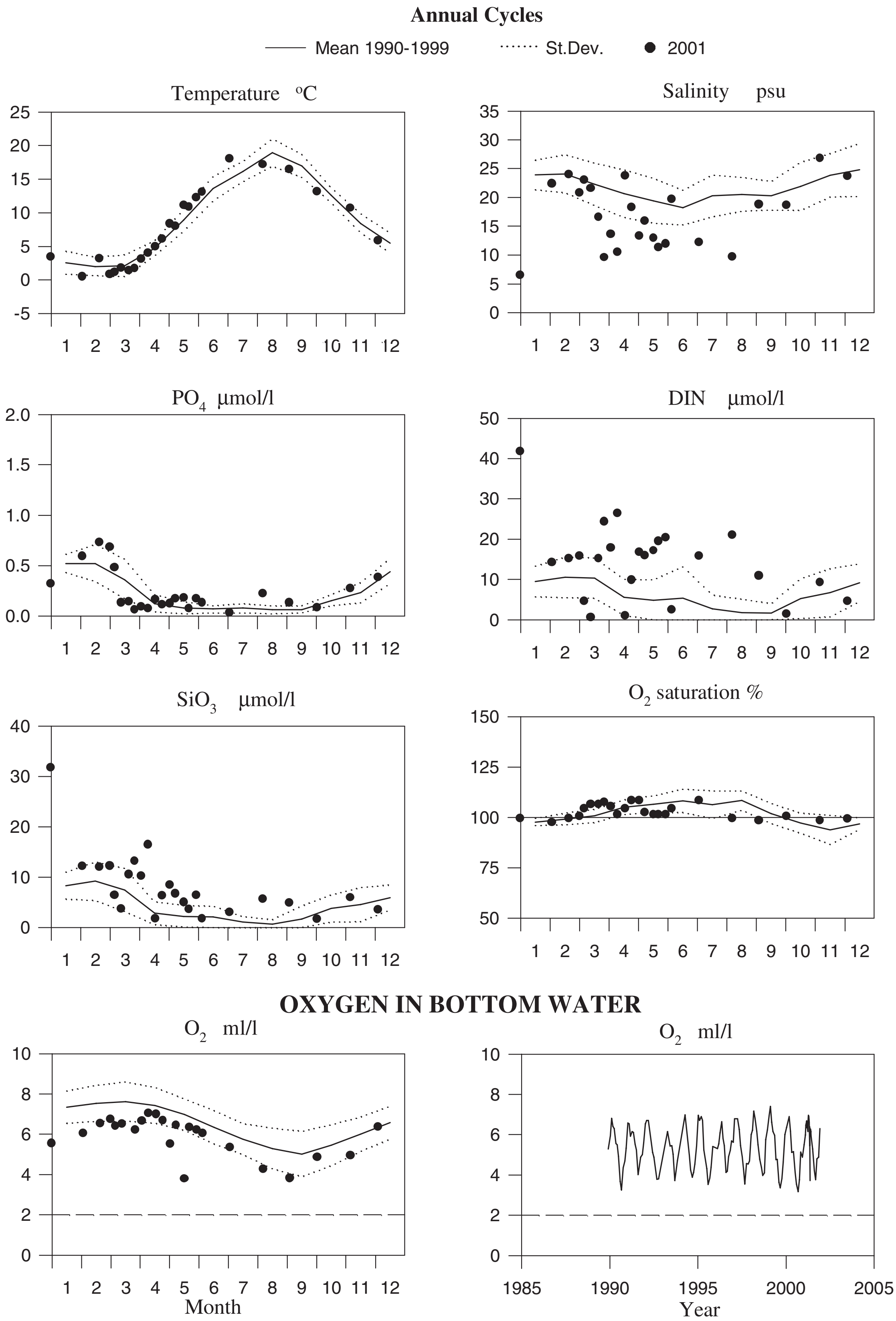

Figure 15.

STATION RÄVUNGARNA SURFACE WATER

Annual Cycles

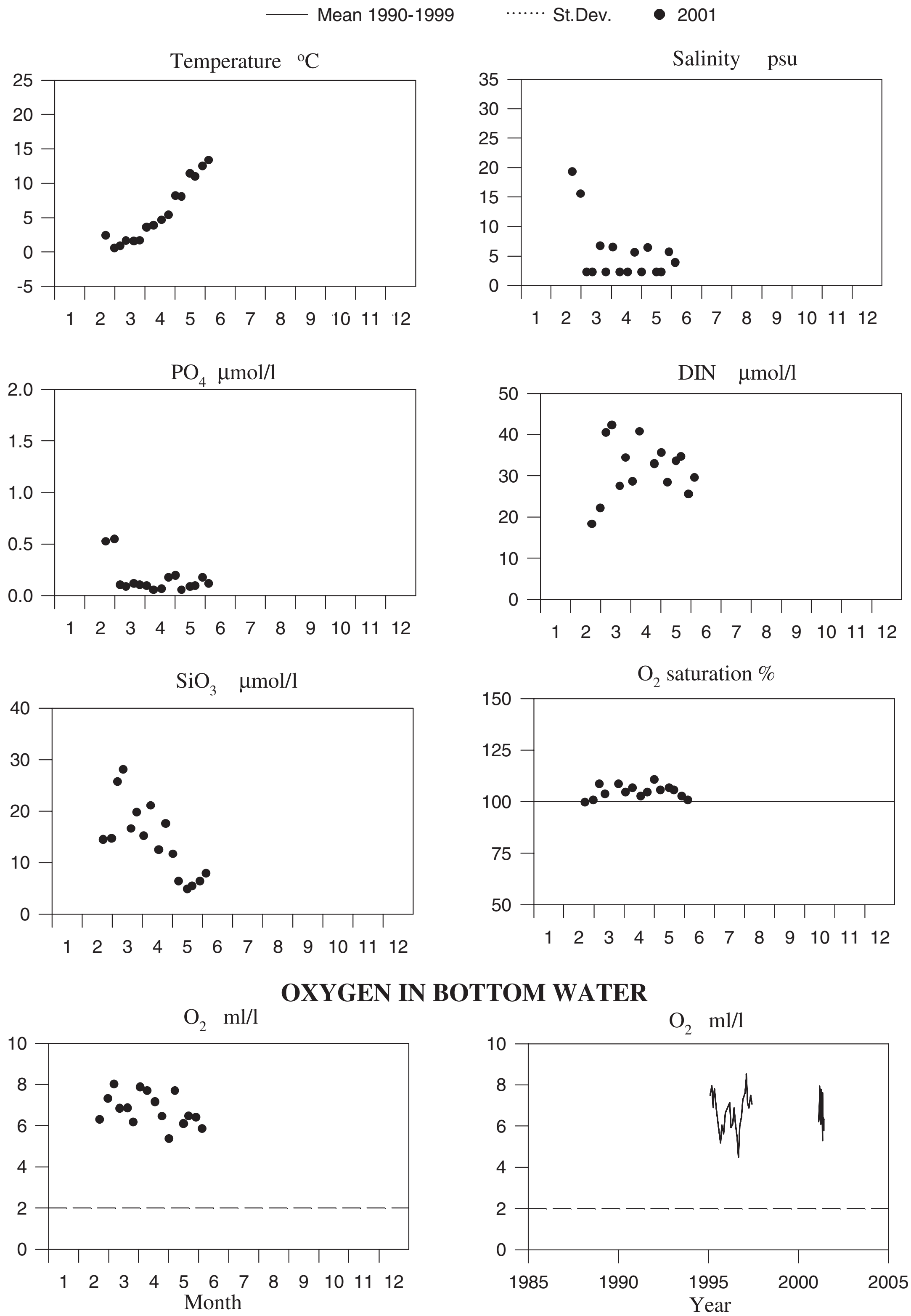

Figure 16. Long term averages are not presented because the time series is short.

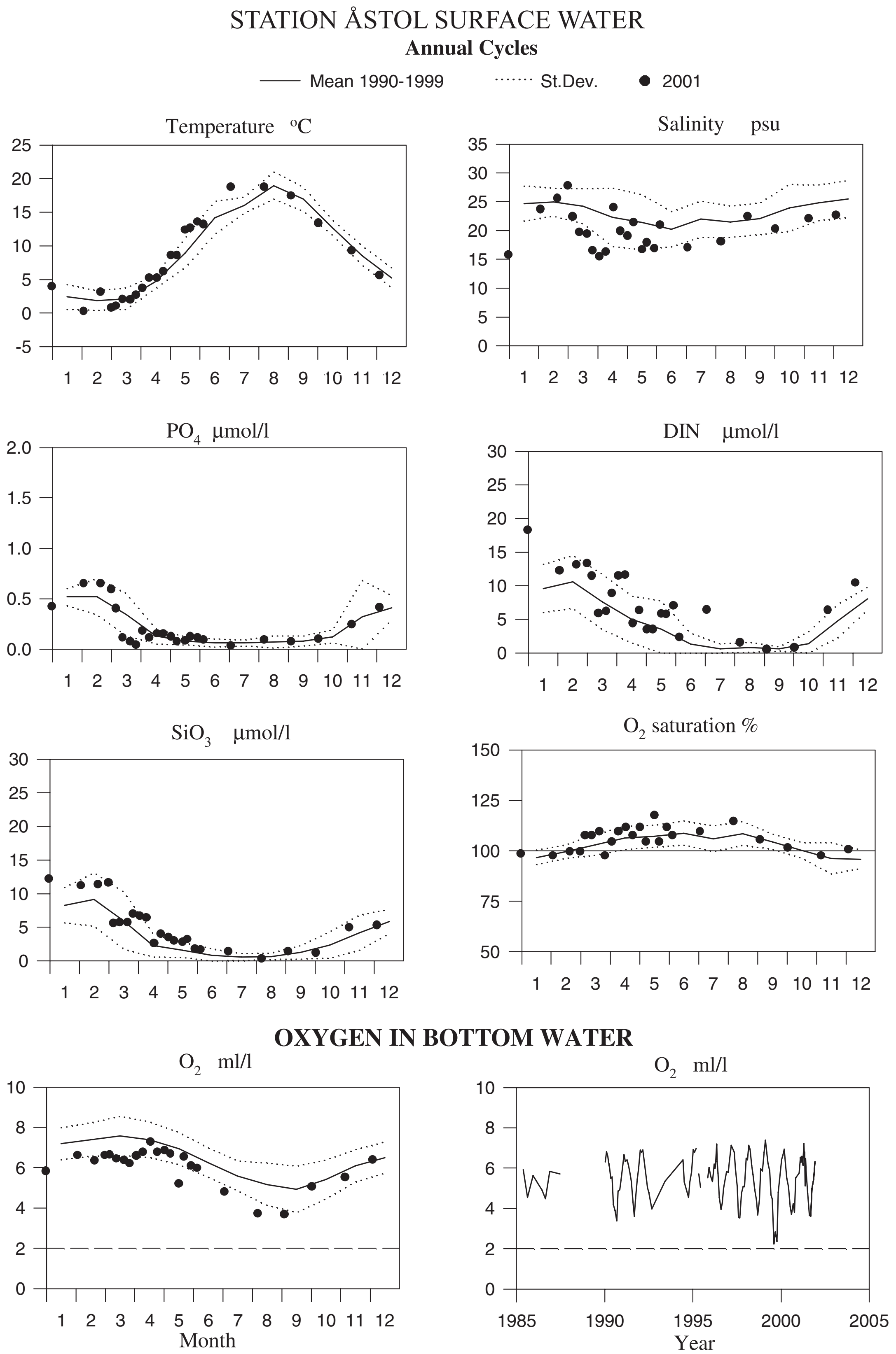
STATION ÅSTOL SURFACE WATER
Annual Cycles
Mean 1990-1999
St.Dev.
2001
Temperature °C
Salinity psu
PO4 µmol/l
DIN µmol/l
SiO3 µmol/l
O2 saturation %
OXYGEN IN BOTTOM WATER
O2 ml/l
Month
O2 ml/l
Year
1985
1990
1995
2000
2005

Figure 17.

