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OXYGEN DEPLETION 1980 - 1983 IN COASTAL WATERS OF THE FEDERAL REPUBLIC OF GERMANY

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Summary

1981 - 1983 observations on oxygen depletion and fish kills in near-bottom waters of the German Bight, of Danish and Swedish coasts and of Kieler Bucht and Mecklenburger Bucht cause concern. A working group was sponsored by the Minister of the Interior of the Federal Republic of Germany to assess, mostly from existing data, whether man made nutrient input into coastal waters may have triggered exceptional phytoplankton blooms which, when decaying, could result in oxygen depletion events. Calculated for the respective bodies of water, input of phosphorus and nitrogen via sewage, rivers, land runoff and atmospheric fallout, per year, is of the same order of magnitude as the nutrient content in winter water in Kieler Bucht; probably input is higher in the German Bight. Phosphorus concentrations in Helgoland winter surface water doubled between 1962 and 1982. In Kieler Bucht, however, phosphorus concentrations were stable 1957 - 1975. The period 1975 - 1983 is too short for a definite statement, that there is an increasing trend for phosphate and nitrate, even if there is some evidence. Year to year loads of nitrogen transported by land runoff and rivers into coastal waters differ widely. Further investigations will tell whether there are correlations with phytoplankton productivity. Year to year weather conditions differ widely, too, and it will be worked out whether oxygen depletion can be correlated to specific weather conditions which enhance stratification of the water masses. Finally, more historical data will brought forward as evidence for extraordinary situations in coastal waters during the past decades. Recommendations for biological monitoring are given.

Zusammenfassung

Beobachtungen 1981 - 1983 über Sauerstoffmangel und Fischsterben in den bodennahen Wasserschichten der Deutschen Bucht, der dänischen und schwedischen Küstengewässer und der Kieler und Mecklenburger Bucht gaben Anlaß zur Besorgnis. Der Innenminister der Bundesrepublik Deutschland beauftragte eine Arbeitsgruppe damit, überwiegend durch Bewertung bereits vorhandener Daten herauszufinden, ob die vom Menschen zu verantwortenden Einträge an Pflanzennährstoffen in Küstengewässer außergewöhnliche Planktonblüten ausgelöst haben, welche beim Abbau zu Sauerstoffmangel führen. Auf die betreffenden Wassermengen bezogen ist die Zufuhr von Phosphor und Stickstoff aus häuslichen Abwässern, mit Flußwasser und mit von Äckern und Weiden ablaufendem Wasser und über die Atmosphäre, pro Jahr gerechnet, ebensogroß wie die Gesamtmenge dieser Nährstoffe im Winterwasser der Kieler Bucht; der Eintrag ist vermutlich sogar größer in der Deutschen Bucht. Die Phosphorkonzentrationen im oberflächlichen Winterwasser bei Helgoland haben sich zwischen 1962 und 1982 verdoppelt. In der Kieler Bucht jedoch blieben die Phosphorkonzentrationen 1957 bis 1975 fast konstant. Der Zeitraum 1975 bis 1983 ist zu kurz, um definitiv festzustellen, daß es seitdem einen zunehmenden Trend bei den Phosphat- und Nitratkonzentrationen gibt, auch wenn manches dafür spricht. Von Jahr zu Jahr sind die Frachten an Stickstoff sehr verschieden, welche mit dem Abfluß von Land und mit Flußwasser in Küstengewässer eingebracht werden. Weitere Untersuchungen müssen zeigen, ob es dabei Korrelationen mit der Phytoplankton-Produktivität gibt. Von Jahr zu Jahr sind auch die Wetterbedingungen sehr verschieden; es soll erarbeitet werden, in welchem Umfang Sauerstoffmangel mit spezifischen Wetterbedingungen korreliert werden kann, welche die Stratifizierung der Wassermassen fördern. Schließlich sollen mehr historische Daten aus vergangenen Jahrzehnten erarbeitet werden, welche über außergewöhnliche Ereignisse in deutschen Küstengewässern berichten. Es werden Empfehlungen für das biologische Monitoring gegeben.

Contents

page

1. Introduction

2. Trends in nutrient input into coastal waters

3. Trends in nutrient concentrations in coastal waters

4. Trends in primary production in coastal waters

1. Introduction

1.1 Oxygen depletion events

First information about reduced oxygen concentrations in the near-bottom water masses of offshore regions of the German Bight were gained from biological studies (Rachor, 1977; Rosenthal et al., 1981). In summer 1981 it could be confirmed that a large area northwest of Helgoland, called the "submarine valley of the postglacial Elbe river", suffered from reduced oxygen concentrations (Fig. 1-2); saturation was only about 40% (Rachor and Albrecht, 1983). Dead fish were observed off the Danish coast (Dyer et al., 1983). In 1982 an area about 50 nautical miles west of Jutland was hit by oxygen depletion; the result was fish kills and dead macrozoobenthos (Dethlefsen and von Westernhagen, 1983). In August 1983 Danish authorities found low oxygen concentrations in the same regions of the North Sea which were hit in 1981 (Miljøstyrelsen, 1984).

In Kieler Bucht the western parts, including Eckernförde Bay, Flensburg Fjord and Kiel Fjord are well known for oxygen deficiency in the near-bottom water during summer periods. However, it had never before been observed that oxygen depletion affected the extended areas in the central and eastern part of Kieler Bucht, as happened in September 1981 (Fig. 3-4). The situation was so extreme that for a few weeks high concentrations of hydrogen sulfide were encountered (Ehrhardt and Wenck, 1984) killing most of the macrozoobenthos species of the region (Weigelt, 1983). Danish authorities reported 1981 many areas with oxygen depletion as well as fish kills in adjacent waters of the Little Belt and Great Belt and in the southern Kattegat (Miljøstyrelsen, 1984). Swedish authorities have been concerned with oxygen depletion in Laholm Bay and adjacent areas of the Southeastern Kattegat since 1980 (National Swedish Environment Protection Board, 1984). In 1982 Danish authorities reported on oxygen deficiency in Køge Bay south of Copenhagen and in Kalø Bay north of Aarhus.

In 1983 oxygen depletion was observed in nearly all regions of the Danish Belt Sea; end of August 1983 oxygen concentrations were in general lower as compared with the same season in 1981. However, in the first week of September 1983 strong winds prevailed, so that from 8 to 12.9.1983 the oxygen situation was normal again (Miljøstyrelsen, 1984). In Kieler Bucht the situation was comparable (see Box 2).

continued on p. 12

Box 1

Subprojects of the Working Group Eutrophication of the North Sea and the Baltic

1. Coordination (S.A.Gerlach, Institut für Meereskunde Kiel)	Box 3, Fig. 7
2. Documentation of the oxygen depletion event 1981 in Kieler Bucht, its effects on benthos fauna, and the regeneration in subsequent years (S.A. Gerlach, Institut für Meereskunde Kiel)	Box 2, Box 11
3. Changes in the macrobenthos of Kieler Bucht 1953 - 1983, and documentation of events which possibly are consequences of eutrophication since the end of the past century (H. Rumohr, Institut für Meereskunde Kiel)	Box 12, Fig. 29
4. Analysis of macrobenthos trends 1965 to 1983 in the German Bight, and macrobenthos surveys in the part of the German Bight known for oxygen depletion (E.Rachor, Institut für Meeresforschung Bremerhaven)	Box 10,
5. Weather situations which are relevant for chemical and biological processes in coastal areas of Germany (H. Graßl, Institut für Meereskunde Kiel)	Box 15, Fig. 31
6. Simulation of currents in the system North Sea - Baltic Sea induced by wind and their importance for eutrophication effects (J. Backhaus, Institut für Meereskunde, Universität Hamburg)	Box 14, Fig. 30
7. Trends in nutrient concentrations at Helgoland (G. Radach, Institut für Meereskunde Hamburg)	Box 6, Fig. 11
8. Amounts of nutrient and phytoplankton in the German Bight: Evaluation of productivity data with regard to the problem of eutrophication (W. Hickel, Biologische Anstalt Helgoland, Litoralstation List/Sylt)	Box 9, Fig. 24
9. Evaluation of nutrient analyses 1979-1983 in the region of the German Bight known for oxygen depletion (U. Brockmann, Institut für Biochemie und Lebensmittelchemie der Universität Hamburg)	Box 4, Fig. 8

10.	Trends in nutrient concentrations in the water of Kieler Bucht (B. Zeitzschel, Institut für Meereskunde Kiel)	Box 5 Box 7, Fig. 12
11.	The image of oxygen depletion events and of the concomitant nutrient pattern in the sediment (G. Wefer, Geologisch-Palaeontologisches Institut der Universität Kiel)	Box 13
12.	Investigations on chemical bounds, diagenesis and accumulation rates of phosphorus in sediments of Kieler Bucht. Construction of a rough budget for phosphorus input and output in the system Kieler Bucht. Bibliographic study on the importance of sediment as sink, buffer and source in the cycling of phosphorus (W. Balzer, Institut für Meereskunde Kiel)	Box 8

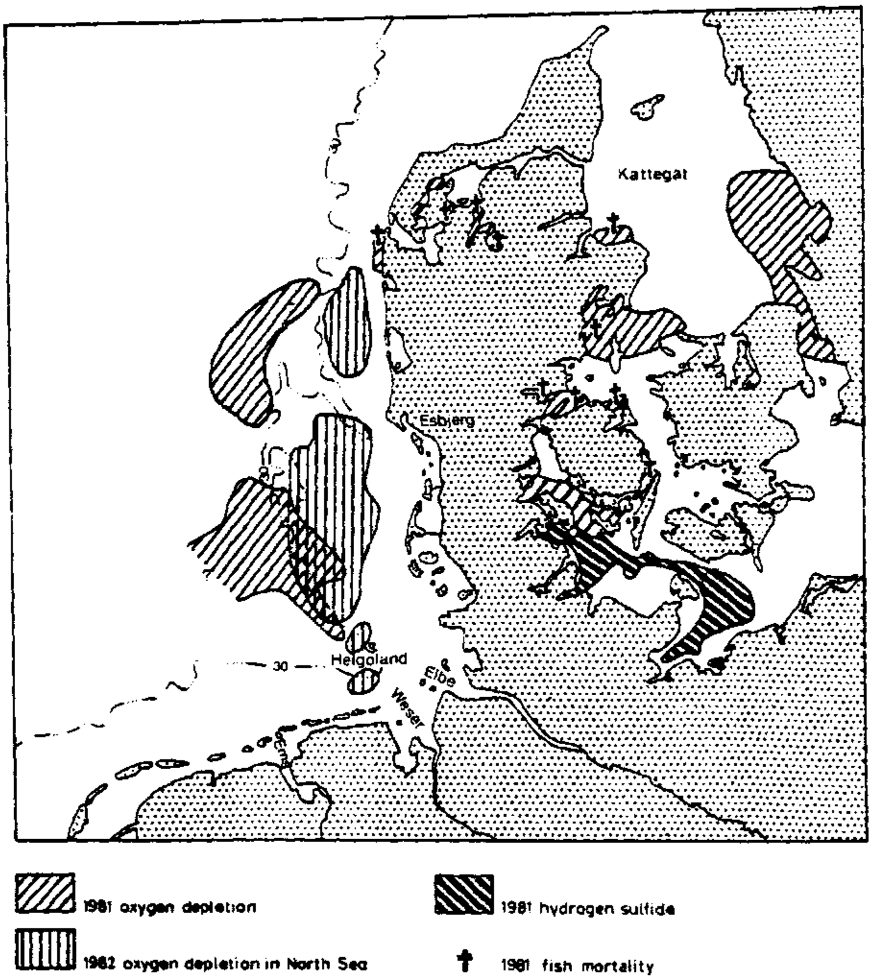

Fig. 1: Localities with events of oxygen depletion 1981 - 1982.
From Miljøstyrelsen, 1984 and Rachor 1983.

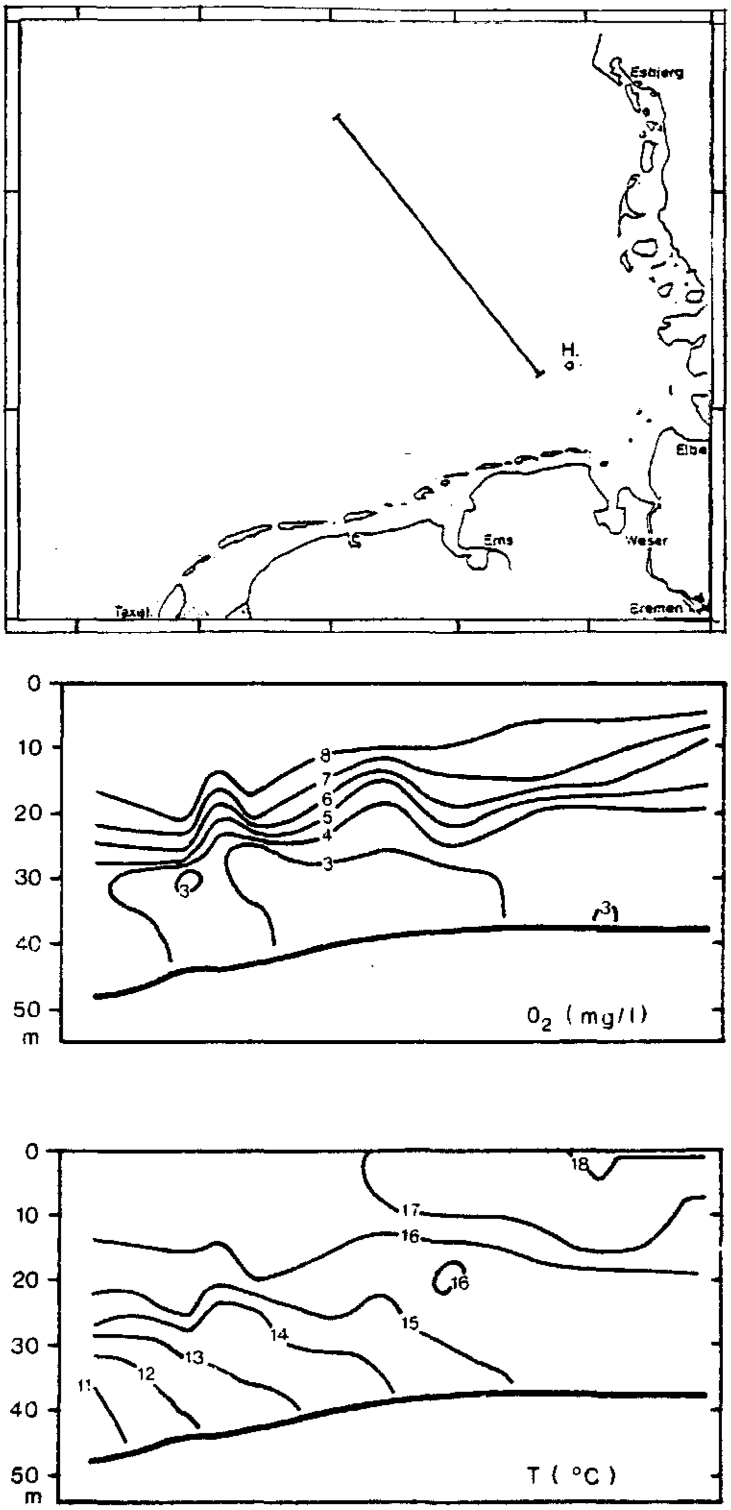

Fig. 2: Oxygen concentration and temperature on a 100 nautical miles long profile from a station west of Helgoland (H) into the German Bight, September 1981.
From Rachor and Albrecht, 1983.

