

Phytoplankton trends in the Baltic Sea

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Monitoring data of phytoplankton abundance and biomass (1979–1999) and Chl. *a* (1979–2000) from surface samples (0–10 m) of the Kattegat, Belt Sea and Baltic proper were investigated for long-term trends. The Mann–Kendall test as well as the LOESS smoother was applied for three taxonomic groups in spring, summer and autumn separately. Chl. *a* trends were analysed by linear regression. Downward trends were found for diatoms in spring and summer whereas dinoflagellates generally increased in the Baltic proper but decreased in the Kattegat. In autumn, diatoms increased at some stations. For cyanobacteria, downward trends were detected mainly in the Kattegat/Belt Sea area. Chl. *a* concentrations showed a general decrease in the Kattegat/Belt Sea area but an increase in the Baltic proper. Observed changes in trends during the two decades might indicate shifts in the ecosystem.

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Introduction

Eutrophication is considered one of the most serious environmental problems in the Baltic Sea (Larsson *et al.*, 1985; Elmgren, 1989; Rosenberg *et al.*, 1990; Nehring, 1992). It is caused by increased nutrient input from the densely populated and intensively cultivated catchment area and from the atmosphere, resulting in an increase in phytoplankton biomass, primary production and turbidity in the euphotic zone and oxygen deficit in deep water layers. 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 the aims was to investigate long-term trends in trophic conditions by the Baltic Monitoring Programme (BMP), which has been conducted since 1979 according to a coordinated sampling schedule and with binding methods.

The winter concentrations of phosphate and nitrate showed positive overall trends in the surface water of all sub-regions of the Baltic proper for the period 1969–1993, with a considerable increase between 1969 and 1978/1983, and subsequent stabilization on a high level and with high variability (Nausch and Nehring, 1996). Comparing the first and second

half of the 1990s, phosphate concentrations in the upper mixed layer of the western Baltic Sea and the Baltic proper decreased significantly, whereas nitrate concentrations did not show a significant decrease (Matthäus *et al.*, 2001).

As primary production is, at least in the summer months, limited mainly by nitrogen (Granéli *et al.*, 1990), phytoplankton biomass should be correlated with nitrogen concentrations. Total phytoplankton biomass can be reflected by Chl. *a* concentration because this constitutes the dominant pigment of photo-autotrophic organisms. Therefore, HELCOM bases its periodic assessments of the state of the marine environment also on Chl. *a* trends. In the 'First Periodic Assessment' (HELCOM, 1987), a significant increase in August Chl. *a* data from the Baltic proper and Mecklenburg Bight was found from 1975–1978 to 1980–1983. The summer values from 1979 to 1988 exhibited an increasing trend in Kiel Bight and Mecklenburg Bight (HELCOM, 1990). The analysis of a 15-year data series (1979–1993; HELCOM, 1996) revealed increasing concentrations at some stations in the Baltic proper but no longer in the Kattegat/Belt Sea area. The data set from 1979 to 1998 (HELCOM, 2002), showed a positive trend only in the Arkona Sea.

Unlike nutrients and Chl. *a*, phytoplankton composition of the Baltic proper has not been analysed statistically for trends by HELCOM and in earlier investigations (Kononen and Niemi, 1984). Reasons for this might include the complicated structure and incomplete quality assurance of the phytoplankton data bank, high variability in species composition for natural and methodological reasons, and data inhomogeneity created by different phytoplanktologists with different skills. Changes in phytoplankton composition may, however, reflect major structural and functional shifts in the ecosystem. Such changes have occurred at both species (e.g. *Prorocentrum minimum*: Hajdu *et al.*, 2000) and higher taxonomic levels (diatom/dinoflagellates: Wasmund *et al.*, 1998; cyanobacteria: Finni *et al.*, 2001).

Our aim is to analyse the 21-year long series of phytoplankton data for trends in abundance and biomass of the most important algal groups for different seasons separately. Different responses among different groups may help to identify indicators of environmental impact on

biodiversity and ecosystem structure, because they are sensitive to eutrophication.

Area of investigation

The Baltic Sea is a shallow intra-continental shelf sea (415 023 km²; mean depth 52 m) that is connected with the North Sea and Atlantic Ocean via the Skagerrak, Kattegat, Sound (Øresund) and Belt Sea (Great Belt, Little Belt, Kiel Bight and Mecklenburg Bight) represent the transitional area between North Sea and Baltic proper, and its shallow straits limit water exchange between the two. The Baltic proper (211 069 km²) stretches from Darss Sill to the entrances to the Gulfs of Riga, Finland and Bothnia and comprises different basins (Figure 1; Table 1) that are stratified by a deep, permanent halocline and a summer thermocline at a depth of 10–30 m. The salinity of surface water decreases to the east and north (Table 1).

