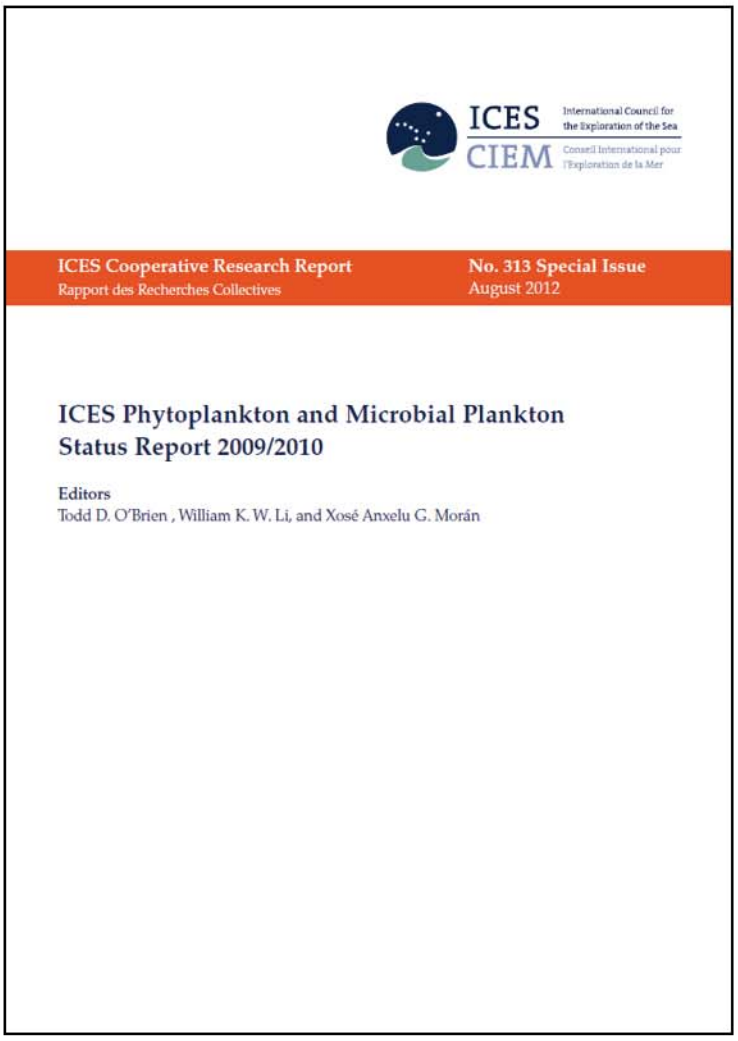

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ICES Cooperative Research Report No. 313. 196 pp.

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5. PHYTOPLANKTON AND MICROBIAL PLANKTON OF THE BALTIC SEA

Norbert Wasmund, Sirpa Lehtinen, Anetta Ameryk, Günther Nausch, and Marie Johansen

The Baltic Sea is a classic example of a shallow intracontinental shelf sea, with a mean depth of 52 m. It is connected to the North Sea only by the shallow and narrow Danish Straits, which limit water exchange between these regions. The Kattegat, Sound (Øresund), and Belt Sea (Great Belt, Little Belt, Kiel Bight, and Mecklenburg Bight) represent the transitional area between the North Sea and the Baltic Proper. The Baltic Proper stretches from Darss Sill to the entrances to the gulfs of Riga, Finland, and Bothnia, and comprises different basins that are stratified by a permanent halocline (at depth of 60–80 m in the deepest basins) and a summer thermocline (at 10–30 m depth). Owing to a limited exchange with the North Sea, the Baltic Sea is a brackish sea with not only a vertical, but also a horizontal, salinity gradient. The salinity of surface water decreases to the east and north. A detailed survey of the state and evolution of the Baltic Sea is given by Feistel *et al.* (2008).

Large rivers import nutrients from the densely populated and intensively cultivated catchment area (Bergström and Carlsson, 1994), resulting in an increase in phytoplankton biomass, primary production, and turbidity in the euphotic zone and oxygen deficit in deep-water layers (Elmgren and Larsson, 2001; Rönnberg and Bonsdorff, 2004). The riparian countries recognized the increasing environmental problems and agreed to establish the Baltic Marine Environment Protection Commission (Helsinki Commission, HELCOM) in 1974. One of its aims was to investigate long-term trends in trophic conditions by the Baltic Monitoring Programme (BMP, later the COMBINE programme), which has been conducted since 1979 according to a coordinated sampling schedule and binding methodology. The data collected by the riparian countries in the frame of the HELCOM monitoring are stored in the ICES databank and form the basis for this analysis.

Already in previous periods, the data have been analysed for trends by the HELCOM community, for example in periodic assessments (e.g. HELCOM, 2002) or in thematic assessments (e.g. on climate change or eutrophication; see HELCOM, 2007, 2009). Specific papers on trends in phytoplankton had to take into account differences between the subareas of the Baltic Sea. In fact, trends in the different regions may even be opposite. For example, trends in chlorophyll *a* concentrations were found to decrease in Mecklenburg Bight, but increase in the Baltic Proper in spring from 1979 to 2005 (Wasmund and Siegel, 2008). Wasmund *et al.* (1998) discovered a strong decrease in diatom biomass in spring blooms in the southern Baltic Proper, but not in Mecklenburg Bight. This sudden diatom decrease at the end of the 1980s was later identified as a regime shift by Alheit *et al.* (2005). The decrease in spring diatoms is compensated by an increase in dinoflagellates (Wasmund and Uhlig, 2003).

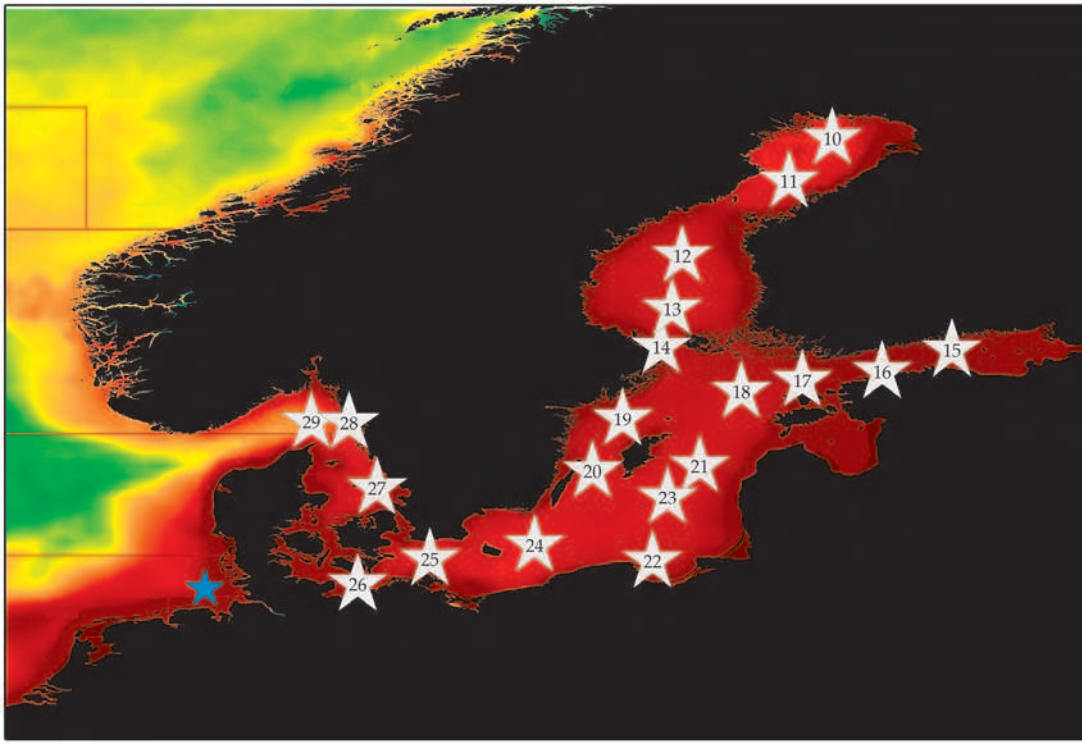


Figure 5.1
Locations of the Baltic Sea plankton monitoring areas (Sites 10–29) plotted on a map of average chlorophyll concentration. Blue stars indicate locations of sites described in the adjacent North Sea and English Channel region (see Section 6).

The diatoms and dinoflagellates demonstrated alternating oscillations: strong spring blooms of diatoms occurred in the 1980s and since 2000, but those of dinoflagellates in the 1990s (Wasmund *et al.*, 2011).

Suikkanen *et al.* (2007) analysed especially the summer phytoplankton communities in the northern Baltic Proper and the Gulf of Finland. They found increasing chrysophyte and chlorophyte biomass in both areas, increasing dinoflagellates in the northern Baltic Proper, and increasing cyanobacteria in the Gulf of Finland, together with an increase in chlorophyll concentrations, temperature, and winter DIN (dissolved inorganic nitrogen) concentrations.

A complex trend analyses with monitoring data of the whole Baltic Sea was performed by Klais *et al.* (2011). They found high variability in the spring bloom biomass, with peaks in the Gulf of Finland, Gulf of Riga, Pomeranian Bight, and the Danish coast of the Kattegat. Dinoflagellates dominate in the northern Baltic Proper, but diatoms in coastal areas and in the western Baltic. In the relatively short period considered (1995–2004), dinoflagellates decreased primarily in the Bornholm Sea and the Gulf of Riga, but increased in the Gulf of Finland and Bothnian Bay. The analysis presented here generally agrees with these previous analyses. Its data basis is, however, more complete than in the older papers, because it involves all data available from the specific sea areas and is not restricted to selected shorter periods (as in Klais *et al.*, 2011) or selected seasons (as in Suikkanen *et al.*, 2007). In contrast to the earlier study of Suikkanen *et al.* (2007), for example, cyanophytes and chlorophytes did not increase in the Gulf of Finland or in the northern Baltic Proper in the analysis in this report.

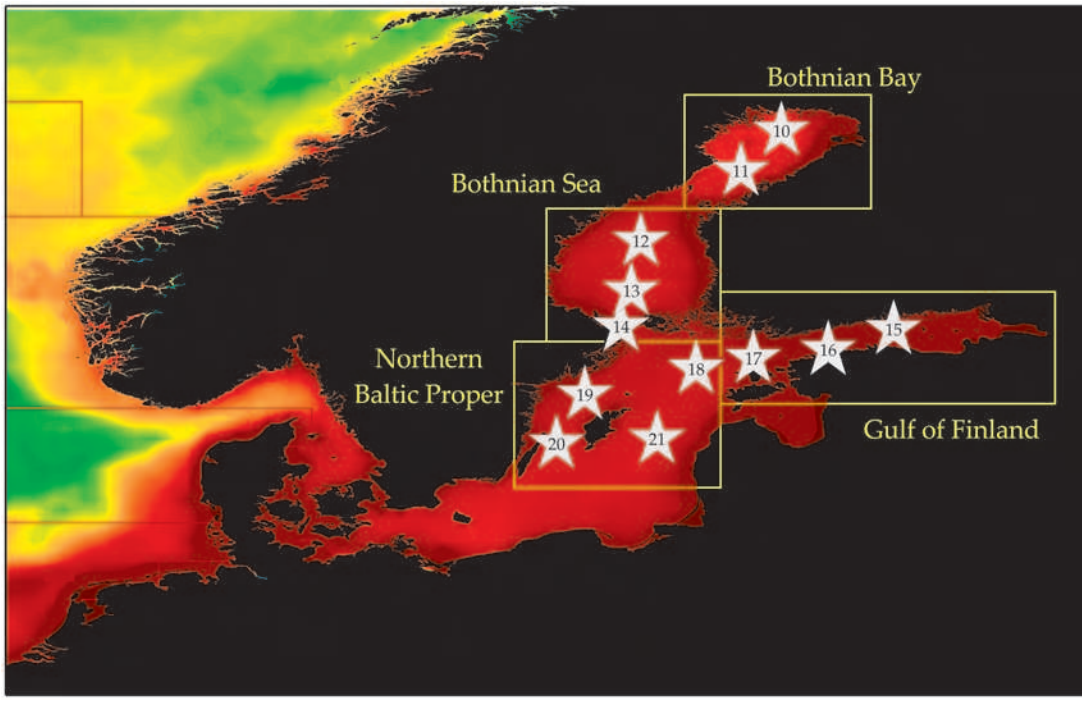
Since the start of the monitoring programme in 1979, the biomass in many phytoplankton groups has increased. Changes in many smaller groups are statistically significant, but the ecological importance of these groups is rather low owing to their small biomass. From the ecologically important groups, the dinoflagellates are increasing, whereas the diatoms are decreasing, especially if spring data are considered, and the diatoms:diatoms+dinoflagellate ratio during the spring bloom period is also decreasing. The sudden decrease at the end of the 1980s, known from the literature, is clearly visible, primarily in the Bornholm Sea and the Eastern Gotland Basin. The diatoms:diatoms+dinoflagellates ratio may be an important indicator of changes in the ecosystem, which may have high relevance for the food chain.

The autotrophic ciliate *Mesodinium rubrum* establishes itself as a third ecologically important group. It is strongly increasing in all seasons, especially in the 1990s, but part of this shift may be an artefact because some contributors may have included this ciliate in the phytoplankton only after the early 1990s. However, the sudden increase of the prymnesiophyte *Chrysochromulina polylepis* since the end of 2007 is well documented. The only major group that is decreasing is cyanobacteria. Only the summer period, when they form blooms, is relevant to this consideration. The decrease in cyanobacteria is especially prominent in July and/or August in the Arkona Sea and Bornholm Sea.

A general increase in temperature was detected in all sea areas, but was not significant in the Eastern Gotland Basin. The concentrations of dissolved inorganic nitrogen (DIN = NO_2+NO_3+NH_4) are decreasing in the long-term dataseries in all open sea areas. This is interesting because nitrogen is considered to be the limiting nutrient in the Baltic Proper, but its decrease has no clear effect on the phytoplankton biomass. The lack of correlations between DIN and chlorophyll concentrations is surprising and needs to be investigated.

5.1 Northern Baltic Sea (Sites 10–21)

Sirpa Lehtinen



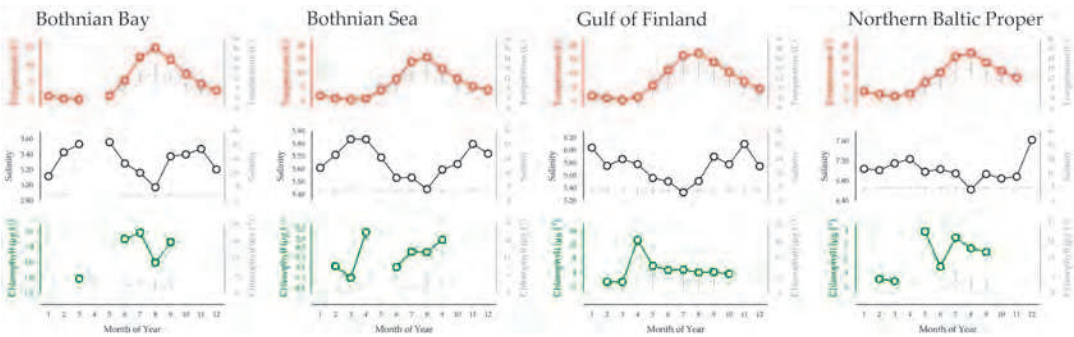


Figure 5.1.1
Location of Finnish Environmental Institute (SYKE) phytoplankton monitoring stations in the northern Baltic Sea (Sites 10–21), and their corresponding environmental summary plots (see Section 2.2.1). The yellow boxes and labels indicate the four subareas described in the report text.