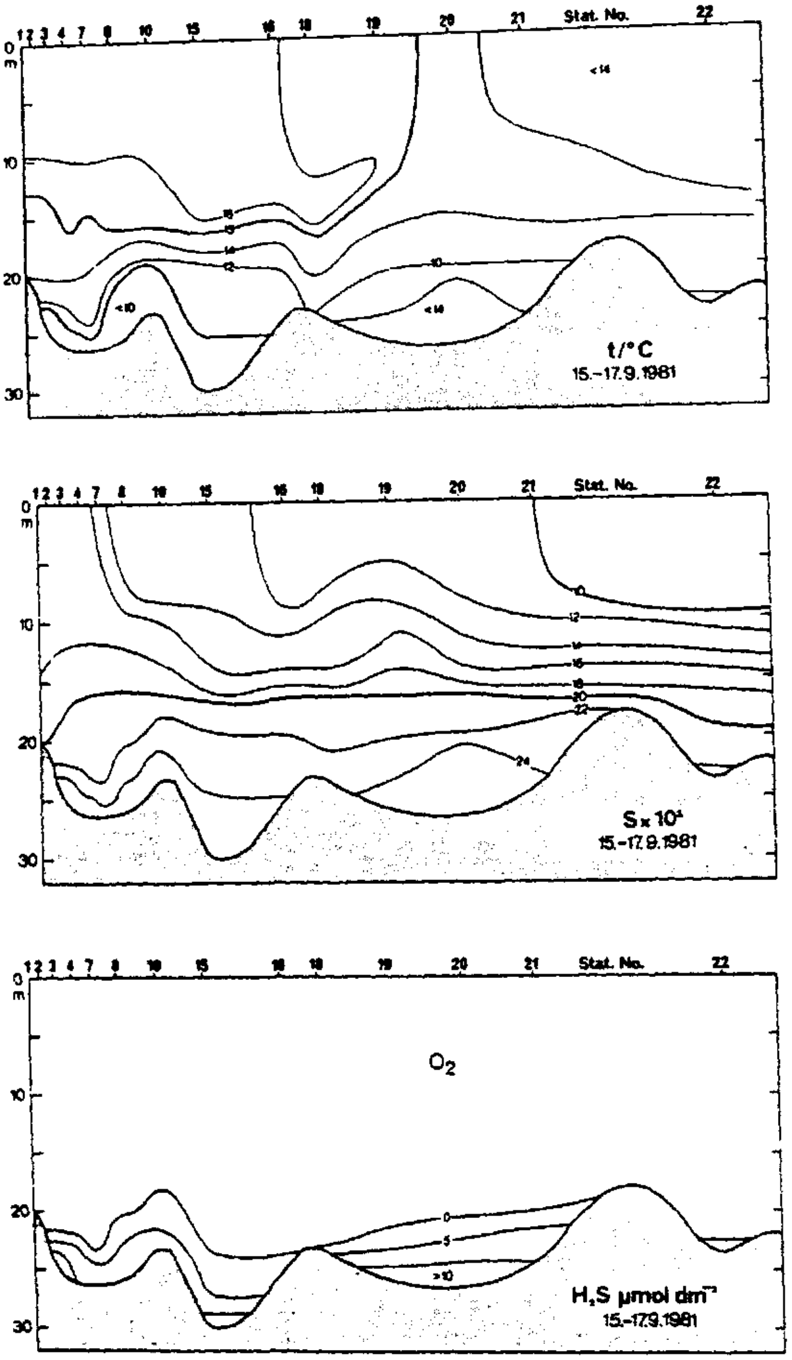

Fig. 3: Distribution of temperature, salinity and hydrogen sulfide on 15-17 September 1981 in Kieler Bucht and Mecklenburger Bucht. The profile runs from Eckernförde Bay (station 10), then in an easterly direction through Vejsnaes Channel (stations 15-18) and through Fehmarn Belt (stations 19-21) to a position in Kadett-Channel east of Gedser.
From Ehrhardt and Wenck, 1984.

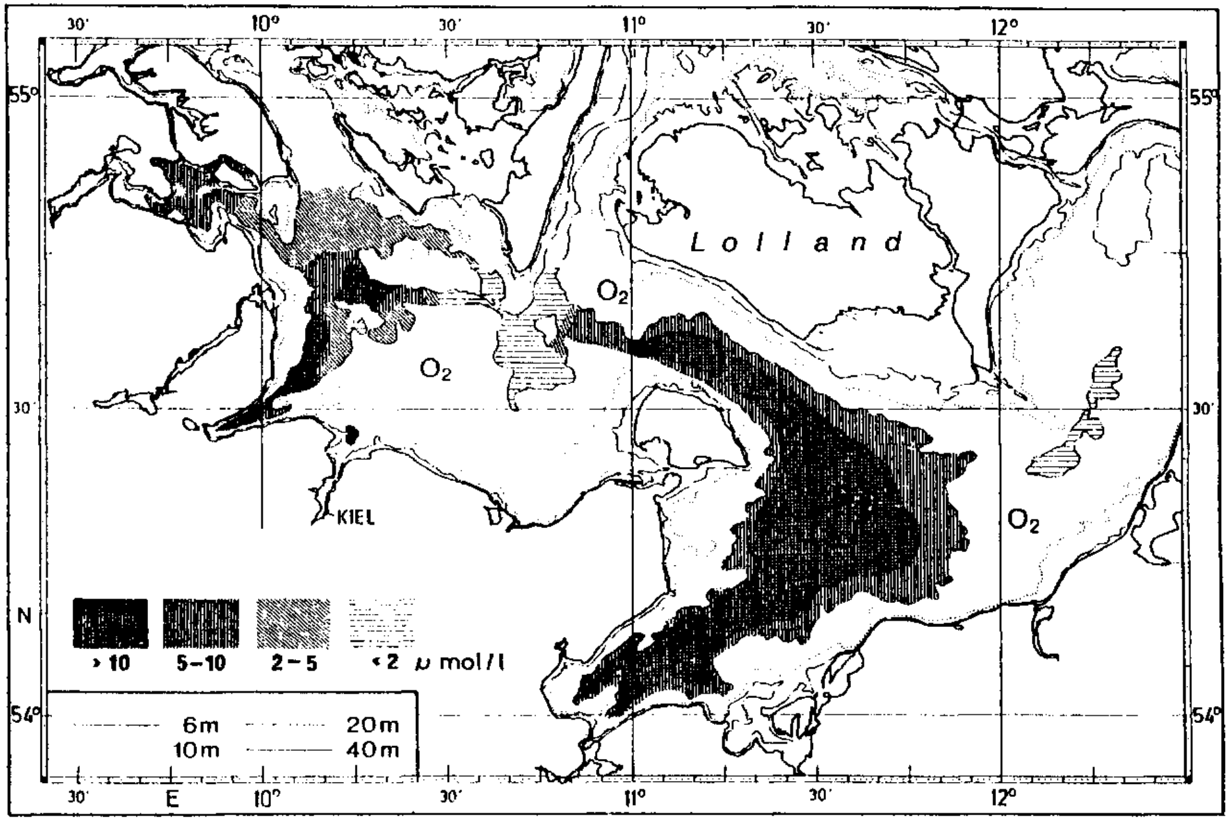

Fig. 4: Distribution of hydrogen sulfide in the near-bottom water of Kieler Bucht and Mecklenburger Bucht 15 - 17 September 1981. From Ehrhardt and Wenck, 1984.

Box 2

Report on Subproject: Macrozoobenthos in Kieler Bucht: Population dynamics in deep areas 1982 - 1983

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In late summer 1981 oxygen deficiency killed most of macrozoobenthos in areas of Kieler Bucht which are below 18 - 20 m water depth, with the exception of the clams Arctica islandica, Astarte spp. and the priapulid worm Halicryptus spinulosus. Demersal fish emigrated to shallower areas. During winter 1981/82 and summer 1982 recolonization by opportunistic worms Polydora spp. and Capitella capitata, subsequently by other benthic animals occurred, so that one year after the oxygen catastrophe benthic abundance and biomass was reestablished, even if some species like the worm Nephtys spp. did not appear again (Weigelt, 1983).

In summer 1982 again there was a tendency in Kieler Bucht for oxygen deficiency caused by calm weather, but in August 1982 westerly gales (up to Beaufort 12) provided exchange of the water mass below the halocline. The recovery of macrozoobenthos in the deeper parts of Kieler Bucht therefore continued, and in summer 1983 species richness, abundance and biomass was generally higher compared with summer 1981, i.e. is before the oxygen catastrophe occurred. In August 1983 oxygen depletion started again. Concentrations of only 1 ml oxygen/l were found below 20 m water depth. It cannot be excluded that in some areas oxygen disappeared totally, because nearly no fish was caught below 20 m water depth, and in some areas empty shells of the bivalve Syndosmya alba were found, in other areas masses of dead polychaete worms. Sensitive zoobenthos species died, resistant ones survived, and opportunistic ones invaded the areas later, after oxygen depletion ceased. However, in spring 1984 there were months with easterly winds or calm weather, and in the beginning of June 1984 the halocline in 16 - 18 m water depth was very strong, and only 3.5 ml oxygen/1 was present in the near-bottom layer. Macrobenthos at this time was even poorer than in November 1983. It could be anticipated that another calm summer with oxygen depletion would severely impact even the resistant species, because apparently the shells of the clam Arctica islandica became thinner and more fragile between 1981 and 1984 indicating stress conditions even for this species. However the second half of June and the month of July 1984 were extremely wet and windy, with frequent northwesterly gales. Therefore oxygen came back to the near-bottom water masses, and one might expect another recovery from oxygen deficiency in 1984.

The above description is from just a superficial glance on benthos and fish sampled during 1982 - 1984. The actual sorting and identification work started in June 1984, and real results will be worked out subsequently.

Reference:

Weigelt, M. (1983): Untersuchungen zur Situation des Benthos nach einer ausgedehnten Periode vollständigen Sauerstoffschwundes im Bodenwasser der Kieler Bucht. Diplomarbeit, Kiel

continued from p. 3

Even if there have been reports on fish kills in the past from several localities, the 1981 oxygen catastrophe seems to be unique in duration, extension and intensity.

Anybody with a basic textbook knowledge of ecology may come to the conclusion that the oxygen catastrophe of 1981 and subsequent years is the consequence of eutrophication: the increasing or accumulating input of plant nutrients like nitrogen and phosphorus via land runoff, via rivers and via the atmosphere should result in a fertilization of the sea water in coastal regions, and subsequently lead to enhanced phytoplankton and phytobenthos production. When dead, the plant biomass produced sinks to the sea bottom, and microbial degradation and remineralization of such surplus dead organic substance consumes extra amounts of oxygen. Oxygen depletion then is the consequence of eutrophication.

1.2 Government and research response

Governments in the Federal Republic of Germany, Denmark and Sweden therefore were concerned about the apparent effects of plant nutrients in washing powder, human feces, dairy feces, mineral fertilizer and atmospheric fallout on the eutrophication of coastal ecosystems. In all these countries marine scientists were asked to investigate the situation and, if necessary, to suggest measures to be taken.

The National Swedish Environment Protection Board initiated a study in 1982 which was completed in October 1983 (National Swedish Environment Protection Board, 1984). It lists up numerous gaps in the scientific knowledge of the eutrophication problem and proposes a research programme "Eutrophication" with priority studies in Laholm-Bay (Kattegat) and in Himmerfjärd Fjord south of Stockholm.

The National Agency of Environmental Protection of Denmark reacted upon the 1981 oxygen catastrophe by creating a working group of scientists who provided a thorough analysis of the situation (Miljøstyrelsen, 1984), which is the basis for a research programme underway at present.

In the Federal Republic of Germany the Federal Minister of the Interior treated the problem in discussions between experts, and in 1983 a research project was initiated: Eutrophication of the North Sea and the Baltic, which became effective on 1.4.1984 (see Box 1).

The task of the working group is to evaluate whether observed cases of oxygen depletion can be the consequence of man made nutrient input into coastal waters.

Oxygen deficiency simultaneously occurred in the German Bight and in the Belt Sea; the working hypothesis had to be that factors are responsible that influence large sea areas of different hydrography. Therefore the working group did not deal with the local or regional inshore problems in estuarine and fjord situations.

1.3. The origin of oxygen depletion

Oxygen depletion occurs when oxygen consumption by microbial and other oxidation processes of carbon, nitrogen and sulfur exceeds the sum of oxygen production by plant photosynthesis plus advection of oxygen from adjacent waters or the atmosphere. The process of oxygen depletion is time dependent; its intensity depends upon the availability of degradable organic substance and on the vitality of degrading microbes and other aerobic organisms. If oxygen depletion occurs in the dark lower compartment of stratified waters, it proceeds until either the stratification is broken up and mixing with the oxygen rich water occurs, or until the bottom water is horizontally replaced by water rich in oxygen. Weather conditions therefore play a dominant role in the development of oxygen depletion.

Oxygen depletion is intensified when additional degradable organic matter becomes available in the deep water or at the sediment-water interface. This may, for instance, occur with a sedimenting plankton bloom stimulated by the input of plant nutrients. Eutrophication together with weather may therefore play a dominant role in the development of oxygen depletion.

2. Trends in nutrient input into coastal waters

2.1 Atmospheric input

The evaluation of trends in nutrient input into coastal waters was not in the focus of the working group; data are expected to come from authorities concerned with freshwater, waste water and atmospheric pollution. Only a few scattered remarks shall be made. Atmospheric input of phosphorus to the sea is generally considered to be of low intensity. Atmospheric input of nitrogen compounds however is noticeable. Input into the German Bight 1965 - 1972 was estimated to be about 1 g N/m^2 per year, of about equal amounts of ammonium and nitrate (Rat der Sachverständigen, 1980, Fig. 4.17). According to newspaper information, the emissions of nitrous oxides into the atmosphere increased in the Federal Republic of Germany from 2 million t in 1966 to 3.1 million t in 1982; 55% of it originates from traffic and is part of the "acid rain" which shows increasing effects upon terrestrial vegetation. According to newspaper reports, farmers in many regions of the Federal Republic of Germany can now reckon with an atmospheric input of 2 g N/m^2 per year and may reduce the application of mineral fertilizer accordingly. Danish authorities conclude from measurements in the southern part of Jutland that the deposition of nitrogen from the atmosphere increased from 0.6 g/m^2 in 1955 to 1.5 g/m^2 in 1977 (Miljøstyrelsen, 1984). Atmospheric input of nitrogen, therefore, is a significant component of total nitrogen input into coastal waters.

For the entire Baltic Sea (about 400 000 km^2) Larsson et al. (1984) estimate the input of nitrogen oxides and ammonium from atmospheric sources to be 322 000 t per year, which is about half the amount transported by rivers into the Baltic Sea (634 900 t) and much more than contributions from municipial sources (88 600 t) and industrial sources (14 200 t). The total amounts to 1 million t of nitrogen per year, plus about 77 000 t of phosphorus per year. That is an annual input of 2.5 g nitrogen and 0.2 g phosphorus per m^2.

2.2 Input from land into the Belt Sea

Summarizing data collected in the frame of the Baltic Marine Environment Protection Commission, Larsson et al. (1984) give the following input of nutrients from land into Belt Sea coastal waters of the Federal Republic of Germany 1972 - 1974 (that is Kieler Bucht and Mecklenburger Bucht. For a detailed analysis see Brandt (1977) who presents similar figures):

	total N	total P
Municipal sewage	1 700t/a	400t/a
Industrial sewage	16t/a	1t/a
Rivers and diffuse load	20 300t/a	2 600t/a
total	22 016t/a	3 001t/a

The draining area of Schleswig Holstein to the Belt Sea is 5 219 km^2, with 56.9% farmland , 16.4% grass land with livestock and 4.0% forest. It is inhabited by 1 189 000 people, of whom 79% are connected to waste water treatment plants. The sea area influenced is the fisheries zone of the Federal Republic of Germany of about 3 400 km^2. The annual man made input is 1.9 - 6.5 g nitrogen and 0.4 - 0.9 g phosphorus per m^2.

For the same area of Schleswig-Holstein, but for the much drier period 1975 - 1976 and achieved with different methods, Hoffmann (1979) presented the following data:

	total N	total P
Municipal sewage directly	2 731t/a	786t/a
Municipal sewage via rivers	1 609t/a	419t/a
Land runoff	2 004t/a	64t/a
total	6 344t/a	1 269t/a

Unfortunately, they are not good for any trend analysis.

Danish authorities tried to elaborate a budget of nutrient input for an area which includes the Kattegat, the Sound, and the Belt Sea including the Danish fisheries zones of Kieler Bucht, Mecklenburger Bucht and Arkona Sea. This is an area of 38 000 km^2 (including 21 000 km^2 of Kattegat), and the respective drainage area is 57 200 km^2 plus 45 000 km^2 which drain into Lake Vänern (Miljøstyrelsen, 1984). The results are presented in Fig. 5. and

continued on p. 19

	total nitrogen t/a				total phosphorus t/a			
	from Denmark	from Sweden	from atmosphere	total	from Denmark	from Sweden	from atmosphere	total
1975	5981o	41868			8467	4444	57o	13481
1976	475o6	3ooo5			8194	4252	57o	13o16
1977	59622	63959			8462	5o17	57o	14o49
1978	672o6	5o914	33564	151684	8625	4671	57o	13866
1979	6947o	46913	5o765	167148	8676	4589	57o	13835
198o	84654	61o77	35536	181267	9oo9	5oo4	57o	14583
1981	9o435	63228	37o48	19o711	9139	4759	57o	14468

Fig. 5: Total input of nitrogen and phosphorus into Danish waters including the Kattegat and the Sound, 38 ooo km^2.
From Miljøstyrelsen, 1984.