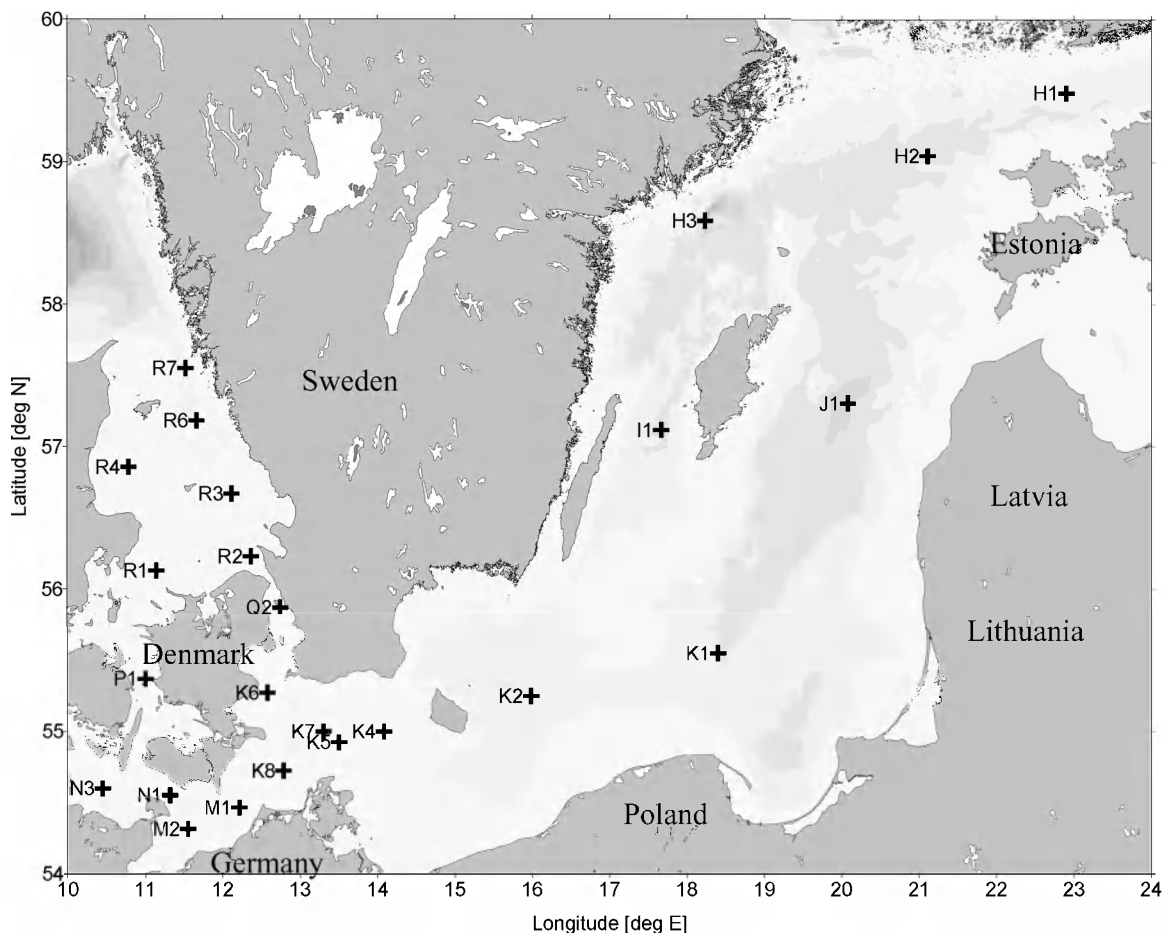


Figure 1. The monitoring stations in the Baltic Sea investigated (for areas see Table 1).

Table 1. Characterization of the Baltic Sea areas investigated in terms of surface area (Ehlin *et al.*, 1974) and surface salinity (for details see Janssen *et al.*, 1999) with identification of representative stations and definition of seasons (after HELCOM, 1996).