The Northern Baltic Sea consists of four subareas: Bothnian Bay, Bothnian Sea, the Gulf of Finland, and the northern Baltic Proper (Figure 5.1.1). In the frame of the international COMBINE-monitoring programme of the Helsinki Commission (HELCOM), the Marine Research Centre of the Finnish Environment Institute (SYKE) samples phytoplankton yearly in August at twelve open-water stations (Sites 10–21) and in numerous coastal stations (not considered in this report). This sampling has been carried out since 1979, with the data available in the main ICES database. Sampling, processing, and analysis of the samples have been carried out according to the compulsory manual and the HELCOM PEG (Phytoplankton Expert Group) taxa and biovolume list (Olenina *et al.*, 2006; HELCOM, 2010). For the purposes of this report, the twelve open-water stations have been combined into four geographical subareas: Bothnian Bay, Bothnian Sea, Gulf of Finland, and northern Baltic Proper. Additional time-series results for the individual sites, as well as additional SYKE coastal monitoring sites, are available online at http://wgpme.net/time-series.

5.1.1 Bothnian Bay (Sites 10–11)

The Bothnian Bay is the most northern part of the Baltic Sea, characterized by low salinity (ca. 2.9–3.5), the strong influence of river waters, and the long duration of ice cover (over 150 d). In addition, Bothnian Bay is the only predominantly phosphorus-limited Baltic Sea subregion, most notibly during summer (Tamminen and Andersen, 2007). The maximum bottom depth is 148 m, with a mean depth of 40 m. The open-water sampling stations in the Bothnian Bay are F2 (Site 10, 65°23'N 23°27'E) and BO3 (Site 11, 64°18'N 22°21'E).

Seasonal and interannual trends (Figure 5.1.2)

Diatoms, especially *Chaetoceros wighamii*, dominate during the spring bloom, but dinoflagellates, like *Peridiniella catenata*, are also important. During summer, cryptophytes and chlorophytes are numerous. In autumn, there is usually another diatom peak. In the Bothnian Bay, the diazotrophic cyanobacteria is not as common as in other parts of the Baltic Sea; one reason for this is probably the predominant phosphorus limitation.

Since the start of the monitoring programme in 1979, salinity has decreased, whereas silicate has increased. Temperature and chlorophyll *a* have a slightly rising trend, but neither is statistically significant. Diatoms, dinoflagellates, cryptophytes, euglenophytes, and heterotrophs have all decreased significantly in the Bothnian Bay since sampling began in the mid-1980s.

5.1.2 Bothnian Sea (Sites 12–14)

Surface salinity in the Bothnian Sea is ca. 5.4–5.9. The maximum depth of the Bothnian Sea is 293 m, with a mean depth of 60 m. The open-sea sampling stations in the Bothnian Sea are US5B (Site 12, 62°35'N 19°60'E), SR5 (Site 13, 61°05'N 19°35'E), and F64 (Site 14, 60°11'N 19°08'E).

Seasonal and interannual trends (Figure 5.1.3)

The phytoplankton community in the Bothnian Sea is usually nitrogen-limited during summer, as it is in all of the other more southern areas of the Baltic Sea. Species such as the mixotrophic haptophyte *Chrysochromulina* spp. and cyanobacteria *Aphanizomenon* sp. and *Nodularia spumigena* are important during summer (Andersson *et al.*, 1996). Other important species are the diatom *Thalassiosira baltica* and dinoflagellate *Peridiniella catenata* in spring, and photosynthetic ciliate *Mesidinium rubrum* after the spring bloom.

Since the start of the monitoring programme in 1979, temperature and chlorophyll *a* have increased, whereas salinity and silicate have decreased. Diatoms, dinoflagellates, cryptophytes, and heterotrophs have decreased significantly, whereas chrysophytes and the endosymbiotic ciliate *Mesodinium rubrum* (not shown) have increased.

5.1.3 Gulf of Finland (Sites 15–17)

The surface salinity in the Gulf of Finland is ca. 5.4–6.1. The maximum depth of the Gulf of Finland is 121 m. The open-sea sampling stations in the Gulf of Finland are LL3a (Site 15, 60°04'N 26°20'E), LL7 (Site 16, 59°51'N 24°49'E), and LL12 (Site 17, 59°29'N 22°54'E).

Seasonal and interannual trends (Figure 5.1.4)

The phytoplankton community structure is complex and shifting, owing to unstable mixing conditions in the Gulf of Finland. Dinoflagellates *Scrippsiella* sp., *Biecheleria baltica*, and *Gymnodinium corollarium* are important spring-bloom species. Late-summer communities in the Gulf of Finland are characterized by cyanobacterial blooms. Nitrogen limitation and low nitrogen-to-phosphorus ratio are supposed to promote the cyanobacterial blooms because diazotrophic cyanobacteria are able to fix nitrogen from the atmosphere. In addition to filamentous cyanobacteria, colonial cyanobacteria and cryptophytes as well as other small flagellates are numerous in the summer communities of the Gulf of Finland.

Since the start of the monitoring programme in 1979, temperature and chlorophyll *a* have increased, whereas salinity and silicate have decreased (Figure 5.1.4). Dinoflagellates have decreased in August, although their biomass and proportion in the spring bloom have increased (Klais *et al.*, 2011). Cryptophytes, euglenophytes, and heterotrophs have also decreased. Suikkanen *et al.* (2007) found that late-summer cyanobacterial biomass increased in the Gulf of Finland from the late 1970s to the beginning of the 2000s. In this August-only analysis, this cyanobacteria increase was not evident in the Gulf of Finland or in the northern Baltic Proper in the 2000s (Figure 5.1.5), possibly owing to differences in time-span or time-series analysis methods.

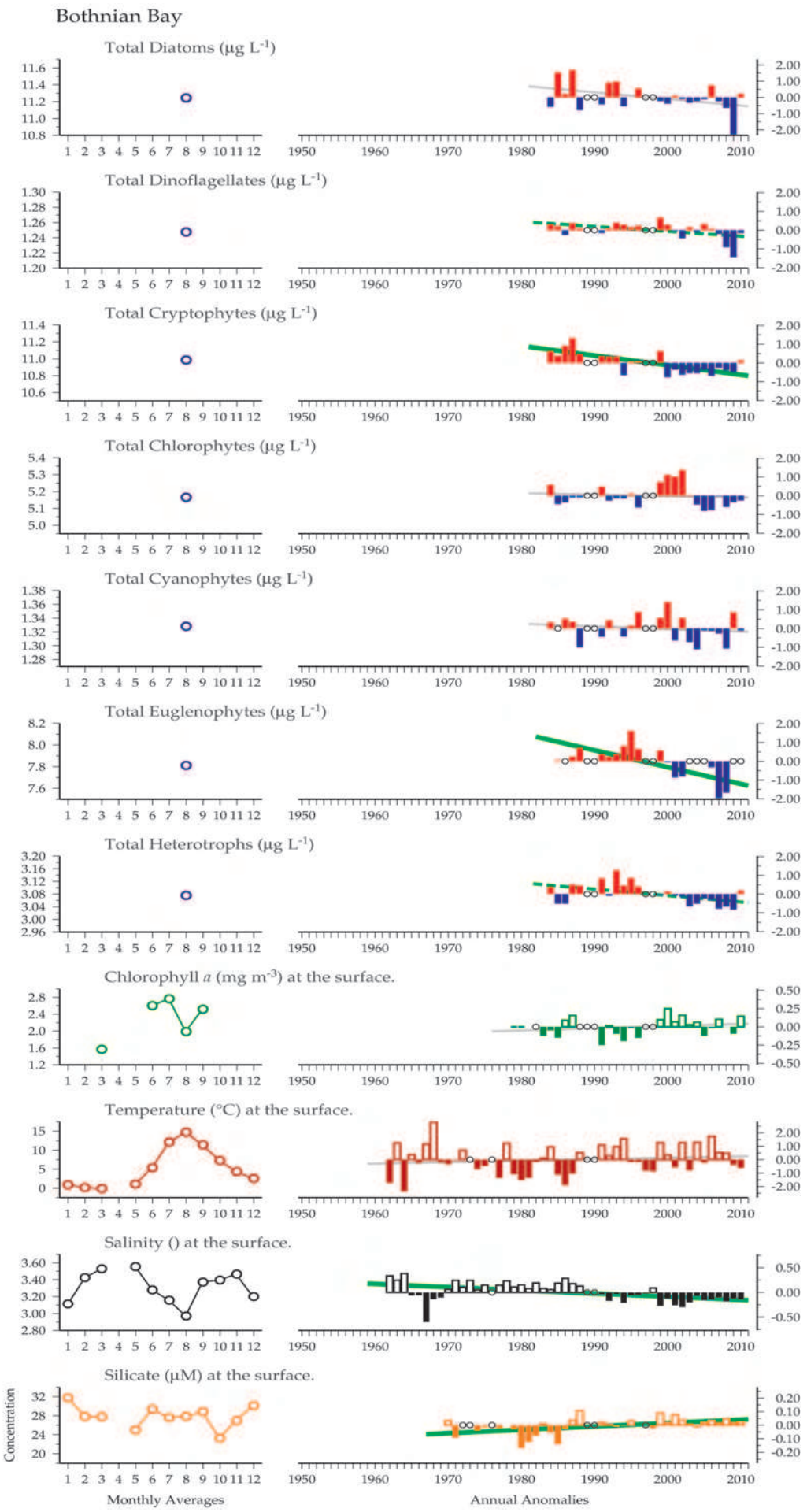
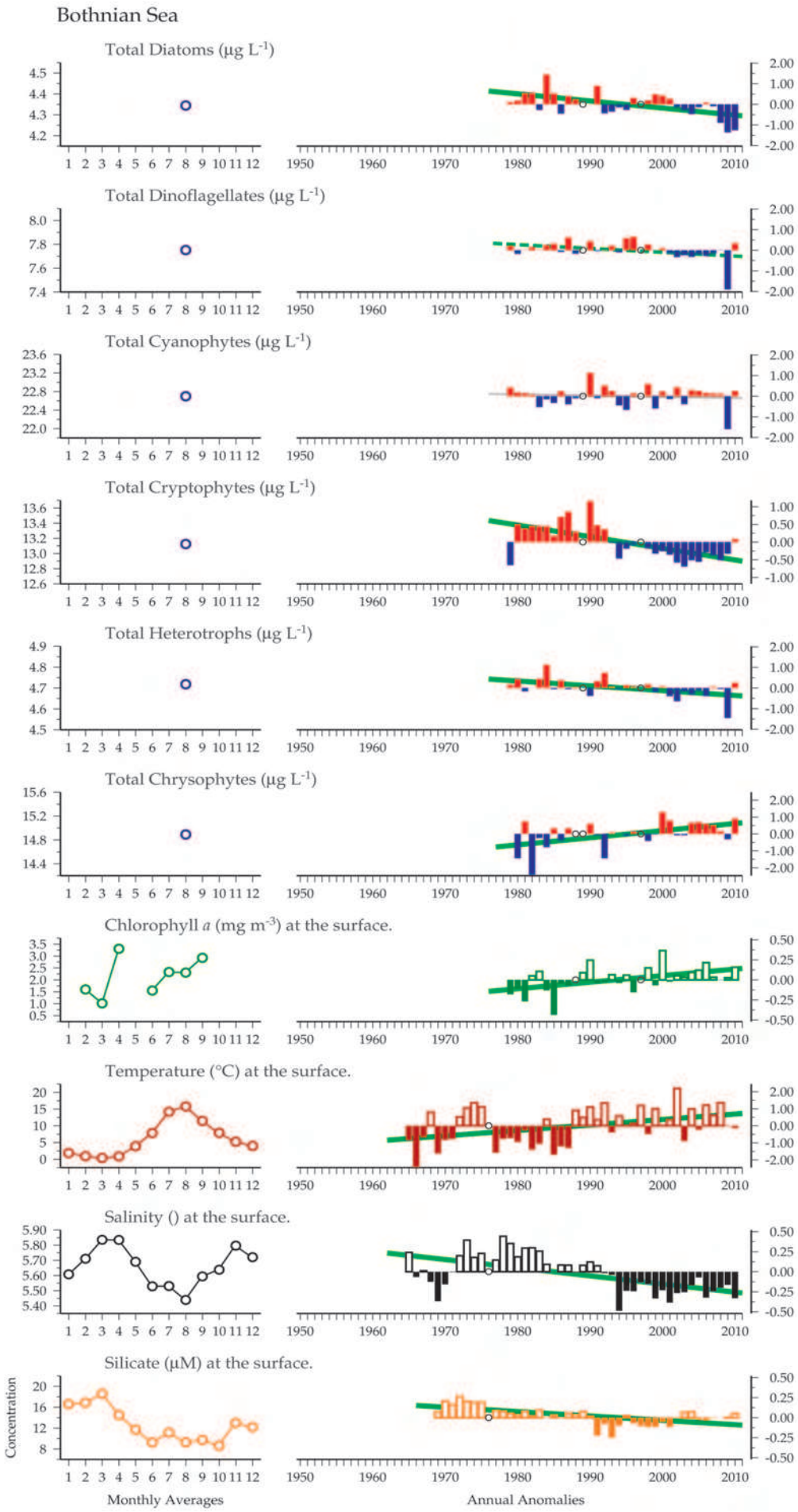


Figure 5.1.2
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Bothnian Bay plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.

Figure 5.1.3
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Bothnian Sea plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.



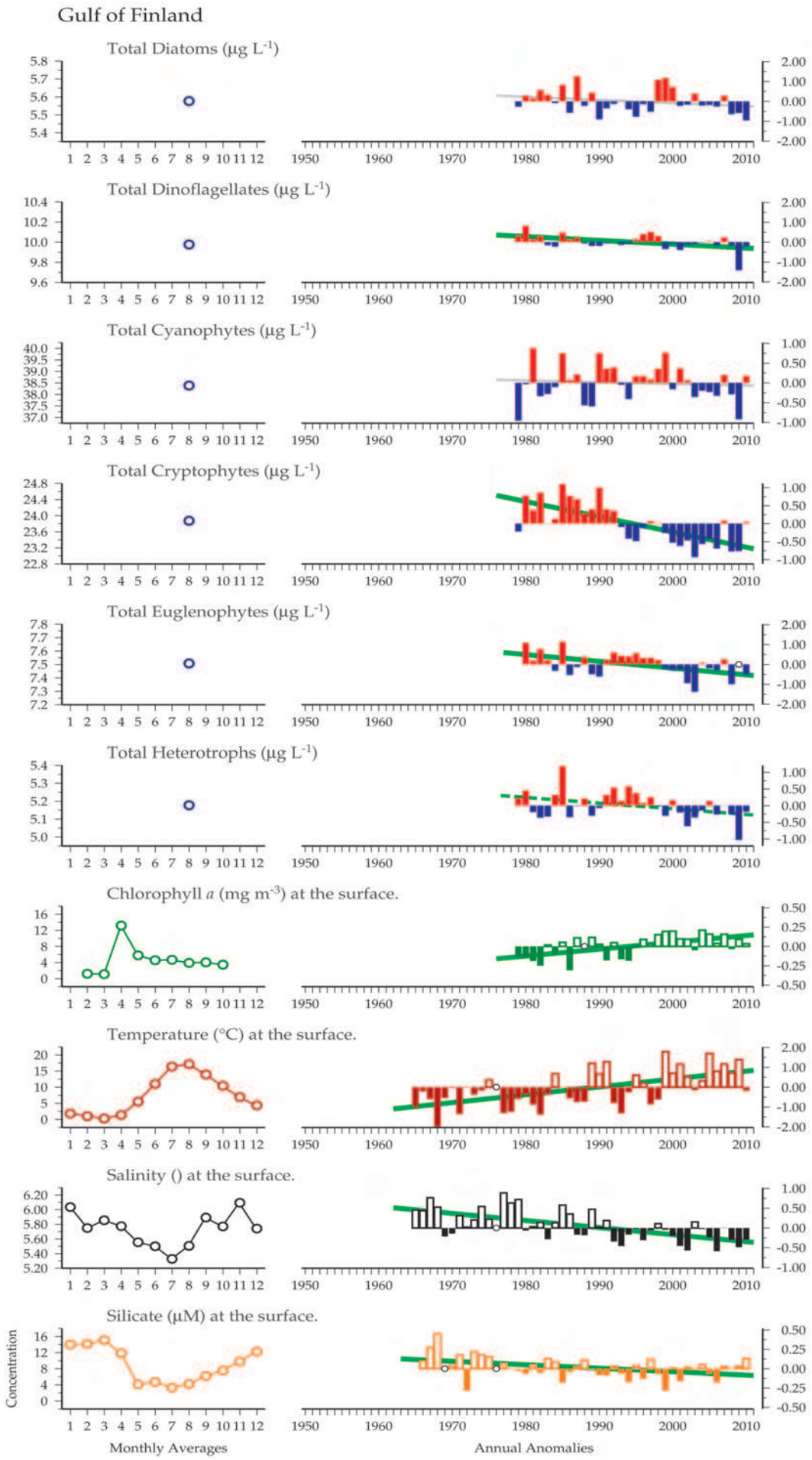


Figure 5.1.4
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Gulf of Finland plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.