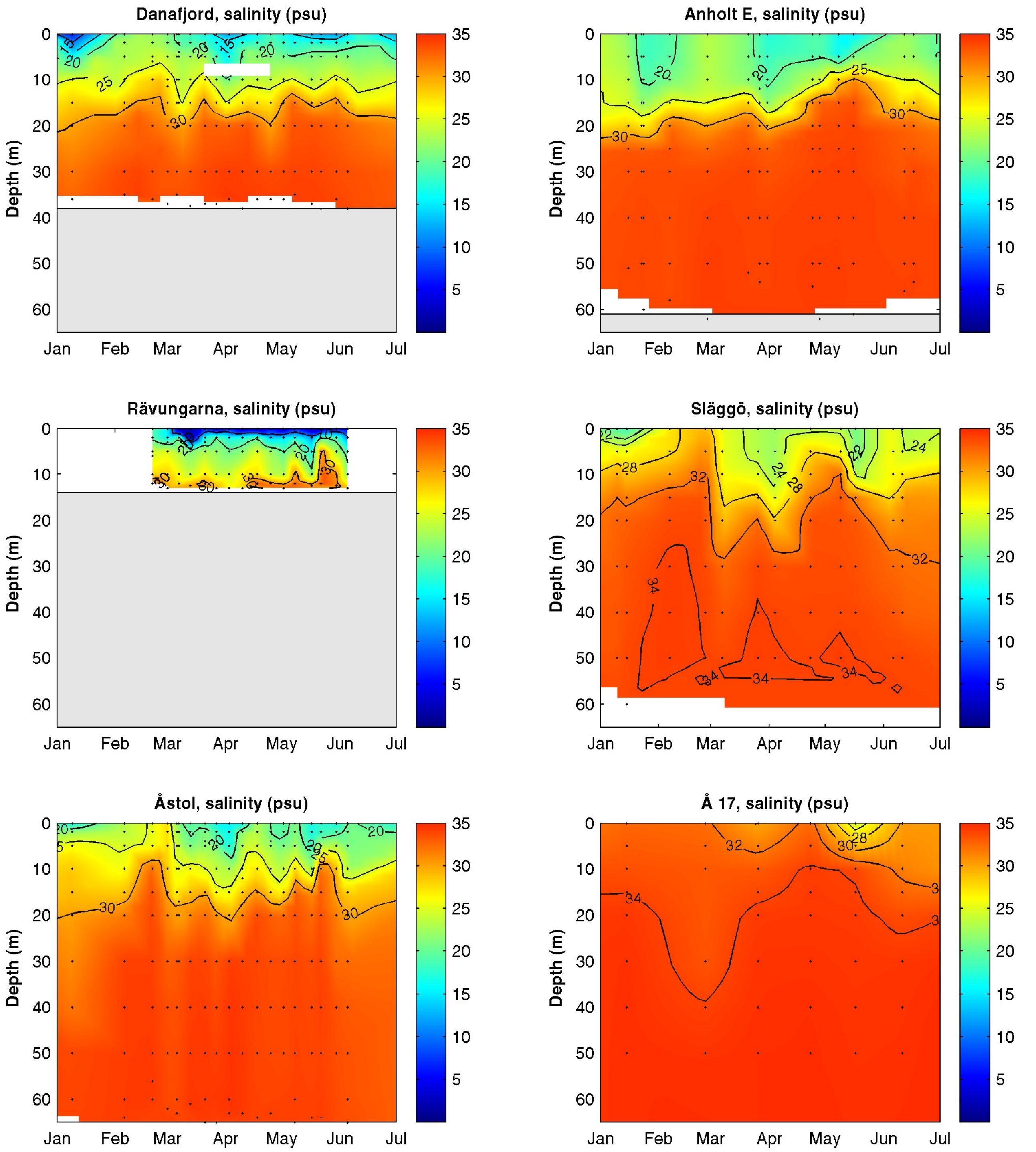

Figure 18. Salinity at selected locations in the Kattegatt-Skagerrak during the first six months of 2001.

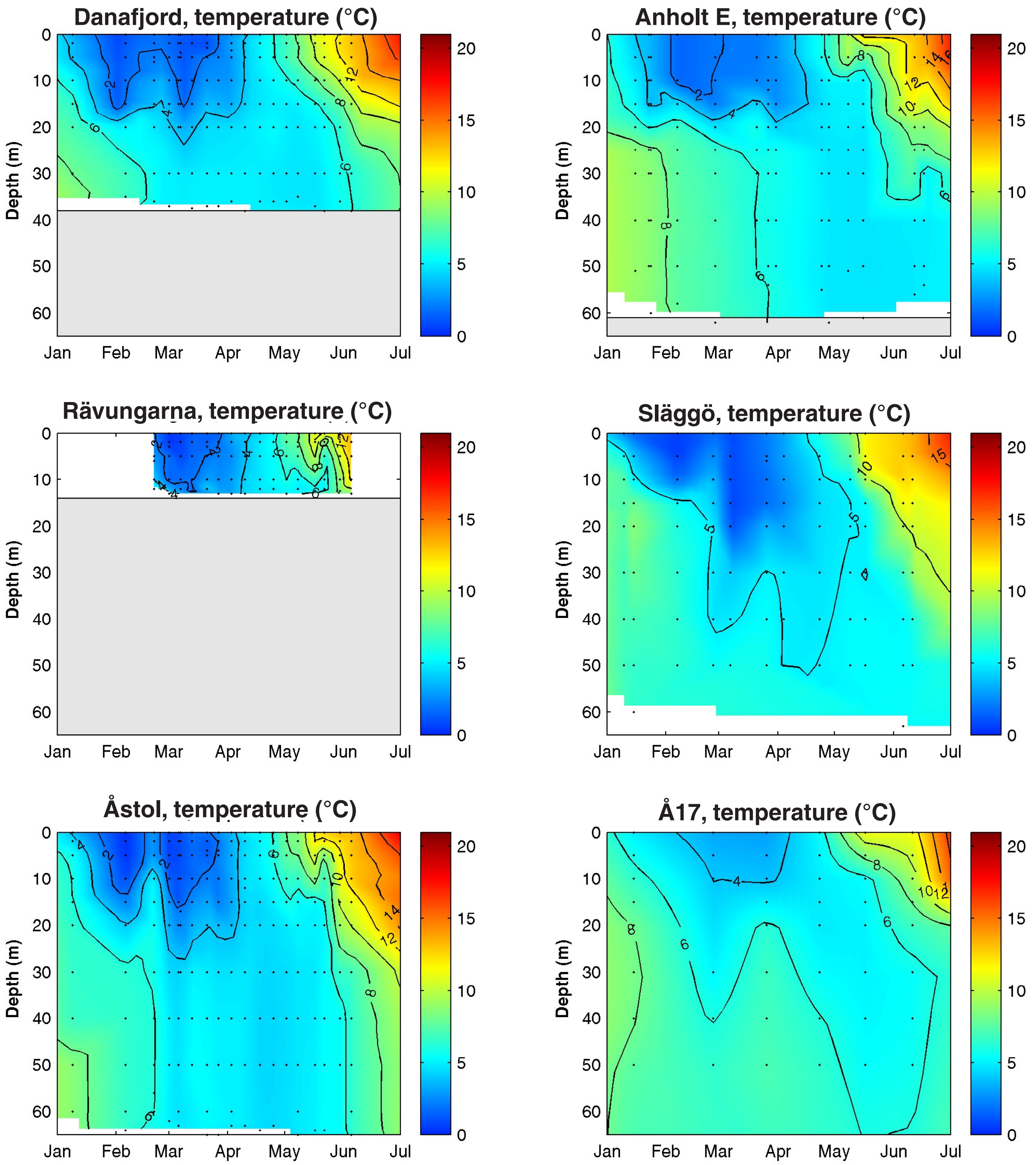

Figure 19.. Temperature at selected locations in the Kattegatt-Skagerrak during the first six months of 2001.

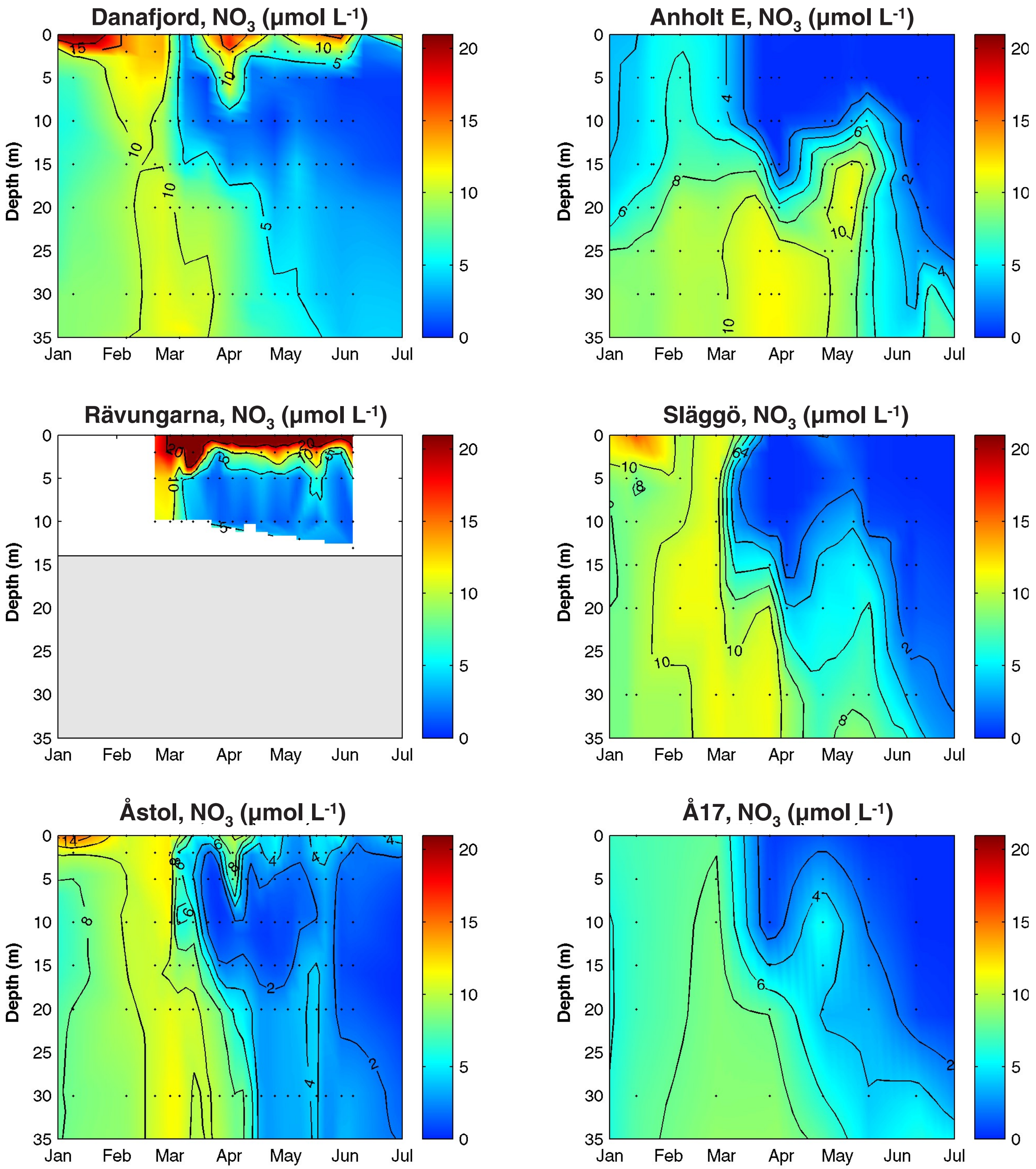

Figure 20. Nitrate concentrations at selected locations in the Kattegatt-Skagerrak during the first six months of 2001.