Area	km ²	Salinity	Stations	Season definition
Kattegat	22 043	15–32	R1, R2, R3, R4, R6, R7	Spring: February–April Summer: May–August Autumn: September–November
Sound	1243	8–20	Q2	
Belt Sea	19 109	9–24	M1, M2, N1, N3, P1	
Arkona Sea	18 673	7.3–10.4	K4, K5, K6, K7, K8	Spring: March–May Summer: June–September Autumn: October–December
Bornholm Sea	38 990	7.0–8.1	K2	
Eastern Gotland Sea	62 633	6.8–7.5	K1, J1	
Western Gotland Sea	34 221	6.2–7.6	I1	
Northern Baltic proper	29 067	5.6–7.0	H1, H2, H3	

Data

Data from the HELCOM database for 1979–1993 were supplemented with data collected within the monitoring framework from 1994 to 1999 and ascertained by the institutes participating: National Environmental Research Institute Roskilde (only abundance data up to 1997), Swedish Meteorological and Hydrological Institute (up to 1998), Institute for Systems Ecology at Stockholm University (up to 1998), Centre of Marine Research Klaipeda (up to 1998), Estonian Marine Institute (up to 1999), Marine Biology Centre of the Polish Academy of Sciences in Gdynia (only Chl. *a* up to 1998) and Baltic Sea Research Institute Warnemünde (up to 1999; Chl. *a* up to 2000). Most data were collected using identical methods, stipulated in the HELCOM (1988) manual. Only samples from a depth of 0–10 m were considered. For Chl. *a*, results from 1, 2.5, 5, 7.5 and 10 m were averaged, whereas phytoplankton samples from these depths were pooled by mixing equal amounts after sampling.

Deviating from the manual, some contributors extracted Chl. *a* from Whatman GF/F filters using 90% acetone, but ensured that the results of their methods were comparable with those of the method prescribed. Absorbance of the extract was measured in a spectrophotometer or fluorometer before and after acidification (Lorenzen, 1967). Phytoplankton was preserved with acetic Lugol solution (KI/I₂), sedimented according to the method of Utermöhl (1958) and counted in an inverted microscope while assigned to species and size classes. Cell volume was calculated from size measurements by using an appropriate stereometric equation and converted to wet weight values assuming that plasma density is equal to water density ($\sim 1 \text{ mg mm}^{-3}$).

Before analysis, each data set was inspected and corrected for input errors. Mixed samples representing a depth range >10 m were excluded. This reduced the number of total phytoplankton species records to 74 950. Because of apparent errors, biomass was recalculated on the basis of counted units, individual cell volume and counting coefficients. Each species name was supplemented with an identifier of the corresponding taxonomic class. Only stations for which sufficient data were available were

considered, while stations with gaps >2 years in the time series were excluded. The remaining 24 stations (Figure 1; Table 2) are largely representative for the central parts of the respective sea areas and were covered by 51–193 samplings per station (excluding winter), with an average of 110 ± 47 . Biomass analyses for most Kattegat stations had to be omitted because of lacking data.

The seasonal phytoplankton development is characterized by spring, summer and autumn blooms of different algal groups (HELCOM, 1996). Only the three most important classes were analysed separately for each station and season, thereby avoiding potential errors in species identification. As the timing of the blooms differs among areas, the definition of the relevant seasons has been adapted accordingly (Table 1). The period for the spring bloom in the Kattegat may not have been appropriate, because blooms occurred as early as January and February in 1997 and 1998 owing to periods of calm and sunny weather. The winter period was generally represented by insufficient data and has therefore not been considered.

Statistical analysis

Phytoplankton concentrations are extremely variable in time and space, as reflected in observations for a given taxon measured at a single station. Aggregating data is a useful way to reduce this variability, especially if sampling is infrequent. Analyses involved logarithmic transformation of the arithmetic mean over all samples for a station within a season. Trend tests were (1) the non-parametric Mann–Kendall (Kendall, 1975) test for a monotonic downward or upward trend, complemented by the Theil slopes of the linear trend line and (2) the test based on the non-linear LOESS smoother.

The Mann–Kendall test is efficient and outlier-resistant in case of a linear trend, but cannot be applied for assessing non-monotonic or highly non-linear trends. The test based on the LOESS smoother (Fryer and Nicholson, 1999; Uhlig, 2001) can also be applied for non-linear and non-monotonic trends, but is not outlier-resistant and the corresponding test examines the underlying linear trend component only. The test statistic is derived from the estimate of the linear trend

Table 2. Results of two methods of trend analysis (MK: Mann–Kendall; LOESS) for (a) abundance and (b) biomass of three phytoplankton groups by season (D, downward; U, upward; empty field, not significant; n.a., not available).