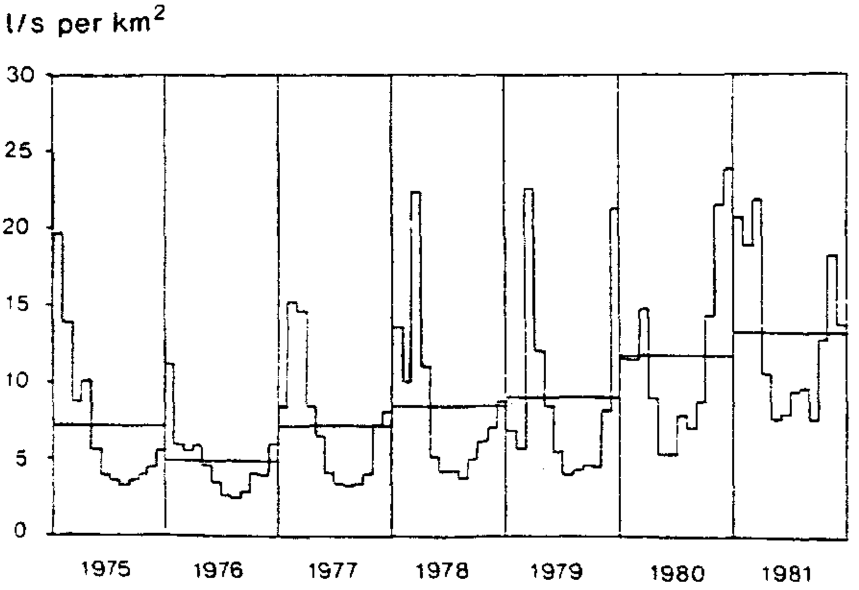

Fig. 6: Freshwater runoff from Denmark (3o 45o km^2) 1975 - 1981.
From Miljøstyrelsen, 1984.

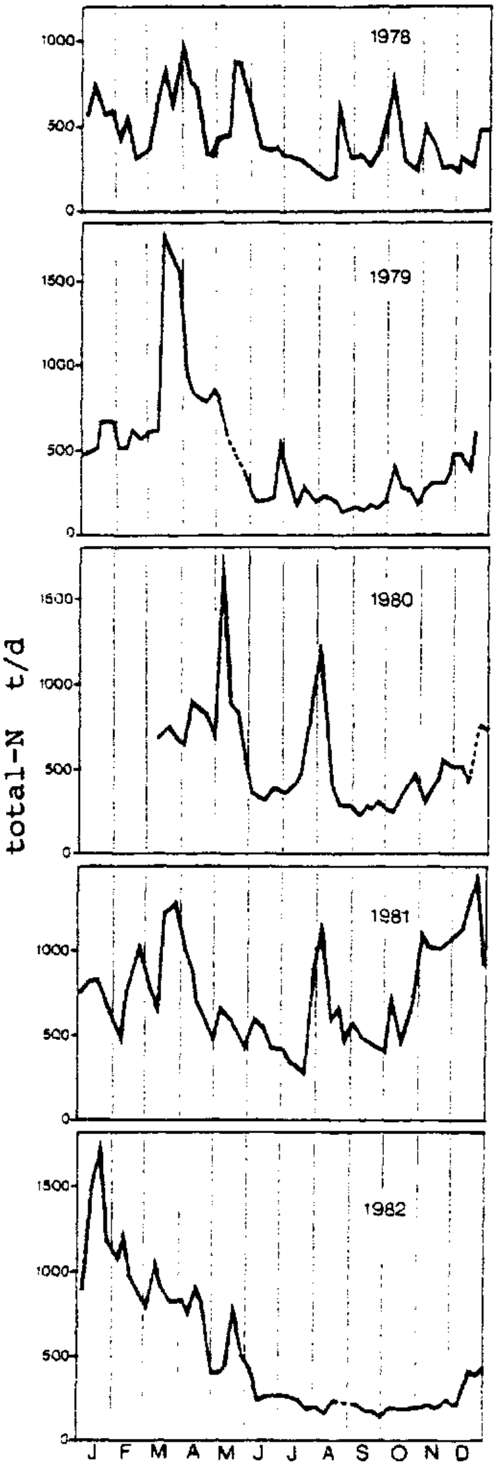

Fig. 7: Load of total nitrogen(NH_4, NO_2 + NO_3+ organic nitrogen) transported with water by the river Elbe in the inland region upstream of Geesthacht.

Compilated by W.Koeve, Institut für Meereskunde, Kiel, data published by Arbeitsgemeinschaft für die Reinhaltung der Elbe 1979 - 1983.

Box 3

Report on Subproject: River flow, nitrogen conditions and nitrogen loads of the Elbe 1978 - 1982

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Data published 1978 - 1982 by Arbeitsgemeinschaft für die Reinhaltung der Elbe have been analyzed in order to see whether for the German Bight there might be a correlation between river flow and nitrogen concentrations in sea water, similar to that found by Danish authorities for the Danish Belt Sea.

Weekly data for concentrations of nitrogen (nitrate, nitrite, ammoniak, organic nitrogen) at station Geesthacht were calculated with river flow on the same day at station Neu Darschau. Both stations are far upstream of Hamburg and are representative for the river entering the territory of the Federal Republic of Germany, but not for the input of the river Elbe into the German Bight. However data may reflect general trends:

river flow	(km^3/a)	nitrogen load (10^3 t/a)
1978	22.5	160
1979	27.6	175
1980	24.7	170
1981	34.2	265
1982	23.3	180

1981 was an extraordinary year with large river flow and nitrogen load. While in 1978, 1979 and 1982 nitrogen loads were low between June and September, in 1980 and 1981 loads were high in July - August. Every year has its characteristic flow pattern which may well influence the nutrient situation in the German Bight.

Reference:

Arbeitsgemeinschaft für die Reinhaltung der Elbe (1977 - 1983): Wassergütedaten der Elbe von Schnackenburg bis zur See

continued from p. 15

amount to a total input of about 150 000t/a of total nitrogen (4 g N/m², increasing tendency, 20% from the atmosphere) and of about 14 000t/a of total phosphorus (0.36 g P/m², no trend, 5% from the atmosphere). The increasing tendency of nitrogen input is explained by an increase of rainwater runoff during 1976 to 1981, demonstrated for the Danish drainage area of 30 450 km² (Fig. 6).

Danish (Miljøstyrelsen, 1984) and Swedish authorities (National Swedish Environmental Protection Board, 1984) can detect high concentrations of nitrogen in land runoff after heavy rain fall. There seems to be a correlation between land runoff and winter concentrations of nitrogen in coastal waters. The amounts of nitrogen transported by land runoff have increased in past decades, as the use of mineral fertilizer has increased, and increasing quantities of liquid manure from cattle, pig and chicken farming are spread on agriculture land.

2.3 Input from land into the German Bight

We are not in a position to establish budgets for the German Bight which is influenced, in addition, by water from the River Rhine. Postma (1978) calculates with a phosphorus load of the Rhine of 3 000t/a in 1932, 7 000t/a in 1955, 30 000t/a in 1970, to demonstrate the increasing tendency in the past decades. It seems probable that nutrient inputs into the German Bight, when calculated per sea surface unit, are even greater than figures for the Baltic and the Belt Sea.

In order to test the hypothesis brought forward by Danish and Swedish scientists that increased nitrogen runoff after heavy rainfall could be a important eutrophication factor, we analyzed the pattern of nitrogen loads which are carried by the river Elbe before it enters the Hamburg area (see Box 3). The concentrations of total nitrogen do not vary very much, except immediately after the onset of heavy rainfall. Probably the effect of running water in eroding nitrogen compounds from soil is counteracted by the dilution effect which rainwater has on the concentration of nitrogen in sewage. So the nitrogen loads are rather well correlated with the freshwater flow. Their effects upon the coastal ecosystem of the German Bight should be different in winter when the water is vertically mixed and in summer when riverine water with its nutrient load spreads during periods of calm weather on the surface of the German Bight (Fig. 8).

2.4 General trends and the relation between input and content

Phosphate input increased most drastically in the 1950s and 1960s with the introduction of washing powder and with the tendency to abolish septic tanks and other local means of waste water treatment and to connect increasing percentages of our population directly via sewage pipes and rivers to the sea. In the 1970s with increasing numbers of waste water treatment plants operating one could expect decreasing input of phosphorus to the sea. Nitrogen compounds from waste water should follow the same pattern as phosphorus input. However, atmospheric pollution with nitrogen increased in the 1970s, as did the use of mineral fertilizer and liquid manure on agriculture land; it seems probable that the input of nitrogen to the sea is increasing even now. Better data should be worked out and published.

For a gross calculation of the situation in coastal waters of the Federal Republic of Germany we may at least reckon with an annual input of 5 g nitrogen (nitrate and ammonium) and 0.5 g phosphorus per m^2. Nutrient concentrations of sea water in winter are in the order of 0.3 g nitrogen and 0.03 g phosphorus per m^3, or 6 g and 0.6 g per m^2 in a water column of 20 m. The annual input corresponds with the total nutrient content in the large bodies of water represented by German Bight and Kieler Bucht.

By the annual addition of the same amount of nutrients as the actual content of the water, one should expect a doubling of the concentrations. Otherwise the surplus must be exported into other areas by flushing of the water, or has to be deposited in the sediment, or it must go to the atmosphere. Apparently the elimination processes are working quite effectively. Considerable amounts of anthropogenic nitrogen and phosphorus have been imported into coastal areas for several decades. However, the increase of nutrient concentrations in coastal waters (outside estuaries and fjords) during the past 25 years seems to be rather small, less than a mere doubling over the entire period.

3. Trends in nutrient concentrations in coastal waters

3.1 Analytical, statistical and regional problems

Even though no monitoring programme was officially effective, there are two long term series of nutrient analyses available for the German Bight (Helgoland) and for the Kieler Bucht (Boknis Eck). Before referring to results and consequences we must, however, point to some problems.

One problem are analytical techniques which for nitrogen compounds have been available only for a few decades so that pre-1970 data are rare. Another difficulty is that seasonal variations are greater than variation on a longer time scale. During winter, when the coastal waters may be well mixed and when plant populations are at a minimum, nutrient concentrations in the water are at a maximum, possibly in steady state with the much higher pore water concentrations and other compounds in the sediment. In summer a large percentage of the nutrient content in the water is enclosed in the cells of phytoplankton, macroalgae and eelgrass, so that concentrations in the water often are below the level of detection, and data are sometimes dubious.

Another problem is the inhomogeneous distribution of nutrients close to sewage outfalls and river mouths. In the German Bight the tongue of riverine water coming from the rivers Weser and Elbe depends on the intensity of freshwater runoff and on the wind and current regime. With southwesterly winds this tongue may be pressed to the east, so that it runs northward very close to the coast of Schleswig-Holstein (see Box 4 and Fig. 8). Helgoland as a fixed station is sometimes situated within this tongue, sometimes outside. Nutrient concentrations therefore differ very much from period to period. High concentrations of nitrate were found in June 1981 when the Ceratium phytoplankton bloom occurred (see Box 9 and Fig. 24). One should correlate the nutrient pattern with weather data (see Box 15 and Fig. 32),

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Note: Quantities of plant nutrients are referred to either in mass units or in molar equivalents.

1 μ mol (= 1 μg - at) nitrogen = 14 μg N

1 μ mol (= 1 μg - at) phosphorus = 31 μg P

continued on p. 30

Box 4

Report on Subproject: Summer concentrations of nutrients in the German Bight 1979 - 1982

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Institut für Biochemie und Lebensmittelchemie
der Universität Hamburg

Hydrographic and nutrient conditions were analyzed on six cruises which cover the area from 6° 24' to 8° 10'E and from 53°50' to 55°10'N. They were done in June 1979, June 1980, June 1981, and in August-September 1981, 1982 and 1983.

The nutrient situation of surface waters differs very much from year to year. In June 1979, two days with easterly winds of 13 m/s transported water rich in nutrients towards the west, and subsequent days with southwesterly winds brought the water back into the investigated area, which then was mostly covered with surface water of above 1 µg-at nitrate/l, large parts above 10 µg-at/l. By contrast, in June 1980 and June 1981, with westerly winds of about 9 m/s, the riverine water was prevented from spreading over the entire German Bight. The tongue of water with more than 5 µg-at nitrate/l was restricted to the southeastern part in 1980, to the western part of the German Bight in 1981. At the end of August 1982 and in the first week of September 1983 southwesterly winds of 15 m/s, later 9 m/s prevailed.They pressed the tongue of riverine water close to the Waddensea of Schleswig-Holstein, that is east of the area investigated, so that concentrations of above 1 µg-at nitrate/l were only measured in the estuarine region of the Elbe river.

In vertical profiles, already in June a thermocline is developed. Compared with winter conditions, there is a decrease of nutrients not only in the upper water masses, but also below the thermocline. In August and September nutrient levels in the lower compartment increase, but it is difficult to evaluate the respective contributions of benthic remineralization, of import via North Sea deep water or import from the Waddensea. Concentrations of dissolved organic nitrogen are several times higher than concentrations of nitrate. Phosphate concentrations increase in water masses where oxygen deficiency is observed. With wind from east or northwest, surface layers of riverine water rich in nutrients can be situated in top of those areas where oxygen deficiency was observed in the deep water.

Box 5

Report on Subproject: The use of satellite data for the evaluation of eutrophication processes in German Bight and Baltic Sea.

Ulrich Horstmann and Bernt Zeitzschel
Institut für Meereskunde, Kiel

Data from the Coastal Zone Color Scanner of the satellite Nimbus - G were used. 168 pictures from 1979 to 1984 are available in channel 3 (550 nm). 8 pictures have been processed. However, there are difficulties in identifying chlorophyll, probably due to high Gelbstoff concentrations and due to interactions of aerosol signals with suspended matter signals. Ground truth data would be necessary to control the results obtained from processing the pictures, before pictures from space could be considered as useful instruments to monitor regional effects of eutrophication in coastal waters of the Federal Republic of Germany.

In future, when research vessel cruises are made for hydrographic and phytoplankton research in the German Bight and in the Belt Sea, one should apply for synchronous satellite information, if possible received on line on the research vessel, but in addition in a form of documentation which can be processed later.

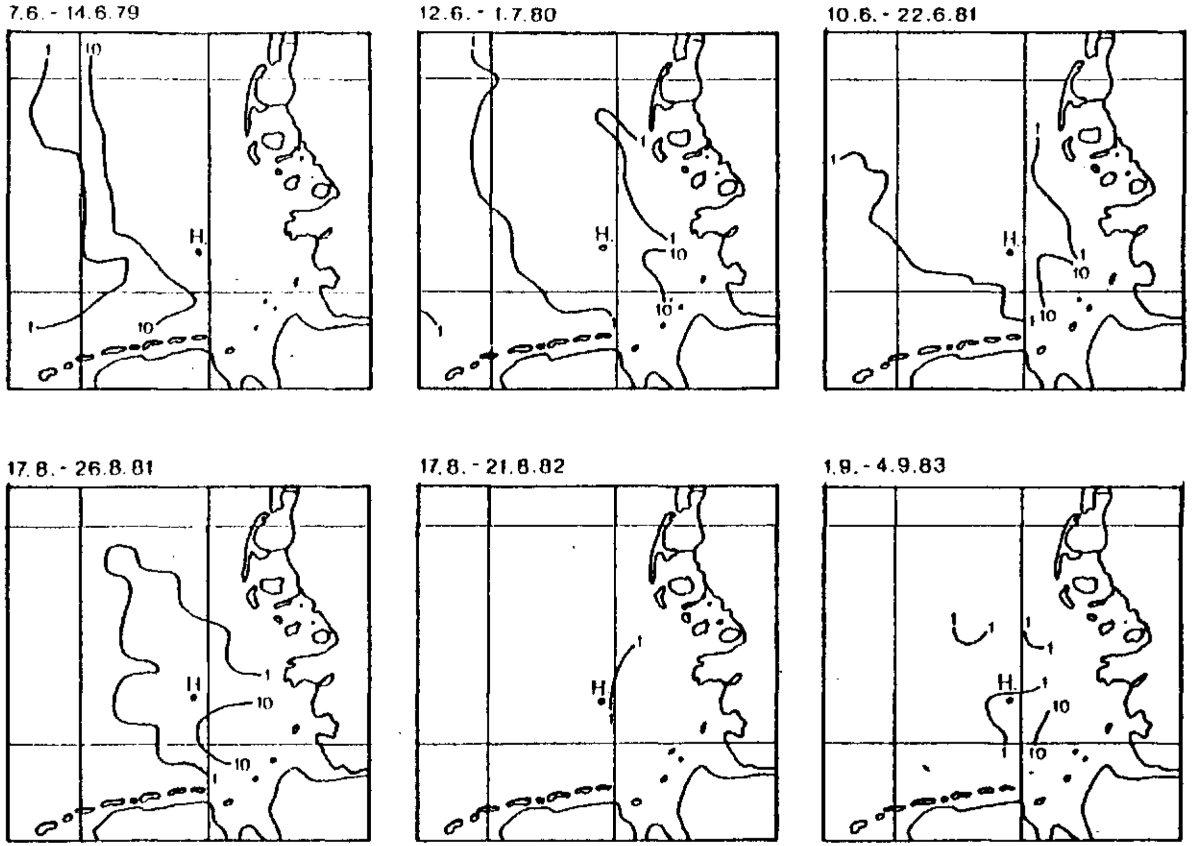

Fig. 8: Quasisynoptic distribution of nitrate in surface waters of the German Bight during six cruises. Figures refer to µg-at/l. H = Helgoland.
Unpublished results kindly provided by Dr.U.Brockmann, Institut für Biochemie und Lebensmittelchemie der Universität Hamburg.

