IV. Variations in the Baltic and its approaches

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Analysis of trends in hydrochemical parameters in the Western Baltic in the 1980s

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Trends in the hydrographic properties and nutrient concentrations of the Western Baltic from 1980 to 1990 are identified from national and HELCOM data (GESPA) and compared with those of the preceding decades. Found to be generally weak, these trends are analysed and discussed as integrated effects of the biological and chemical sink capacities of the ecosystem, natural effects (meteorological and hydrographic changes and water exchange), and anthropogenic factors. Measurements in the Kiel Bight are used to study modifications of annual cycles due to climatic fluctuations. It is demonstrated that the Kiel Bight area is representative of a considerable part of the Baltic Sea. The generation of artificial trend signals is discussed as a consequence of non-matching scales of processes and sampling frequencies and of changes in annual cycles, and effects of non-random properties of the data used for statistical treatment. The results of this discussion are used to evaluate the trends observed during the past decades. The congruence of the observed nutrient trends in the Kiel Bight and the descriptive and prognostic results of the Wulff and Stigebrandt budget model for the Baltic Sea and some subareas are examined.

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Introduction

The particular situation of the Baltic Sea has drawn scientific as well as public interest to temporal changes which might reflect anthropogenic disturbance of the environment. Relevant time scales range from years to decades or even centuries. The identification of systematic changes within these scales and their causal relation to natural and/or anthropogenic processes are the basis for possible measures to improve the environmental state of the Baltic Sea. In the course of this presentation I use the term "trend" for systematic changes of at least five years, while "long-term trends" are calculated for periods of several decades.

The area

The actual hydrobiological property of sea water is the consequence of numerous processes involving a wide variety of time scales and resulting in a considerable spatial variability (patchiness). For practical reasons the collection of time-series data has to be restricted to a limited number of representative stations, where "representative" means: situated in a horizontally homogeneous water body of uniform vertical variability.

As a matter of fact, the definition of a homogeneous location always requires the compromise of ignoring spatial variability within the limits set by the actual scientific problem. However, the basic characteristics and the dominating processes are identical for the Kattegat, the Belt Sea, and the Baltic Proper (Fig. 1).

The haline stratification separates deeper areas into surface layer and bottom water and reduces vertical exchange. A particular feature of the Baltic Sea, especially the western areas, is that, on average, the low saline surface water is outflow from the Baltic and the deep water of higher salinity is inflow of North Sea or Atlantic water. During periods of reduced or missing inflow the deep water is kept under stagnant conditions. A permanent input of material from land and atmosphere is counteracted by internal sinks, sedimentation, exchange with adjacent areas (or, in the case of nitrogen,

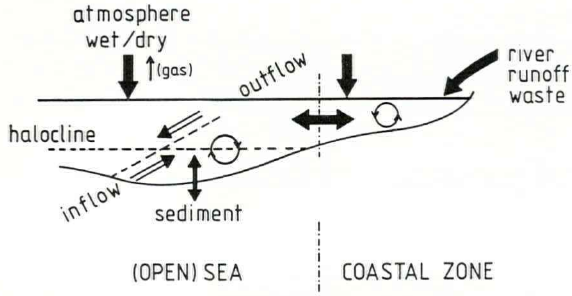

Figure 1. Exchange processes controlling the nutrient concentrations in the Western Baltic.

with the atmosphere) and, finally, exchange with the Atlantic.

The input from land has to pass a coastal area with specific processes which may act as filter for the input material.

The basic hypothesis is that net sink capacities of the Baltic Sea are relatively constant, allowing changes (increases) in inputs to change (increase) the concentrations in the water correspondingly. The inversion of this hypothesis states that trends and long-term changes in concentrations would reflect changes in inputs.

Long-term trends

The dominating hydrobiological parameters are phosphorus and nitrogen compounds (phosphate and organic phosphorus, nitrate, nitrite, ammonia, and organic nitrogen), oxygen, temperature and salinity. With respect to the reliability of analytical results, trend investigations may consider data back to at least 1960. Though some parameters are sufficiently reliable before that date, data are too scarce for systematic trend statistics. Related to the problem of eutrophication, primary production would be an important parameter; however, the quality of data older than some 15 years does not seem to justify trend analysis.

One of the main problems in the compilation of data for long-term trend analysis is the fact that only very few stations are serviced sufficiently frequently to produce reliable data bases. "Good" stations are serviced once a month, some national stations even more often; however, national stations are normally coastal stations and less representative of larger areas.

The assiduous work of the experts for the second periodic HELCOM assessment of the Baltic Sea has provided us with a most comprehensive compilation of trends to which we have added a set of data from the Kiel Bight (Table 1).

The expressed annual cycles in all of the hydrobiological parameters suggest that for trend analyses only a selected proportion of the year's data is useful. The common decision is to take winter data (Jan+Feb), where biological activity and inhomogeneity are low. Because the plankton growth is based on the supply of nutrients in the photic layer, the surface values seem to be the most significant data.

Unfortunately, the selection criteria of the data in Table 1 differ a great deal. Trends are calculated for various periods from 5 to 25 years, some for surface waters, some for deep waters or the entire water column. However, despite the marked variability in results and regional differences, we may derive a reliable description of the long-term trend development in the western areas of the Baltic Sea.

The observed long-term trends in the winter surface layer are very similar for all areas of the Western Baltic. Inorganic nitrogen and phosphate show positive trends if calculated back to 1965 or 1960. The trends decrease or even invert the more the calculation period is reduced toward the last decade. Phosphate concentrations have roughly doubled since the 1960s (0.3 μmol dm^{-3} to 0.6 μmol dm^{-3}) and inorganic nitrogen has reached nearly threefold concentrations (4.5 μmol dm^{-3} to >13 μmol dm^{-3}). Silicate has significantly decreased, in some areas to less than half the 1960s concentration.