5.1.4 Northern Baltic Proper (Sites 18–21)

Surface salinity in the northern Baltic Proper ranges from 6.6 to 7.6. Bottom depths in the Baltic Proper can exceed 400 m. The open-sea sampling stations in the northern Baltic Proper are LL17 (Site 18, 59°02'N 21°08'E), LL23 (Site 19, 58°35'N 18°14'E), BY15 (Site 20, 57°19'N 20°03'E), and BY38 (Site 21, 57°07'N 17°40'E).

Seasonal and interannual trends (Figure 5.1.5)

Dinoflagellates *Scrippsiella* sp., *Biecheleria baltica,* and *Gymnodinium corollarium* are dominant spring-bloom species in the northern Baltic Proper, and cyanobacteria blooms are typical in late summer (Wasmund *et al.*, 2011).

Since the start of the monitoring programme in 1979, temperature and chlorophyll *a* have increased, whereas silicate and salinity have decreased. Cryptophytes and euglenophytes have also decreased significantly.

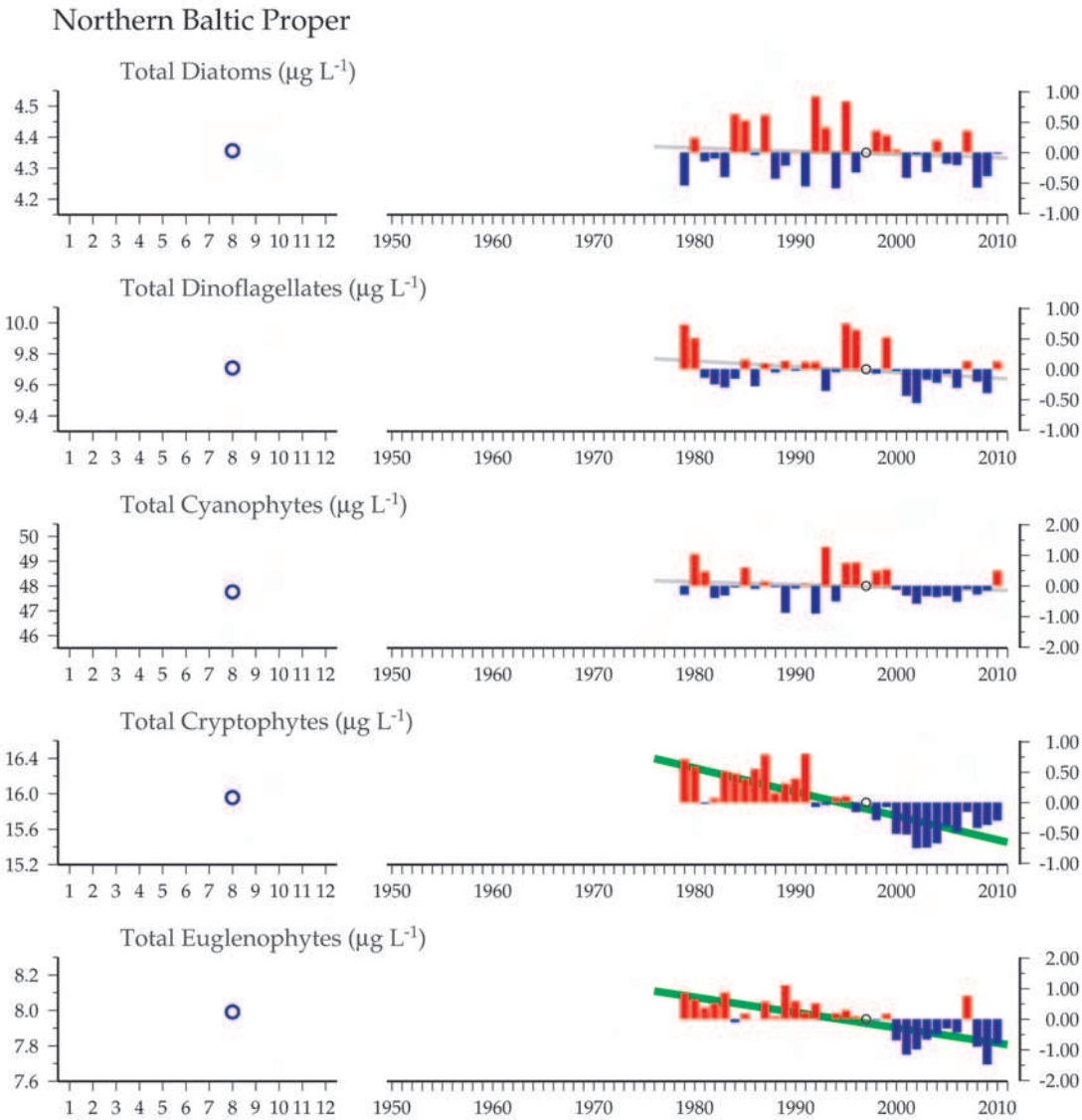
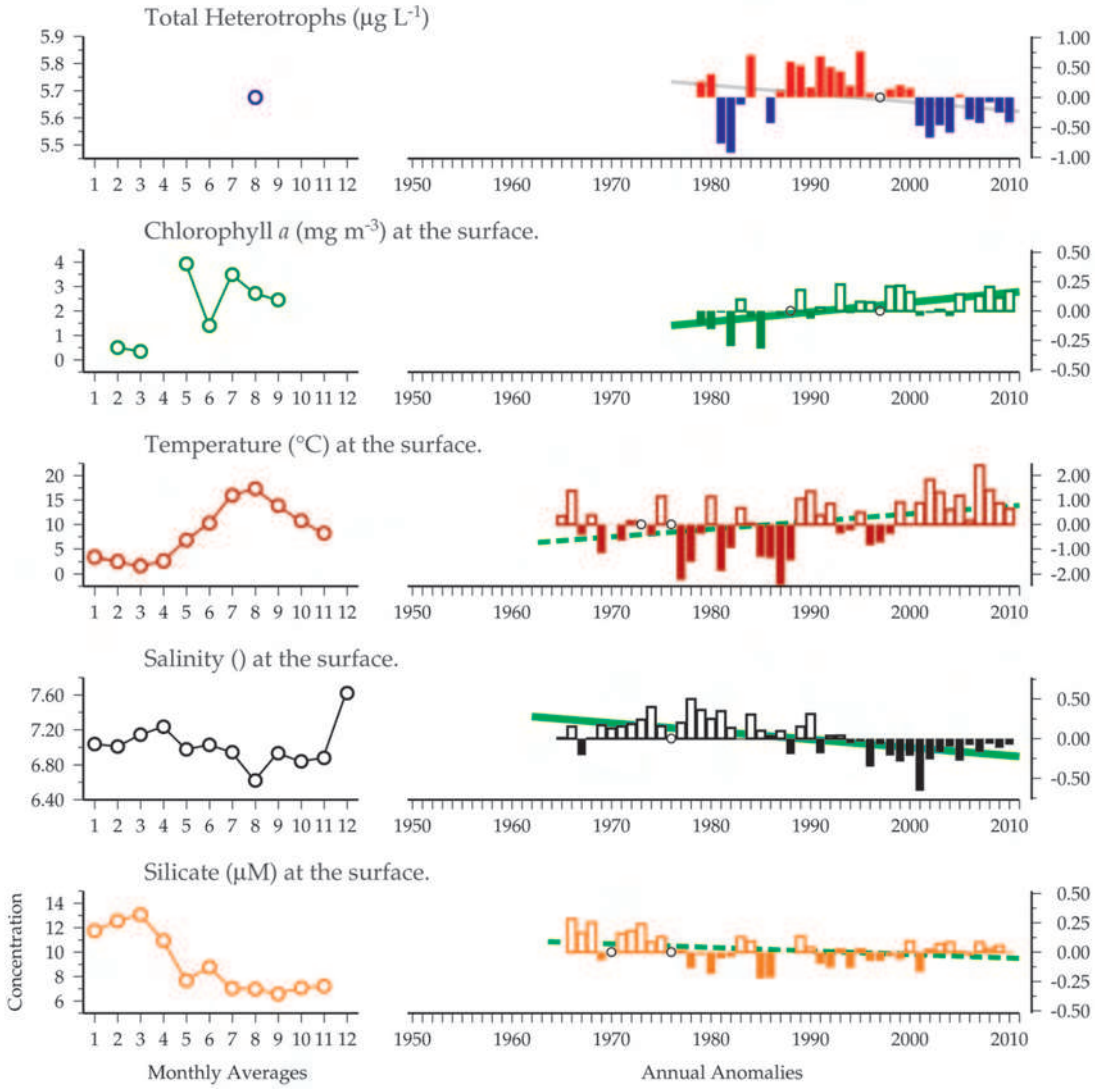


Figure 5.1.5 (continued on facing page)
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the northern Baltic Proper plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.



5.1.5 Overall northern Baltic trends

Since the start of the monitoring programme in 1979, chlorophyll *a* has increased in all northern subareas. Although chlorophyll *a* has increased, the biomass of major phytoplankton groups has generally decreased based on the results of microscopic phytoplankton counts. The chlorophyll *a* increase could be the result of, for example, an increase in picoplankton, which is not included in the phytoplankton results because its analysis would require special samples that need to be counted with an epifluorescence microscope. Also, for some reason, chlorophyll *a* production may have been more efficient than in earlier years. Diatoms have decreased, especially in the Bothnian Bay and the Bothnian Sea, and dinoflagellates have also decreased significantly in all subareas except the northern Baltic Proper. In this long-term data from August, the diatoms:diatoms+dinoflagellates ratio did not show any trend (figure not shown), although Klais *et al.* (2011) have demonstrated that in the spring bloom, the share of dinoflagellates has generally increased in the Baltic Sea owing to the increase in dinoflagellate biomass and decrease in diatom biomass.

Cryptophytes, euglenophytes, and heterotrophic flagellates have decreased in all subareas. Chrysophytes have increased in the Bothnian Sea, and the endosymbiotic ciliate *Mesodinium rubrum* has increased in the Bothnian Sea (figure not shown, but available online). There is a possibility that *M. rubrum* has not been counted consistently from all earlier samples, which may affect the results.

5.2 Gdańsk Basin (Site 22)

Anetta Ameryk, Sławomira Gromisz, Janina Kownacka, Marianna Pastuszak, and Mariusz Zalewski

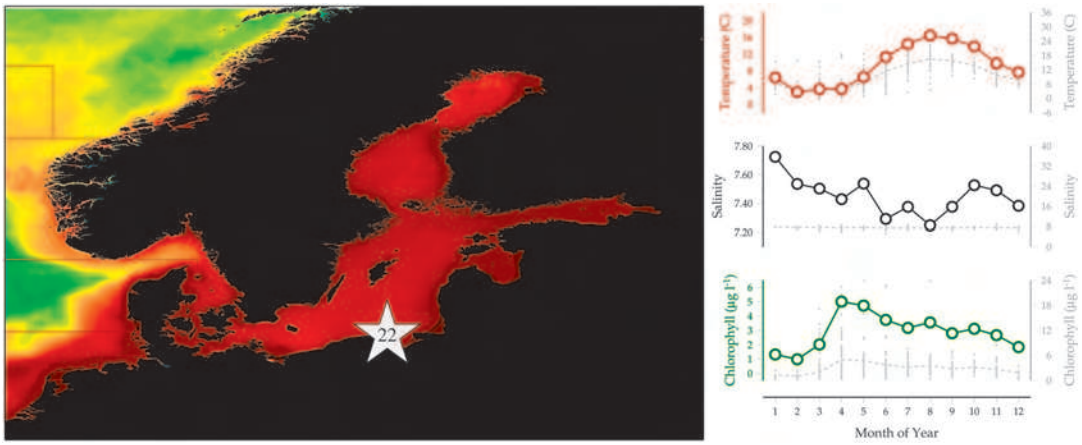


Figure 5.2.1
Location of the Gdańsk Basin plankton monitoring area (Site 22), plotted on a map of average chlorophyll concentration, and its corresponding environmental summary plot (see Section 2.2.1).

The National Marine Fisheries Research Institute (NMFRI) has a long-term database which covers a number of parameters measured in the southern Baltic Proper. NMFRI has been monitoring chlorophyll *a* concentrations since 1977, phytoplankton species since 1987, and additional microbial plankton since 1995. The database has, however, some gaps, especially in phytoplankton and bacterial parameters. Cruises were made 6–10 times a year in the 1980s in all seasons, and only two times a year, in spring and summer, over the last ten years. The data were collected at numerous sampling stations in the Gdańsk Basin, and the whole study area was placed into one box (longitude 017°54' 019°36'; latitude 55°36'to the coastline). The Gdańsk Basin includes waters sheltered by the Hel Peninsula (Gulf of Gdańsk) and the open waters. This region is relatively deep (60–80 m) and it is influenced by the Vistula River (the second largest river in the Baltic catchment).

Samples were collected with 2–5 l Nansen or Niskin bottles at five fixed depths from 0 to 10 m. Over the first 15 years of the studies, measurements of chlorophyll *a* concentrations were carried out with spectrophotometers, whereas in the years that followed, two parallel techniques were used: spectrophotometric and fluorometric. The phytoplankton samples were preserved with Lugol's solution (Edler, 1979) and then analysed using an inverted microscope (Utermöhl, 1958). Autotrophic dinoflagellates were distinguished from the heterotrophic ones using chlorophyll autofluorescence excited with blue light. Thecate dinoflagellates were determined after staining with fluorochrome Calcofluor White MR2, which is a specific stain for cellulose in the thecal plates. Phytoplankton taxa were identified to species or general groups. Both abundance and average bacteria cell volume were determined by direct counting and by measuring the length and width of bacteria (dyed with acridine orange) under epifluorescence microscopes.