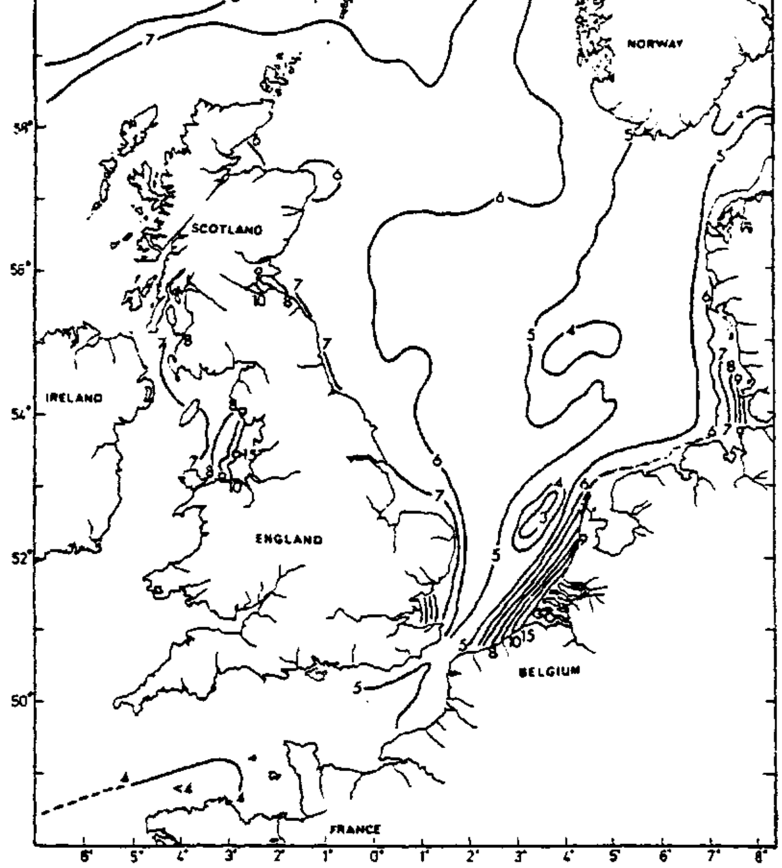

Fig. 9: Generalized distribution of phosphate concentrations in the North Sea during winter. Figures refer to 10^{-7} µg-at/l and should be multiplied by 3.1 to get concentrations in µg/l. Figure of Mc Intyre and Johnson 1975 reproduced from Gerlach, 1981.

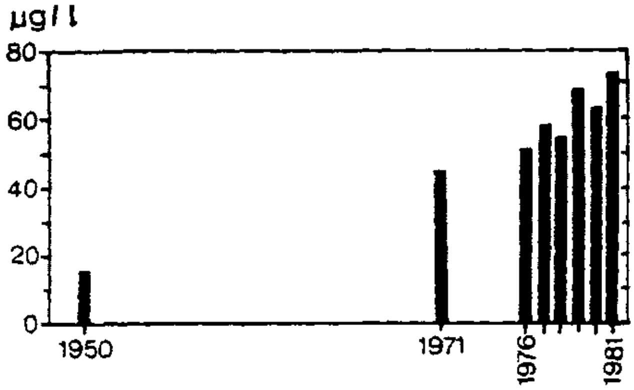

Fig. 1o: Trends of yearly mean phosphate-phosphorus concentrations at station Marsdiep (between the island of Texel and the Dutch mainland) 195o - 1983.
From de Wit et al., 1982.

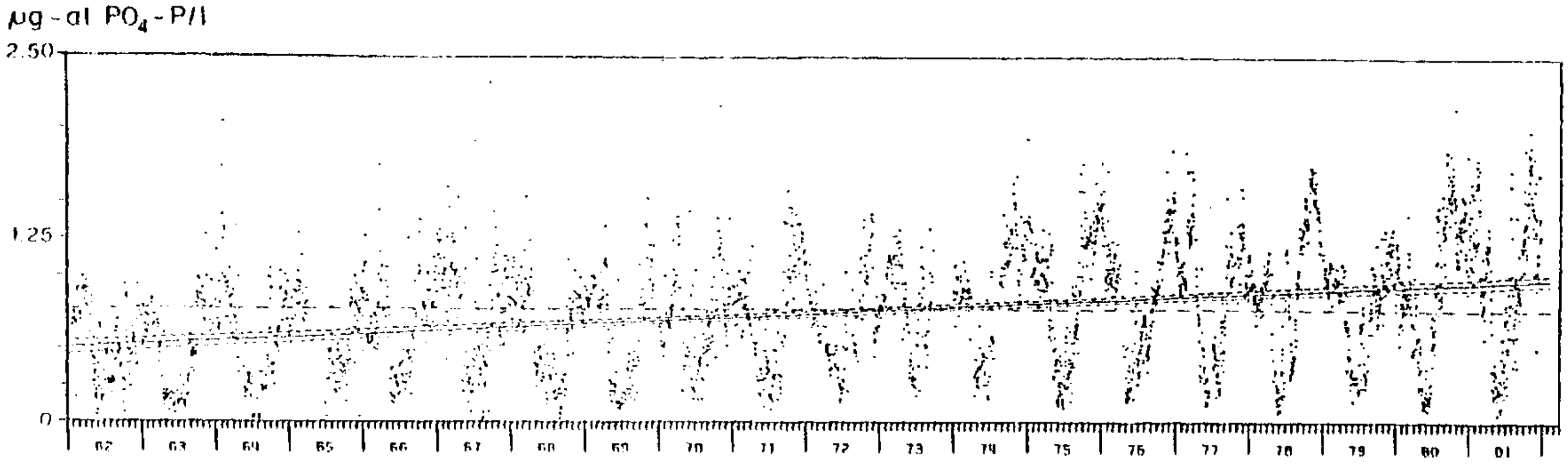

Fig. 11: Concentrations of phosphate in surface waters at Helgoland 1962 - 1981, and linear regression over the entire period.
Unpublished result kindly provided by Dr. Radach, Institut für Meereskunde, Universität Hamburg.

Box 6

Report on Subproject: Trends in concentrations of plant nutrients at Helgoland Reede 1962 -1981

G. Radach und J. Berg
Institut für Meereskunde, Universität Hamburg

The best data set available on variation of parameters in the German Bight is from surface waters at a station between the island of Helgoland and Düne, sampled since 1962 5 times per week by scientists and technicians of Biologische Anstalt Helgoland. Results regarding phosphate, nitrogen compounds, silicate, salinity and temperature have been published (Jahresberichte Biologische Anstalt Helgoland) from 1978 onward or have been presented as monthly means (Hagmeier, 1978), corrected for salinity in order to eliminate the influence of the changing position of the tongue of Elbe river water (Lucht and Gillbricht, 1978), or using data from specific months of the year (Gillbricht, 1983). In general, an increasing trend of phosphate concentrations could be demonstrated; however, the situation is rather complicated, with large fluctuations from year to year.

A new approach was started to process all available data with appropriate computer programmes. The problem is that seasonal variations of most parameters are larger than variations on larger time scales. Another problem is that data depend on freshwater and nutrient input via the rivers Elbe and Weser; Helgoland is sometimes in the center of the tongue of river water, sometimes the island is east, sometimes west of this tongue, depending on wind and currents. Data depend further on the total amount of freshwater runoff and on the intensity with which the freshwater is mixed with the sea water of deeper layers in the German Bight.

The aim of this project is to correlate data measured at Helgoland with Elbe river runoff and with meteorological observations at Elbe 1 lightvessel.

In a first approach it was tested whether the situation can be described by linear regressions covering the entire period 1962 - 1981 (20 years).

Surface water temperatures increased from 1962 to 1981 by 1.1 ° C, which confirms results found for the period 1960 - 1973 by Becker und Kohnke (1978).

Salinity has no significant trend. Silicate decreased from 1966 to 1981.

Phosphate concentrations increased from about 0.5 µg - at/l in 1962 to about 1.0 µg - at/l in 1981 (significant at the 99% level). This trend is also obvious when only winter concentrations are considered.

As there is no trend in salinity, the conclusion should be that the increase of phosphate in sea water at station Helgoland was not caused by a general change of water masses in this region. Therefore the phosphate trend may be due to increased man made nutrient input via the rivers.

Statistical analysis of time intervals shorter than 20 years, and other statistical procedures (filtering out of high frequency components) have to be applied, before a meaningful correlation with river data and meteorological data can be undertaken.

References:

Hagmeier, E. (1978): Variations in phytoplankton near Helgoland. Rapp. P.-v. Reun. Cons. int. Explor. Mer 172: 361 - 363

Lucht, H. and M. Gillbricht (1978): Long-term observations of nutrient contents near Helgoland in relation to nutrient input of the River Elbe. Rapp. P.-v. Reun. Cons. int. Explor. Mer 172: 358 - 360

Gillbricht, M. (1963): Eine "red tide" in der südlichen Nordsee und ihre Beziehungen zur Umwelt. Helgoländer Meeresuntersuchungen 36: 393 - 426

Becker, G. and D. Kohnke (1978): Long-term variations of temperature and salinity in the inner German Bight. Rapp. P.-v. Reun. Cons. int. Explor. Mer 172: 335 - 344

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with the simulated current situation (see Box 14) and with nitrogen loads of the rivers (see Box 3 and Fig. 7). For the future there is some hope that observation from space may better allow to detect the position of riverine water masses (see Box 5).

If we look at the distribution of nutrients in surface winter water of the entire North Sea (Fig. 9) it becomes clear that Helgoland is situated in a region characterized by a gradient of nutrient concentrations. According to the dominant wind regime, estuarine water from the river Rhine is transported very close to the Dutch and Niedersachsen Waddensea in eastward direction. This stream receives nutrient inputs from the mineralization of organic matter in the Waddensea, gets the nutrient input from the rivers Ems, Weser, Elbe and Eider and from the Schleswig-Holstein Waddensea, and runs northward close to the Jutland coast of Denmark. What answer could we expect from long term measurements at station Helgoland regarding eutrophication ? Whether the gradient fróm high inshore nutrient concentrations to low open North Sea concentrations has changed in the past decades, whether its isolines for average nutrient concentrations in winter have moved from southeast to northwest.

Trends observed at Helgoland cannot be extrapolated for the North Sea further offshore. There eutrophication effects will be less distinct. At the other side, trends observed at Helgoland cannot be extrapolated for the more inshore situations between Helgoland and the estuaries of Weser and Elbe. Eutrophication effects there should be much more noticeable due to the steeper gradient of nutrient concentrations, indicated by the isolines of Fig. 9. Data from Helgoland stand only for waters which have a similar position between the open North Sea and inshore conditions.

3.2 Trends in nutrient concentrations in the German Bight

The only long term set of data available from the German Bight are the samples collected five times per week at Helgoland 1962 - 1984. The new analysis of data (see Box 6 and Fig. 11) confirms earlier statements (Fig. 20) that there is an increase in mean phosphate concentrations from about 0.5 µg - at P/l in 1962 to about 1.0 µg - at P/l in 1981. Subsequent statistical treatment will define possible trends during shorter intervals of time and during specific seasons of the year. They will be correlated with meteorology, hydrography and freshwater runoff. Nitrogen data and silicate data will be included in the study.

The evidence for increasing nutrient concentrations at Helgoland is sustained from the Netherlands. Increasing phosphate concentrations have been observed in the Marsdiep since 1950, and concentrations 1979 - 1981 are about five times higher than in 1950 (Fig. 10). The station, however,is more inshore than Helgoland. The increase of nitrogen compounds is less spectacular, but a doubling between 1961/62 and 1971 has been documented (De Wit et al., 1982).

In conclusion, a trend of increasing nutrient concentrations over the past 20 - 25 years has been documented. It seems probable that man is responsible for this increase, and that the eutrophication effects observed in the German Bight are, at least partly, man made.

3.3 Trends in nutrient concentration in Kieler Bucht

There is a good time series available for total phosphorus concentrations at station Boknis Eck in the western part of Kieler Bucht, starting in 1958 (see Box 7). The series was interrupted 1976 - 1979, but there is some hope that it will be supplemented by other information from this period.

During the observation period 1958 - 1975 there was no significant trend in total phosphorus concentrations. However, data from winter 1980, 1981 and 1984 are higher, so that recent years winter concentrations exhibit an increasing trend (Fig. 12). This is in accordance with data from stations south of Langeland and Fehmarnbelt achieved out in the framework of the Danish Belt Project (Aertebjerg et al., 1981) and summarized by Danish authorities (Miljøstyrelsen, 1984). There was a decrease 1975 to 1978 and an increase 1980 to 1983 in phosphate, and an increase 1975 to 1983 in total inorganic nitrogen concentrations (Fig. 13 - 14). Similar observations were made in the Kattegat and in the Great Belt, where phosphate winter concentrations in 1981 - 1983 were about as high as in 1975.

Certainly, the period 1975 to 1983 is too short for a definite statement that there is an increasing trend in nutrient concentrations. It might well be that high concentrations are the result of special meteorological and hydrographical conditions, and that the years 1980 - 1983 are compensated by other years with low conditions, both reflecting extremes of the normal variability. However, the evaluation of the situation cannot wait for some

continued on p. 35

Box 7

Report on Subproject: Trends in nutrient concentrations in Kieler Bucht.

Brigitta Babenerd and Bernt Zeitzschel
Institut für Meereskunde Kiel

Nutrient analyses from waters of Kieler Bucht date back to 1903; however, the only long term series which can be used is total phosphorus from station Boknis Eck 1958 - 1975 (Krey et al. 1978). Boknis Eck is situated in the western part of Kieler Bucht where oxygen depletion is a regular feature nearly every year and, in consequence, phosphorus concentrations in the water below the halocline increase very much in late summer, which can be demonstrated by average values for 1958 - 1975 (Babenerd, 1980).

If one analyzes all total phosphate data from 1958 to 1975, there is no trend, not in different water depths, not in special seasons of the year. However, in 1958 - 1966 the variability of data is larger than 1967 - 1975. There is additional information from 1980-81 and from 1984 on total phosphorus at Boknis Eck station in winter (January - February). In these years concentrations were higher than in the period 1958 - 1975.

There are many additional published and unpublished data on nutrients in Kieler Bucht, which at present are in the process of critical evaluation. It seems that winter phosphate - phosphorus concentrations at Boknis Eck were below 1.0 µg-at/l 1958 - 1961, were about 1.0 µg-at/l in 1972 - 1978 and above 1.0 µg-at/l in 1980, 1981 and 1984, but further confirmation is necessary. There is no clear trend for total inorganic nitrogen; it seems that silicate decreased from 1973 to 1982. For near-shore areas like Strander Bucht (situated south of the Bülk sewage outfall) it seems that phosphate concentrations in 1935/36 (Wattenberg and Meyer, 1936) were much lower compared with 1983/84 (data of C.Stienen, IfM Kiel).