The trends show systematic tendencies during the last three decades. Trends calculated back to 1970 or before are significant and strong (positive for inorganic nitrogen and phosphate, negative for silicate). Ranging the calculation from today to about 10 years back results in weak trends (still mostly positive for inorganic nitrogen, but slightly negative for phosphate). This is much more obvious in the graphs and seems to be a general feature for the Western Baltic and the Baltic Proper. Figure 2 shows inorganic nitrogen and phosphate concentrations in the winter surface water of the Kiel Bight back to 1960 (a–b) and the corresponding data from Gotland Sea stations (c–d, Nehring *et al.*, 1990). The observed changes are nearly congruent.

Figure 3 displays the atmospheric wet deposition over central Sweden which has increased at a rate of 0.73 mmol m^{-2}yr^{-1} from about 10 to nearly 40 mmol m^{-2}yr^{-1} during the last 35 years. An interesting feature of the graph is that splitting the trend into three periods shows the same feature as for the nutrients in winter surface waters.

Until 1980 the calculated loads from land and atmosphere and the concentrations of inorganic nitrogen and phosphate were closely correlated. It seemed justified to relate the strong increase of phosphorus and nitrogen during 1970 to 1980 to the increasing anthropogenic inputs.

Eutrophication has increased since 1960. This is supported by observations of elevated primary productivity and by increasing contents of organic matter in sediments. Unfortunately most of the primary productivity data are not measurements of production rates but production capacities. The calculation of production rates from capacity measurements requires a number of assumptions which reduce the reliability of the results.

Table 1. Annual accumulation rates [μmol dm^{-3}yr^{-1}] (Nehring *et al.*, 1990; Trzosinska *et al.*, 1990; BIOMON, 1990).

Ar	Sa	Years	Phos.	ΣN	Sili.	TOT N	TOT P	Comment
R	5	74–88		0.42				surf., wi.
R	5	74–88 83–88		0.35 0.74[1] 0.36[2]	−0.55		0.032	waterc. wi. [1] R6 = 2.07 [2] exclus. R6
R6	1	65–89	0.017	0.21[3]				surf., wi. [3] nitrate
R6	1	65–89	0.013	0.1[3]				deep, yr
N	4	79–89	−0.01	0.09	−0.24	1.11	−0.07	surf., wi.
N	4	60–89	0.023	0.28				surf., wi.
N	4	79–89	−0.02	−0.25	−0.78	0.70	−0.09	deep, wi.
N	4	79–89	0.01	−0.04	0.20	0.01	0.01	surf., yr
N	4	79–89	0.03	0.03	0.84	−0.06	0.01	deep, yr
N	2	74–88		0.35				surf., wi.
N	2	74–88		0.14				deep, wi.
N	2	74–88 83–88		0.46 0.11	−0.49		0.04	waterc., wi.
M	4	70–89	0.014	0.13[3]				surf., wi.
M	4	80–89		−0.26[3]				[3] nitrate
M	1	74–88		0.25				surf., wi.
M	1	74–88		0.08				deep, wi.
M	1	74–88 83–88		0.26 0.54	−0.57 −0.27		0.27	waterc., wi

Ar = area/station code, Sa = numbers of pooled stations, surf. = surface, wi. = winter, waterc. = entire water column.

Trends in the 1980s

The "easy" times are gone for the evaluation and interpretation of trends. As shown above, the increases of N and P in winter surface waters in the 1970s due to increasing loads were high enough to override most other processes. So the quantification may be debatable, but the trends were statistically significant and the interpretations and the conclusions acceptable. Speaking in physical terms, the signal we were looking for was strong compared to the noise level. Maybe this is the reason why most experts preparing the 2nd Periodic HELCOM Assessment of the Baltic Sea preferred to calculate trends back to the 1970s or 1960s.

As mentioned above, most international stations are serviced once a month or even less. This means that a trend analysis of for example winter surface waters for a period of 10 years is based on less than 30 values.

Figure 4a represents the phosphate daily means at the Fladen station (after Engström and Fonselius, 1989). The accumulation rate of 0.017 μmol dm^{-3}yr^{-1} is statistically significant for the 22 years' period.

Calculating the accumulation rates for 10-year periods (Fig. 4b), however, gives a good impression of the random nature of trend figures for 10 years at a single position. More realistic 10-year trends may be calculated if data from "similar" stations are pooled, where "similar" means that the dominating processes controlling the concentrations are identical. If the absolute values differ too much they may be normalized. Such trends are given in Tables 1 and 2 for the areas N and M (defined in HELCOM BMP-Guidelines). They show insignificant accumulation (or even decrease) of phosphate, less accumulation of inorganic nitrogen in the Kiel Bight, and a considerable decrease (–0.26 μmol dm^{-3}yr^{-1}) in the Bay of Mecklenburg. The negative trend in silicate is continued.

The literature offers us only few descriptions of changes within the 1980s but there are numerous reports comparing findings in the 1980s to the 1970s, e.g.

- Increase of N and P in surface and bottom waters.
- Increase of N-load from the atmosphere, especially an increase of ammonia.
- Increased primary production (25–30%).
- Decrease in oxygen concentrations.
- Spreading of low-oxygen or H_2S in bottom layers.
- Increased number of dead fish and invertebrates in benthic catches.