Seasonal and interannual trends (Figure 5.2.2)

In the Gdańsk Basin, the spring bloom of small, rapidly growing diatoms is followed by the post-bloom peak of dinoflagellates. Cyanobacteria and nanoflagellates (not shown) bloom later, as they prefer conditions of thermal stratification in summer. A second peak of large diatoms is observed in autumn, usually accompanied by the photosynthetic ciliate *Mesodinium rubrum*, whereas winter is characterized by the phytoplankton minimum (Niemi, 1975; Smetacek *et al.*, 1984; Bralewska, 1992; Gromisz and Witek, 2001; Feistel *et al.*, 2008).

Nitrogen-fixing cyanobacteria dominate the phytoplankton communities in summer, when the N:P ratio is very low and water stratification is well established. Observations show a shift in time of appearance of cyanobacterial blooms. Over the years, the blooms shifted from July–August to June–July. Summer is also the time of highest microbial activity, which depends on phosphorus concentrations (Ameryk *et al.*, 2005).

Since the beginning of hydrographic sampling, temperature has increased significantly, whereas surface salinity and phosphate have decreased. Diatoms, dinoflagellates, and cyanobacteria show slight, but non-significant, decreases. This may be the result of the biological variables' shorter year coverage compared with the hydrographic data.

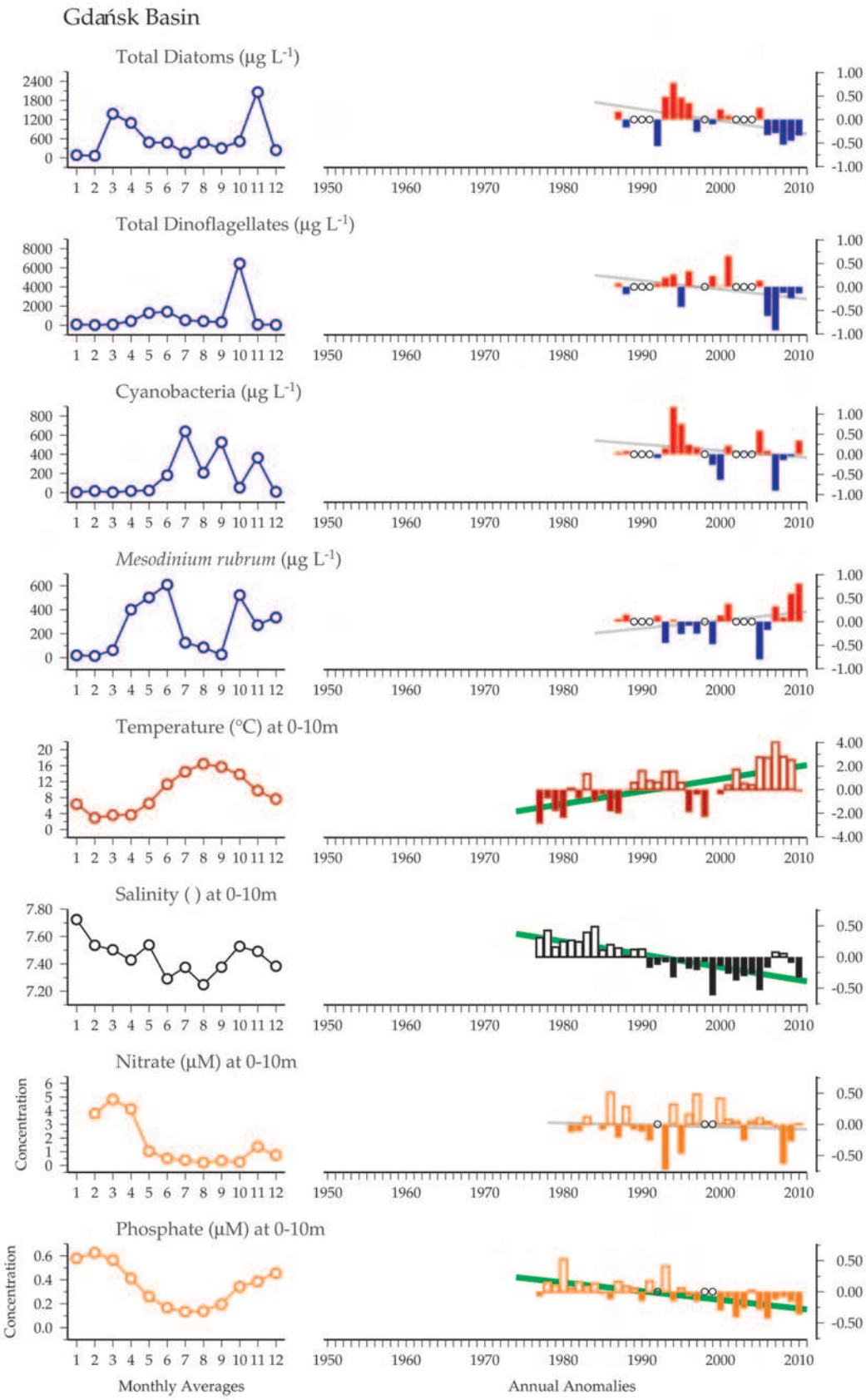


Figure 5.2.2
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Gdańsk Basin plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.

5.3 Eastern Gotland Basin (Site 23)

Norbert Wasmund and Günther Nausch

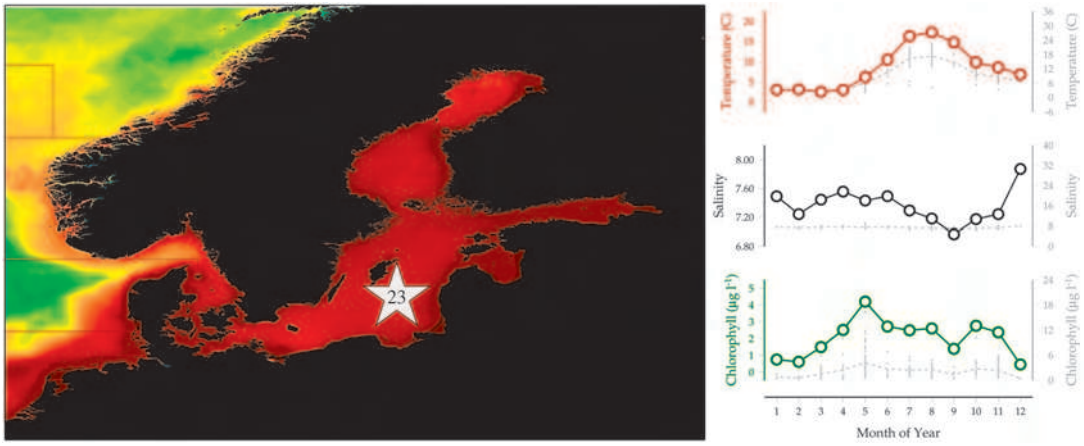


Figure 5.3.1
Location of the Eastern Gotland Basin plankton monitoring area (Site 23), plotted on a map of average chlorophyll concentration, and its corresponding environmental summary plot (see Section 2.2.1).

The Eastern Gotland Basin is part of the Baltic Proper, with a maximum depth of 249 m. In the frame of the international monitoring programme of the Helsinki Commission (HELCOM), two representative stations were sampled and combined for this report: BMP J1 at the Gotland Deep (57°18.3'N 20°4.6'E) and BMP K1 of the southern part of the Gotland Basin (55°33'N 18°24'E). Only integrated surface samples of the upper 10 m are considered. Sampling and processing of the samples and the data was carried out according to the compulsory manual (HELCOM, 2010).

This analysis is based on data collected in the frame of the monitoring programme of the Helsinki Commission (HELCOM) and contributed by the riparian countries of the Baltic Sea. The data are available from the ICES databank. Some data were personally supplied by Susanna Hajdu and Svante Nyberg (Stockholm University, Sweden), Sławomira Gromisz and Janina Kownacka (NMFRI Gdynia, Poland), as well as by Irina Olenina (Centre of Marine Research Klaipeda, Lithuania).

Seasonal and interannual trends (Figure 5.3.2)

The annual development of the phytoplankton is characterized by three blooms of different intensity, from which the summer bloom demonstrates a surprisingly high biomass, whereas the spring (May) and autumn blooms are mainly reflected in the chlorophyll data. The spring bloom is dominated by dinoflagellates in recent times, but it is accompanied by *Mesodinium rubrum*, which may appear very early. Blooms of nitrogen-fixing cyanobacteria are typical in summer. The autumn bloom is dominated by diatoms, mainly *Coscinodiscus granii* (Wasmund and Siegel, 2008).

Since the start of the monitoring programme in 1979, the biomass in most phytoplankton groups is increasing. The major group, the dinoflagellates, forms blooms in spring, primarily in May, with the intensity of these spring blooms increasing mainly from 1986 to 1987. The long-term increase from 1979 to 2010 does not contradict the finding of a long-term decrease in dinoflagellate spring biomass in this area by Klais *et al.* (2011), because they considered only the period 1995–2004.

Another important group, the diatoms, contributed less to the spring bloom and mainly to the early stages of the bloom. Diatoms exhibited a strongly decreasing trend, especially in May, with the steepest decrease from 1988 to 1989, mainly owing to the decrease in *Achnanthes taeniata* (Wasmund *et al.*, 2011). The diatoms:diatoms+dinoflagellates ratio during the spring bloom period exhibited a significant decrease. Klais *et al.* (2011) demonstrated that dinoflagellates dominate in the open waters, but diatoms in the coastal waters of the Eastern Gotland basin during spring. The main appearance of diatoms was in August. The occurrence of diatoms is not highly correlated to other phytoplankton groups or abiotic parameters in this region.

The autotrophic ciliate *Mesodinium rubrum* has established itself as the third important group. It is strongly increasing in all seasons, but this may be partly an artefact because some contributors may have started counting that ciliate only in the 1990s.

Changes in the smaller groups are statistically more significant, but the ecological importance of these groups is rather low owing to their small biomass. Prasinophytes and prymnesiophytes are increasing in almost all seasons. Especially the prymnesiophyte *Chrysochromulina polylepis* increased suddenly since the end of 2007 (Hajdu *et al.*, 2008). Cryptophytes increased if July and October were considered. Chrysophytes (including Dictyochophyceae) shifted from negative to positive anomaly in the mid-1990s. Cyanobacteria have been increasing since the start of monitoring in 1979. Additional analysis at the monthly level shows that the bulk of this increase occurs over the period March–June, a period of lower cyanobacteria biomass. During the July–August period of peak biomass, this trend disappears.

In contrast to the other areas of the Baltic Proper, the increasing tendency of temperature was not significant. The decrease in the components of dissolved inorganic nitrogen (NO_3 + NO_2 + NH_4) was only slightly significant. This is an important trend, as nitrogen is considered to be the limiting nutrient in the Baltic Proper. Chrysophytes, cryptophytes, and prasinophytes are strongly correlated with the DIN trend ($p < 0.01$). As the chlorophyll *a* concentrations are increasing, they show a slightly negative correlation with the DIN concentrations ($p < 0.05$).

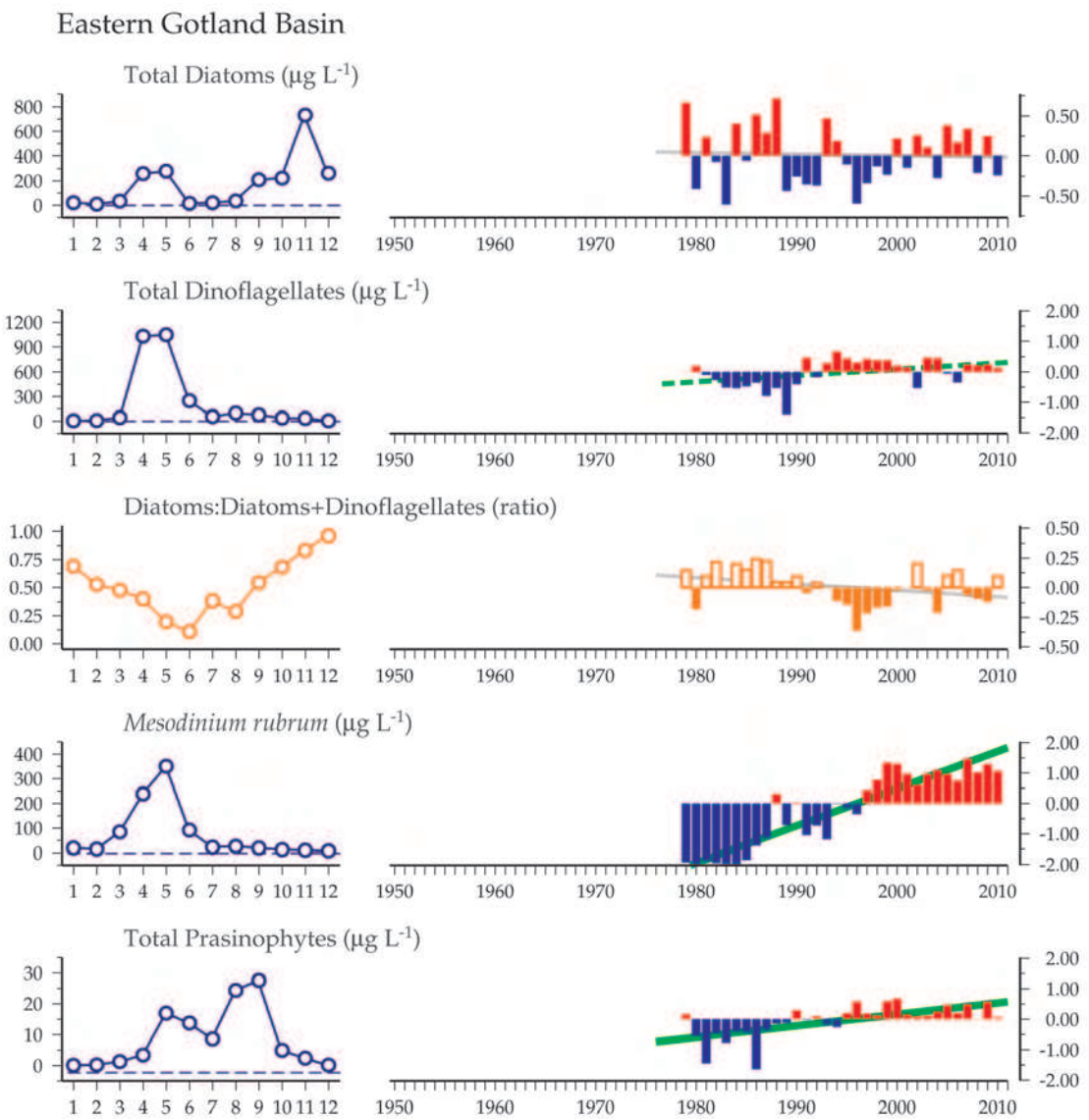
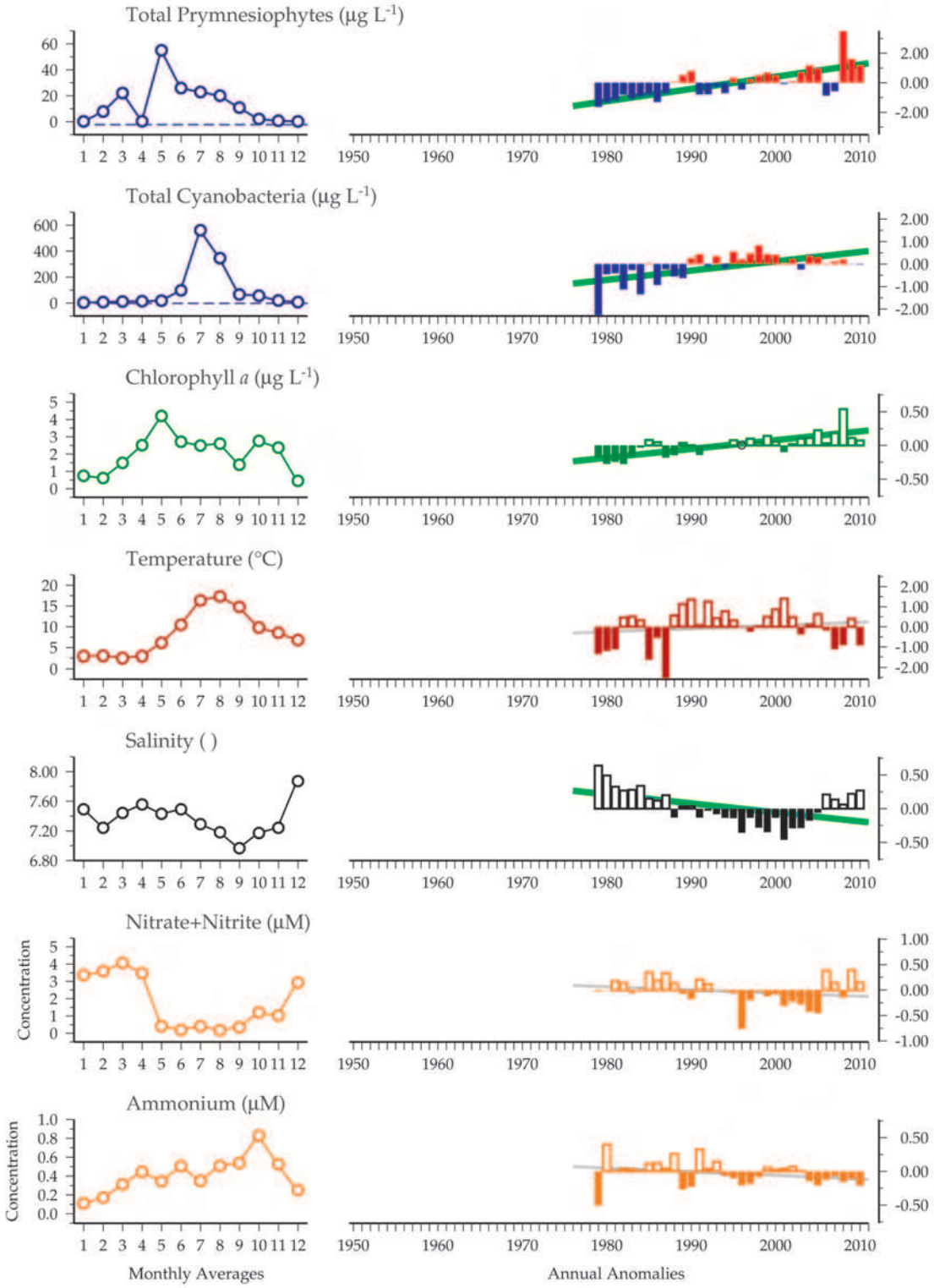