Station	Period	Method	Bacillariophyceae			Dinophyceae			Cyanobacteria		
			Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn
<i>(a) Abundance (24 stations)</i>											
H1	1980–1995	MK									U
		LOESS									
H2	1980–1996	MK					U				
		LOESS					U				
H3	1979–1996	MK									
		LOESS									
I1	1979–1996	MK	D		U	U			D		
		LOESS	D		U	U					
J1	1979–1999	MK				U					
		LOESS	D			U					
K1	1979–1999	MK				U					
		LOESS				U					
K2	1979–1999	MK				U					
		LOESS				U					
K4	1979–1999	MK		D		U					
		LOESS		D		U					
K5	1981–1999	MK				U					
		LOESS									
K6	1985–1993	MK							U		
		LOESS							U		
K7	1979–1997	MK								D	D
		LOESS									D
K8	1989–1999	MK						U			
		LOESS									
M1	1980–1999	MK									
		LOESS									
M2	1980–1999	MK					U				n.a.
		LOESS									n.a.
N1	1979–1997	MK	D								
		LOESS					U				
N3	1986–1999	MK			U	U	U		n.a.		n.a.
		LOESS			U	U	U		n.a.		n.a.
P1	1979–1997	MK							n.a.	D	
		LOESS		D					n.a.	D	
Q2	1979–1997	MK							n.a.	D	D
		LOESS					D		n.a.	D	
R1	1979–1997	MK					D		n.a.	D	D
		LOESS		D			D		n.a.	D	D
R2	1985–1993	MK	D				D		n.a.	n.a.	n.a.
		LOESS	D				D		n.a.	n.a.	n.a.
R3	1979–1997	MK					D		n.a.		n.a.
		LOESS							n.a.		n.a.
R4	1981–1997	MK	D	D		D	D		n.a.	D	n.a.
		LOESS		D		D	D		n.a.	D	n.a.
R6	1980–1993	MK	D						n.a.	n.a.	n.a.
		LOESS	D						n.a.	n.a.	n.a.
R7	1980–1993	MK		U	U				n.a.	n.a.	n.a.
		LOESS			U				n.a.	n.a.	n.a.
<i>(b) Biomass (15 stations)</i>											
H1	1980–1999	MK	D						U		
		LOESS							U		
H2	1980–1999	MK	D						U		
		LOESS	D						U		
H3	1979–1996	MK							n.a.	n.a.	n.a.
		LOESS							n.a.	n.a.	n.a.
I1	1979–1996	MK			U	U			D		
		LOESS			U	U					
J1	1979–1999	MK	D			U		U	U		U
		LOESS	D					U	U		U

Table 2 (continued)

Station	Period	Method	Bacillariophyceae			Dinophyceae			Cyanobacteria		
			Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn
K1	1979–1999	MK				U					U
		LOESS				U					U
K2	1979–1999	MK				U				D	
		LOESS				U				D	
K4	1979–1999	MK				U	D				
		LOESS				U	D				
K5	1981–1999	MK				U					
		LOESS				U					
K8	1989–1999	MK				U					
		LOESS				U					
M1	1980–1999	MK	D		U						
		LOESS									
M2	1980–1999	MK					U				n.a.
		LOESS					U				n.a.
N3	1986–1999	MK			U				n.a.	D	n.a.
		LOESS			U				n.a.	D	n.a.
R6	1980–1996	MK	D						n.a.	n.a.	n.a.
		LOESS			U				n.a.	n.a.	n.a.
R7	1980–1993	MK	D		U				n.a.	n.a.	n.a.
		LOESS							n.a.	n.a.	n.a.

component and the residual variance of the LOESS smoother (Hastie and Tibshirani, 1990).

Results

The results of trend analyses for abundance and biomass by the two methods are compiled in Table 2. Graphs with the LOESS smoother are shown only for significant biomass trends (Figure 2). Both abundance and biomass of diatoms (Bacillariophyceae) revealed significant downward trends in spring and summer in some areas (Figure 2a–f). Also in those areas where trends were not significant, concentrations tended to decline. However, upward trends were found in autumn in the western Gotland Sea, Belt Sea and Kattegat (Figure 2g–k). In the remaining areas of the Baltic proper, autumn trends were not significant because strong diatom autumn blooms in 1988 and 1989 caused an upward tendency in the 1980s and a downward tendency in the 1990s.

For dinoflagellate (Dinophyceae) abundance, upward trends were found in all seasons in the Baltic proper and the Belt Sea, whereas downward trends were found in the Kattegat and Sound. These upward trends are supported by biomass data (Figure 2l–u), except for Station K4.

Cyanobacteria occur in high biomass in the Baltic proper in summer. Summer cyanobacteria exhibit downward trends (Figure 2z–aa), mainly caused by strong blooms in the beginning of the 1980s. Spring and autumn upward trends (Figure 2v,w,y, ab–ac) are of less relevance for the ecosystem because biomass levels are relatively low at those times of the year.