References:

Krey, J., B. Babenerd, J. Lenz (1978): Beobachtungen zur Produktionsbiologie des Planktons in der Kieler Bucht: 1957 - 1975. 1. Datenband. Ber. Inst. Meereskunde Kiel 54, 1-113

Babenerd, B. (1980): Untersuchungen zur Produktionsbiologie des Planktons in der Kieler Bucht - mit einer Auswertung der monatlichen Terminfahrten aus den Jahren 1957 - 1975. Dissertation Univ. Kiel, S. 1 - 226

Wattenberg, H. and H. Meyer (1937): Der jahreszeitliche Gang des Gehaltes des Meerwassers an Planktonnährstoffen in der Kieler Bucht im Jahre 1935. Kieler Meeresforschungen 1, 264 - 278

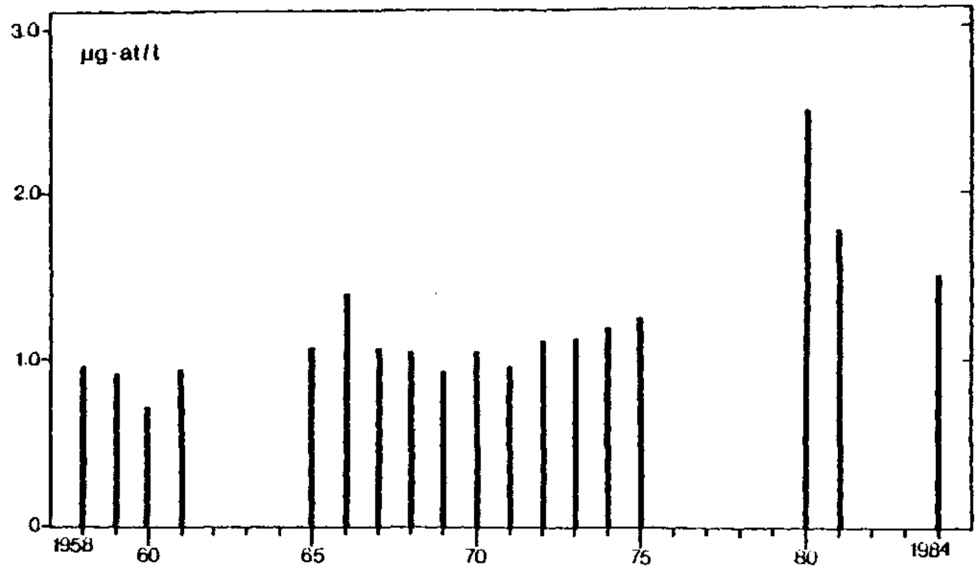

Fig. 12: Mean winter (January/February) values for total phosphorus concentrations 1958-1984 in the water column at station Bokniseck, Kieler Bucht.
Unpublished data kindly provided by Dr.Brigitta Babenerd, Institut für Meereskunde, Kiel.

continued from p. 31

20 years more. Whether or not observations made in the past few years really reflect an increasing trend: the possible causes should be discussed immediately.

3.4. Possible causes of increased nutrient concentrations since 1975

In the case of phosphorus, increasing man made input probably cannot be the cause; an analysis of river loads will show that the input has not increased much over the past couple of years, a consequence of waste water treatment plants which eliminate a certain percentage of phosphorus, even if they are not equipped with special elimination techniques like in Sweden and Finland.

However, it might well be that continuous input of phosphorus to the coastal sea by now surpasses the buffering capacity of the sediment. It seems likely that part of the phosphate which reaches the sea with sewage and river water is bound as inorganic phosphorus compounds, mostly with iron, in the sediment. Phosphorus reaching the sea bed with organic components too may be transformed into inorganic phosphorus compounds. The phosphorus concentrations in the sediment (dissolved in the pore water and particulate) are many times higher than concentrations in sea water (Box 8 and Fig. 15). There is also a release of phosphorus from the sediment to the sea water, and the hypothesis has some appeal that at the end of the winter period some kind of steady state is reached between high sediment concentrations and corresponding low water concentrations.

If there should be some proportionality between sediment and water concentrations and if, in the course of the past decades, phosphorus concentrations in the sediment should have increased due to the input from anthropogenic sources, then one could imagine higher sea water concentrations now. It seems, however, that this is more a research proposal than a reliable argument in establishing whether man, by year to year input, finally changes the sediment-water system of phosphorus concentrations in such a way that a future increase in concentrations can be foreseen.

The problem is made more difficult by the fact that up to 10 times more phosphorus is released from the sediment when the sediment surface and overlying water suffers from oxygen depletion (Fig. 16). As a result, high

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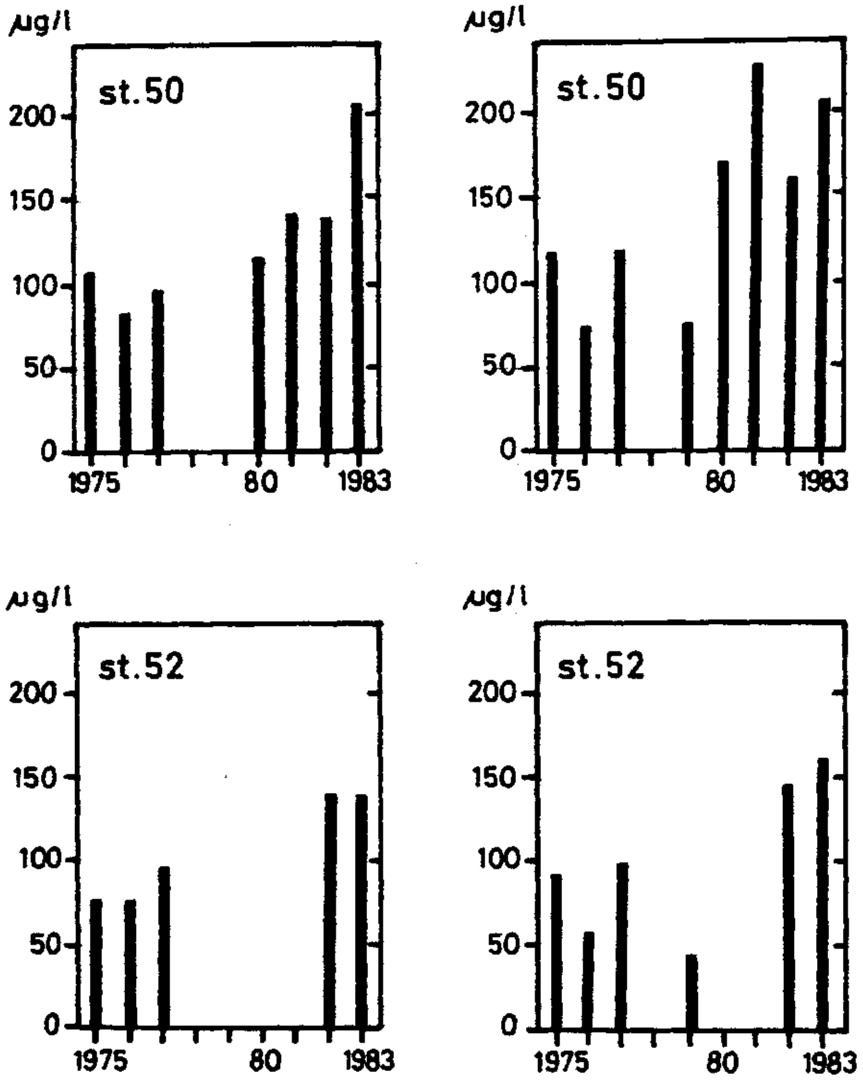

Fig. 13: Mean winter (January to March) concentrations 1975 - 1983 of total inorganic nitrogen at station Kelds Nor, south of Langeland(5o) and station Fehmarnbelt(52).
Left: surface water. Right: deep water.
From Miljøstyrelsen, 1984.

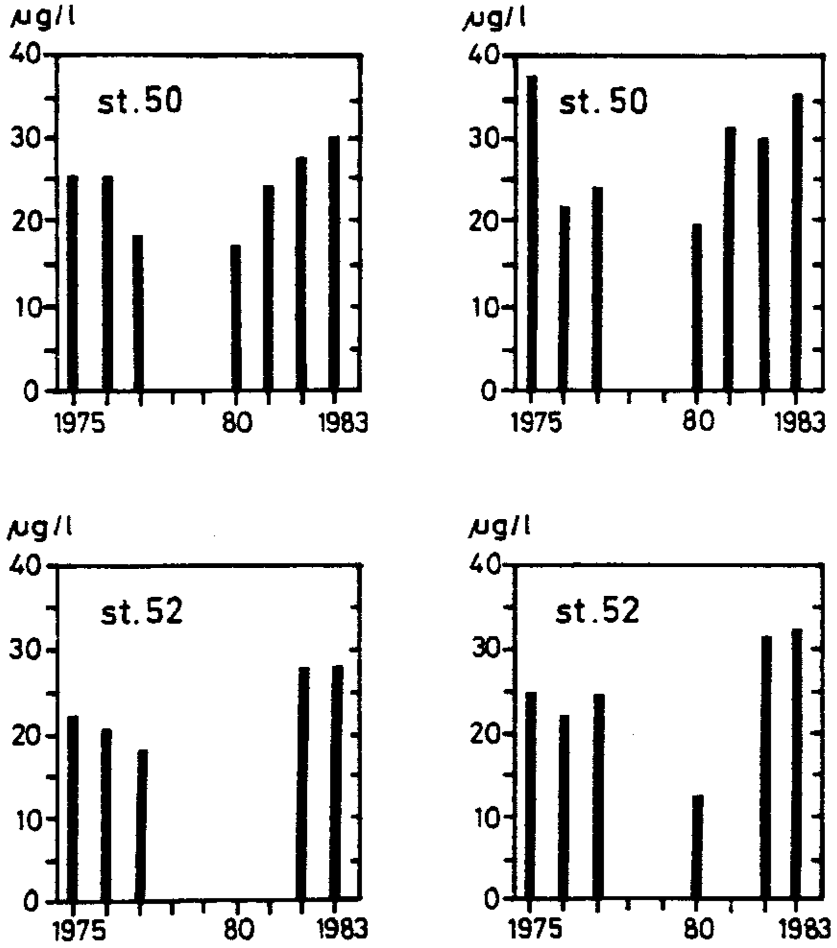

Fig. 14: Mean winter (January to March) concentrations 1975 - 1983 of phosphate phosphorus at station Kelds Nor, south of Langeland (5o) and station Fehmarnbelt(52).
Left: surface water. Right: deep water.
From Miljøstyrelsen, 1984.

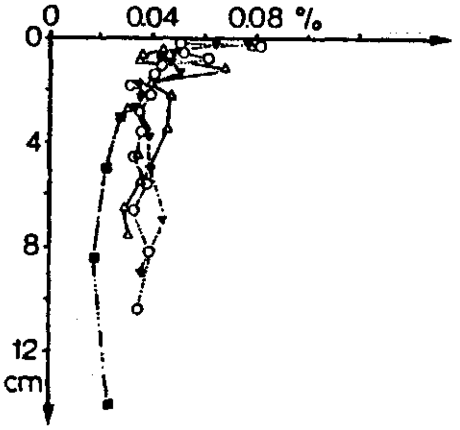

Fig. 15: Sediment profile of inorganic phosphorus at station Bokniseck 2o m. Concentrations refer to % sediment dry weight.
From Balzer, 1978.

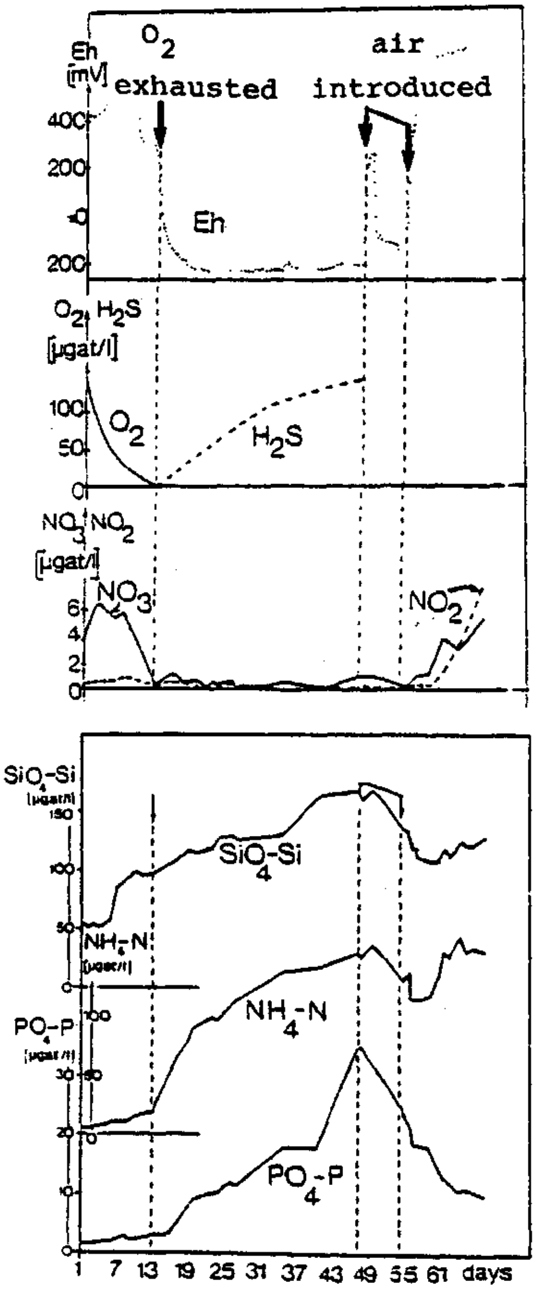

Fig. 16: Processes in the water enclosed by a bell jar experiment on the sea bottom at Bokniseck, Kieler Bucht, 2o m depth. During the first 13 days redox potential (Eh) dropped, oxygen (O_2) and nitrate (NO_3) disappeared. During the anoxic phase (day 14 - 47) hydrogen sulfide (H_2S), silicate (SiO_4 - Si), ammonium (NH_4 - N) and phosphate (PO_4-P) increased. When the system was aerated after day 48, phosphate concentrations decreased because phosphorus was bound to the sediment.
From Balzer et al., 1983.

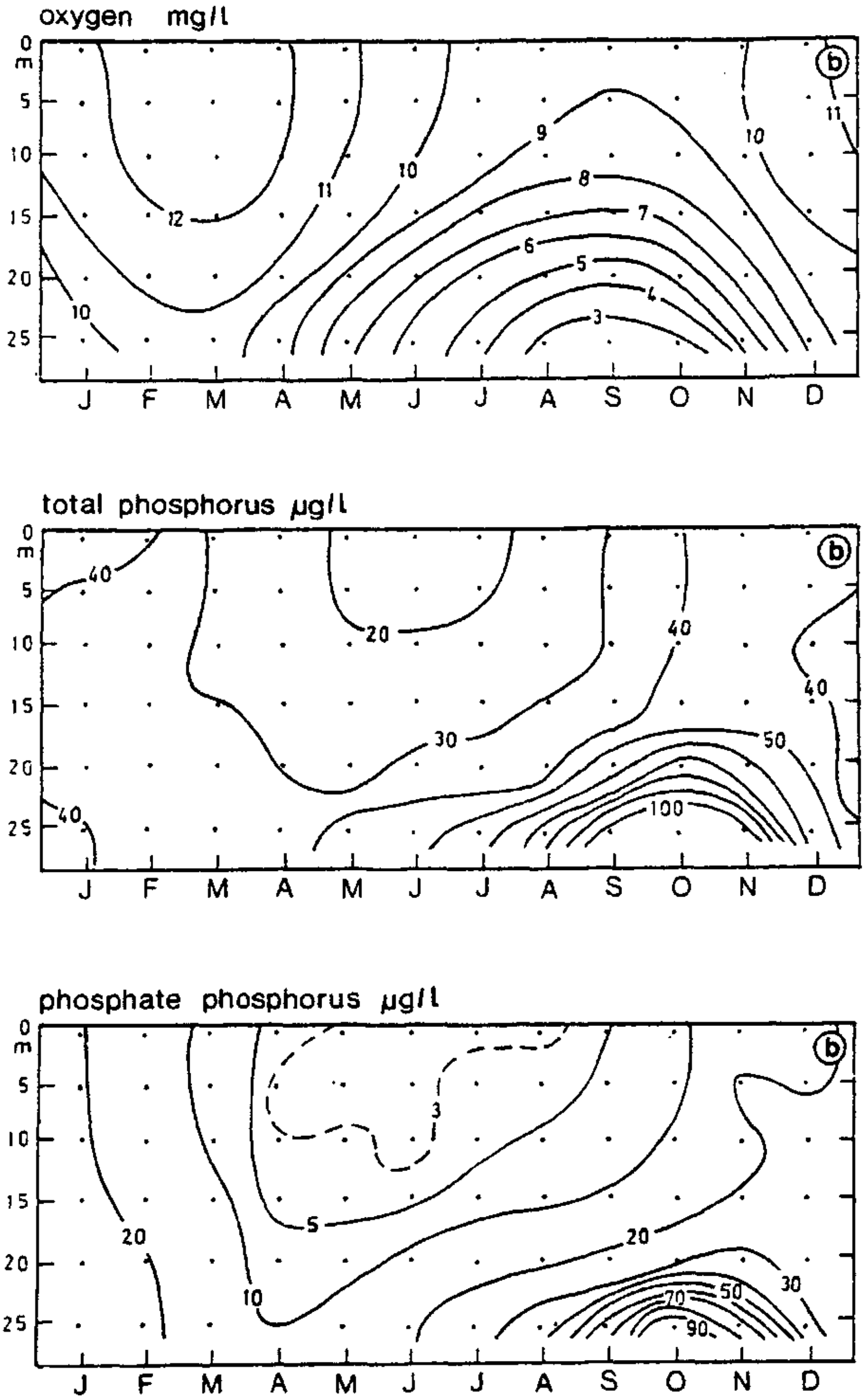

Fig. 17: Mean seasonal distribution of oxygen, total phosphorus and phosphate phosphorus 1957 - 1975 at station Bokniseck in the western part of Kieler Bucht.
From Babenerd, 198o.