These observations may represent delayed consequences of the drastic changes during the 1970s or are related to processes within the 1980s which are not reflected in the long-term trends. For a more detailed analysis of processes within the short period of the last 10

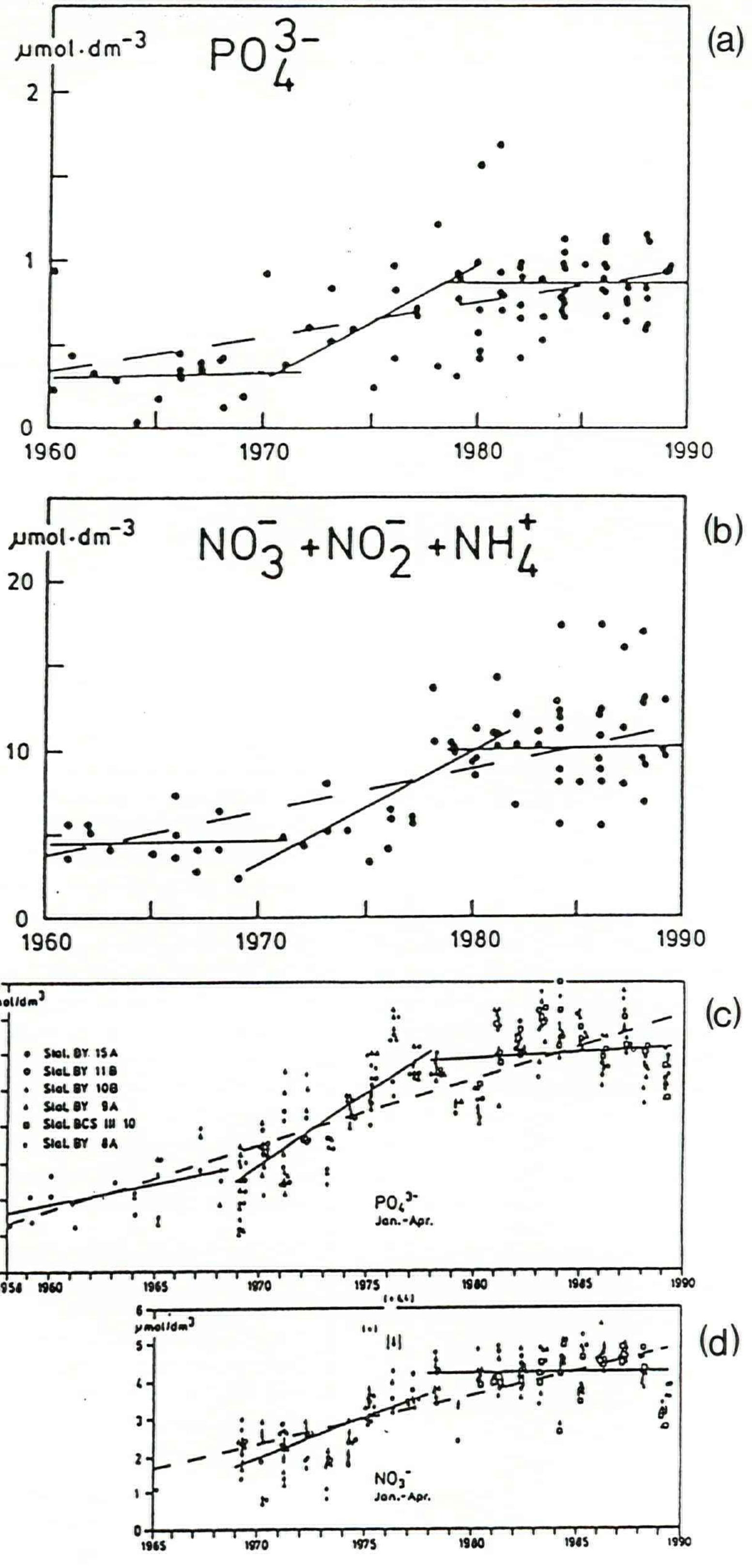

Figure 2. Long-term trends of nutrients (Nehring *et al.*, 1990, original figures adjusted). (a) PO_4^{3-} and (b) ΣN, Kiel Bight, January + February. (c) PO_4^{3-} and (d) NO_3^{-3}, Gotland Sea, January–April.

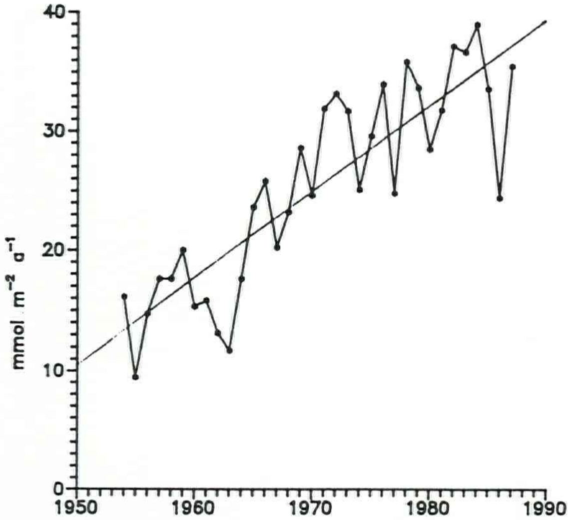

Figure 3. Atmospheric wet deposition of NO_3^- and NH_4^+ over Central Sweden (after SEPA, 1990). Accumulation rate: 0.73 mmol m^{-2}a^{-1}.

Table 2. Trends of hydrological parameters in the Kiel Bight from 1979 to 1989 (Area N, four stations pooled).

	Jan+Feb		Jan–Dec	
	surf	bott	surf	bott
Temperature [°C]	0.25	0.19	0.13	0.23
Salinity [PSU]	0.25	0.17	−0.06	−0.05
tot N [μmol dm^{-3}]	1.11	0.70	0.01	−0.06
tot P [μmol dm^{-3}]	−0.07	−0.09	0.01	0.01
Oxygen [cm^{-3}dm^{-3}]	-0.06	−0.07	−0.01	−0.10
^{1}Aug-Sep			0.01^1	−0.08^1

years we have to concentrate on data from an example area with small spatial variability and high sampling frequency. For reasons of convenience (availability) we used data from stations in the Kiel Bight.