Available Chl. *a* data were used in simple linear analysis to enable direct comparisons with earlier analyses. A

significant ($p = 0.05$) negative slope of the regression line was found at station M2 (Figure 3a). In the central Arkona Sea, a significant ($p = 0.01$) increase could be ascertained if the three closely located stations K4, K5 and K7 were pooled (Figure 3b). The tendency in Chl. *a* concentrations, although not significant, is downward at all stations in the Kattegat/Belt Sea area and upward in the Baltic proper.

Discussion

The main trend observed in diatoms was the significant reduction in the spring blooms in many areas: northern Baltic proper (Stations H1, H2), Gotland Sea (I1, J1), Belt Sea (M1, N1) and Kattegat (R2, R4, R6, R7). In contrast, autumn diatom biomass reached higher levels in the 1990s than in the 1980s (Figure 2g–k). In the southern Baltic proper (K1–K8), the spring decline was not significant. Wrzolek (1996) and Wasmund *et al.* (1998) noted a reduction in spring diatom biomass also for this area. Trzosińska and Łysiak-Pastuszak (1996) noted a drop in silicate demand and a reduction in the annual amplitudes of silicate concentrations in the Gdańsk Basin. Wasmund *et al.* (1998) also detected a reduced silicate consumption in spring particularly since 1989 or 1990. In these years, a period of mild winters started. During mild winters, surface temperature does not fall below the temperature at which the water density is highest. Therefore, the water column remains stratified and deep mixing is prevented. Diatoms need mixed waters whereas flagellates take advantage of a stable water column (Harrison *et al.*, 1986).