Figure 5.3.2 (continued overleaf)
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Eastern Gotland Basin plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.

Figure 5.3.2 (continued from previous page)



5.4 Bornholm Sea (Site 24)

Norbert Wasmund and Günther Nausch

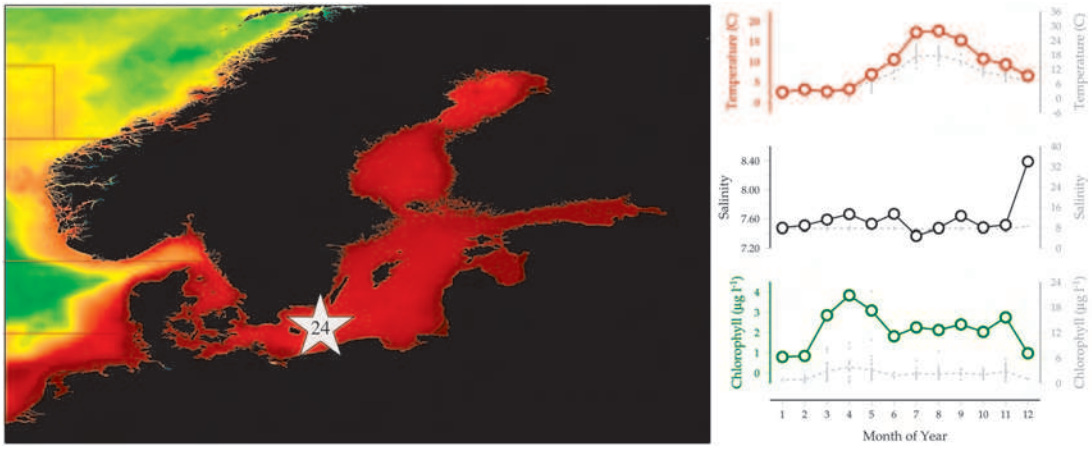


Figure 5.4.1
Location of the Bornholm Sea plankton monitoring area (Site 24), plotted on a map of average chlorophyll concentration, and its corresponding environmental summary plot (see Section 2.2.1).

The Bornholm Sea is part of the southern Baltic Proper, with a maximum depth of 92 m. In the frame of the international monitoring programme of the Helsinki Commission (HELCOM), the central station BMP K2 of the open sea was sampled: 55°15'N 15°59'E. Only integrated surface samples of the upper 10 m are considered. Sampling and processing of the samples and the data was carried out according to the compulsory manual (HELCOM, 2010).

This analysis is based on data collected in the frame of the monitoring programme of the Helsinki Commission (HELCOM) and contributed by the riparian countries of the Baltic Sea. The data are available from the ICES databank. Some data were personally supplied by Susanna Hajdu and Svante Nyberg (Stockholm University, Sweden), Sławomira Gromisz and Janina Kownacka (NMFRI Gdynia, Poland), as well as by Henrik Jespersen (Bornholms Regionskommune, Denmark) and Bente Brix Madsen (Orbicon, Denmark).

Seasonal and interannual trends (Figure 5.4.2)

The annual development of the phytoplankton is characterized by three blooms of different intensity, from which the summer bloom demonstrates a surprisingly high biomass whereas the spring and autumn blooms are mainly reflected in the chlorophyll data. In the spring bloom, a succession from diatoms to dinoflagellates occurs, but it is accompanied by *Mesodinium rubrum*, which may appear very early. Blooms of nitrogen-fixing cyanobacteria are typical in summer. The autumn bloom is dominated by diatoms (Wasmund and Siegel, 2008).

Since the start of the monitoring programme in 1979, the biomass in most phytoplankton groups is increasing. Dinoflagellates frequently form blooms in spring, and the intensity of their spring blooms has been increasing, mainly from 1990 to 1991. Another major group, the diatoms, forms spring, summer, and autumn blooms. Diatoms dominate the spring bloom in this area (Klais *et al.*, 2011). A slight, but non-significant, increasing trend is found in the diatoms. The annual-only analysis of this report does not show the decreasing trend in spring blooms, based on silicate consumption, noted in Wasmund *et al.* (1998). Obviously, some diatom blooms of the 1980s were not properly recorded owing to undersampling; therefore, the decreasing trend could not be proven on the basis of biomass data (Wasmund *et al.*, 2011). Despite the lack of a trend in diatom biomass, the diatoms:diatoms+dinoflagellates ratio during the spring bloom period demonstrated a slightly significant decrease.

The autotrophic ciliate *Mesodinium rubrum* has established itself as the third important group. It is strongly increasing in all seasons, especially from 1993 to 1994. Its short-term shift may be an artefact, because some contributors may have counted that ciliate to the phytoplankton only after 1993.

Changes in the smaller groups are statistically more significant, but the ecological importance of these groups is rather low owing to their small biomass. Prasinophytes and prymnesiophytes are increasing in almost all seasons. Especially the prymnesiophyte *Chrysochromulina polylepis* increased suddenly since the end of 2007 (Hajdu *et al.*, 2008). Cryptophytes increased if May and July were considered, and euglenophytes in the months March and November. Chrysophytes (including Dictyochophyceae) shifted from negative to positive anomaly from 1998 to 1999.

Cyanobacteria, which form blooms in July and August, decrease if only August is considered. The slight increase in April and May is less relevant as the biomass level is low in spring. Also, the chlorophytes decrease in July, August, and September, but this group is unimportant in the brackish water.

The general increase in phytoplankton biomass may be related to increasing temperature. The component concentrations of dissolved inorganic nitrogen (where DIN = NO_2 + NO_3 + NH_4) are decreasing in the data collected since 1979. Nitrogen is considered to be the limiting nutrient in the Baltic Proper, but its trend does not agree with that of the phytoplankton biomass. Only the decrease in chlorophytes is related to the DIN trend. Euglenophytes, dinoflagellates, and *Mesodinium rubrum* are negatively correlated to salinity. The increase in phytoplankton biomass was verified by an increase in chlorophyll *a* concentrations (Wasmund and Siegel, 2008).

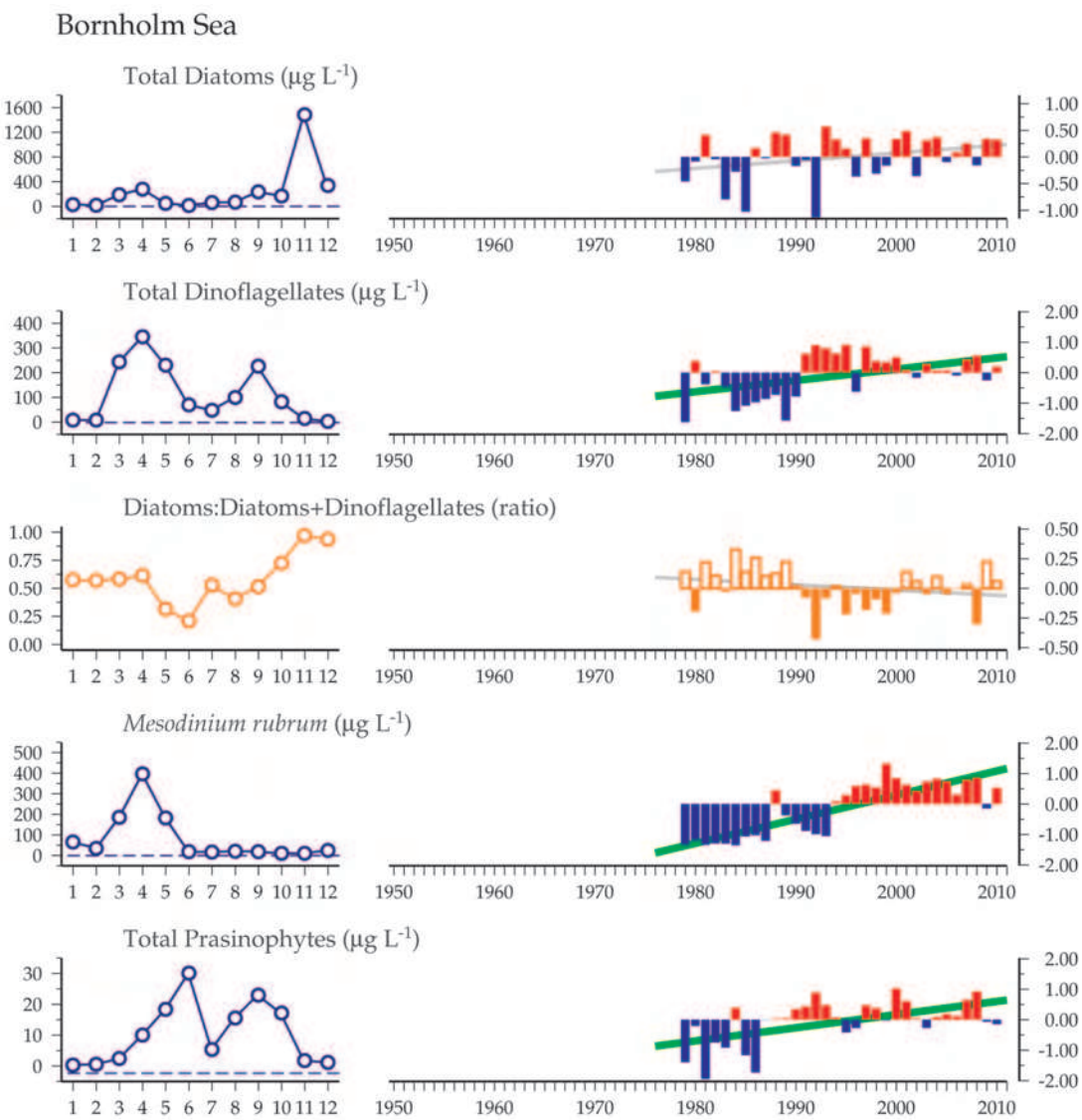
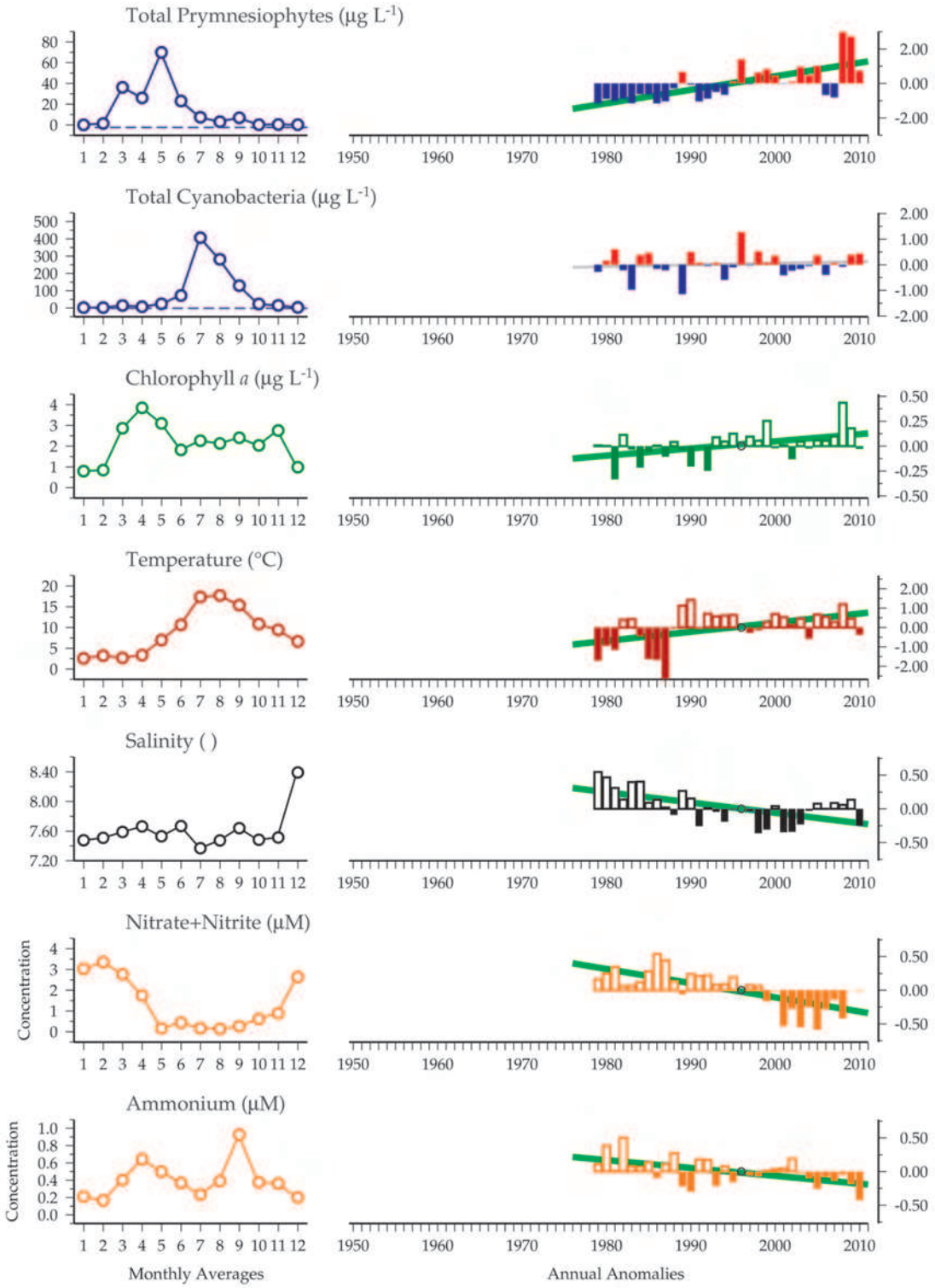


Figure 5.4.2 (continued on facing page)
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Bornholm Sea plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.