Results from the Kiel Bight

The Kiel Bight (Fig. 5) may be regarded as a model for the Baltic Sea. Most of the deeper areas (>25 m) show a permanent halocline. From the inflow to the Baltic Sea through the Great Belt and the Fehmarn Belt, water of higher salinity is pushed through a system of channels and small basins. During periods of missing or weak inflows some of the basins turn to stagnant conditions with sometimes anoxic bottom conditions, e.g. the national station Boknis Eck from which time series back to 1960 and many detailed studies are available. This area is well covered by both national and international BMP stations. All discharges from land and meteorological parameters are monitored and well documented.

The changes in nutrient loads from land can be assumed to be about the same here as for other countries around the Western Baltic, with the exception of the former GDR because of similar developments in sewage treatment, industry, and agriculture. Atmospheric nitrogen deposition as a more global parameter can be extrapolated from Swedish measurements (SEPA, 1990) considering an increasing tendency from central Sweden toward central Europe. For the Belt Sea the data suggest a mean annual wet deposition of about 80 mmol m^{-2}yr^{-1} inorganic nitrogen (1 t km^{-2} yr^{-1}) during the 1980s.

Total runoff, nitrogen and phosphate load, and the N/P ratio of loads from Schleswig-Holstein are displayed

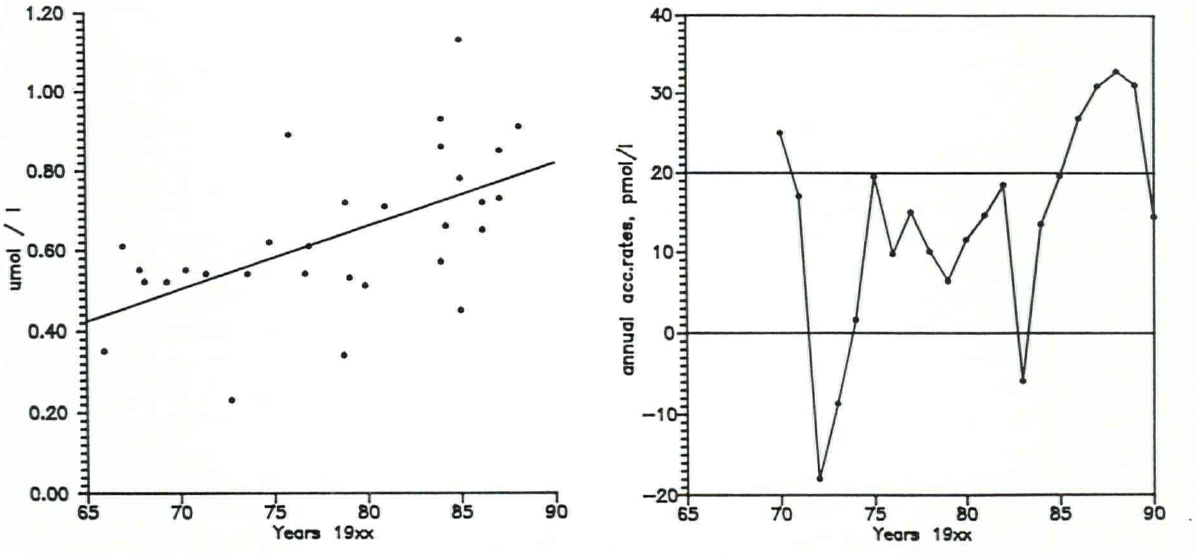

Figure 4. (Left) Phosphate daily means (Station Fladen). (Right) Trends of preceding 10 years.