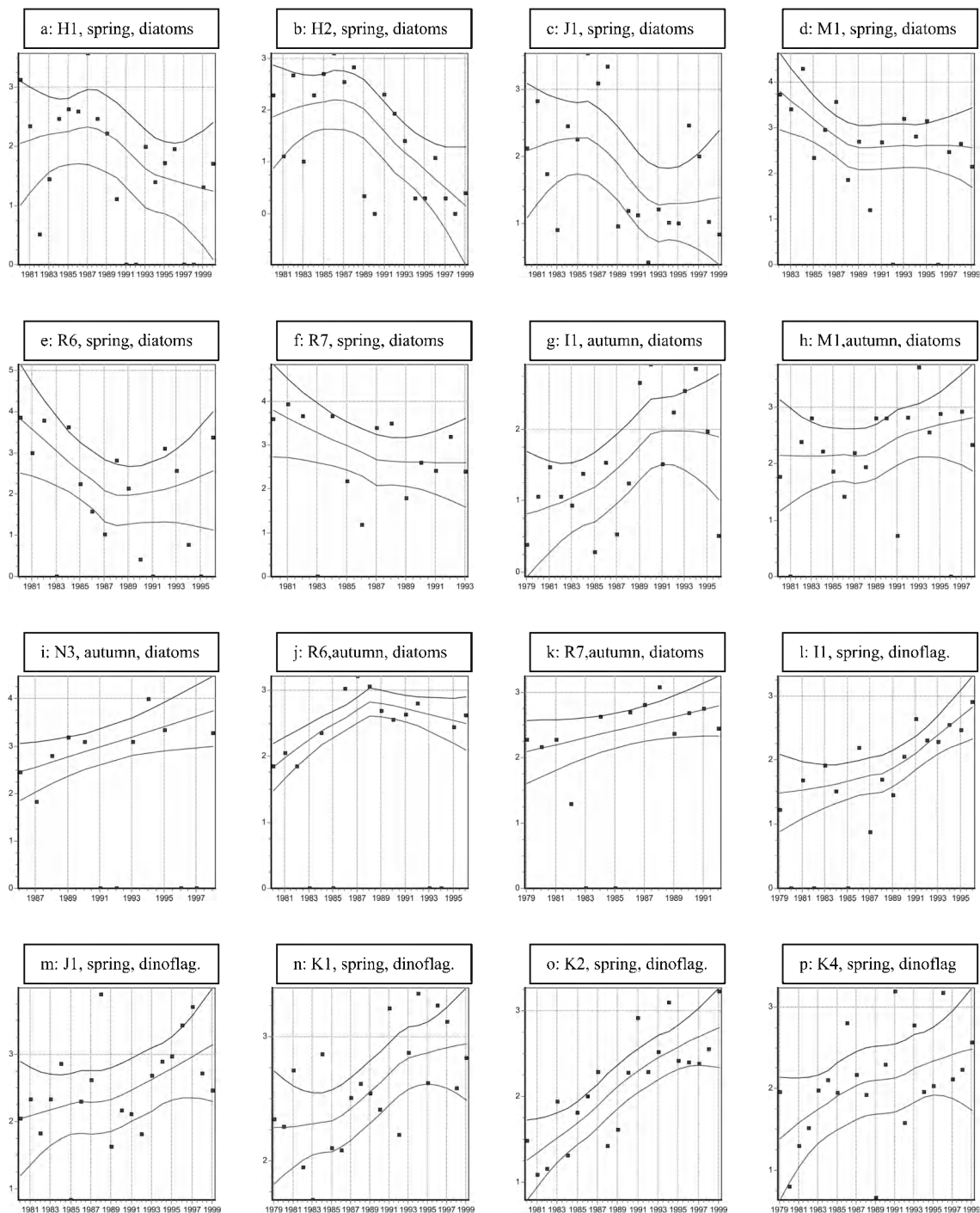


Figure 2. Summary plot of significant trends in mean biomass by station and season for diatoms, dinoflagellates and cyanobacteria, exemplified by the LOESS smoother. Upper and lower lines represent the limits of the approximative pointwise 95% confidence limits for the trend line. Y-axis represents $10 \log \text{Biomass}$ (in mg m^{-3}).

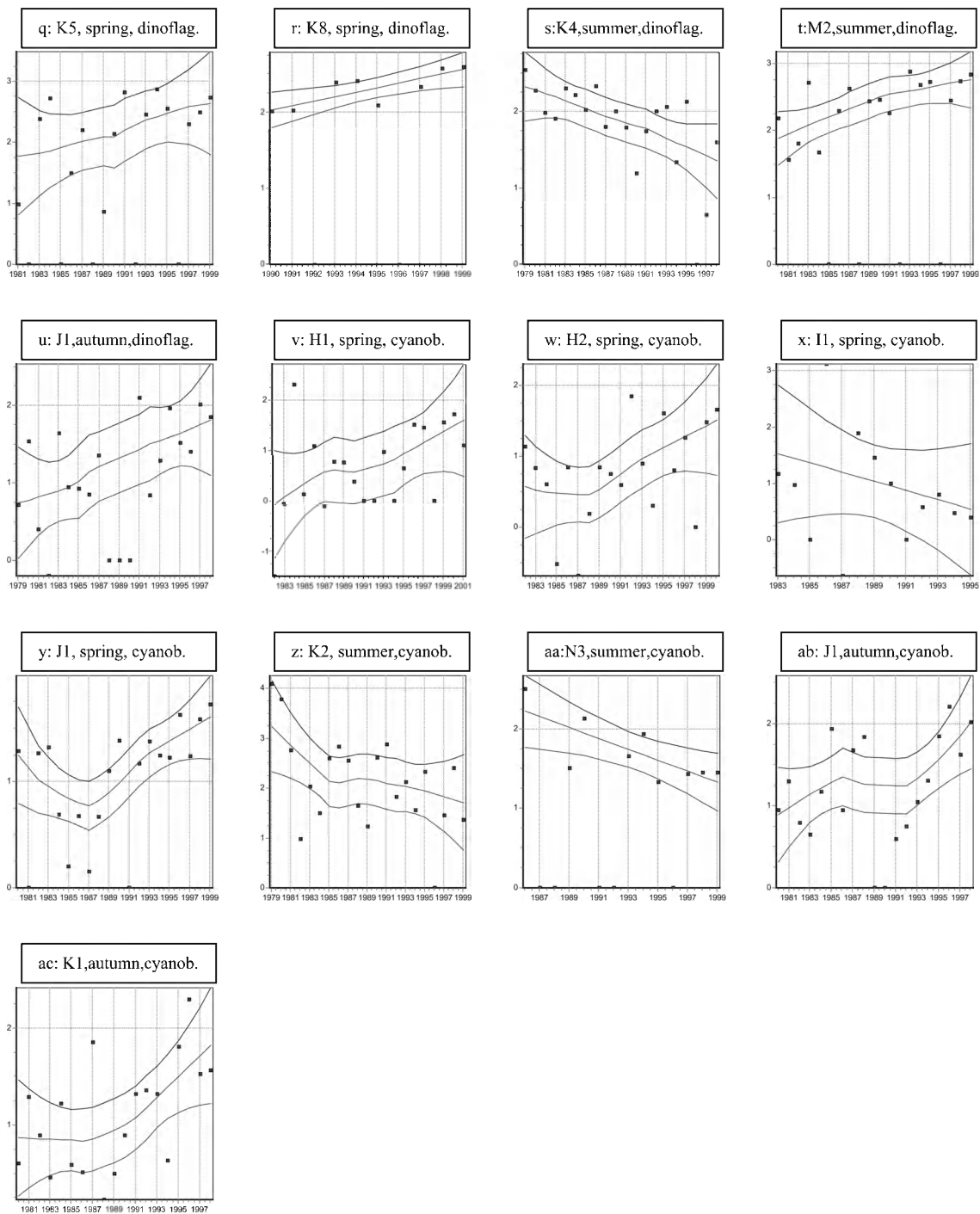


Figure 2 (continued)