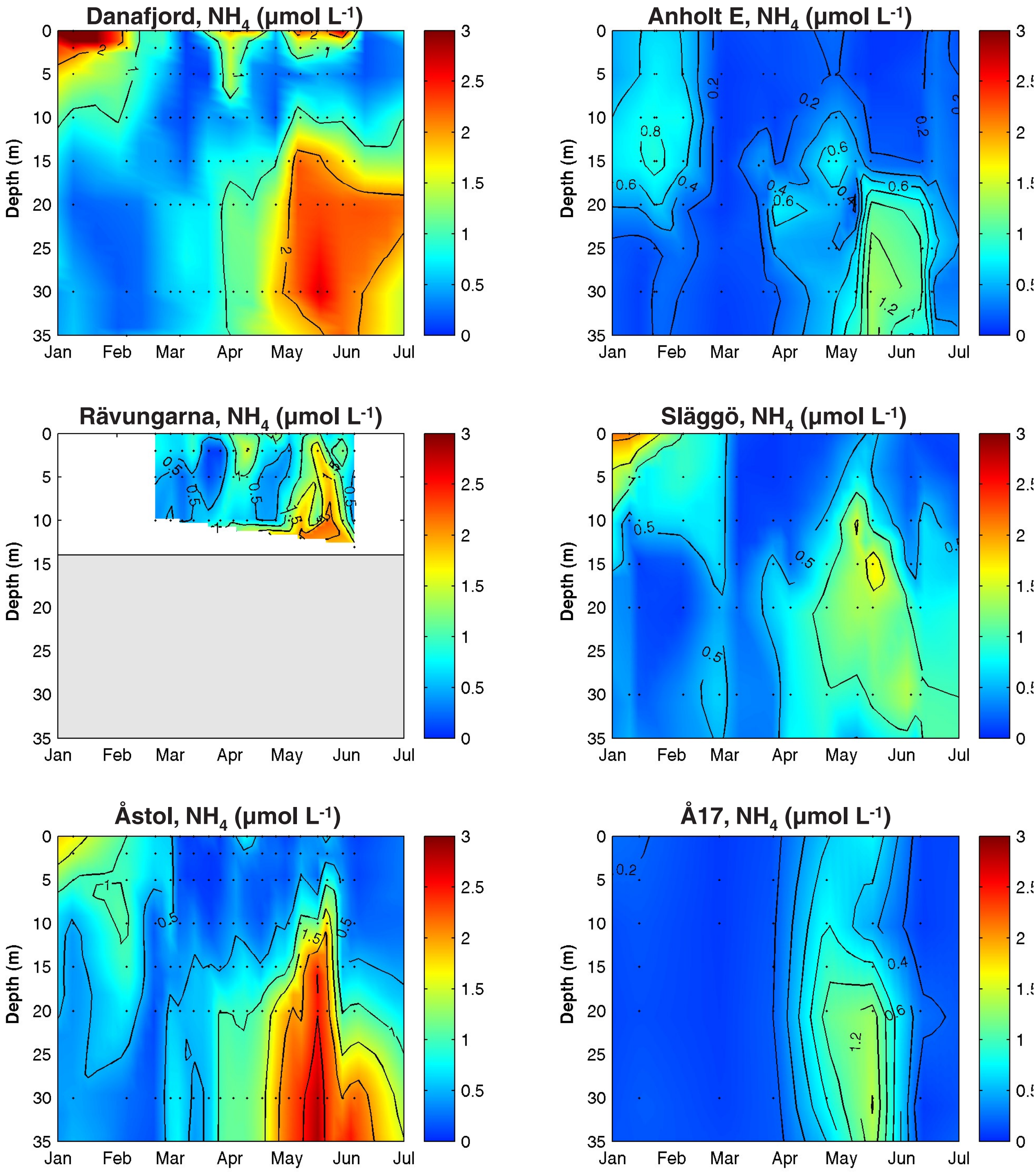

Figure 21. Ammonium concentrations at selected locations in the Kattegatt-Skagerrak during the first six months of 2001.

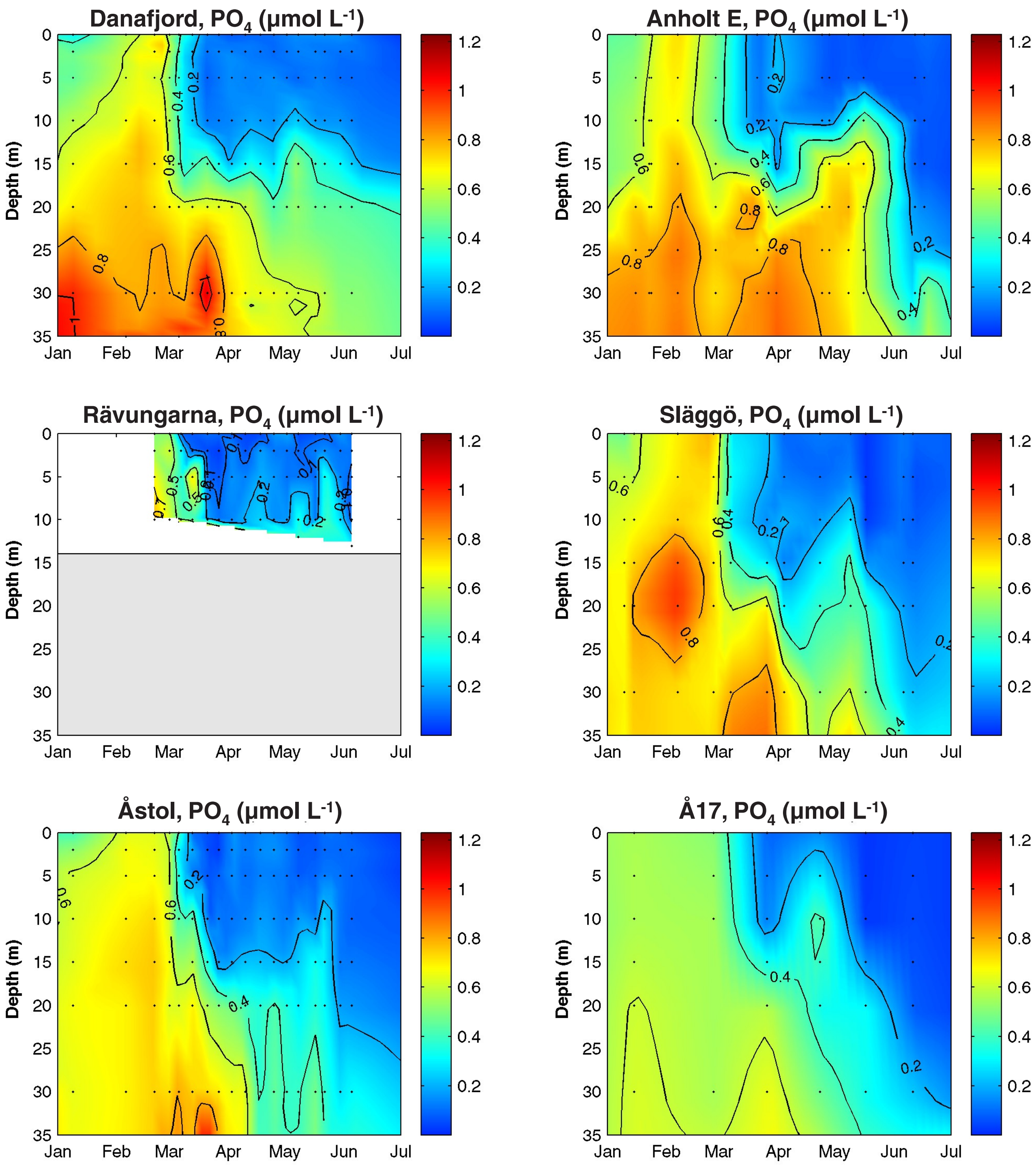

Figure 22. Phosphate concentrations at selected locations in the Kattegatt-Skagerrak during the first six months of 2001.

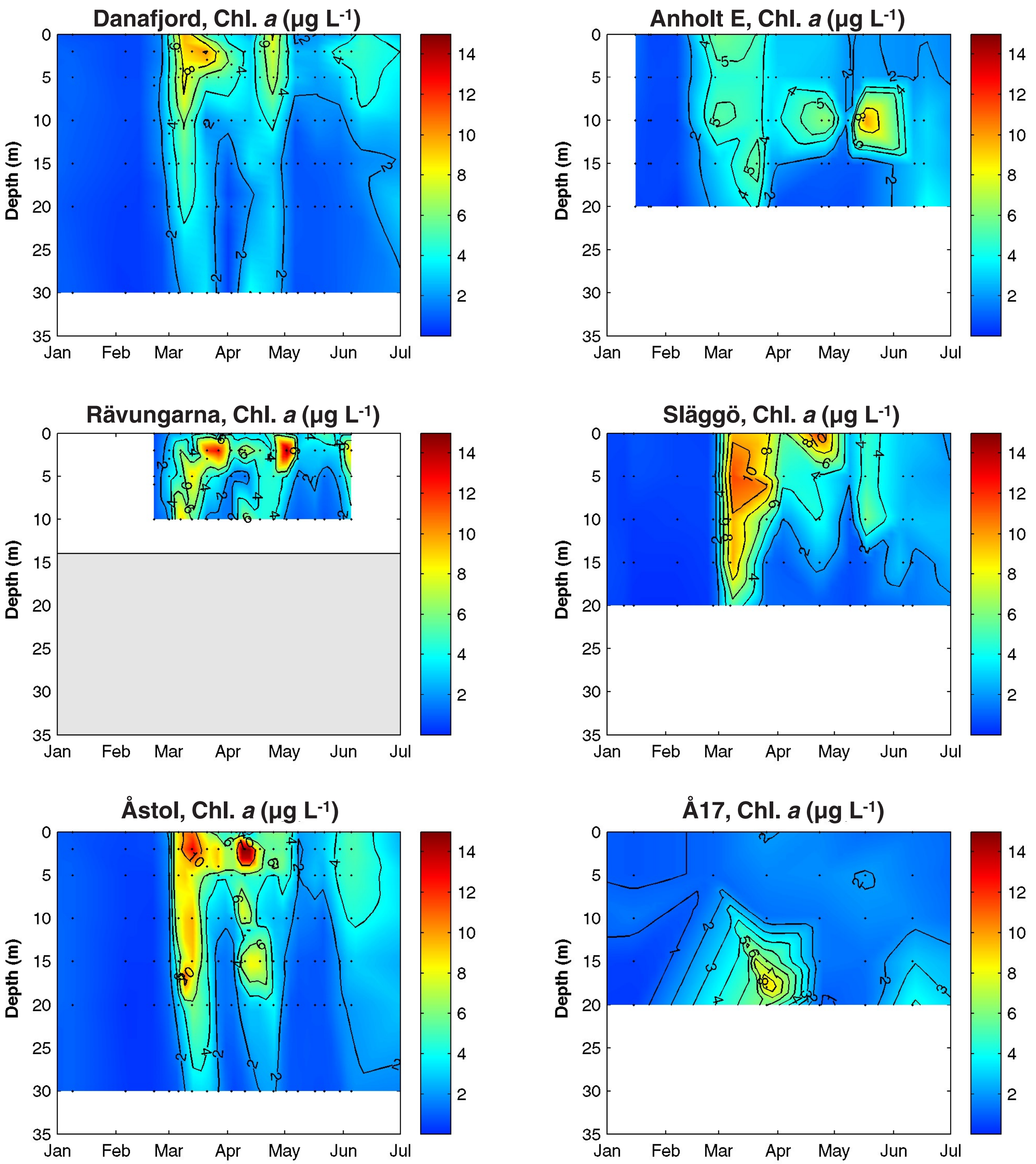

Figure 23. Phytoplankton biomass expressed as chlorophyll *a* concentrations at selected locations in the Kattegat-Skagerrak during the first six months of 2001.