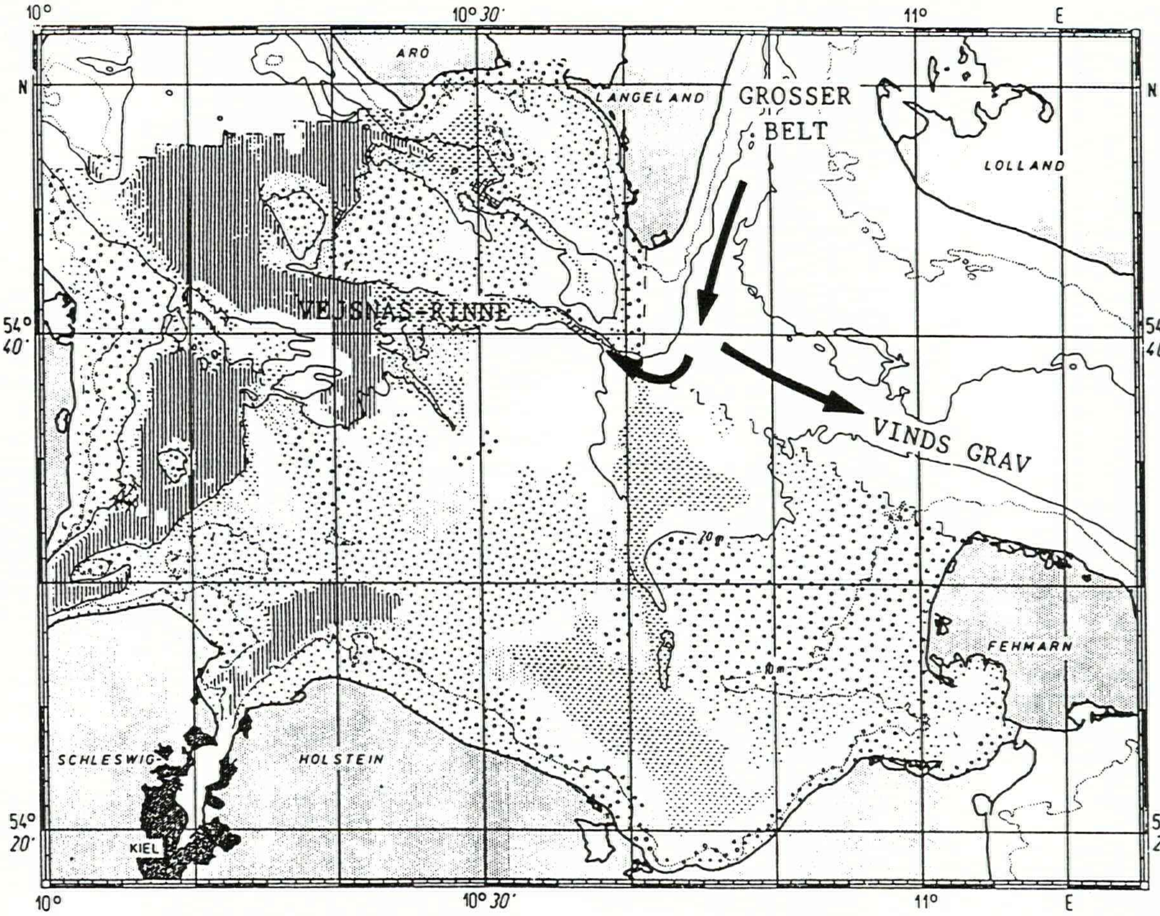

Figure 5. The Kiel Bight. Sediments: mud = shaded, sand = points. The decreasing density of points corresponds to decreasing mud contents in the sand (after Balzer, 1985).

in Figure 6a–c (LWK, 1990). About 56% of this discharge enters the Kiel Bight. There is a decrease in nitrogen load (Fig. 6a) which is, however, caused mainly by one extremely high value in 1981 and an extremely low value in 1989, both coinciding with corresponding signals in runoff (rain).

It is very difficult to calculate the atmospheric contribution to the nitrate load in the 1980s. The measurements show high year-to-year variations and a statistically significant trend cannot be calculated. The phosphate load decreases significantly from about 1000 in 1980 to 300 t yr^{-1} in 1989, obviously reflecting the reduction of phosphate contents in washing powders.

A trend in primary production during spring bloom cannot be established. The peak signal is too short to be represented by the few samples. The primary production values during the summers of 1986 to 1988 were nearly twice as high as during 1979 to 1984, while chlorophyll *a* did not increase. This may be interpreted as increasing "new production" relatively to "regenerated production" due to eutrophication or changes in vertical exchange processes. The small trends in salinity (Table 2) resulting in reduced salinity differences between surface and bottom waters could stimulate increased vertical exchange; however, the trends are only weak. Other possible explanations are increased grazing or variations in species composition modifying the assimilation ratio (BIOMON, 1990).

There are some additional indications of biological changes during the second half of the 1980s. Some species (*Porocentrum minimum* and *Heterocapsa triquetra*) which have not been reported before 1985 are now found regularly in sometimes high concentrations in some of the fjords. Since 1983 blooms of *Dictyocha (Distephanus) speculum* are reported during April and May. A remarkable phenomenon is that this species found in the Kiel Bight does not develop the siliceous skeletons which normally characterize the genus *Dictyocha*. This may be intrepreted as a result of environmental changes (Jochem and Babenerd, 1989).

The sub-halocline zoobenthos community has clearly suffered from the oxygen deficit in 1981. The species composition has changed in a way that long-living species vanish for several years while short-living, highly productive species of usually low biomass start to dominate (Weigelt, 1987; Weigelt and Rumohr, 1986). Low