Box 8

Report on Subproject: Chemical bounds, diagenesis and accumulation of phosphorus in sediments of Kieler Bucht.

W. Balzer
Institut für Meereskunde Kiel

The intention is to work out the balance for a 20 m station at Boknis Eck. The sum of the phosphorus released after remineralisation to the water plus the organic phosphorus accumulated in the sediment is only 77 % of the phosphorus sedimented as organic matter. Probably a transformation to inorganic phosphorus compounds occurs. Rates for the accumulation of inorganic phosphorus can be calculated from profiles of inorganic phosphorus in sediment and sedimentation rates. The amount of inorganic phosphorus contained in the upper sediment layer (about 0.05 % of sediment dry weight or about 13 g/m^2 in the upper 2 cm) is many times higher than the amount of phosphate in the overlying water column (about 30 $\mu g/l$ or 0.6 g/m^2 in winter).

If the bottom water is enclosed over the sediment (in experiments of bell jar type) oxygen concentrations drop within 13 days to zero during summer. Subsequently the release of phosphate from the sediment to the overlying water masses increases due to solution of iron-phosphate compounds.

The increase is about tenfold compared with rates under oxic conditions. If in such enclosure experiments oxic conditions are reestablished by bubbling with air, phosphate concentrations in the water drop rapidly because phosphate is fixed to the sediment (Balzer et al., 1983).

Reference:

Balzer, W., K. Grasshoff, P. Dieckmann, H. Haardt, U. Petersohn (1983): Redox turnover at the sediment/water interface studied in a large bell jar system. Oceanol. Acta 6, 337-344

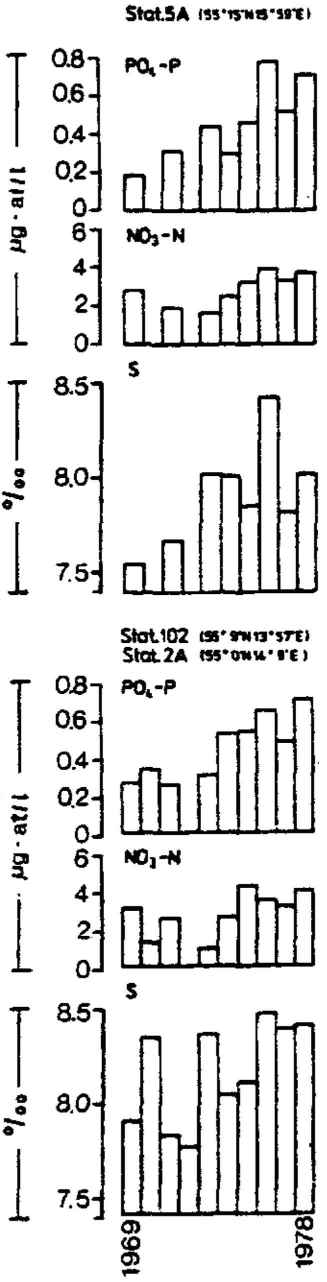

Fig. 18:Phosphate, nitrate and salinity during February in the mixed water layer above the halocline 1969 to 1978. Station 5 A = east of Bornholm, station lo2 - 2 A = west of Bornholm.
From Nehring, 1981.

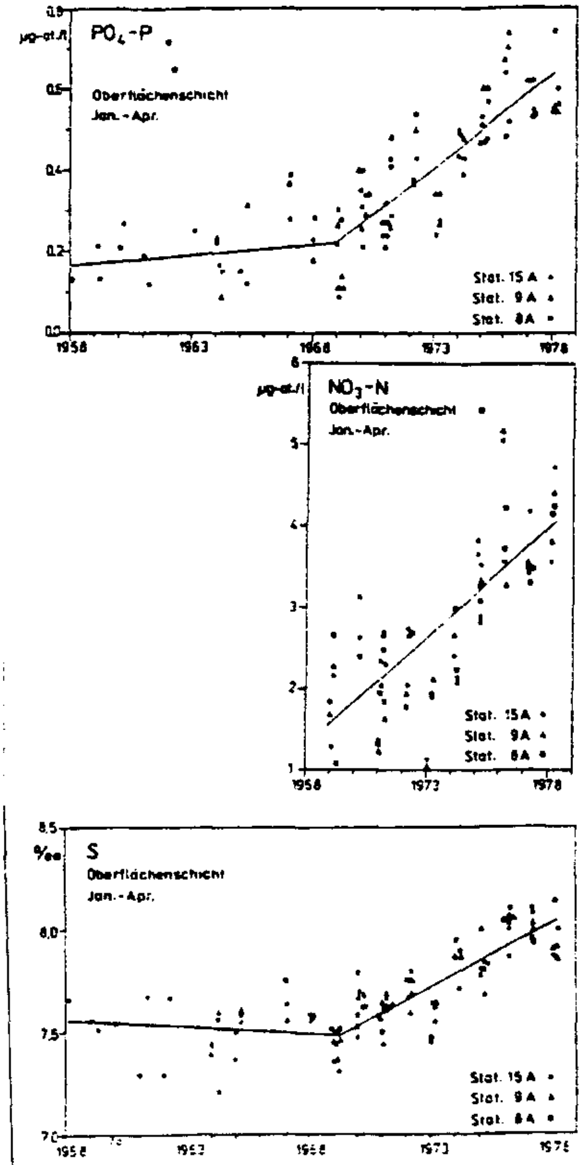

Fig. 19: The increase of phosphate. nitrate and salinity which has occurred since 1969 in the Southern Gotland Sea, Baltic, between Gotland and Öland and the USSR. Data are from winter and from the mixed water masses above the halocline, about 0 - 5o m water depth.
From Nehring, 1981

continued from p. 35

phosphate concentrations appear in the near-bottom water in areas like the western part of Kieler Bucht, when oxygen concentrations decrease (Fig.17). While one fundamental argument is that phosphorus (via plankton algae growth and mineralisation of biomass) is the cause of oxygen depletion, we have to recognize the puzzling fact that oxygen depletion (from whatever reason) is responsible for the mobilization of phosphorus from the sediment and for increased concentrations of phosphorus in the sea water. If in certain sea areas there is an increasing trend towards oxygen depletion in the near-bottom water, one would invariably find a corresponding increase of phosphate in the water.

For nitrogen compounds, the situation is even more complex, as the potential for microbial nitrogen fixation (transforming molecular nitrogen into organic nitrogen) and for microbial denitrification (transforming nitrate into molecular nitrogen or nitrogen oxides) is very much influenced by the type of sediment and the redox conditions. At the border between oxic and anoxic layers in the sediment, nitrification plays an additional role, transforming ammonium into nitrate. It seems premature to make models for the respective processes occurring in the sediments of coastal areas of the Federal Republic of Germany, even if we realize that a better understanding of these processes may be the prerequisite to understand why concentrations of plant nutrients in sea water increase or do not increase.

It is well known that the North Sea surface water is poor in nutrients compared with the Atlantic Ocean. An import of nutrients from the Atlantic into the German Bight occurs with deep water under certain hydrographic conditions which need to be studied. Similarly, deep water from the Great Belt, originating from Kattegat or Skagerrak flows into Kieler Bucht and through Fehmarnbelt into Mecklenburger Bucht. This deep water transports not only salt but nutrients too.

Mecklenburger Bucht and Kieler Bucht are influenced by water flowing out from the Baltic. Nehring (1981) studied the long-term trends of salinity, phosphate and nitrate in the surface waters of the Baltic in winter. There were increasing concentrations 1969 to 1978 of all three parameters, most prominent in the southern Gotland Sea, but visible too in the Bornholm Sea and even in the Arkona Sea which is adjacent to Mecklenburger Bucht (Fig. 18). In the southern Gotland Sea the data set goes back to 1958 for salinity and phosphate and demonstrates stable conditions until 1969 and an increase from 1969 to 1979 from 7.5 to 8.0 ‰ salinity, 0.2 to o.6 µg-at P/l phosphate and 1.5 to 4 µg-at N/l nitrate (Fig. 19). The conclusion of

Nehring is that nutrient concentrations were influenced by an identical hydrographical factor intensified vertical mixing as salinity, and that the phenomena can be explained assuming that annually 200 km^3 of deep water with 10 $^0/_{00}$ salinity, 2.0 µg-at/l phosphate and 10 µg-at/l nitrate are transported into the surface layer above the halocline.

Swedish scientists (National Swedish Environment Protection Board, 1984) calculated that 106 000 t of nitrogen are transported annually with Baltic water into the Belt Sea and into the Sound. In the region Belt Sea and Sound, the input from land is calculated at 90 000 t/a, the atmospheric input at 46 000 t/a. The water flowing into the Belt Sea is Baltic surface water mixed with more saline water in the Arkona Sea west of Bornholm. It should make a difference if winter water concentrations of Baltic water are 4 µg-at N/l as in 1978, or 1.5 µg-at N/l as they were in 1969.

Kieler Bucht is a gulf adjacent to the Fehmarnbelt - Great Belt stream which transports most of the outflowing water from the Baltic. Kieler Bucht water therefore should be influenced by changes in nutrient concentrations in Baltic water. Unfortunately, scientific knowledge of water exchange in Kieler Bucht at present seems not to be adequately developed to make a calculation whether the apparent increase of nutrient concentrations since 1975 can be explained simply with the parallel increase of Baltic nutrient concentrations. In summary, even if there are good arguments to assume that the increase in nutrient concentrations of coastal waters of the Federal Republic of Germany is the effect of man made nutrient input, one should carefully analyze the effects of other components of the total system.

4. Trends in primary production in coastal waters

4.1. Primary production in the German Bight

The ongoing discussion on possible nutrient trends, of increasing nutrient concentrations is only meaningful with the assumption that higher concentrations of nutrients generate higher amounts of organic matter, being produced by pelagic or benthic algae or other plants. Can such enhanced primary production be documented for offshore coastal waters of the Federal Republic of Germany ?

Hagmeier (1978) documented yearly averages of phytoplankton carbon 1962 -

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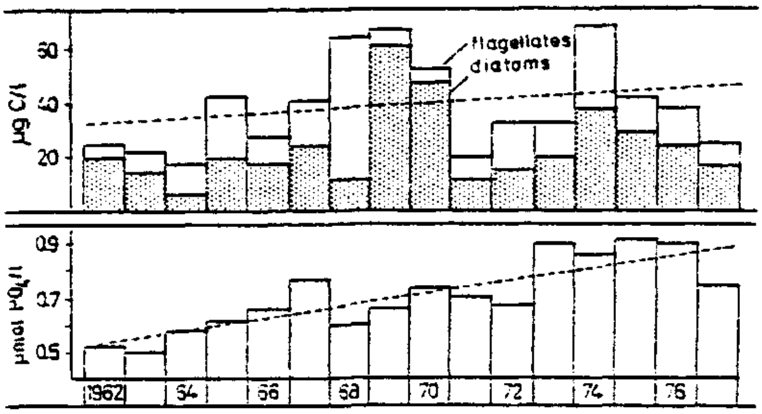

Fig. 2o: Yearly mean values of phytoplankton and phosphate 1962 to 1977 at station Helgoland (surface samples).
Data of Hagmeier from Gerlach, 1981.

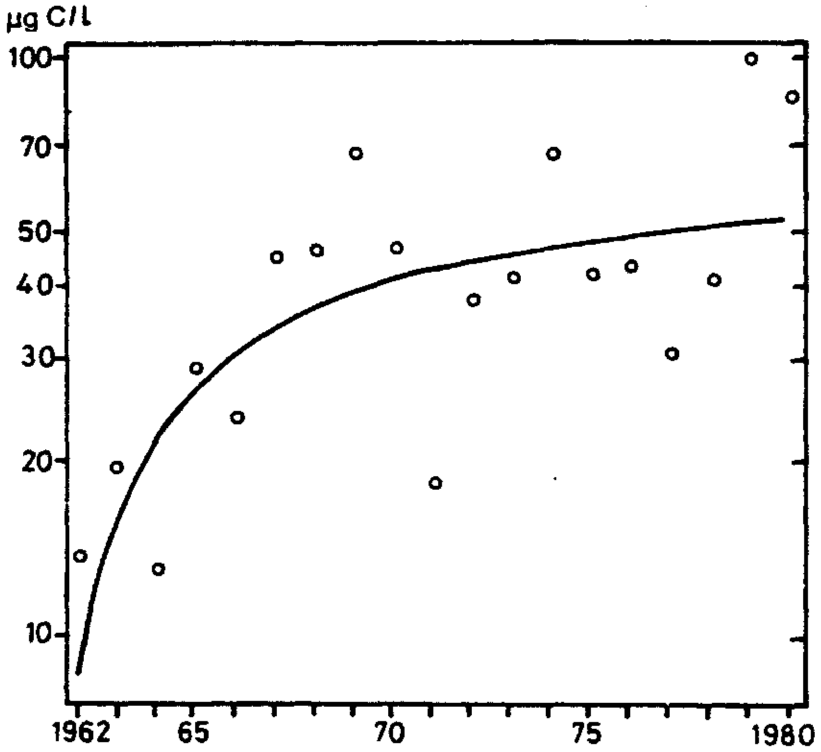

Fig. 21: Mean summer (April to September) concentrations of phytoplankton 1962 to 198o at station Helgoland. Logarithmic scale.
From Gillbricht, 1982.

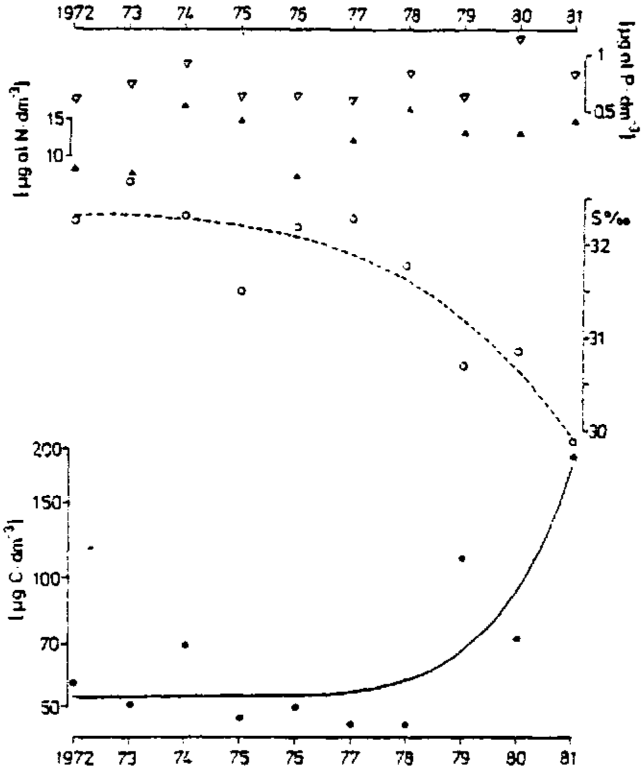

Fig. 22: Mean July to September values 1972 to 1981 of phosphate, inorganic nitrogen, salinity and phytoplankton - carbon (logscale !) at station Helgoland (surface samples). From Gillbricht, 1983.