Total Prymnesiophytes (µg L-1)
Total Cyanobacteria (µg L-1)
Chlorophyll a (µg L-1)
Temperature (°C)
Salinity ( )
Nitrate+Nitrite (µM)
Ammonium (µM)
Concentration
Monthly Averages
Annual Anomalies

5.5 Arkona Sea (Site 25)

Norbert Wasmund and Günther Nausch

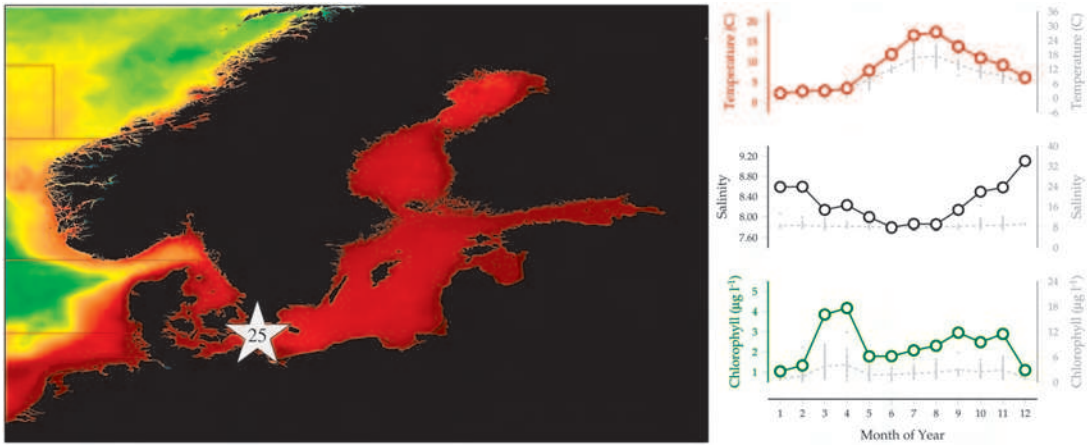


Figure 5.5.1
Location of the Arkona Sea plankton monitoring area (Site 25), plotted on a map of average chlorophyll concentration, and its corresponding environmental summary plot (see Section 2.2.1).

The Arkona Sea is part of the southern Baltic Proper, with a maximum depth of 47 m. In the frame of the international monitoring programme of the Helsinki Commission (HELCOM), four stations of the open sea were sampled: BMP K4, BMP K5, BMP K7, and BMP K8. The data from these stations are pooled to a representative dataset of this sea area. Only integrated surface samples of the upper 10 m are considered. Sampling and processing of the samples and the data were carried out according to the compulsory manual (HELCOM, 2010).

This analysis is based on data collected in the frame of the monitoring programme of the Helsinki Commission (HELCOM) and contributed by the riparian countries of the Baltic Sea. The data are available from the ICES databank. Some data were personally supplied by Susanna Hajdu and Svante Nyberg (Stockholm University, Sweden), as well as by Henrik Jespersen (Bornholms Regionskommune, Denmark) and Bente Brix Madsen (Orbicon, Denmark).

Seasonal and interannual trends (Figure 5.5.2)

The annual development of the phytoplankton is characterized by three blooms of different intensity. In the spring bloom, a succession from diatoms to dinoflagellates and/or *Mesodinium rubrum* occurs. In summer, large-celled diatoms may dominate the diverse community, whereas cyanobacteria blooms are only sparsely developed. The autumn bloom is dominated by diatoms (Wasmund and Siegel, 2008).

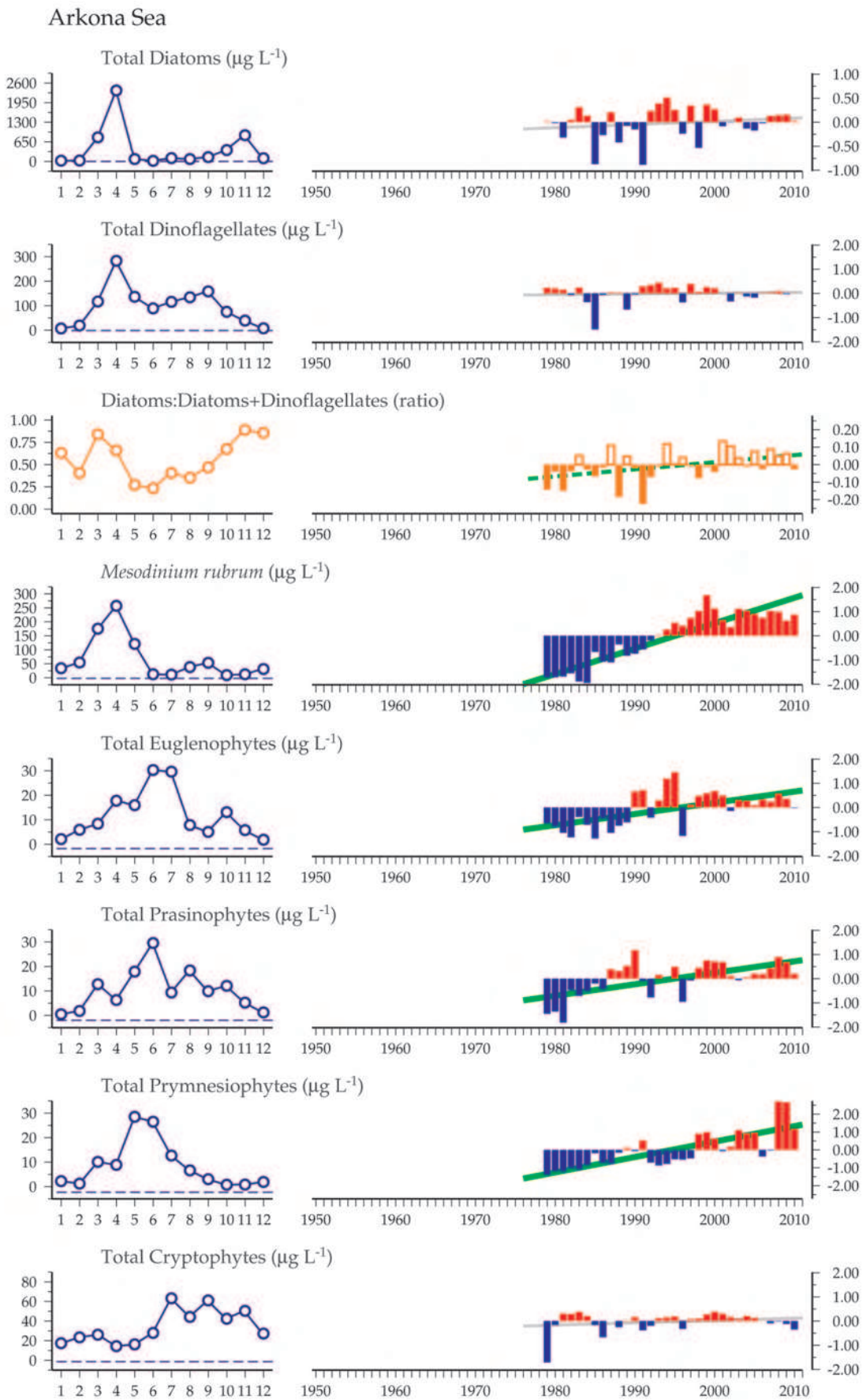
Since the start of the monitoring programme in 1979, the biomass in many phytoplankton groups is increasing. The important group of dinoflagellates may contribute to the spring blooms. It increased slightly if March and April are considered, but this increase was absent in the annual-level results of this study. Another important group, the diatoms, showed a spring bloom in March–April, but again had no general long-term trend at the annual level. The diatoms:diatoms+dinoflagellates ratio during the spring bloom is decreasing, but not as sudden as in the Bornholm Basin and the Eastern Gotland Basin. The autotrophic ciliate, *Mesodinium rubrum*, has established itself as the third most important group. It is strongly increasing in all seasons, especially from 1993 to 1994. This short-term shift may be an artefact because some contributors may have counted that ciliate to the phytoplankton only after the early 1990s. Independently of this problem, *Mesodinium rubrum* has also increased in datasets that included that species from the beginning of the observation.

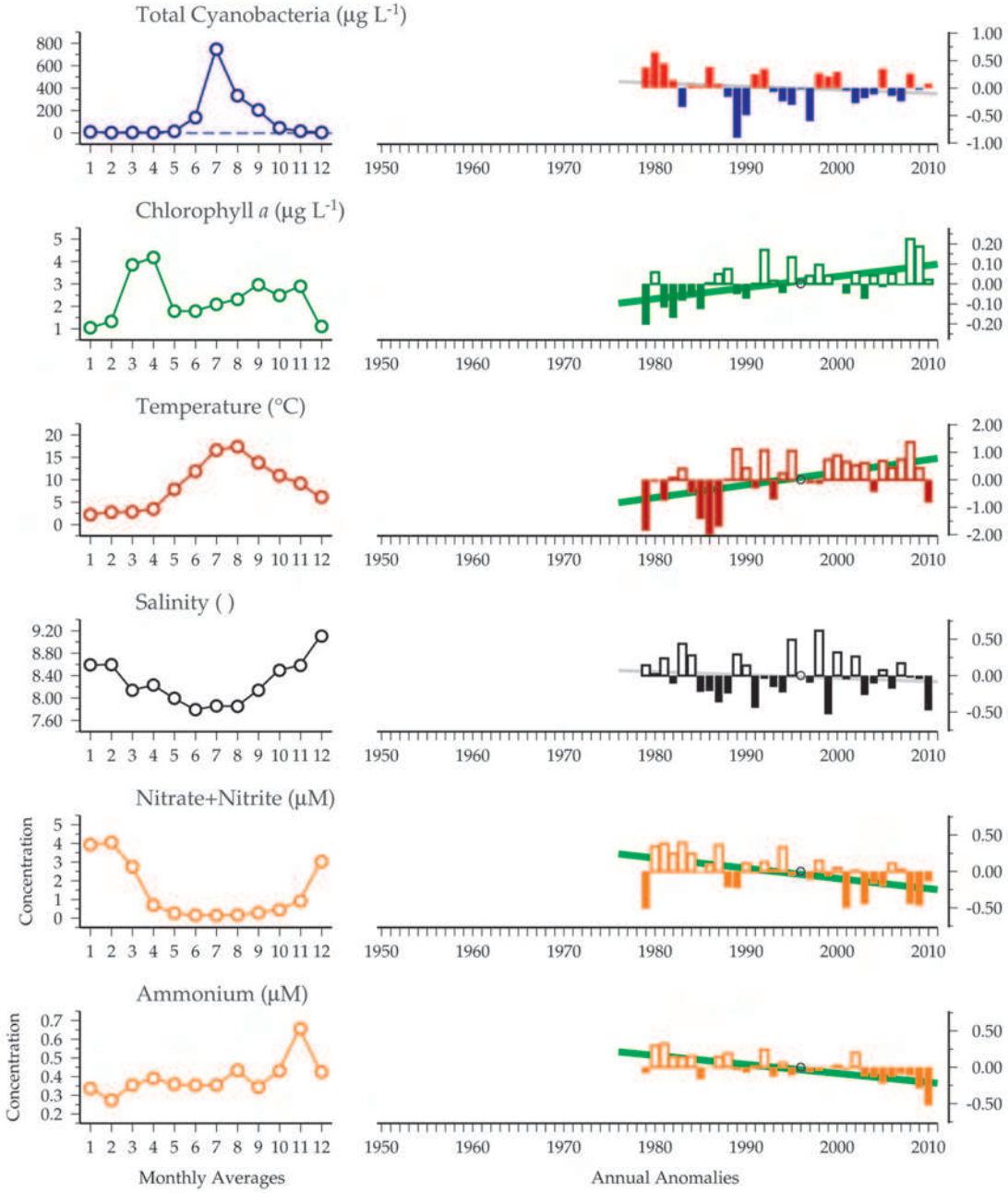
Changes in the smaller groups are statistically more significant, but the ecological importance of these groups is rather low owing to their small biomass. Euglenophytes, prasinophytes, and prymnesiophytes are increasing in all seasons, especially the prymnesiophyte, *Chrysochromulina polylepis*, which increased suddenly since the end of 2007 (Hajdu *et al.*, 2008). Cryptophytes exhibited a long-term increase in April and May mainly after 1991, but this may be caused only by a better identification after phytoplankton courses by the HELCOM Phytoplankton Expert Group (PEG). Chrysophytes (including Dictyochophyceae) shifted from negative to positive anomaly from 1998 to 1999 in all seasons.

The only major group that is strongly decreasing is the cyanobacteria. In July and August, when they may form blooms in the Arkona Sea, they showed mostly positive anomalies until 1987, and negative anomalies since the year 2000. On the other hand, cyanobacteria biomass increased strongly in March, April, and May. This increase is less relevant because the biomass level in spring is low compared with summer. This tendency was already found and thoroughly discussed by Wasmund *et al.* (2011).

The general increase in phytoplankton biomass may be related to increasing water temperatures. The concentrations of dissolved inorganic nitrogen (represented as NO_2 + NO_3 + NH_4) are decreasing in the long-term dataseries. Nitrogen is considered to be the limiting nutrient in the Baltic Proper, but its trend does not agree with that of the phytoplankton biomass. The increase in phytoplankton biomass was verified by an increase in chlorophyll *a* concentrations (Wasmund and Siegel, 2008).

Figure 5.5.2 (continued on facing page)
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Arkona Sea plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.




Total Cyanobacteria (µg L-1)
Chlorophyll a (µg L-1)
Temperature (°C)
Salinity ( )
Nitrate+Nitrite (µM)
Ammonium (µM)
Concentration
Monthly Averages
Annual Anomalies

5.6 Mecklenburg Bight (Site 26)

Norbert Wasmund and Günther Nausch

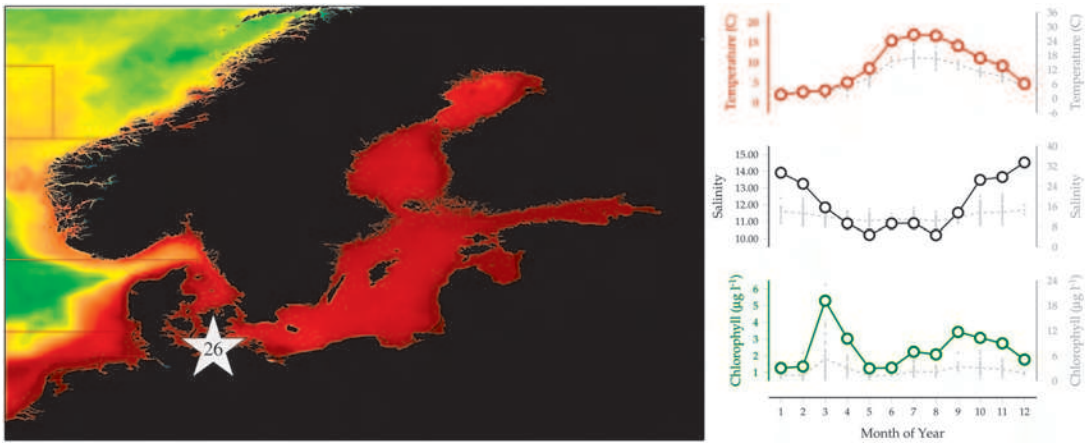


Figure 5.6.1
Location of the Mecklenburg Bight plankton monitoring area (Site 26), plotted on a map of average chlorophyll concentration, and its corresponding environmental summary plot (see Section 2.2.1).