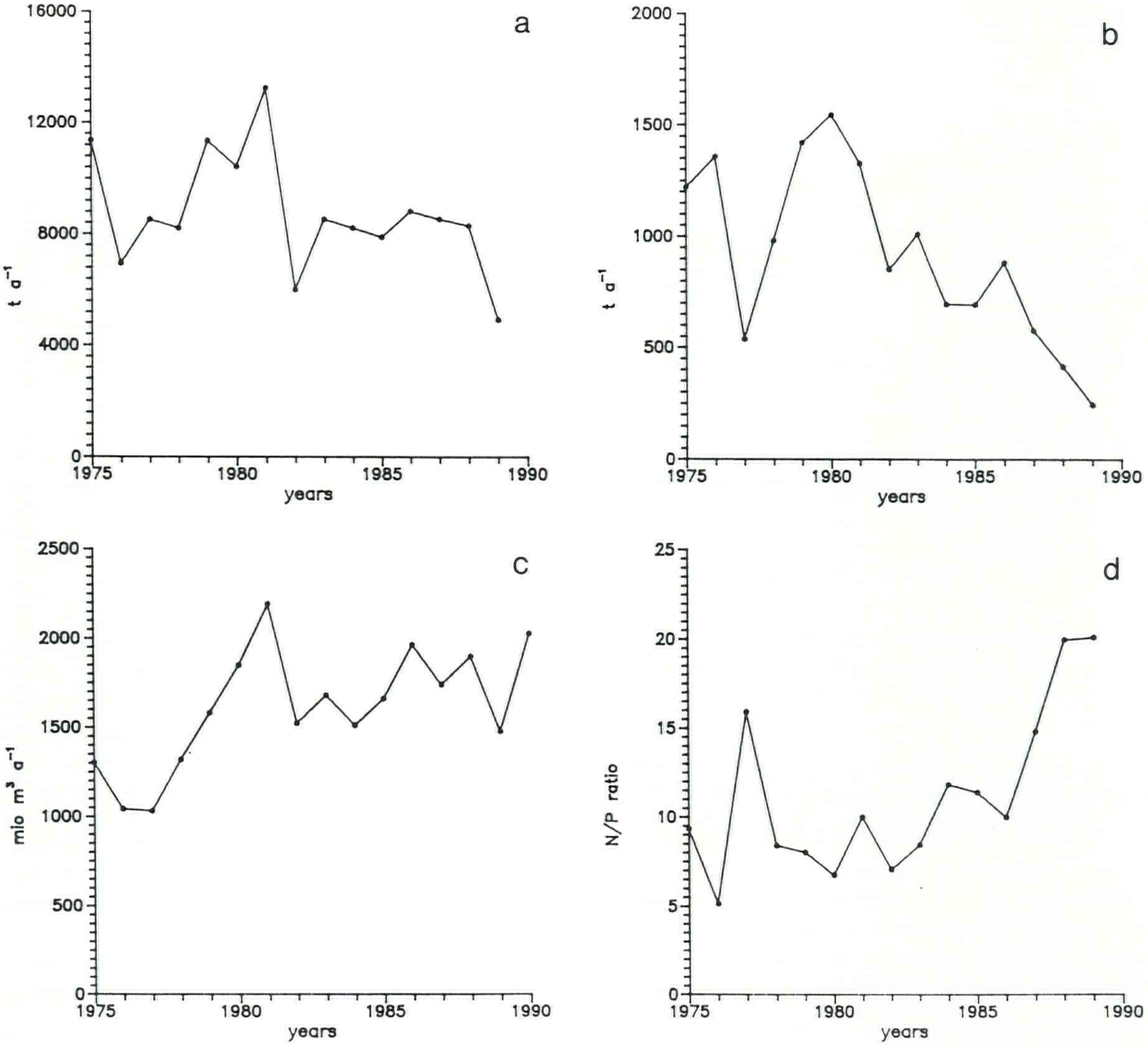

Figure 6. Loads and runoff to the Baltic Sea from Schleswig-Holstein, 1975–1989. (a) Inorg. nitrogen, (b) phosphate, (c) total runoff, (d) N/P ratio.

oxygen conditions in the Kiel Bight until 1989 have retarded the recovery of the benthic community.

Conclusions and discussion

The computation of the nutrient loads as well as the nutrient concentration measurements in the winter waters suggest that conditions in the Kiel Bight have not changed toward higher eutrophication within the 1980s. The symptoms of eutrophication, however, e.g. primary production, oxygen deficits, negative development of benthic fauna, are contradictory.

The Baltic Sea nutrient budget model of Wulff and Stigebrandt (1989) allows us to check the relation between nutrient load and observed concentrations in winter surface waters. These authors assume increasing loads for P until 1975 and for N until 1980 and constant loads since then. They predict a continuing weak increase in nitrogen concentrations until 1980 and a nearly constant level after this time, while the phosphorus concentrations will increase significantly until the end of the century.

The model fits quite well with respect to nitrogen. The nitrogen load from land is slightly decreasing but compensated by still increasing atmospheric loads. The concentrations of total N in winter surface waters are increasing by about 1 μmol dm^{-3}yr^{-1}.

For phosphorus loads it seems that the Western Baltic area is slightly better off than the Baltic Proper. The loads from land have been decreasing significantly (to about 30%). Thus the phosphorus concentrations in surface waters are no longer increasing (actually they are slightly decreasing), and, as opposed to the model prediction, the N/P ratio is not decreasing significantly.

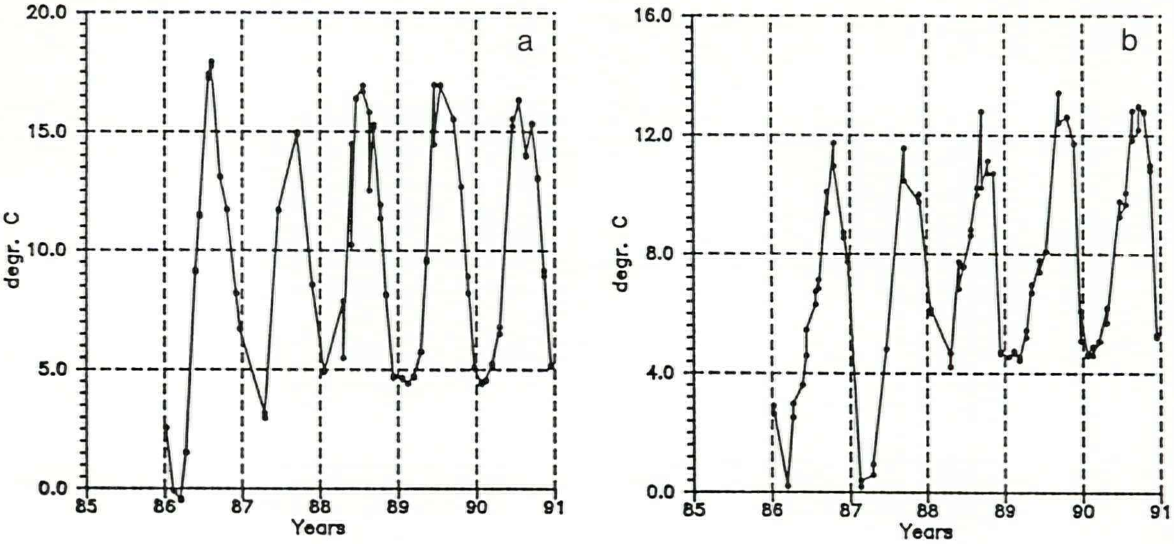

Figure 7. Temperature, station Boknis Eck, 1986–1990. (a) Surface, (b) bottom.

So the nutrient pool does not explain the "eutrophication symptoms" mentioned above and we have to look in more detail for changes within the 1980s which could possibly

- mask, produce, or simulate trends in the winter data
- affect the oxygen concentrations
- increase primary productivity during summer.

There is at least one additional factor influencing the oxygen situation: The general explanation for decreasing oxygen concentrations in bottom waters is an increased amount of organic material and the consequent oxygen demand by microbial degradation. During the second half of the 1980s, however, we have an unusual meteorological situation, which may affect the oxygen conditions even more. The last cold winter was 1985/1986. Since then the minimum water temperatures (Figs. 7a–b) have increased from about zero to 5°C. One consequence is that the oxygen solubility is 1.2 $\mathrm{cm}^{-3}\mathrm{dm}^{-3}$ less than in "normal" years. The additional oxygen uptake during the cooling period (mainly February) is illustrated in Figure 8b. The interannual variability corresponds with the variability of the summer minimum values (Fig. 8a).