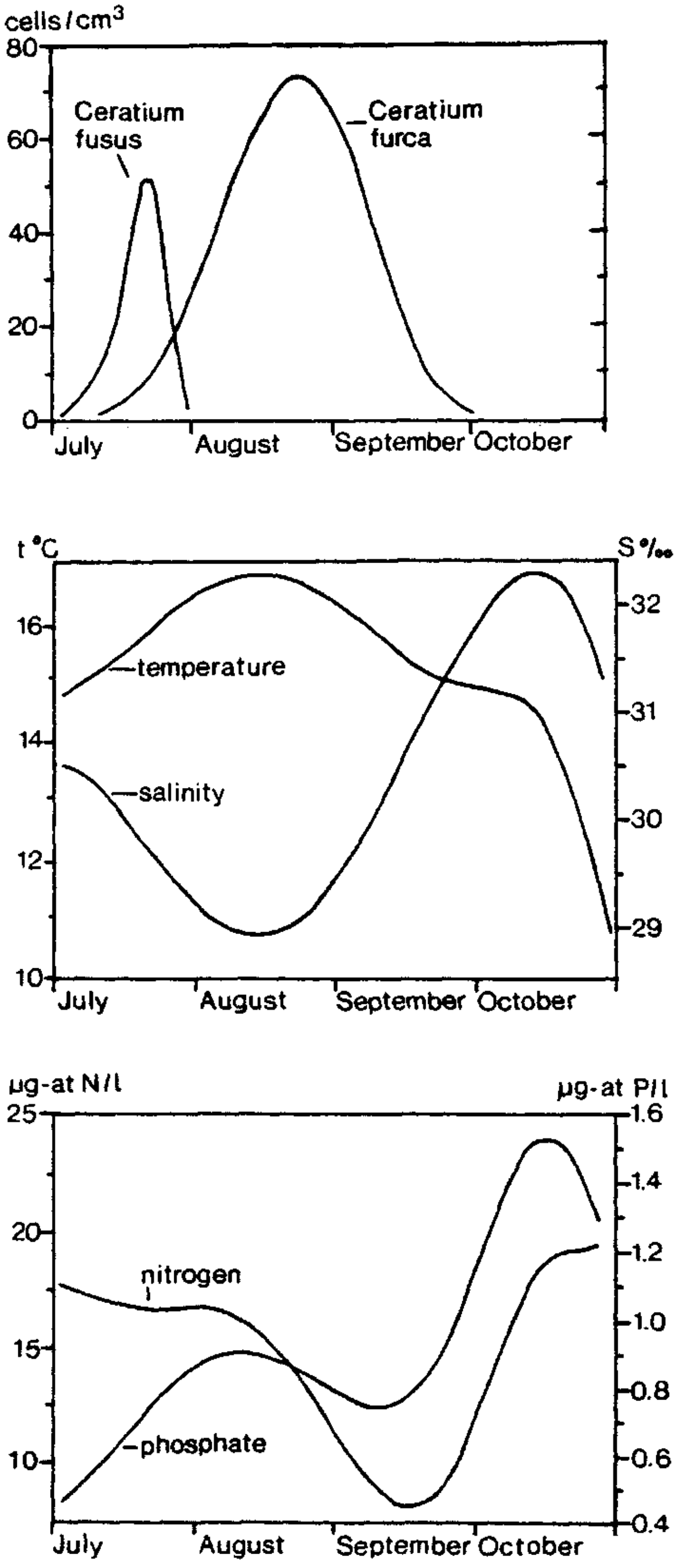

Fig. 23: The *Ceratium* bloom July to October 1981 at station Helgoland (surface samples), and environmental parameters salinity, temperature, inorganic nitrogen and phosphate. Compiled from Gillbricht, 1983.

continued from p. 43

1977 at the station between Helgoland and Düne already quoted in the context of nutrient trends (Fig. 20). Variations from year to year are large, and a trend of increasing phytoplankton biomass was supposed, but not statistically safe. Data since 1978 have been published in Jahresberichte der Biologischen Anstalt Helgoland. With logarithmic scale and with more sophisticated statistical treatment of the data, Gillbricht (1980) tried to document a trend of phytoplankton increase from about 10 µg C/l as the average of April to September observed in 1962 to about 40 µg in 1970 and about 50 µg in 1980 (Fig. 21). A new evaluation of the data should be done with appropriate computer facilities in order to differentiate trends more accurately within the entire period and to investigate possible cyclic phenomena, and correlations with nutrients and salinity.

For the period 1972 to 1981 Gillbricht (1983) differentiated between spring (April and May), summer (July to September) and winter (December to February). For winter and spring he postulates a steady increase of phytoplankton between 1972 and 1981 (with winter 1976/77 being exceptional). If this increase can be confirmed, it would refer to the spring phytoplankton bloom which depends (among other factors like light in the water and stratification of the water column) on the quantity of nutrients available. For the summer period July to September Gillbricht could not find a trend in nutrients for 1972 to 1981 (Fig. 22); however he documents high phytoplankton concentrations in 1979 and especially in 1981, which are well correlated with low salinity during the same summer months, caused by hydrographic conditions and, possibly, by heavy river flow in 1981 (see Fig. 7). The conclusions of Gillbricht are that low salinity of surface water is an indicator for stability of the water masses and for stratification. Stratification should be the main factor controlling phytoplankton blooms during summer.

In summer 1981 phytoplankton at Helgoland was dominated by dinoflagellates (peridineans) of the genus Ceratium. There was a July bloom of Ceratium fusus (50 cells/cm^3) followed by a bloom of Ceratium furca which culminated at the end of August with 70 cells/cm^3 and declined during September, when salinity increased and temperature decreased, indicating a loss of stability of the water column. Even when cells of Ceratium were in maximum numbers in the water, nutrients were not depleted.

Dinoflagellates are mobile and are able to swim up and down in the water column with speeds of up to one meter per hour. They are known for their capacity to live with low concentrations of nutrients. Dinoflagellate

continued on p. 52

Box 9

Report on Subproject: Particulate nitrogen in the German Bight and its potential oxygen demand.

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Suspended particulate organic matter (organic seston) in the German Bight was analyzed as particulate nitrogen (PN), and its potential oxygen demand under aerobic decomposition calculated. Dissolved inorganic nitrogen was included for comparison. Data from eight quasisynoptic cruises covering the German Bight were considered, three of them in winter, five in summer.

PN plus dissolved inorganic N concentrations in the water column of the German Bight amounted to about 4-8 g/m^2, with maxima of about 12 g/m^2. PN stocks alone amounted to about 1-3 g/m^2 in normal summers, 2-4 g/m^2 in high productivity summers and about 4-10 g/m^2 in areas of dense phytoplankton blooms (like Ceratium red tides in August 1981).

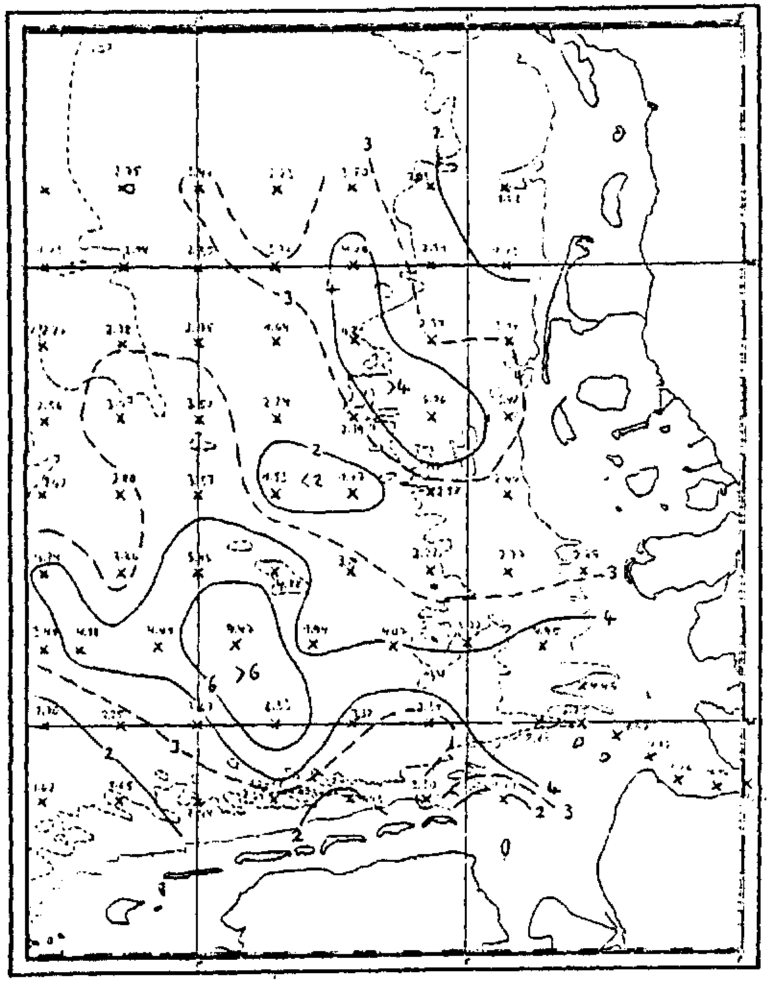
The ratio PN/inorg. N in winter was about 0.1 - 0.2 offshore, 0.2 - 0.5 inshore and in the Elbe estuary. In summer, this ratio used to be greater than 0.5; in areas with phytoplankton blooms almost all N was particulate. An increase of the PN/inorg. N ratio from estuarine towards offshore waters was obvious in summer, showing how dissolved inorganic N became incorporated into organic seston.

Assuming 20 g oxygen for complete oxidation of 1 g N (bound in an "average" organic molecule), the potential oxygen demand for the organic seston was calculated and compared with the available dissolved oxygen in the deep (below thermocline) water (about 8.5 g/m^3).

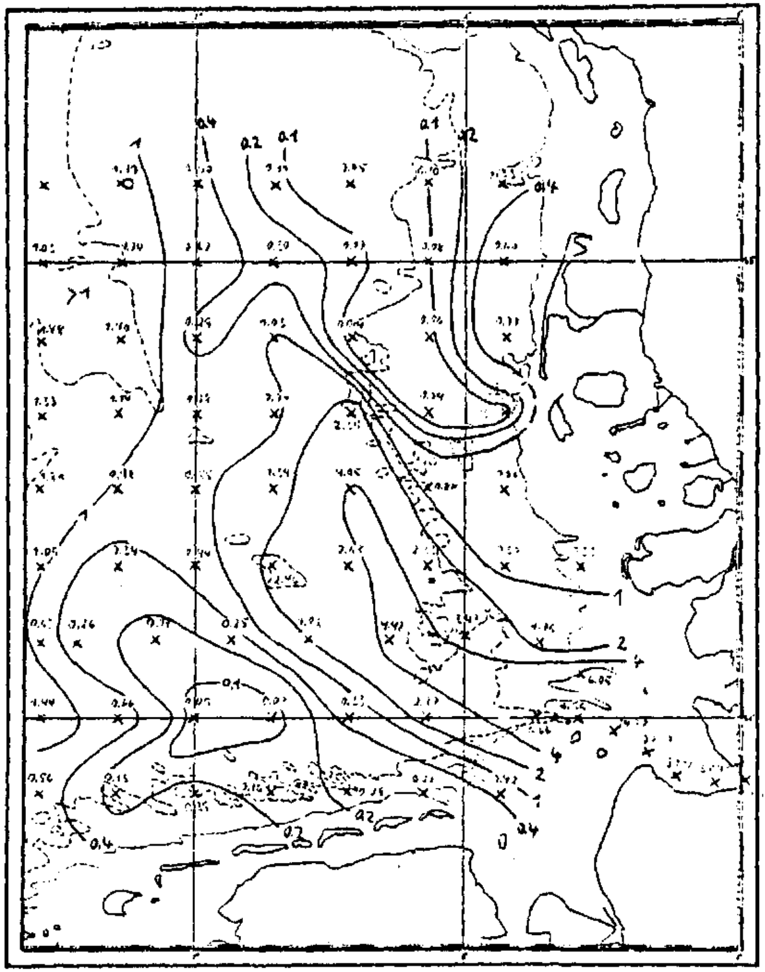
This oxygen demand of the above PN stocks in the water column, e.g. 2, 4 and 10 g/m^2, would thus be 40, 80 and 200 g oxygen. Assuming an average depth of 30 m and an average depth of thermocline of 15 m, about 130 g O_2/m^2

would be available in the deep water layer at the beginning of vertical stratification.

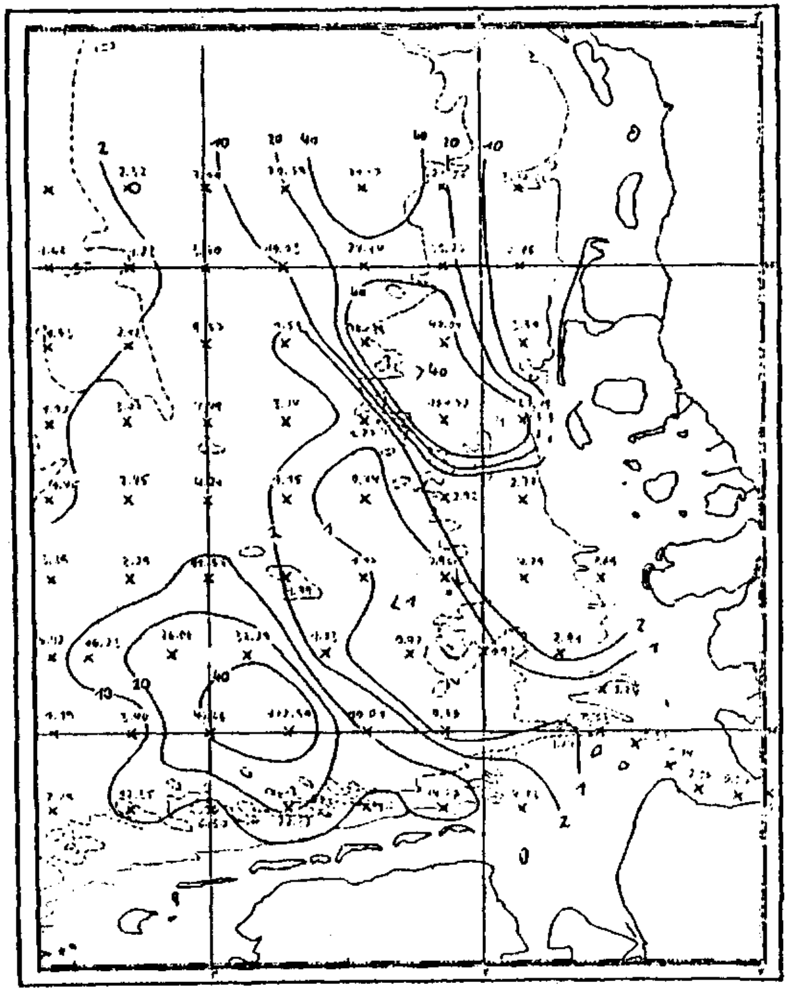
Should the organic seston settle down to the deep water during calm weather periods, it could use up about half of the dissolved oxygen there in "normal" years, and deplete the oxygen in areas of dense phytoplankton blooms. The Ceratium furca red tides, observed in August 1981, had a higher potential oxygen demand than the dissolved oxygen content of the deep water in the same place.



particulate nitrogen, g/m^2



NO_3+ NH_4- nitrogen, g/m^2



particulate nitrogen / inorganic nitrogen

Fig. 24: Quasisynoptic distribution of particulate nitrogen (mostly incorporated in phytoplankton cells) and dissolved inorganic nitrogen ($NO_3 + NH_4$) in the German Bight during the peak phase of the *Ceratium furca* bloom, 17 - 26 August, 1981. Data refer to the water column. Unpublished results kindly provided by Dr.W.Hickel, Biologische Anstalt Helgoland.

continued from p. 47

blooms sometimes start offshore and enter near-shore areas with deep water. A special symposium of ICES will be held in October 1984 in Copenhagen to investigate to what extent blooms of dinoflagellates are the consequence of eutrophication. The answer is of some importance for public health because certain dinoflagellate species (not Ceratium) produce toxic substances which are dangerous for man when taken up with the meat of plankton feeding animals like mussels and oysters.

To summarize, there seems to be a trend of increasing phytoplankton biomass 1962 to 1983 at Helgoland which may become noticeable during the spring phytoplankton blooms and could well reflect increasing nutrient concentrations. There were exceptional summer blooms 1979, 1981 and 1982.

Can a plankton bloom be described and explained by comparing smoothed year to year biomass and nutrient data measured at one station ? Can one exclude nitrogen as a controlling factor because it never, during the bloom, was limiting at Helgoland station ? Should not a bloom be considered to be the specific reaction of the phytoplankton to specific conditions in the pelagic environment which specifically need to be worked out ? It may be that some results of the working group on eutrophication could be assembled to form a more coherent picture.