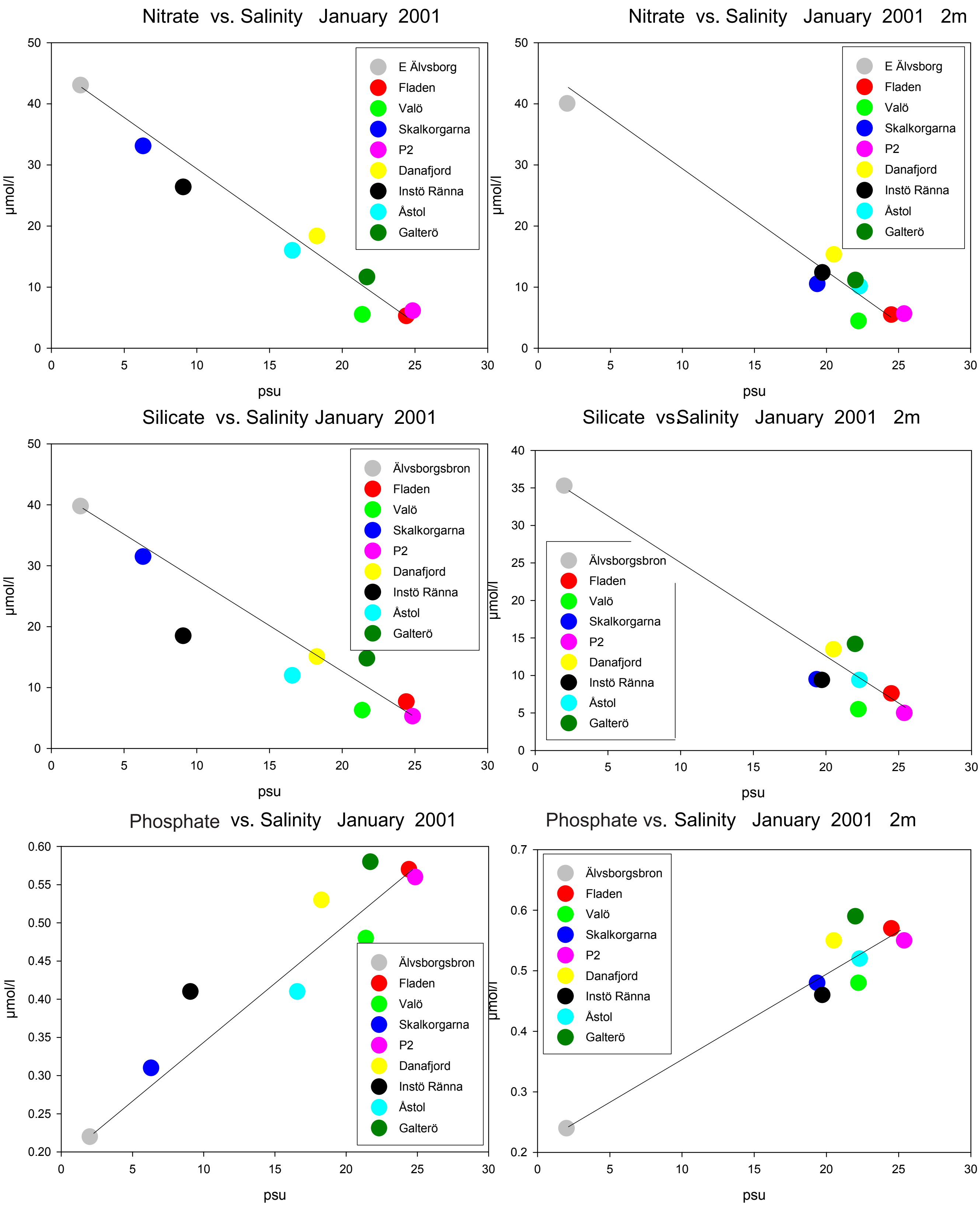

Figure 24. Nutrient concentrations versus salinity at the surface and 2 m depth from selected stations in the Kattegat/ Skagerrak in January 2001.

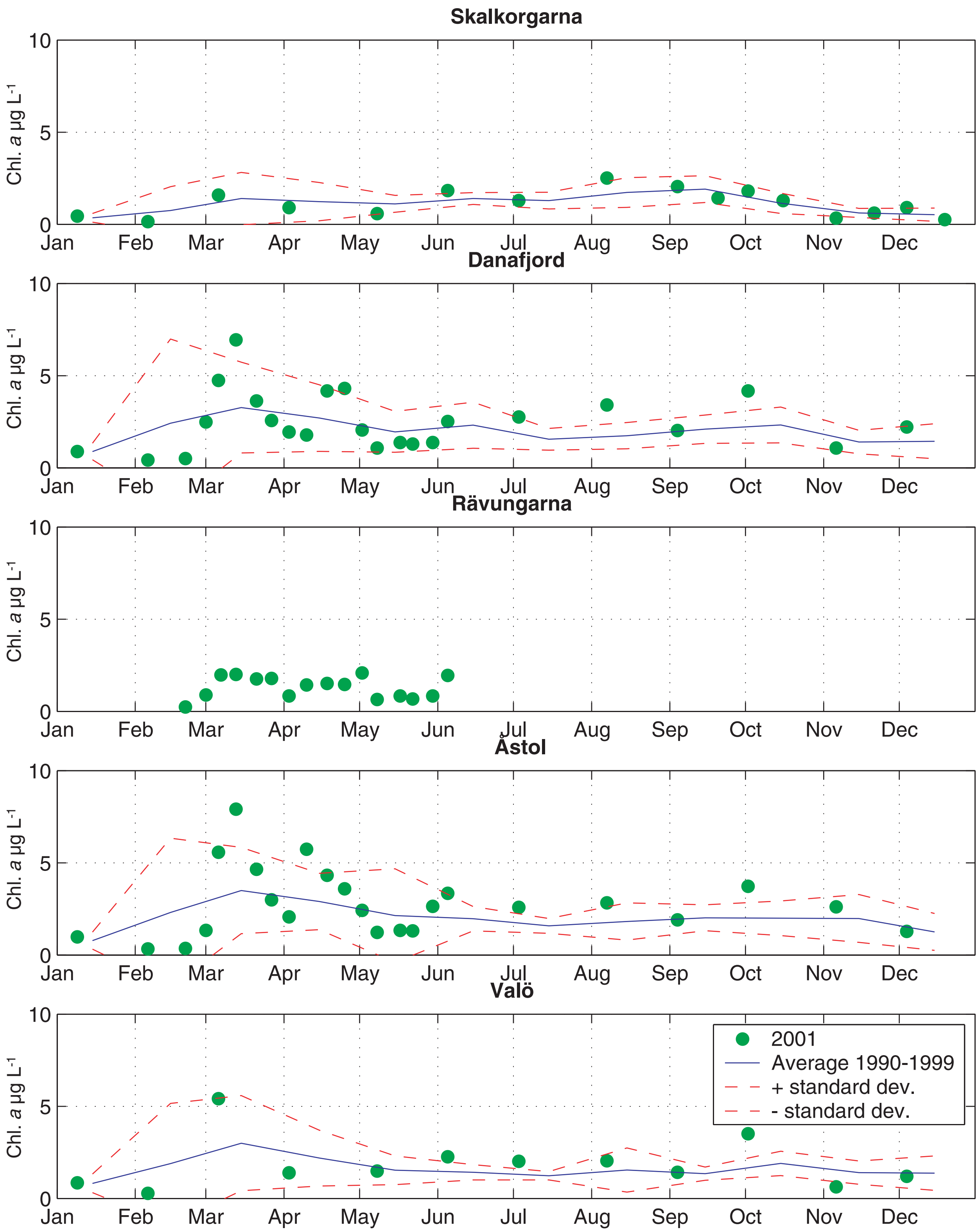

Figure 25. Chlorophyll a concentrations integrated 0-30 m. The depth-averaged concentration is shown..

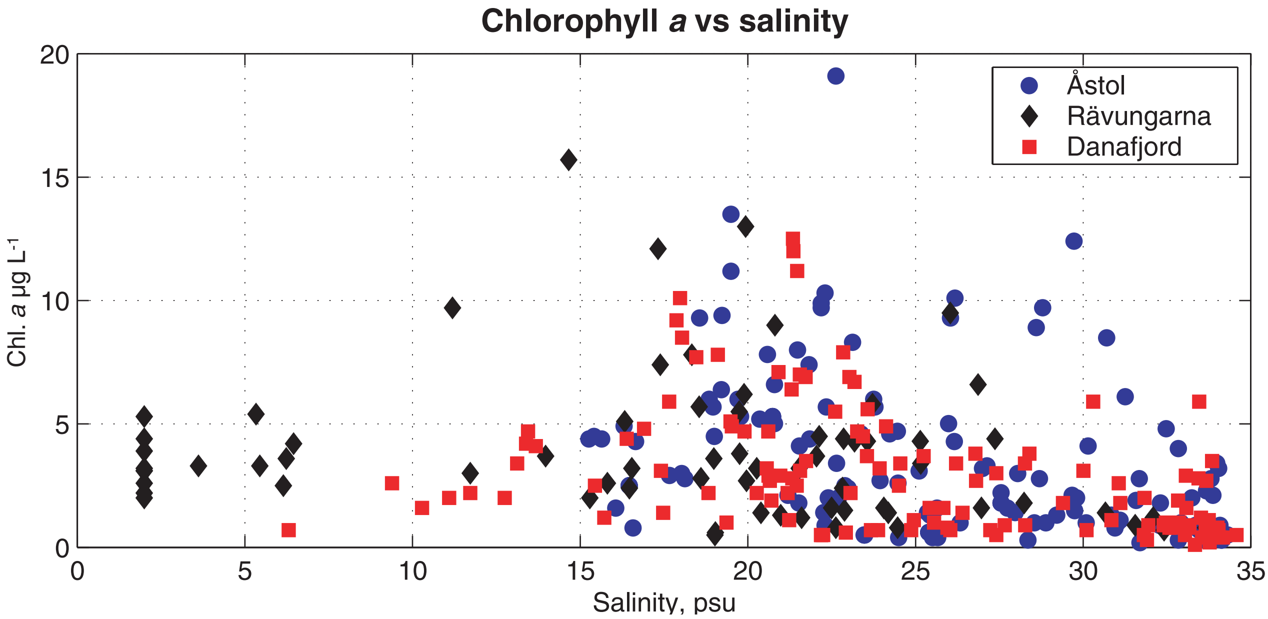

Figure 26. Chlorophyll a concentrations vs salitity at three stations in the area close to the mouth of the Göta river. Data from 1 January to 30 June 2001, depths 0-30 m.

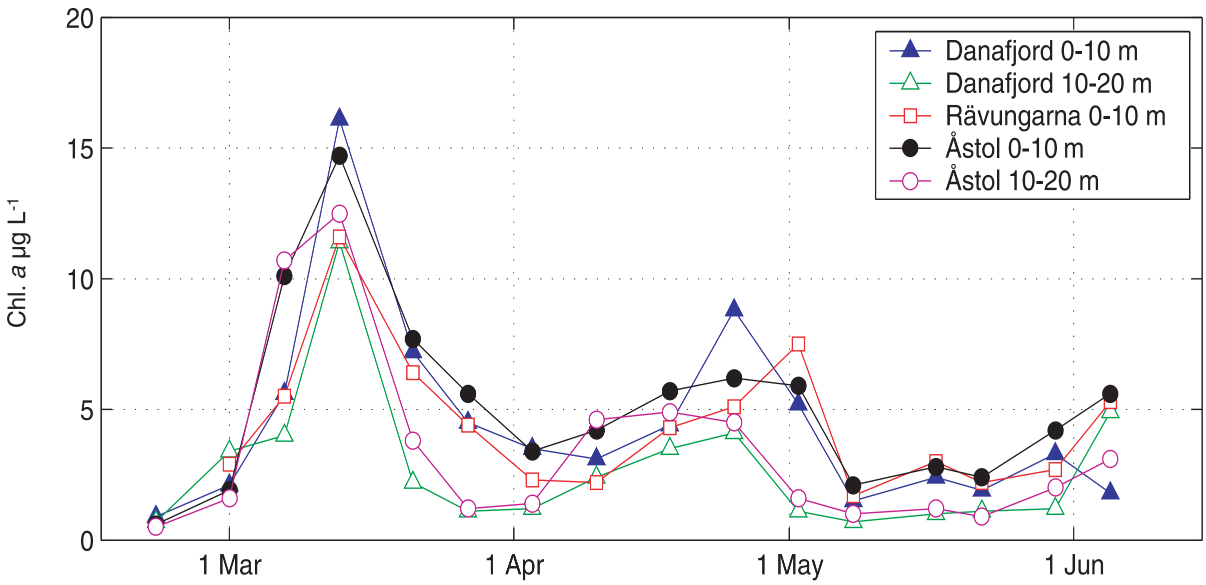

Figure 27. Chlorophyll *a* concentrations from tube sampling 0-10 m.and 10-20 m.