Let us assume a small local basin (bowl) of 1 m depth which turns to stagnation during summer, which means

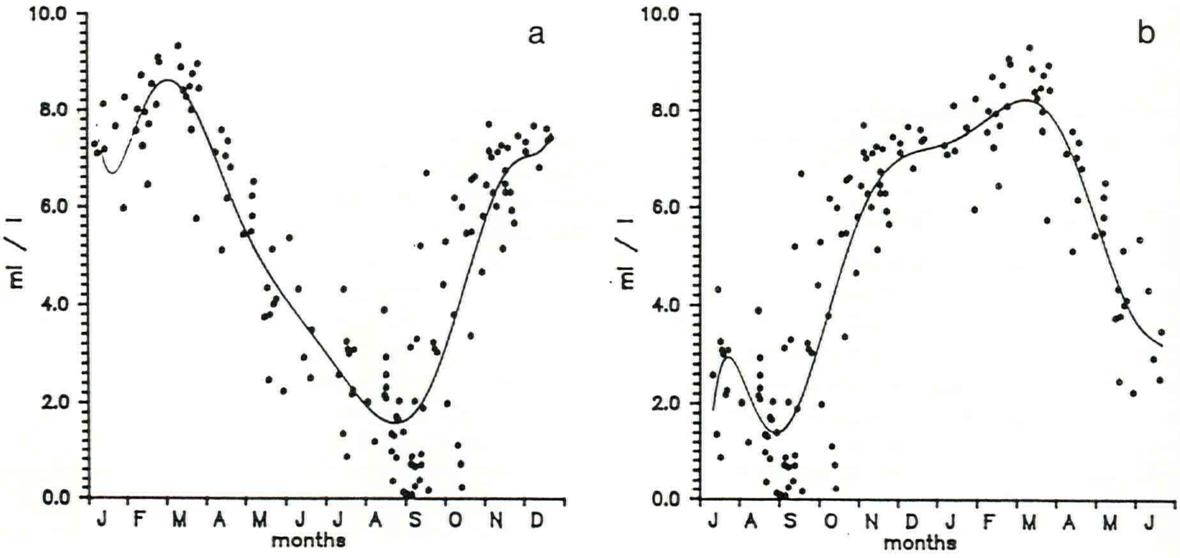

Figure 8. Means of bottom oxygen concentrations, Fehmarn Belt, 1979 to 1991. (a) January–December, (b) July–June.

that stratification restricts vertical resupply. Oxygen consumptions of sediment surfaces in the Kiel Bight are about 500 cm^{-3}m^{-2}d^{-1} (Balzer, 1978; Hansen, 1980). The bottom water would become anoxic by oxygen consumption of the sediment surface after 14 days of stagnation instead of 17 days in "normal" years. Taking into consideration the additional bacterial oxygen consumption in the water column, we may find local anoxic conditions after just 8 days of stagnation (instead of 10 days). This may well explain some of the oxygen deficiency problems during the last five years.

Some additional interesting features are found in a detailed investigation of the annual fluctuations of parameters. To evaluate annual cycles we calculated polynomial optimization functions of the discrete sampling data versus the time of year. We arranged the sequence of months with respect to the time of interest, because polynomial approximations are not valid close to the data boundaries.

Figure 9a–b displays the mean annual cycles for phosphate and nitrate in surface waters of the Boknis Eck station (1986 to 1990) produced by polynomial approximation. Other methods (see e.g. Matthäus, 1971) give identical results.

The maxima – especially in phosphate – are sharper for a one-year annual cycle. One conclusion is obvious. The definition of "winter water nutrients" as the mean of January and February measurements is a very problematic compromise. As a general feature, the phosphate values (in Kiel Bight) are already decreasing after January while nitrate is still increasing until March. This phase shift is a consequence of the different remineralization rates of organic phosphorus and nitrogen. Surprising, however, is the decrease of phosphate starting as early as January. Neither primary productivity nor chlorophyll *a* confirm plankton growth at that early time of the year (main spring phytoplankton bloom is during March). This may indicate something like "luxury uptake" of nutrients. However, I will leave this discussion to the biologists. A second finding which I cannot explain at this moment is a systematic delay of the occurrence of the maxima in both phosphate and nitrate since 1979 (Fig. 10a–b). This may be a consequence of either biological or meteorological changes, but it could also be caused by changes in the nutrient load (time of release) from agriculture.

Here I would like to present a curiosity regarding the sampling in the Kiel Bight. For good scientific reasons all laboratories try to service "their" stations at regular (mostly monthly) intervals. For less scientific reasons nobody wants to sample just after New Year's day. The result is displayed in Figure 11.

Sampling at monitoring stations is concentrated around the middle of the month. We should remember that statistical treatment of data aiming at the identification of systematic concentration trends assumes that the data either represent the maximum peak or are distributed randomly over the maximum range. If not, statistical calculations may produce artificial results which could indicate accumulation or decrease but actually only reflect non-random properties of the sampling.