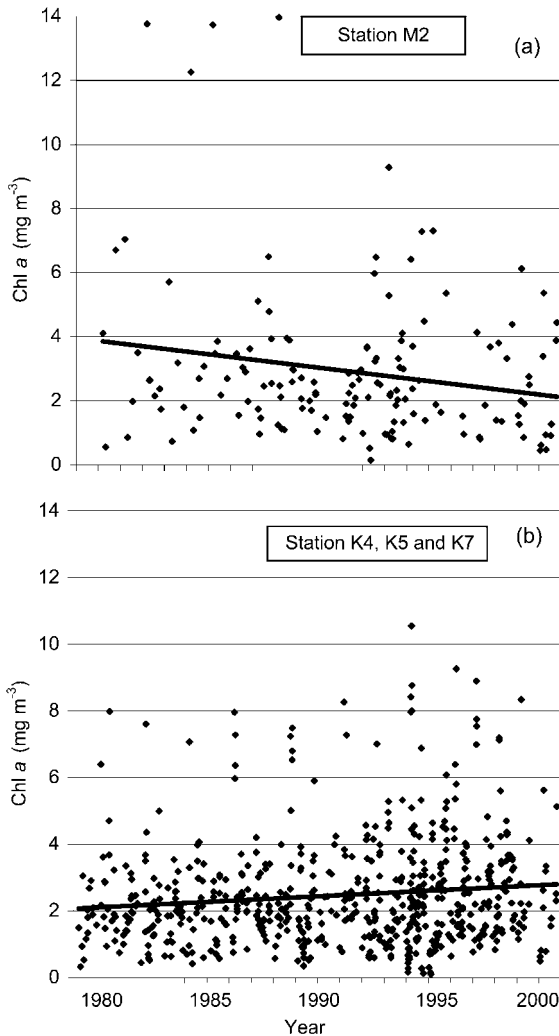


Figure 3. Significant trends in Chl. *a* concentration (mean from 0 to 10 m depth): (a) Mecklenburg Bight, 1980–2000 ($n = 152$; $r = -0.19$); (b) Arkona Sea, 1979–2000 ($n = 624$; $r = 0.12$).

The spring bloom seems to have shifted to earlier periods in some areas, especially in the Kattegat (R1, R3, R5, R6), where in 1997 and 1998 they started already in January/February. Because the January data have been excluded from our analysis, the downward trends in this area may have been slightly overestimated. Trzosińska and Łysiak-Pastuszek (1996) reported that pre-bloom nutrient peaks in Gdańsk Basin shifted from March to February in spring 1979–1993, also indicating that spring blooms tended to start earlier. However, our definition of spring season (March/May) in the Baltic proper would still cover the entire spring bloom, whereas the definition of a spring season lasting from April to June (Trzosińska and Łysiak-Pastuszek, 1996; Wrzolek, 1996) would miss the early stages.

The decrease in spring diatoms coincides with an increase in dinoflagellates. More generally, the short diatom bloom is followed by dinoflagellate growth in the southern Baltic proper (Wasmund *et al.*, 1998). If the diatom bloom fails, the dinoflagellates not only fill this gap but their biomass may even more than compensate for the loss in diatom biomass. As a consequence, the dinoflagellate increase is much stronger than the diatom decrease. Overall, Chl. *a* increases in spring at Stations K1 and K2 (Wasmund *et al.*, 1998), whereas the increase in the annual data set for these stations is not significant. Dinoflagellates increase only in the Baltic proper and Kiel Bight, while their abundance decreases in spring and summer in the Kattegat. Correspondingly, Chl. *a* in the Kattegat/Belt Sea area shows in general a negative tendency. This may be a result of decreasing nutrient concentrations, particularly of phosphorus, which is becoming increasingly important as a co-limiting nutrient in this area (HELCOM, 2002).