The Mecklenburg Bight is part of the Belt Sea within the western Baltic Sea. Its maximum depth is 27 m. The area is influenced by periodical inflow of marine water or outflow of Baltic brackish water and, therefore, is highly variable. In the frame of the international monitoring programme of the Helsinki Commission (HELCOM), three stations were sampled: BMP M1 (54°28'N 12°13'E), BMP M2 (54°18.9'N 11°33'E), and O22 (54°6.6'N 11°10.5'E). The data of these stations are pooled to a representative dataset of this sea area. Only integrated surface samples of the upper 10 m are considered. Sampling and processing of the samples and the data was carried out according to the compulsory manual (HELCOM, 2010).

This analysis is based on data collected in the frame of the monitoring programme of the Helsinki Commission (HELCOM) and contributed by the riparian countries of the Baltic Sea. The data are available from the ICES databank.

Seasonal and interannual trends (Figure 5.6.2)

The annual development of the phytoplankton is characterized by three blooms of different intensity, from which the summer bloom demonstrates a surprisingly high biomass, whereas the spring and autumn blooms are mainly reflected in the chlorophyll data. The spring bloom is, in most years, dominated by diatoms, but in some years also by Dictyochophyceae, which are included in the chrysophytes in this study. Dinoflagellates and *Mesodinium rubrum*, which contribute significantly to the spring bloom in the Baltic Proper, are of minor importance in the Mecklenburg Bight in spring. Also, cyanobacteria biomass does not normally grow up to bloom concentrations. However, the diatoms can reach a second peak in summer. The autumn bloom is dominated by dinoflagellates and/or diatoms (Wasmund and Siegel, 2008).

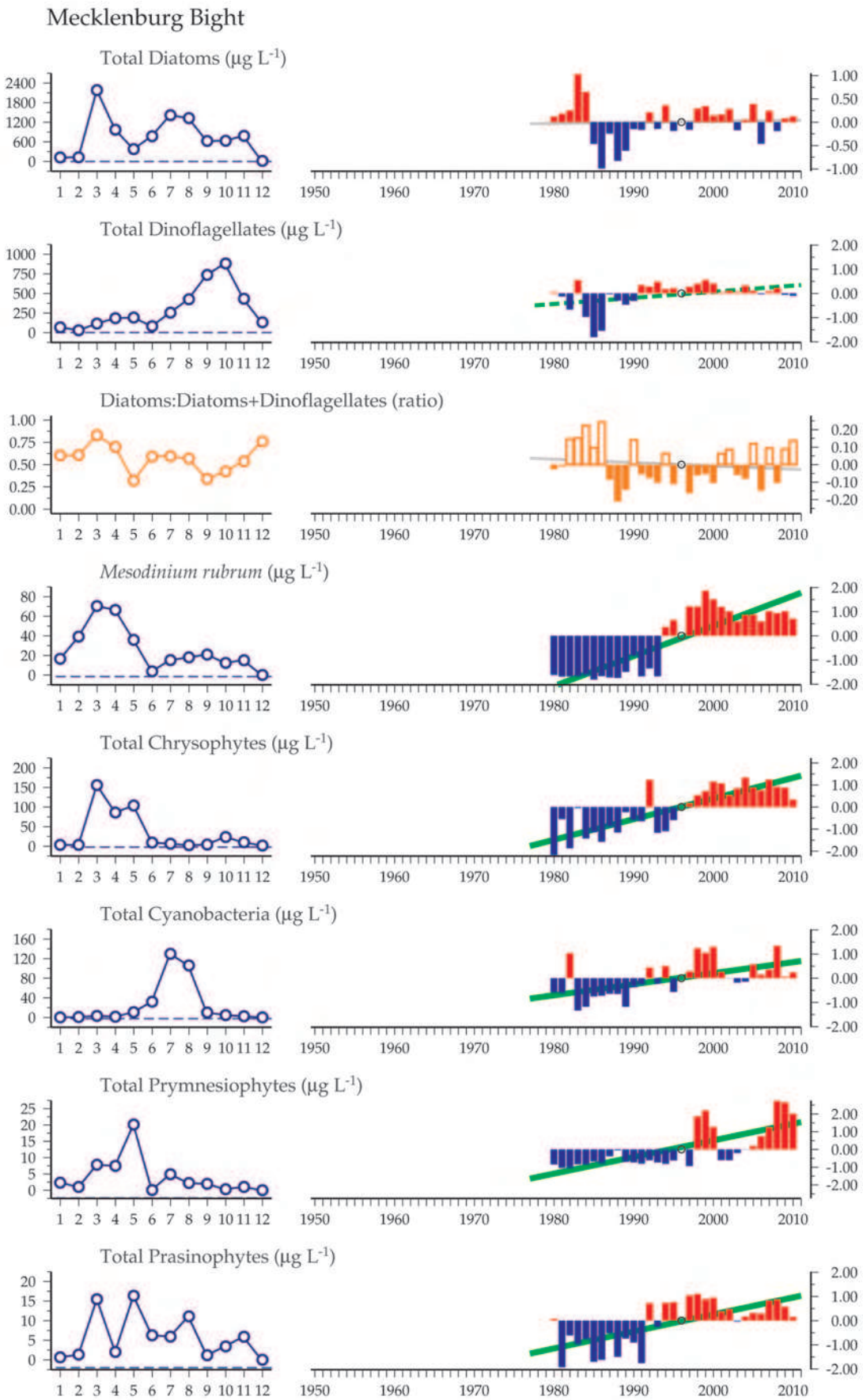
Since the start of the monitoring programme in 1979, the biomass of phytoplankton groups is decreasing in spring but increasing in summer in this area, as demonstrated by Wasmund *et al.* (2011). The important group of dinoflagellates is increasing, mainly in March. On the other hand, diatom spring biomass is decreasing. As a result, the diatoms:diatoms+dinoflagellates ratio during the spring bloom period is decreasing. The Dictyochophyceae (i.e. chrystophytes) become more important in spring. The autotrophic ciliate *Mesodinium rubrum* increased in the Baltic Proper, but probably the result of a changed counting strategy (cf. chapter on the Arkona Sea). The cyanobacteria biomass is increasing. Monthly

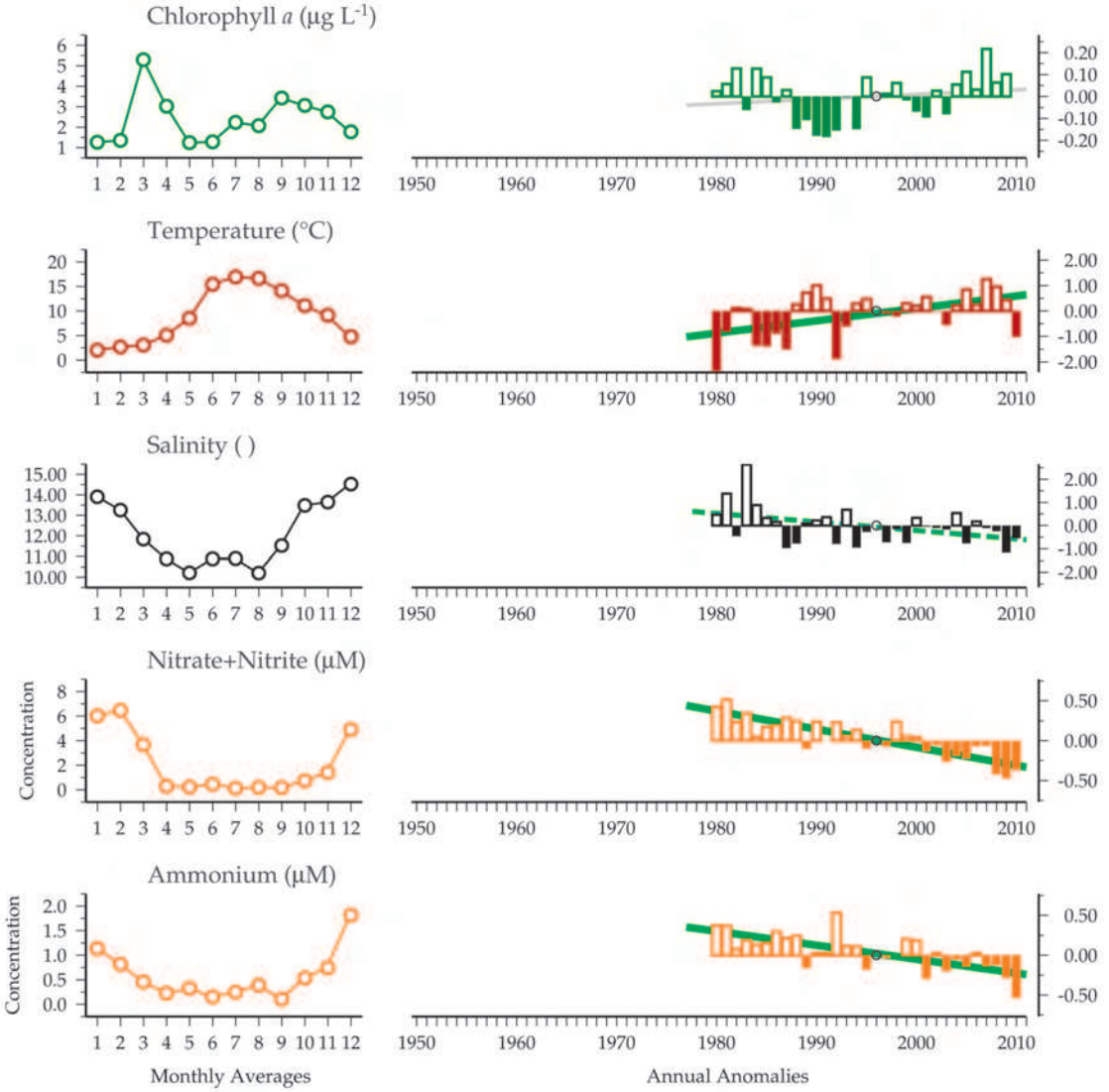
analysis finds no trend in summer, and the increase is evident only in the months of April and September, when their biomass is generally low, and an increase can be detected.

Changes in the smaller groups are statistically more significant, but the ecological importance of these groups is rather low owing to their small biomass. The prymnesiophytes and prasinophytes increased in all seasons, with the prymnesiophytes increasing especially since the end of 2007 (Hajdu *et al.*, 2008).

A general increase in temperature was also detected in the Mecklenburg Bight. The concentrations of the main components of dissolved inorganic nitrogen (i.e. DIN = NO_2+NO_3 + NH_4) were decreasing in the long-term dataseries. Nitrogen is considered to be the limiting nutrient in the Baltic Proper, but its trend does not agree with that of the phytoplankton biomass. Chrysophytes, prymnesiophytes, prasinophytes, and *Mesodinium rubrum* are negatively correlated to this DIN trend. The chlorophyll *a* concentration is not correlated to any other parameter and demonstrates no general trend. Only seasonal-level trends (January–March) reveal a significantly decreasing trend in the chlorophyll *a* concentrations.

Figure 5.6.2 (continued on facing page)
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Mecklenburg Bight plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.




Chlorophyll a (µg L-1)
Temperature (°C)
Salinity ( )
Nitrate+Nitrite (µM)
Ammonium (µM)
Concentration
Concentration
Monthly Averages
Annual Anomalies

5.7 Kattegat and Skagerrak Monitoring (Sites 27–29)

Marie Johansen

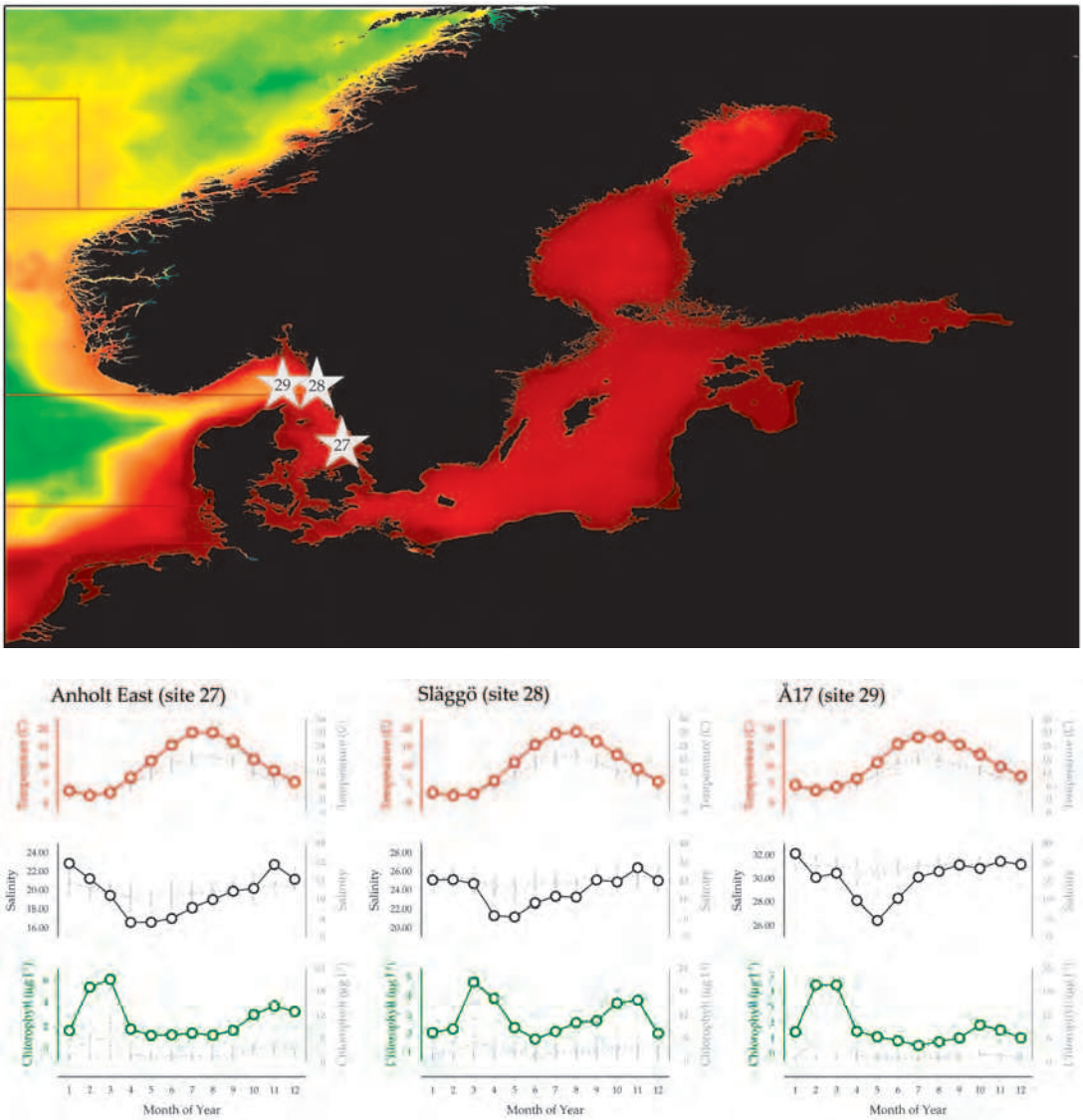


Figure 5.7.1
Locations of the Kattegat and Skagerrak plankton monitoring areas (Sites 27–29), plotted on a map of average chlorophyll concentration, and their corresponding environmental summary plots (see Section 2.2.1).