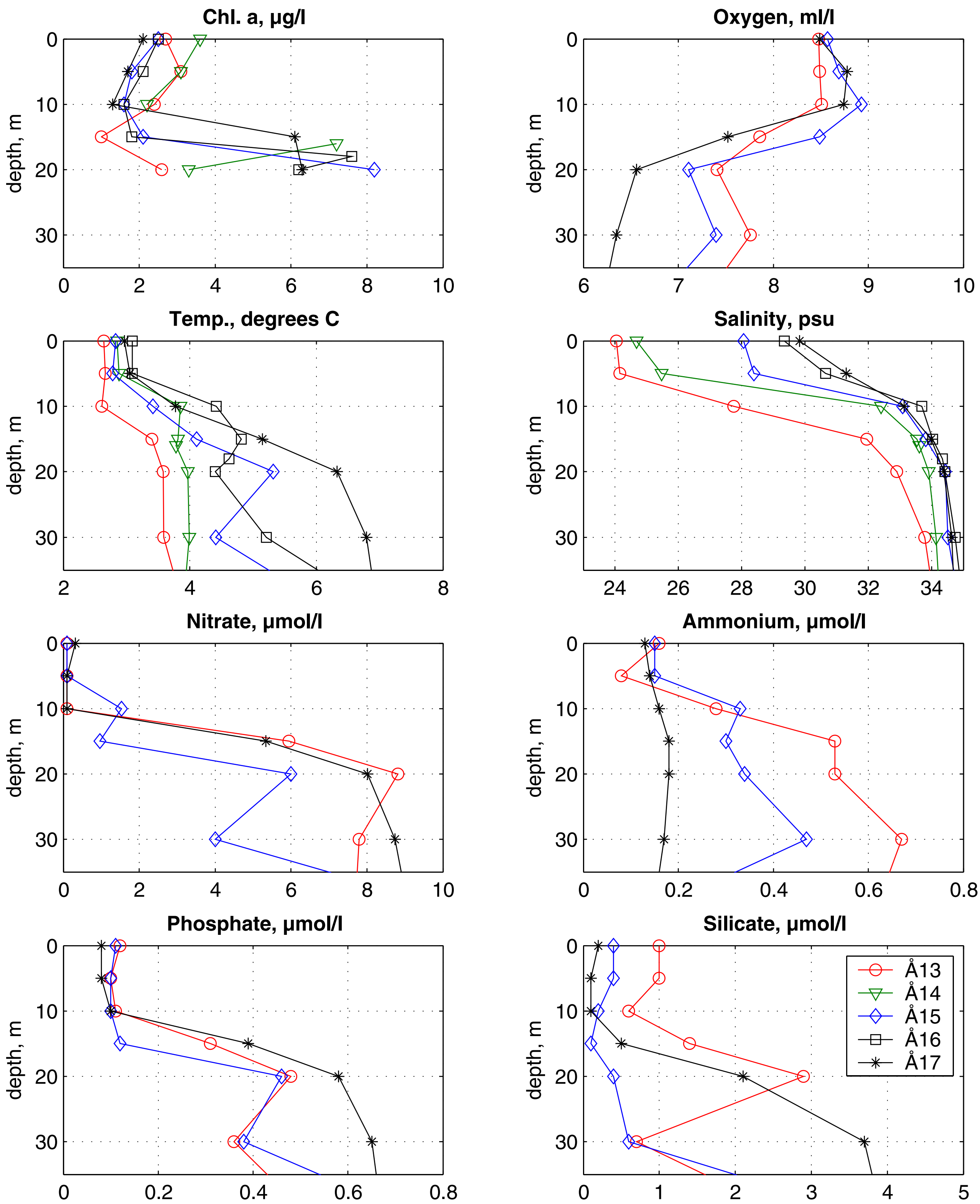

Figure 28. The graphs show conditions during the end of the *Chattonella*-bloom at five stations along the Å-transect which is indicated on the map in fig. 2.

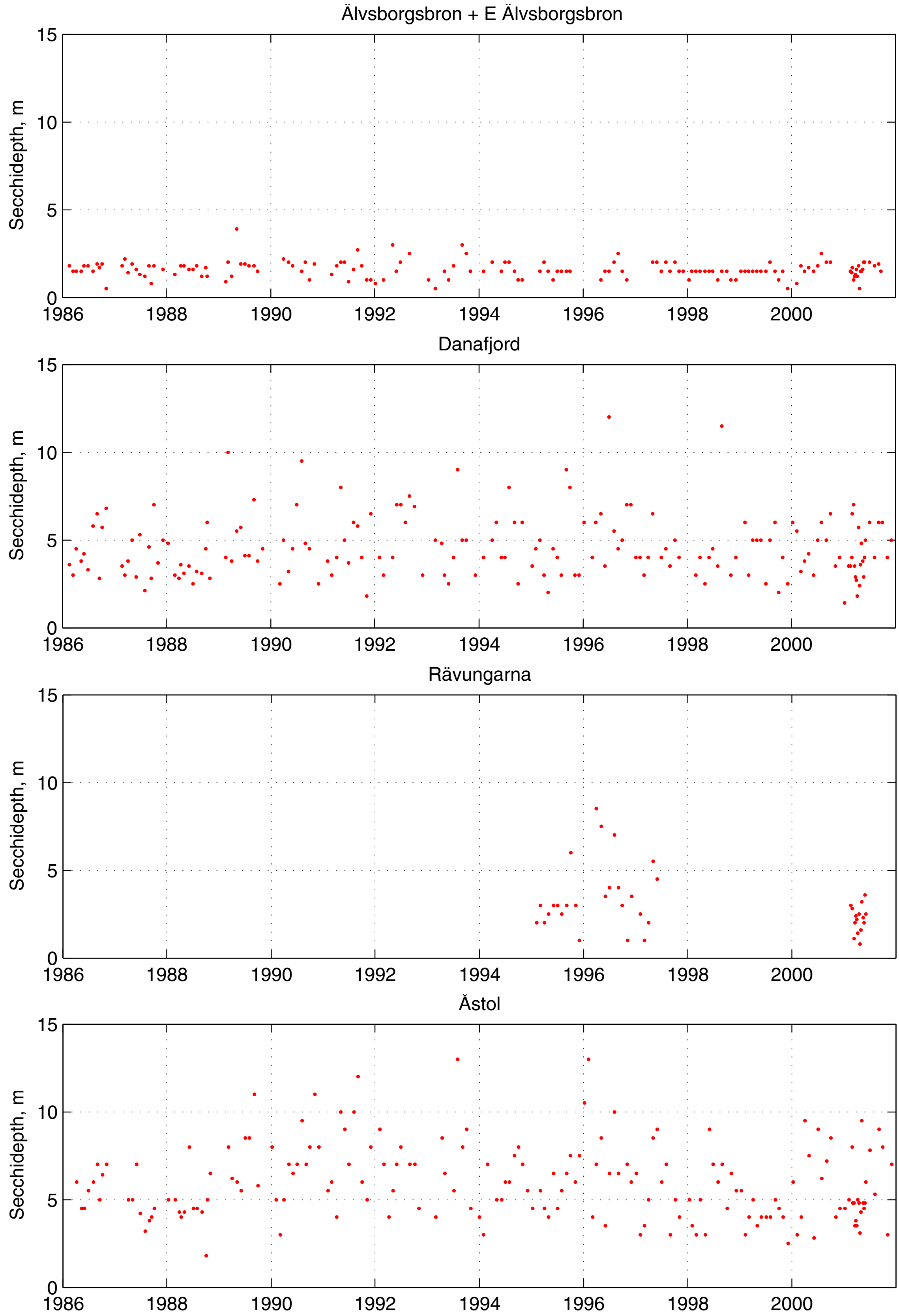

Figure 29. Secchi depth at four locations close to the mouth of the river Göta älv.

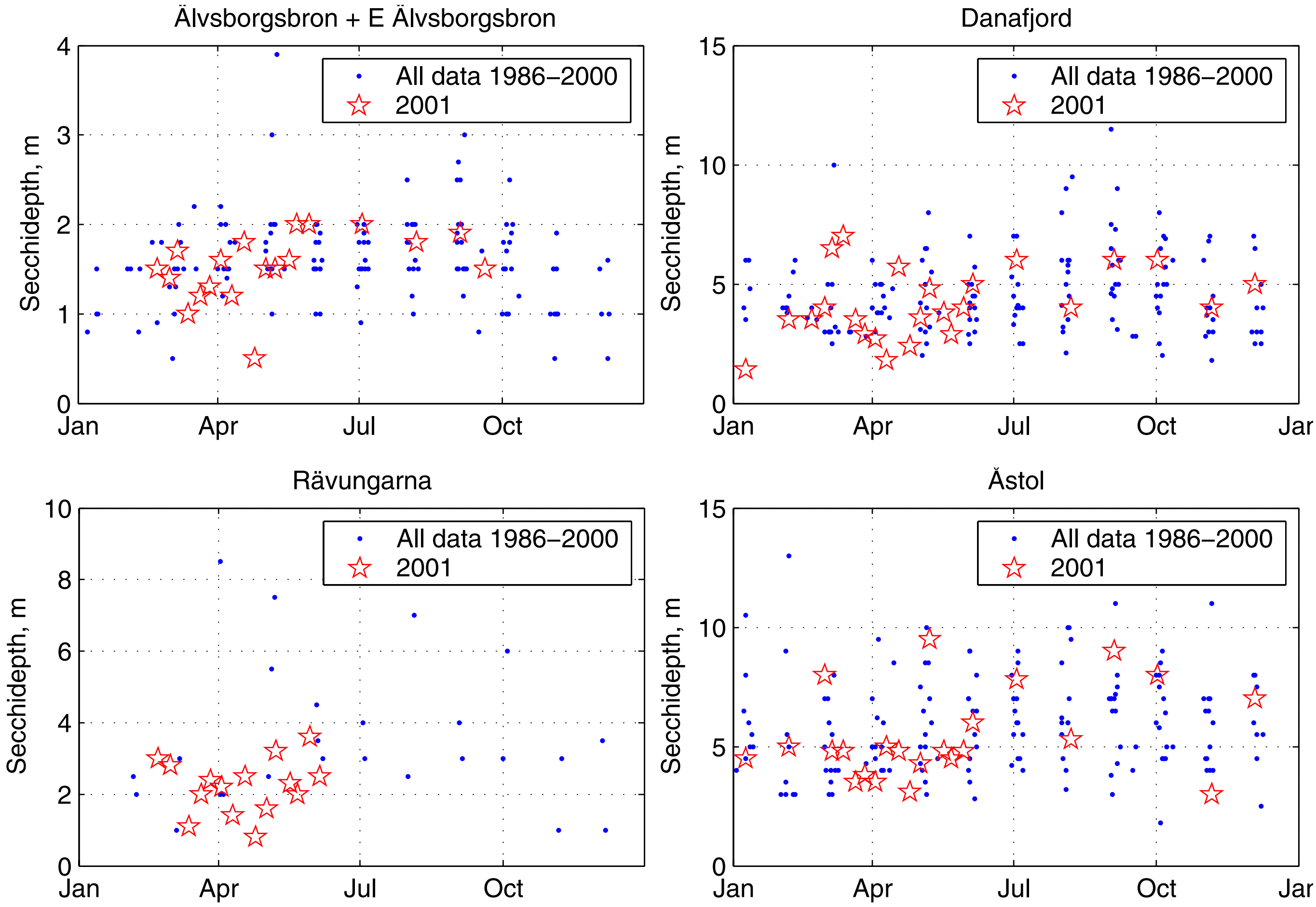

Figure 30. Secchi depth at four locations close to the mouth of the river Göta älv. The data is the same as presented in Fig. x.

Primary production

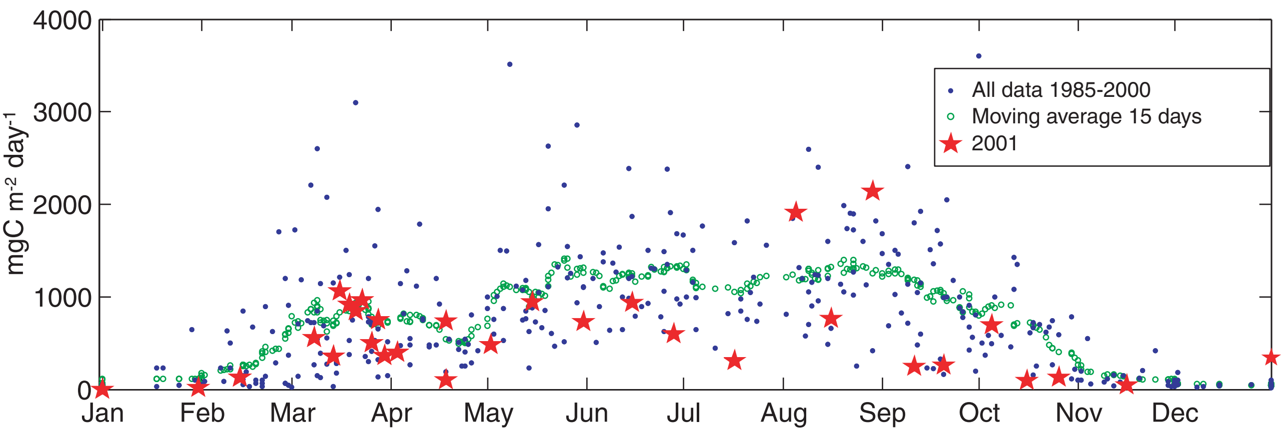

Figure 31. Primary production has been measured using in situ incubations at the mouth of the Gullmar fjord since 1985. Data courtesy of Odd Lindahl, Kristineberg, Marine Research Staion, who has performed the measurements on commission from the Gullmaren monitoring programme.