Bloom-forming cyanobacteria play an important role in the Baltic ecosystem because of their nitrogen fixation capabilities and their toxicity. Impressive surface blooms of *Aphanizomenon* sp. and *Nodularia spumigena* occur regularly in summer in the Baltic proper, but have not been observed in the Kattegat and the northern Gulf of Bothnia (Kahru *et al.*, 1994; Wasmund, 1997). Cyanobacterial blooms have been reported from the open Baltic Sea already in the 19th century, but their intensity and frequency seem to increase (Finni *et al.*, 2001). Hübel and Hübel (1980) and Melvasalo and Viljamaa (1987) observed intensive blooms in the Baltic proper since 1969, while Postel (2000) found high biomass of net plankton in the western Baltic Sea in 1972/1973, 1983 and 1992. Large blooms were detected by satellite also in 1982–1984 and 1991–1993 (Kahru *et al.*, 1994). In the Tvärminne area at the entrance to the Gulf of Finland, Kononen (1992) observed a cyanobacterial biomass $>100 \text{ mg C m}^{-3}$ in 1979, 1983, 1986 and 1987. In Gdańsk Basin, cyanobacteria seem to decrease from 1979 to 1993 (Wrzolek, 1996).

The HELCOM data show high cyanobacterial biomass in summer 1979–1981, 1985–1986, 1991–1993 and 1998 (Figure 2z). Apparently, cyanobacterial blooms are more variable than those of diatoms and dinoflagellates and it is difficult to deduce steady trends. Nevertheless, downward trends could be observed in summer data of some stations, mainly those from the Kattegat (cf. Table 2), where the general level of cyanobacterial biomass is, however, relatively low. One outstanding problem is that representative sampling of cyanobacterial blooms is difficult because of their inhomogeneous distribution in time (seasonal and short-term changes) and space (both horizontal and vertical). However, overall there is no indication that summer blooms have increased over the period 1979–1999, while in some areas there is a tendency to decrease. Cyanobacteria may become more important in spring and autumn, if the upward trends found mainly in the Baltic proper (Figure 2v,w,y,ab,ac) will continue.

Because Chl. *a* concentrations can be determined much easier and with higher precision than phytoplankton biomass, they may serve as a useful proxy. Most trend analyses for Chl. *a* in the Baltic proper refer to linear regression. The analysis of annual means for 1979–1988 (HELCOM, 1990) revealed no significant trends over the entire area of investigation, whereas a significant increase was observed in summer mean values for Kiel and Mecklenburg Bights and in May values for the Gotland Sea. The increase was significant in the Kattegat for annual means for 1974–1988 (Schulz *et al.*, 1992). A Spearman rank correlation of the summer (15 April–15 October) medians versus years indicated an increasing trend for 1960–1989 in Kiel Bight (Maske, 1994).

The analysis of the 15-year data series (HELCOM, 1996) by the non-parametric Whirsch test revealed increasing Chl. *a* trends at station K7 (Arkona Sea, all annual data), decreasing trends in the Bornholm Sea (summer data), increasing trends in the eastern Gotland Sea (autumn data) and in the northern Baltic proper (at H1 in summer and H2 in autumn). Extending the analysis of the monitoring data up to 2000, the particularly strong increase in the Kattegat/Belt Sea area of the 1970s and 1980s has obviously changed to a downward tendency, significantly so in the Mecklenburg Bight. The increasing trend in the Arkona Sea (HELCOM, 1996) continued in the 1990s. In the Bornholm Sea, however, the increase was significant only until 1997, and the lack of a significant trend in the time series up to 2000 might be a sign of an ongoing drop in Chl. *a* during the last years.

The high variability in phytoplankton in both time and space makes species-specific trend analyses difficult, especially if sampling frequency is low. However, the consistent time series of >20 years provides some insight into long-term changes of phytoplankton biomass and biocoenosis structure. The aggregation over species to taxonomic classes (simple addition) and over samples (averaging means) reduced the variability and the effect of identification and counting errors and, moreover, allowed to include unidentified species within each class. These procedures led to estimates of the true means of biomass and abundance at the class level by seasons. Geometric means are more difficult to interpret, especially when taking into account that temporal peaks for individual species may appear at different times. For trend analysis, logarithmic transformation of the mean values was required to obtain a time series with approximately constant variance and symmetric random deviations. Zero counts occur frequently at the species level, but can be avoided at higher taxonomic levels.

The test methods applied have limitations. The non-parametric Mann–Kendall test can be applied for investigating monotonic trends, even for data that are not normally distributed. The test based on the LOESS smoother loses power in case of non-normality, but even then the significance level obtained (probability to reject the null hypothesis erroneously) is close to the formal significance

level (α ; typically 1 or 5%). However, if sampling frequency is extremely variable from year to year, the weighted LOESS smoother (Uhlig, 2001) might be an appropriate alternative.

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