The Kattegat is the transition area between the Baltic and North seas. It is included as part of the Baltic Sea in the HELCOM Convention area, but also as part of the North Sea in the OSPAR Convention. The mean depth is only ca. 20 m, and half the area has a depth of < 25 m (Fonselius, 1995), although the maximum depth exceeds 90 m at the northern, Skagerrak boundary. Close to the Swedish coastline, it has a connection with Skagerrak deep water through a deeper channel with elongated basins that run in a mainly north–south direction. The Kattegat has a strong halocline, with an average salinity of around 23 in the upper part (0–15 m) and ca. 32–33 in the deep water (below 60–80 m; Dyrssen, 1993). Surface water generally comes from the low saline Baltic Proper via the Danish Straits, whereas the North Sea delivers more saline deeper waters from the north. The Baltic outflow from the Danish Straits coalesces in the eastern Kattegat to form the north-flowing Baltic Current. At the northern limit of the Kattegat, North Sea water from the Jutland Coastal Current splits, with some flowing as a bottom current into the Kattegat, whereas the remainder eventually combines with the Baltic Current, which is further augmented by significant freshwater outflows as it becomes the Norwegian Coastal Current in the Skagerrak. The Kattegat, thereby, forms a hydrographic transition zone between the Baltic Sea and the North Sea, with a substantially higher salinity range (and variability) than in nearby sea areas.

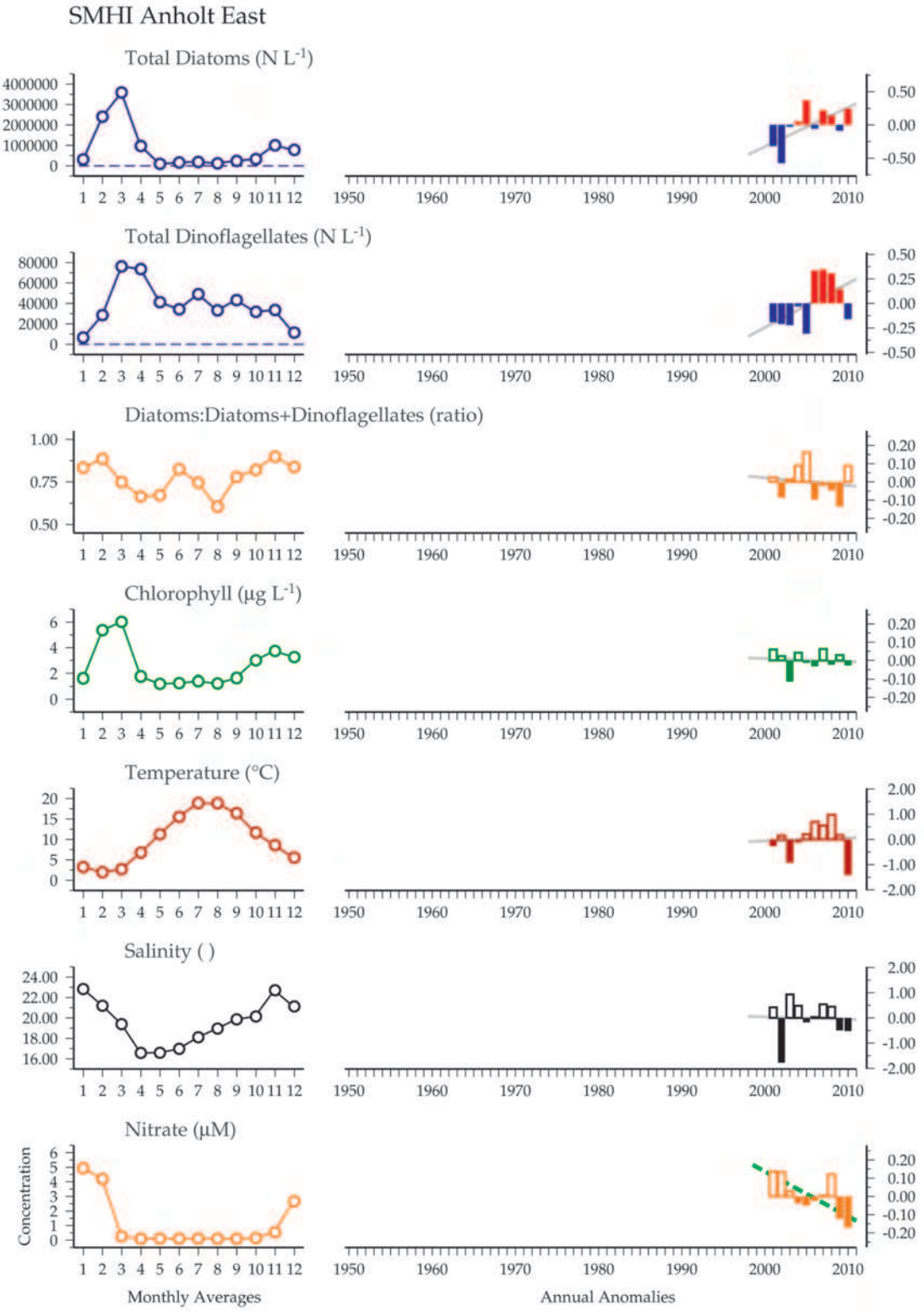
In the frame of the international monitoring programme of the Helsinki Commission (HELCOM), two stations are sampled by SMHI (Swedish Meteorological and Hydrological Institute) in the Kattegat; Anholt East (Site 27, 56°40'N 12°07'E) and N14 Falkenberg (56°56.40'N 12°12.7'E). Station N14 Falkenberg has only been sampled for a couple of years and is not included in the graphs. Two stations are sampled in the Skagerrak Släggö (Site 28, 58°15.5′N 11°26′E) and Å17 (Site 29, 58°16.5′N 10°30.8′E). Sampling and sample processing are conducted according to the HELCOM COMBINE manual for phytoplankton (HELCOM, 2010). All individuals were taxonomically identified to the lowest possible taxonomic level, but were presented as general taxonomic groups in the study. Data for 2002–2010 are presented, with a gap of no data in 2003.

Seasonal and interannual trends (Figures 5.7.2, 5.7.3, and 5.7.4)

Although seasonal patterns and magnitudes of temperatures across the three sites were comparable, average salinities increased from 20 to 25 to 30 as the site location moved from east to west (approaching the North Sea). All three sites featured a 6–8 psu seasonal difference in salinity between the higher-salinity winter and lower-salinity summer periods. Chlorophyll concentrations exhibited a large March peak, followed by a significantly smaller October/November peak. The spring phytoplankton population was numerically dominated by diatoms in all three sites. The seasonal abundance of dinoflagellates peaked during this spring period only at the Anholt East site, whereas this period was the seasonal lowest abundance for dinoflagellates at the other two sites. This relationship between diatoms and dinoflagellates was less clear in terms of the diatoms:diatoms+dinoflagellates ratio plots. In all three sites, the diatom maximum abundance and decrease corresponded to nitrogen availability, with dinoflagellates becoming more abundant during the low nitrogen periods.

Interannual trends within the three sites were not conclusive. This is likely the result of the combination of the relative shortness of sampling years in each site, combined with strong variability owing to the dynamic hydrographic conditions present within each of the sites.

Figure 5.7.2
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Anholt East plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.



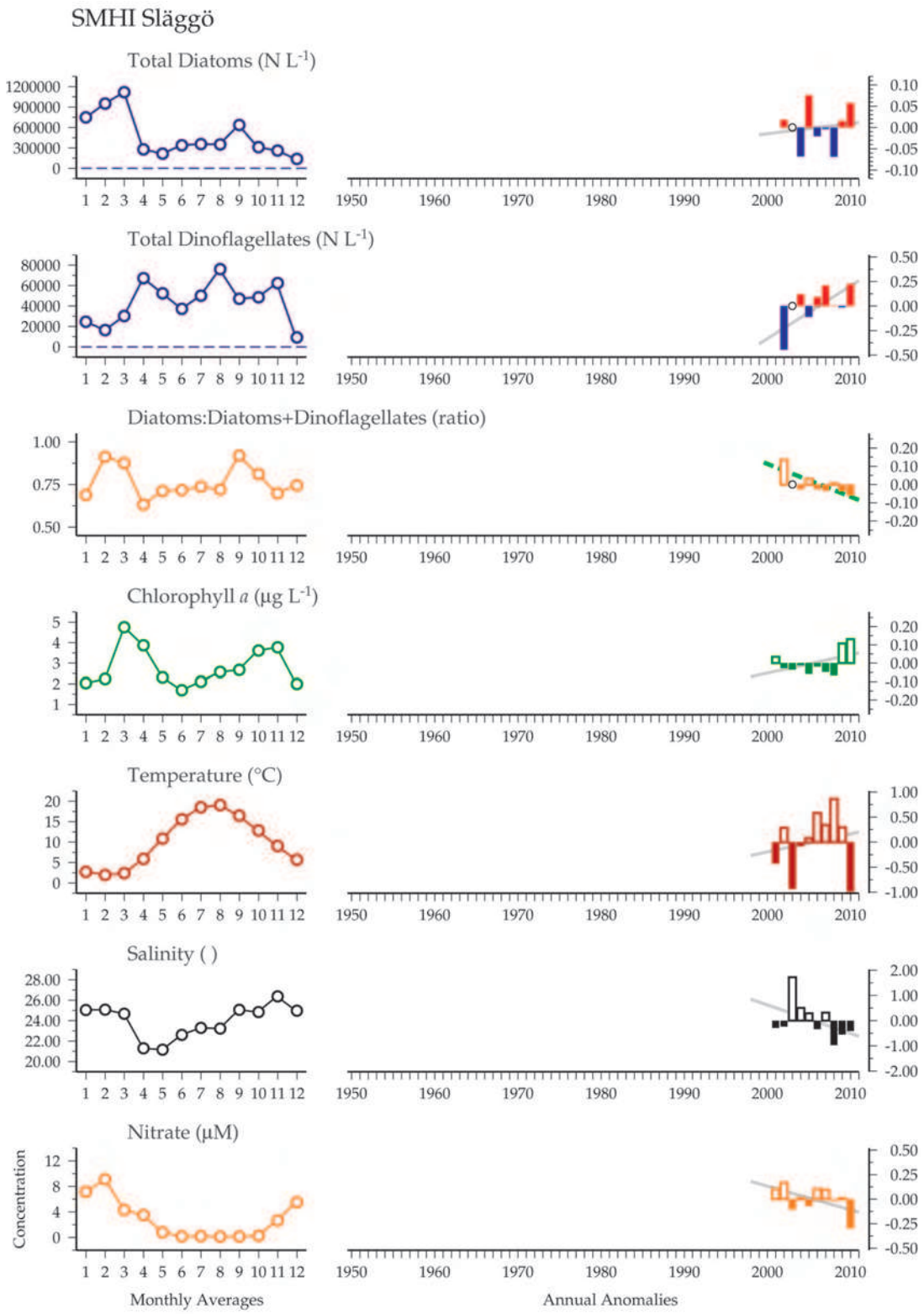


Figure 5.7.3
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Släggö plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.

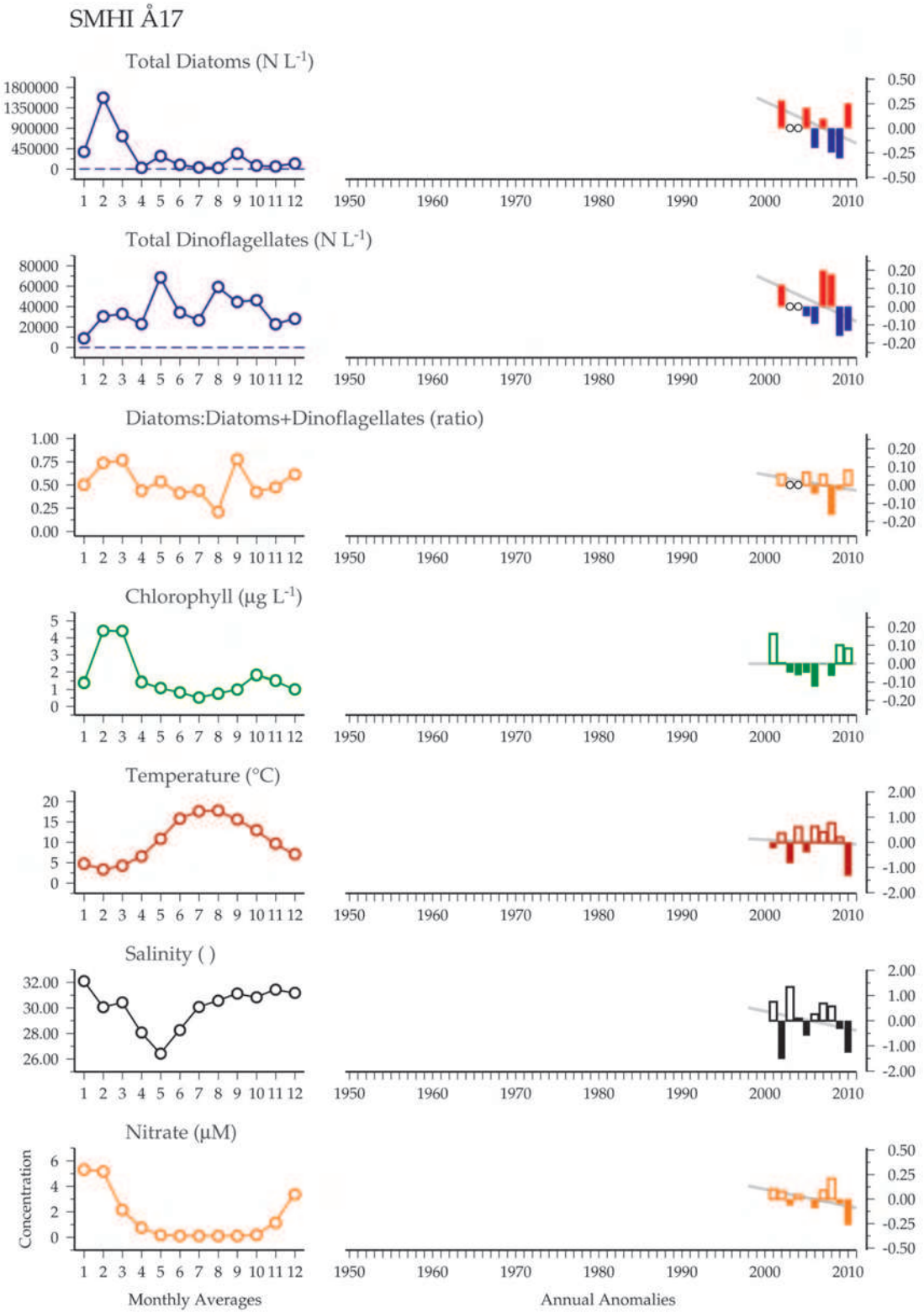



Figure 5.7.4
Multiple-variable comparison plot (see Section 2.2.2) showing the seasonal and interannual properties of select cosampled variables at the Å17 plankton monitoring site. Additional variables from this site are available online at http://wgpme.net/time-series.