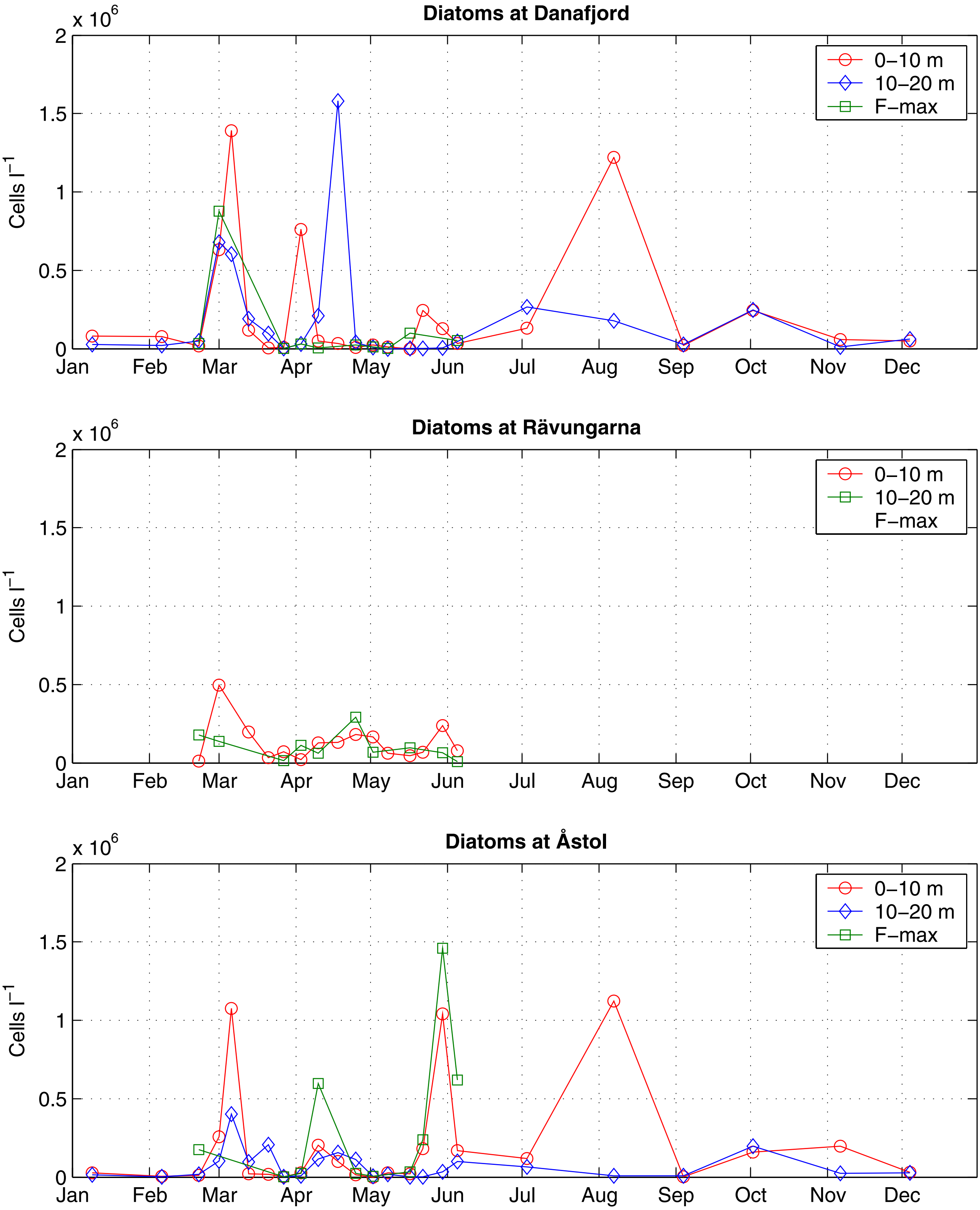
Diatoms at Danafjord
x 10^6
Cells l^-1
0
0.5
1
1.5
2
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max
Diatoms at Rävungarna
x 10^6
Cells l^-1
0–10 m
10–20 m
F–max
Diatoms at Åstol
x 10^6
Cells l^-1
0–10 m
10–20 m
F–max

Figure 32.

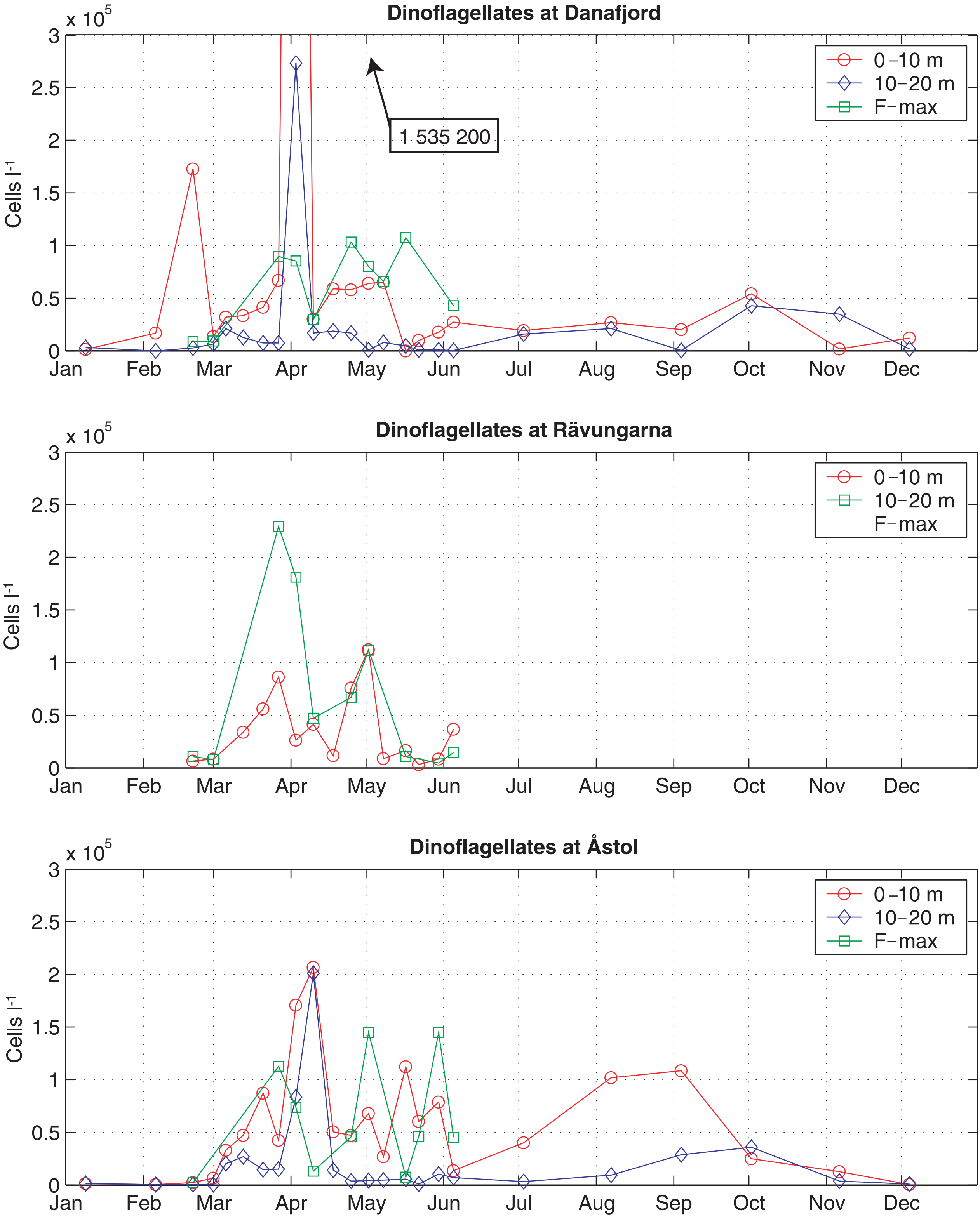
Dinoflagellates at Danafjord
x 10^5
Cells l^-1
3
2.5
2
1.5
1
0.5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1 535 200
0–10 m
10–20 m
F–max
Dinoflagellates at Rävungarna
x 10^5
Cells l^-1
0–10 m
10–20 m
F–max
Dinoflagellates at Åstol
x 10^5
Cells l^-1
0–10 m
10–20 m
F–max

Figure 33.

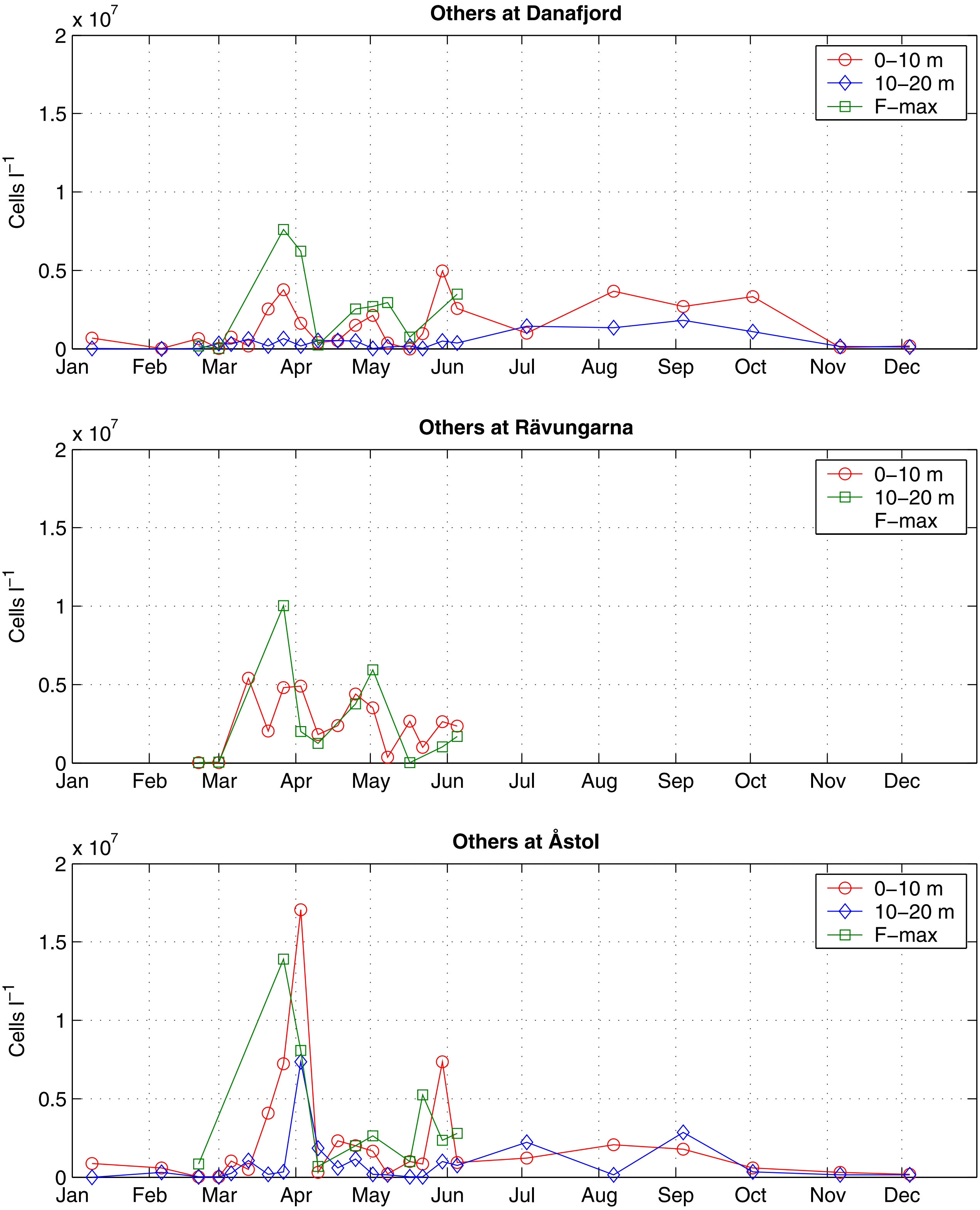

Figure 35. "Others" include all phytoplankton that do not belong to the Diatomophyceae (Diatoms) or Dinophyceae (Dinoflagellates).