All these findings strongly support the idea of a change of sampling strategies for trend and budget calculations as suggested for example by Wulff and Stigebrandt. It seems much more promising to concentrate on a few representative stations which are serviced sufficiently often to access the annual cycles and identify, quantify, and eliminate short-term extrema caused

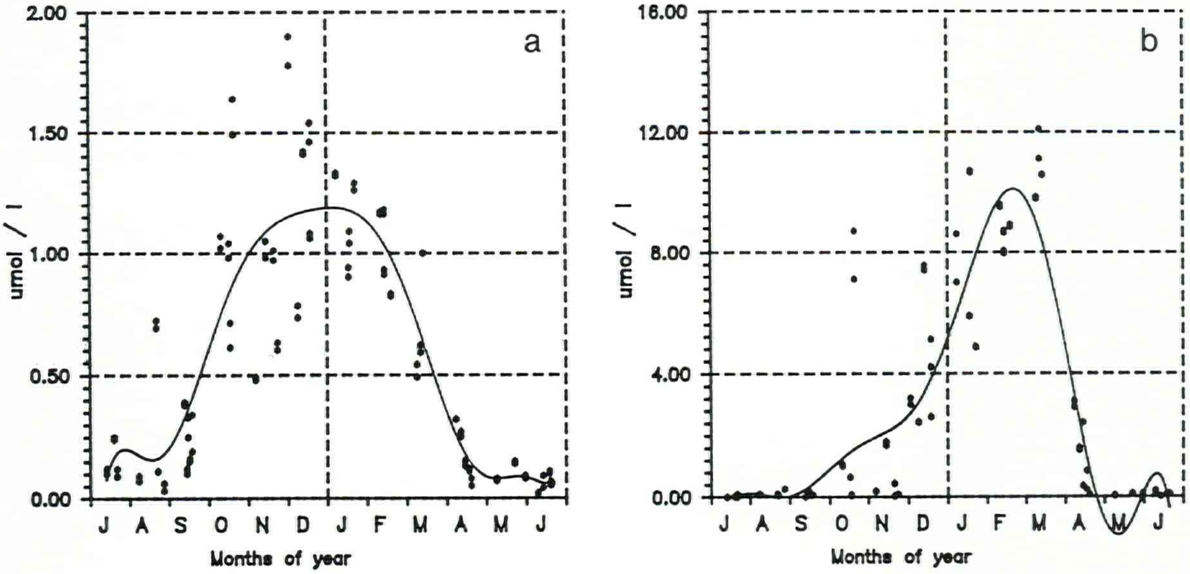

Figure 9. Mean annual cycles, surface, Boknis Eck, 1986–1990. (a) Phosphate, (b) nitrate.

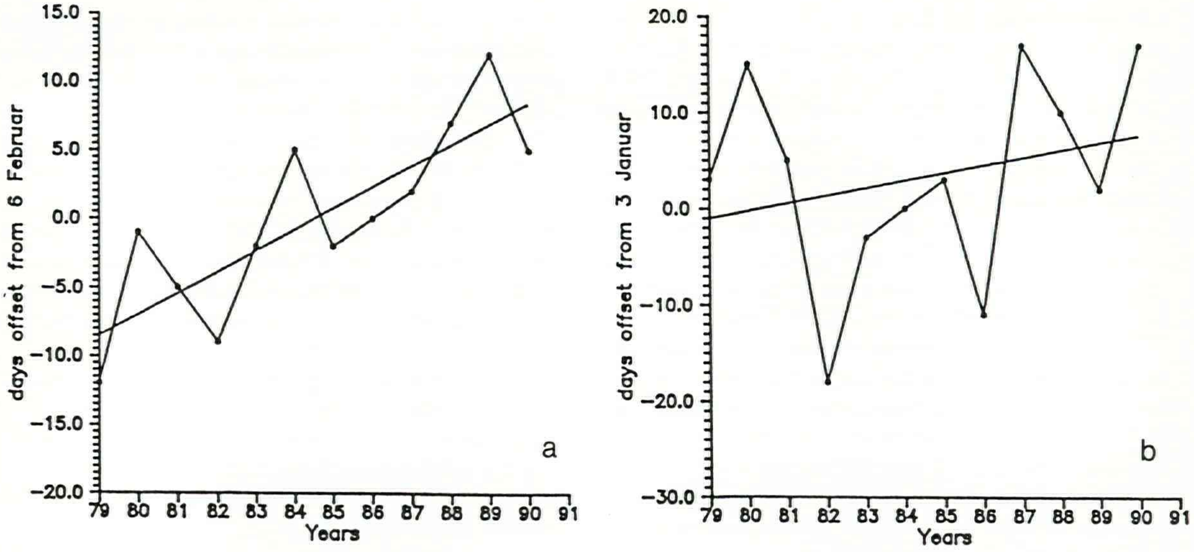

Figure 10. Shift of surface winter maxima (Boknis Eck). (a) Phosphate, days rel. to 4 January, (b) nitrate, days rel. to 8 February.

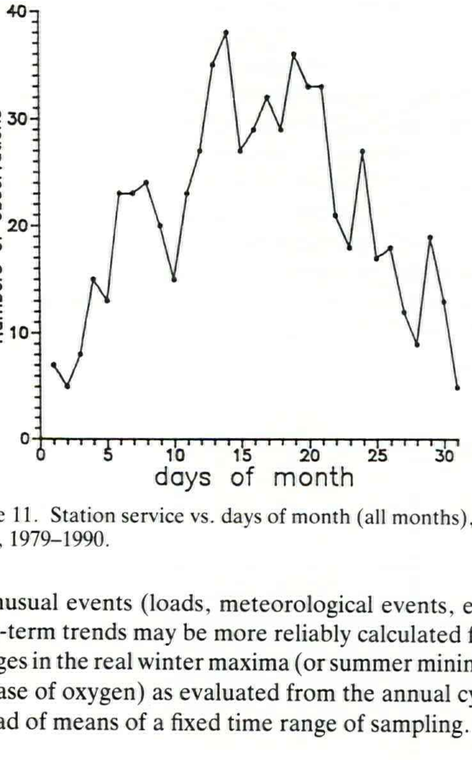

Figure 11. Station service vs. days of month (all months), Kiel Bight, 1979–1990.

by unusual events (loads, meteorological events, etc.). Long-term trends may be more reliably calculated from changes in the real winter maxima (or summer minima in the case of oxygen) as evaluated from the annual cycles instead of means of a fixed time range of sampling.

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