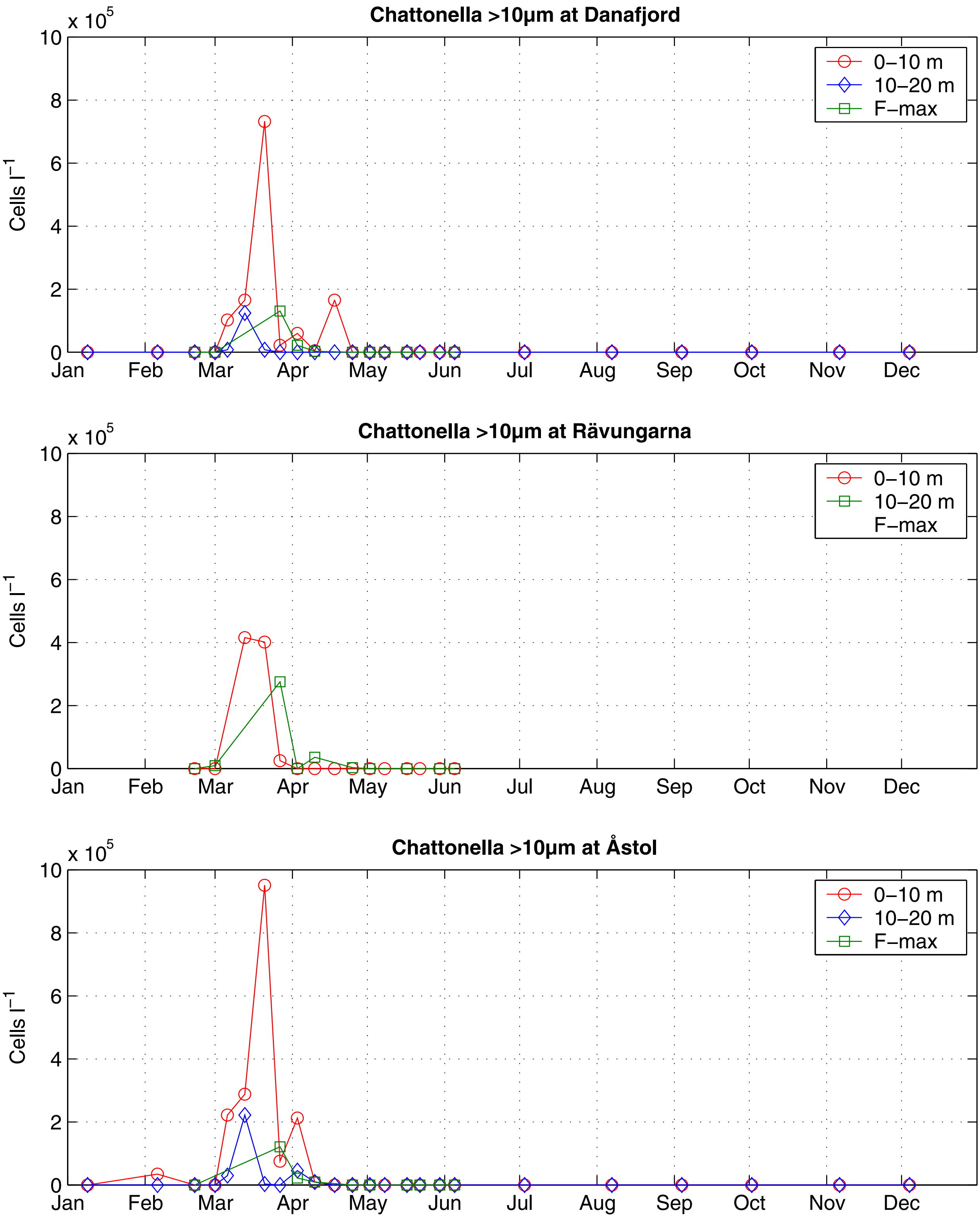
Chattonella >10µm at Danafjord
x 10^5
Cells l^-1
0
2
4
6
8
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max
Chattonella >10µm at Rävungarna
x 10^5
Cells l^-1
0
2
4
6
8
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max
Chattonella >10µm at Åstol
x 10^5
Cells l^-1
0
2
4
6
8
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max

Figure 36.

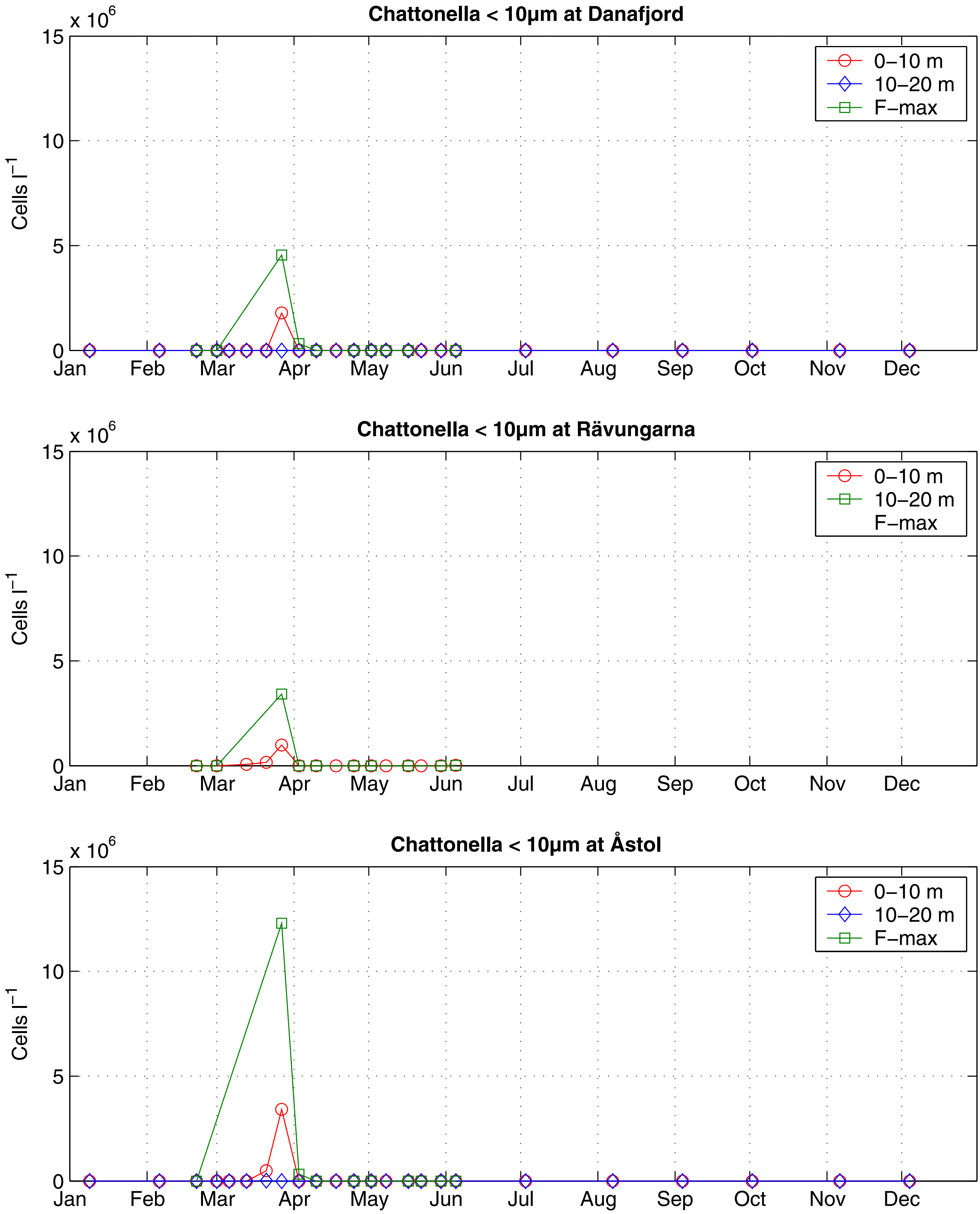
Chattonella < 10µm at Danafjord
x 10^6
Cells l^-1
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max
Chattonella < 10µm at Rävungarna
x 10^6
Cells l^-1
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max
Chattonella < 10µm at Åstol
x 10^6
Cells l^-1
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0–10 m
10–20 m
F–max

Figure 37.

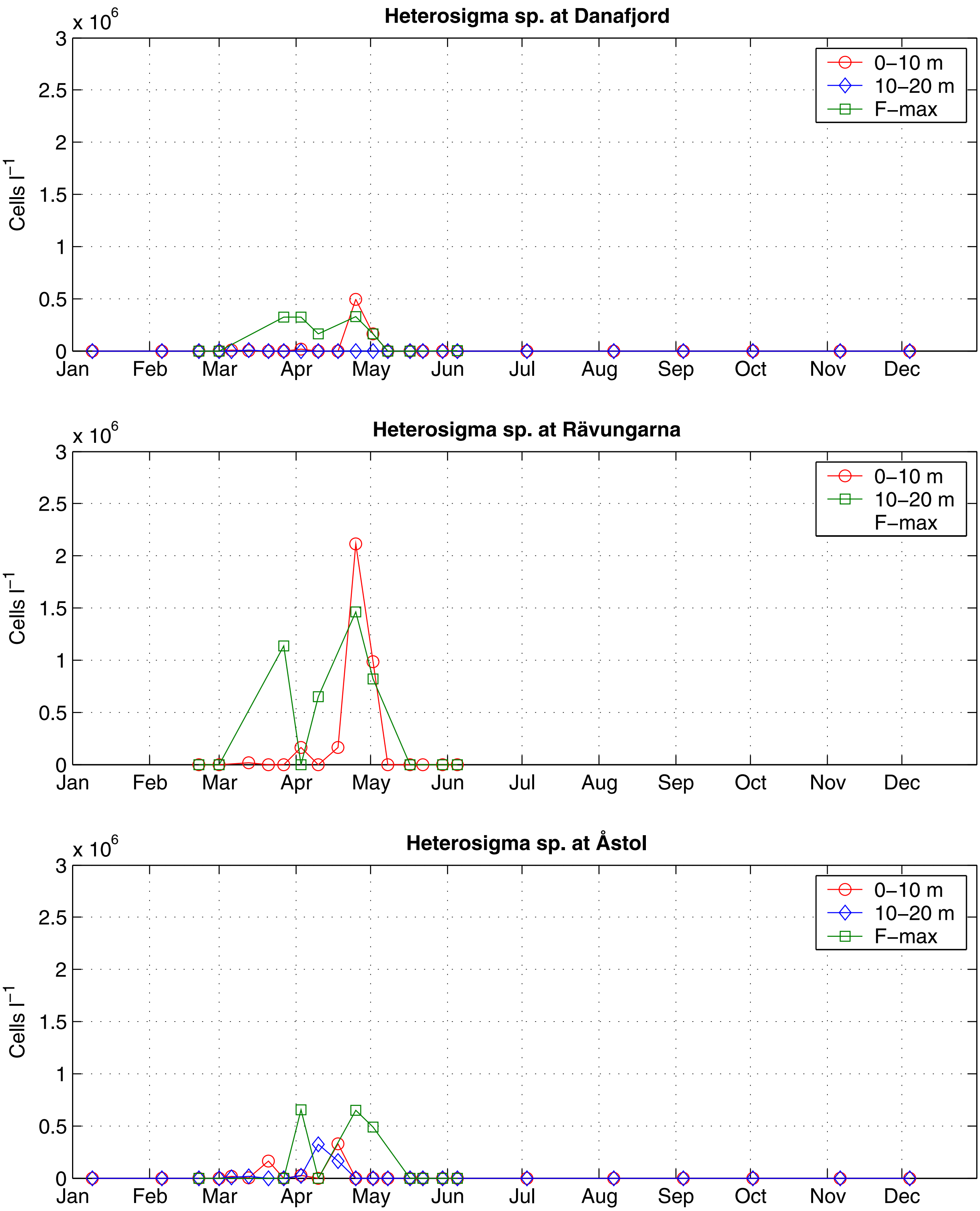
Heterosigma sp. at Danafjord
x 10^6
Cells l^-1
3
2.5
2
1.5
1
0.5
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0–10 m
10–20 m
F–max
Heterosigma sp. at Rävungarna
x 10^6
Cells l^-1
0–10 m
10–20 m
F–max
Heterosigma sp. at Åstol
x 10^6
Cells l^-1
0–10 m
10–20 m
F–max

Figure 38.

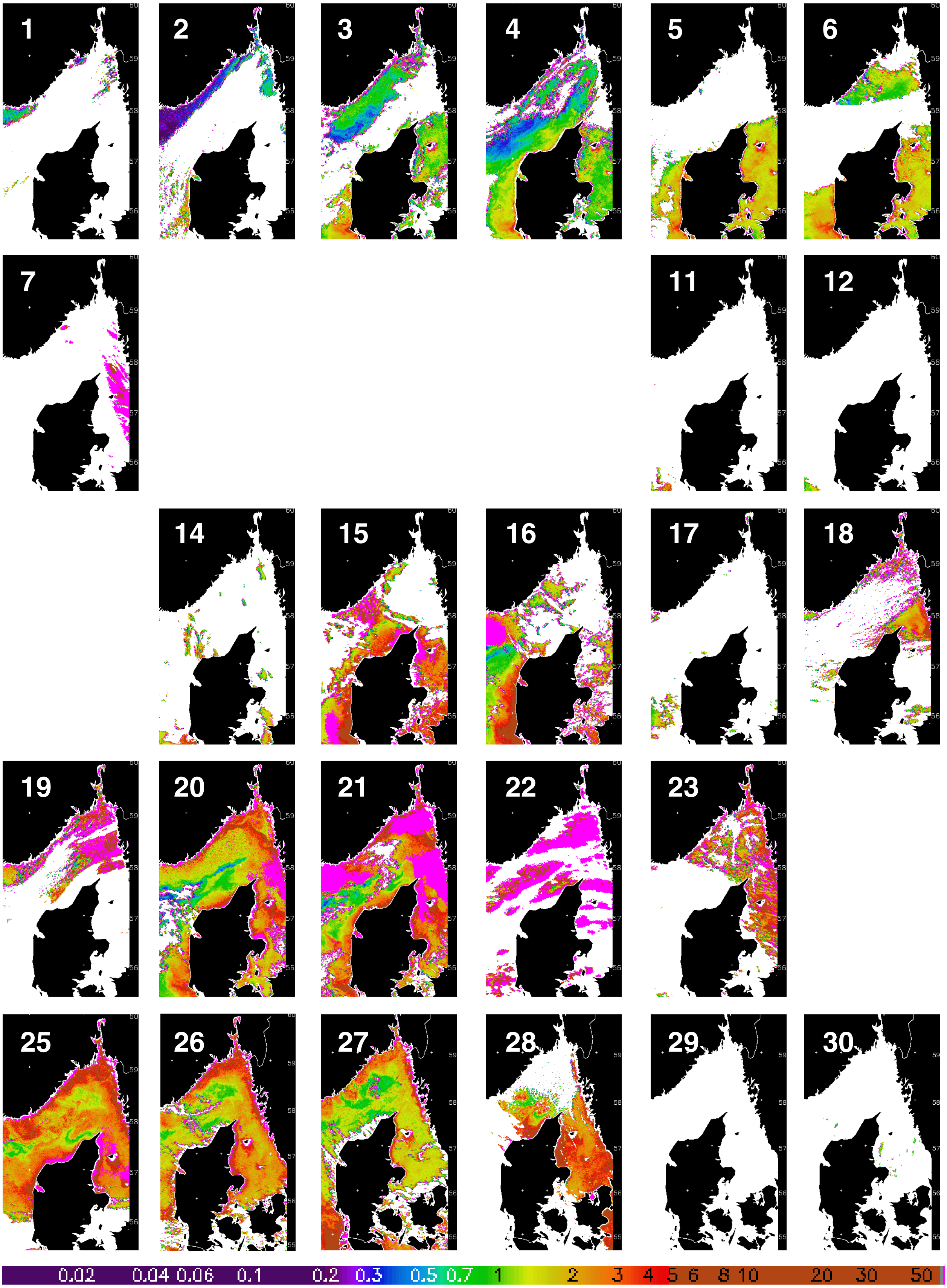

Figure 39. Satellite images indicating the biomass of phytoplankton in surface water in March 2001. During some days no images were available. White areas are cloud covered and in violet areas the data was outside the range of the chlorophyll algorithm. Unit is chlorophyll *a* mg/m^3. Copyright NASA SeaWiFS project Team/Orbital Imaging Corp. by courtesy of remote Sensing Group, Plymouth Marine Laboratory, U.K. and Nansen Environmental and Remote Sensing Center, Norway.

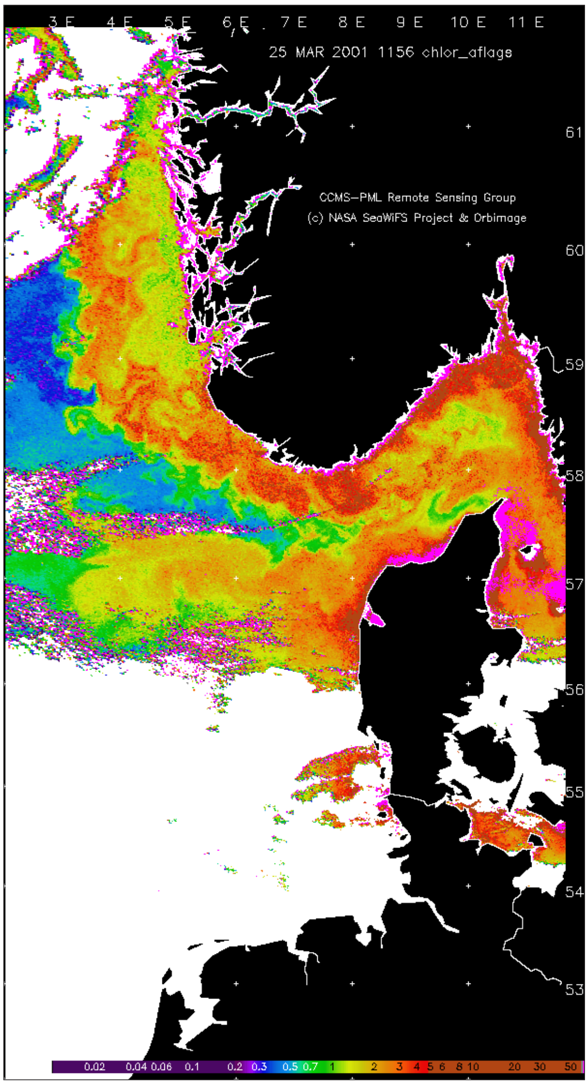

Figure 40. Satellite image 25 March 2001 indicating the biomass of phytoplankton in surface water during the late stage of the *Chattonella* bloom. The scale is the same as in Fig. x. White areas are cloud covered and in violet areas the data was outside the range of the chlorophyll algorithm. Unit is chl. *a* mg/m^3. Copyright NASA SeaWiFS project Team/Orbital Imaging Corp. by courtesy of remote Sensing Group, Plymouth Marine Laboratory, U.K. and Nansen Environmental and Remote Sensing Center, Norway.

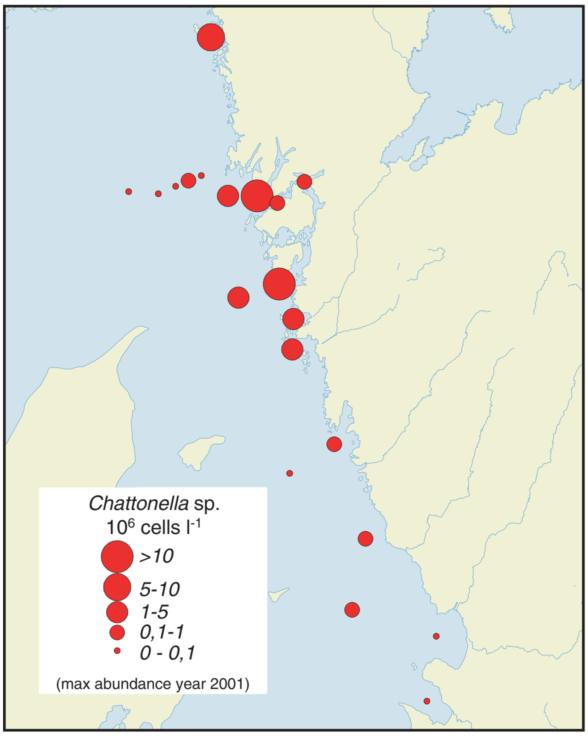

Figure 41. The map shows the highest cell numbers of *Chattonella* sp. recorded during year 2001. The maximum abundances were recorded in the end of March or in the beginning of April at the surface or in integrated samples 0-10 m. The *Chattonella* cell numbers include both cells < 10 µm and cells > 10 µm.

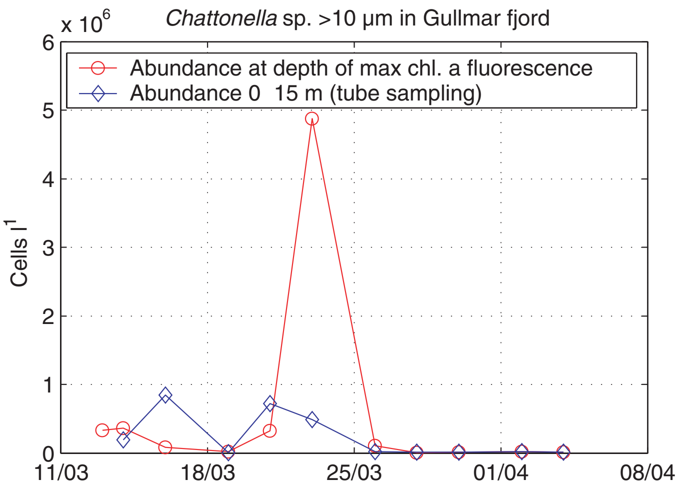

Figure 42. Abundance of *Chattonella* sp. > 10 µm. F-max is the depth of maximum chlorophyll *a* fluorescence.

Appendix 1 List of sampling occasions

Date	Monthly monitoring	E Älvsborgsbron	Danafjord	Rävungarna	Åstol
2001-01-09	x[1]	x	x	x	x
2001-02-06	x[1]	x	x		x
2001-02-21		x	x	x	x
2001-03-01		x	x	x	x
2001-03-06	x[1]	x	x		x
2001-03-07			x[2]	x	x[2]
2001-03-13		x	x	x	x
2001-03-21		x	x	x	x
2001-03-27		x	x	x	x
2001-04-03	x[1]	x	x	x	x
2001-04-10		x	x	x	x
2001-04-18		x	x	x	x
2001-04-25		x	x	x	x
2001-05-02		x	x	x	x
2001-05-08	x[1]	x	x	x	x
2001-05-17		x	x	x	x
2001-05-22		x	x	x	x
2001-05-30		x	x	x	x
2001-06-05	x[1]	x	x	x	x
2001-07-03	x				
2001-08-07	x				
2001-09-04	x				
2001-09-20		x[3]			
2001-10-02	x				
2001-11-06	x				
2001-12-04	x				

[1]Stations E Älvsborgsbron, Danafjord and Åstol are a part of the monthly monitoring by SMHI on commission from the water quality association of the Bohus coast. On the indicated occassions the sampling was enlarged.

[2]Only chlorophyll sampling using a tube was performed on this date. The other parameters were measured the day before.

[3]Sampling for a project for safe sea routes to Gothenburg harbour.

Appendix 2 List of sampling stations and their positions

Stations sampled by SMHI using R/V Sensor

Station	*Latitude*	*Longitude*
Byttelocket	N 58°21,20’	E 11°14,40’
Brofjorden	N 58°20,60’	E 11°24,20’
Inre Gullmarn	N 58°23,60’	E 11°37,60’
Alsbäck	N 58°19,40’	E 11°32,80’
Koljöfjord	N 58°13,80’	E 11°34,80’
Havstensfjorden	N 58°18,75’	E 11°46,40’
Byfjorden	N 58°20,00’	E 11°53,00’
Galterö	N 58°06,55’	E 11°48,60’
Åstol	N 57°55,18’	E 11°35,60’
Instö Ränna	N 57°54,07’	E 11°40,00’
Rävungarna	N 57°47,09’	E 11°41,70’
Danafjord	N 57°40,05’	E 11°41,20’
Skalkorgarna	N 57°40,73’	E 11°46,10’
E Älvsborgsbron	N 57°41,50’	E 11°54,40’
Valö	N 57°33,00’	E 11°48,50’

Stations sampled by SMHI using R/V Argos

Station	*Latitud*	*Longitud*
Anholt E	N 56°40’	E 12°07’
Fladen	N 57°11,5’	E 11°40’
P2	N 57°52’	E 11°18’
Släggö	N 58°15,5’	E 11°26’
Å13	N 58°20,2’	E 11°02’
Å14	N 58°19’	E 10°56,5’
Å15	N 58°17,7’	E 10°51’
Å16	N 58°16’	E 10°43,5’
Å17	N 58°16,5’	E 10°30,8’

Stations sampled by Kristineberg Marine Research Stations using R/V Arne Tiselius

Station	*Latitude*	*Longitude*
Gullmarsfjorden	N 58°16,5’	E 11°29’

Stations sampled by Tjärnö Marine Biological Laboratory using R/V Nereus

Station	*Latitude*	*Longitude*
Kosterfjorden	N 58°52,10’	E 11°06,20’

Appendix 3 SMHI publications

SMHI publishes six report series. 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.

Names of the Series	Published since
RMK (Report Meteorology och Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985

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)

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 the eutrophication status in the Kattegat and the Skagerrak, OSPAR assessment 2002.

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