In the period 17 - 26 August 1981, which is the peak period of the Ceratium furca bloom at Helgoland station (Fig. 23), the distribution of dissolved inorganic nitrogen (nitrate plus ammonium) and the distribution of particulate nitrogen (mostly nitrogen bound as organic nitrogen in phytoplankton cells) were both patchy and correlated: in patches with algal blooms, particulate nitrogen in the water column was above 4 g/m^2, while dissolved inorganic nitrogen was below 0.1 g/m^2; the relation of particulate nitrogen to dissolved inorganic nitrogen was between 10 : 1 and 40 : 1. In the tongue of Elbe-Weser water which spread northwest far beyond Helgoland (Hickel and Martens, 1983 for salinity data), dissolved nitrogen amounted to more than 2 g/m^2, particulate nitrogen to less than 4 g/m^2, so that the relation of particulate to dissolved nitrogen was between 1 : 1 and 2 : 1 (see Box 9 and Fig. 24).

Water masses like this have the nutrient potential to carry a large plankton bloom, while in the center of patchy bloom areas nitrogen concentrations are low: most of the nitrogen is bound in the phytoplankton cells. This statement does not have to mean that in the patches the bloom could not go on with a few doublings of cells. It is well known that some phytoplankton is able to store nitrogen and phosphorus internally, enough to supply a few future generations with these nutrients. A production of organic matter which finally needs oxygen for its degradation may, therefore, go on even in water practically free of nutrients. However, initially, phytoplankton needs nutrients to produce a bloom. In 1981 nitrogen was available in the German bight in high concentrations (Fig. 8). In 1981 the loads of nitrogen being transported by the rivers into the German Bight were much greater, probably twice as much as usual (Fig. 7). It seems probable that the freshwater runoff from the low lying marsh areas bordering the German Bight depends on rainfall too and provides additional nitrogen loads to the German Bight when heavy rainfall occurs.

The above discussion does not, but should, include phosphorus, an element which may become a limiting factor for growth when there is a surplus of nitrogen. From freshwater and brackish water situations there are many examples that phosphorus is the limiting factor. Phosphorus elimination in waste water treatment plants and reduction of phosphorus in washing powder then may have an immediate effect to reduce phytoplankton and benthic macrophyte growth. Under more marine conditions nitrogen seems quite often to play a role as a limiting factor. This has to be worked out from existing bibliography. Before any definite statement is possible it must be confirmed whether German Bight and Kieler Bucht are regions with predominant nitrogen, phosphorus or silicium limitation.

The problem is difficult to answer because during one season, even during one bloom, the limiting factor changes.

Certainly there are many problems to be solved before agreement on the final cause of specific phytoplankton blooms can be reached. Causes of extreme spring plankton blooms are certainly different from causes of a summer plankton bloom like 1981. Certainly different phytoplankton species create blooms in different years. The reason for each event must be analyzed separately. This could only be done if data from the past were available which could be correlated with bloom data. However, most blooms have been documented when they became obvious on the water surface as "red tides", not in their origins. The 1981 "red tide" in the German Bight is one of the very rare occasions where long term data from a monitoring station are available, and several quasisynoptical hydrographic cruises were done and supply additional data. This example should be worked out, and it should be evaluated to what extent the situation in the German Bight can be compared with the Danish Belt Sea situation and the Laholm Bay situation where Danish and Swedish scientists tried to correlate phytoplankton growth to freshwater runoff and nitrogen input into coastal waters.

4.2. Comparison with the 1976 oxygen depletion in New York Bight

Further, the German Bight situation should be compared with the New York Bight event 1976, which was reviewed by Gunnerson, 1981: From July to October 1976 an area of 8600 km^2 on the continental shelf of the New York Bight experienced mass mortalities of benthic organisms. During September, 1500 km^2 had no oxygen at all, hydrogen sulfide was observed at a number of localities. About 180 000 t of surf clam (Spisula solidissima were killed. The cause of the oxygen depletion: more unusual conditions occurred in 1976 than in preceding years. During February to May a warm spring caused an extremely large flow of freshwater from the Hudson River, which promoted the density stratification in the coastal waters six weeks earlier than usual. While ordinarily the wind does not shift to the south until April, in 1976 the southerly component prevailed from February to June and established a potential for upwelling of bottom waters along the New Jersey coast. There was also a reversal of the normal current system, so that from mid-May through July the alongshore surface current was flowing northward, and, in June, there was bottom water flowing northeastward into the Apex region of New York Bight. An unusual Ceratium tripos bloom was observed as early as January. In May and early June Ceratium was observed to aggregate at the base of the pycnocline. This bloom declined rapidly during July, sedimented and added to oxygen depletion. Apparently waste inputs did not start the 1976 anoxic event, but there is slight evidence of a gradual decrease of oxygen concentrations over the years preceding 1976, and there is the feeling that the imbalance could be influenced by the wastes of 45 million people.

4.3. Primary production in Kieler Bucht

Unfortunately, documentation of trends in phytoplankton growth dynamics of Kieler Bucht later than 1975 is poor. The analysis of monthly data 1957 - 1975 on chlorophyll a, particulate carbon, particulate nitrogen, and net plankton from Bokniseck station (Krey et al., 1978) does not exhibit a trend at a first glance, but this should be worked out more closely. Up to now only mean values over the entire period have been documented (Babenerd, 1980). From this and other stations, and from the period since 1975 many data are available which could be screened for possible trends. In 1983 a non toxic Prorocentrum bloom was observed in Kiel Harbour. Danish authorities (Miljøstyrelsen, 1984) reported on phytoplankton growth conditions in the Great Belt (station 39 Halsskov Rev) and in Kieler Bucht south of Langeland (station 50 Kelds Nor). It seems that there is a long term increase in primary production since 1953 (Fig 25). For the season April to June and for the season July to September primary production was extremely high in one or several years between 1979 and 1982 (Fig. 26). This can be correlated with high nitrogen concentrations. The conclusion of Danish scientists is that high nitrogen concentrations in surface waters and in deep water together with a stable water stratification were the causes for the extreme phytoplankton productivity 1981 in Danish waters in general.

Rainfall on the land area of Schleswig-Holstein which drains into Kieler Bucht and Mecklenburger Bucht is different from year to year.

Precipitation data for the meteorological station Schleswig are:

1972	746 mm/a	1978	1054 mm/a
1973	983	1979	991
1974	873	1980	1120
1975	685	1981	1020
1976	591	1982	835
1977	871	1983	911

It seems probable that in Kieler Bucht heavy rainfall in the appropriate season may promote water stratification and increase nitrate concentrations in the surface water, in a way similar to that proposed for Danish waters and the German Bight.

In summary it is probable that elevated nutrient concentrations in winter water result in higher phytoplankton production during spring phytoplankton blooms. For summer blooms several factors work together, nutrients are necessary, of course. The hypothesis has some probability that nutrient

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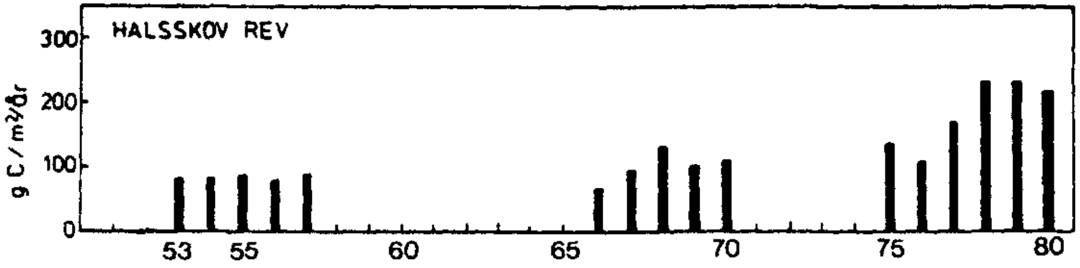

Fig. 25: Annual Production of Phytoplankton at Halsskov Rev. Lightvessel 1953 - 197o and at the station Halsskov Rev 1975 - 198o.
From Miljøstyrelsen,1984.

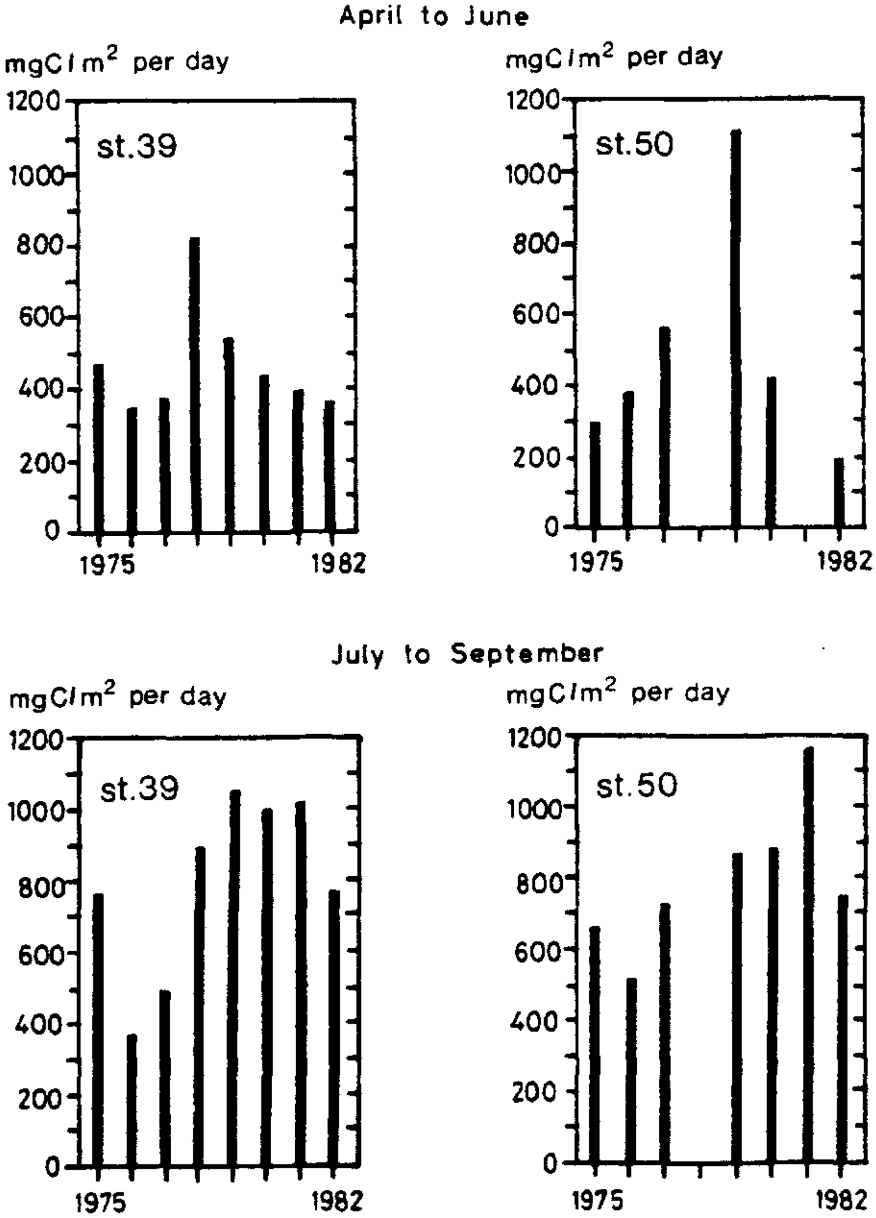

Fig. 26: Mean daily phytoplankton production April to June and July to September 1975 - 1982 at station Halsskov Rev, Great Belt (39) and at the station Kelds Nor, south of Langeland (5o). From Miljøstyrelsen, 1984.

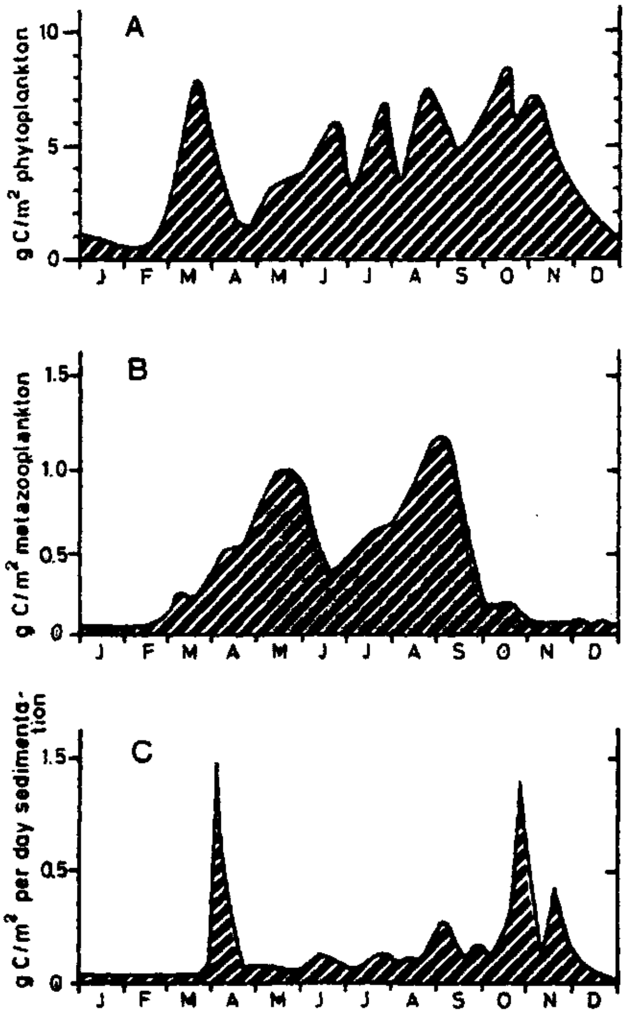

Fig. 27: Typical seasonal development of phytoplankton biomass (A.), metazooplankton (mostly herbivorous copepods, B) and organic matter sedimenting to the sea floor in Kieler Bucht. According to Smetacek et al., 1984.

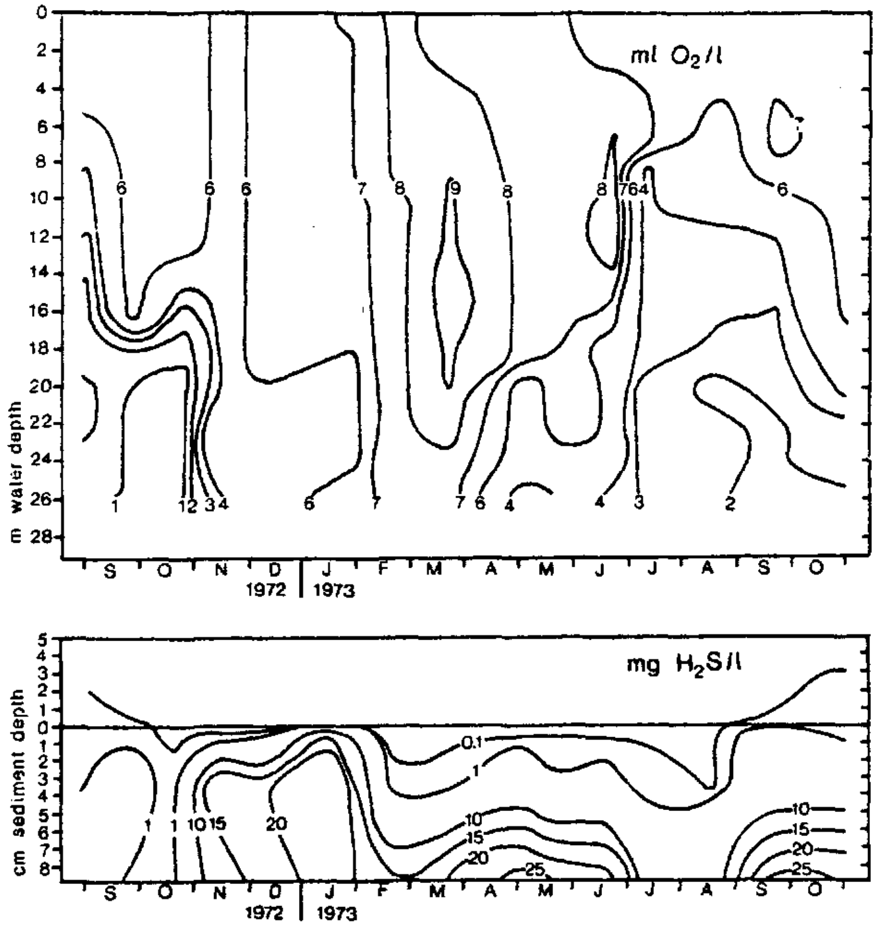

Fig. 28: Seasonal variation of the oxygen concentration in the water column and of the hydrogen sulfide concentration in the water immediately above the sediment and in the pore water of the sediment 1972 - 1973 at a station at the entrance of Eckernförde Bay, Kieler Bucht, 28 m water depth.
From Reimers, 1976.

continued from p. 55

loads from land, if delivered to coastal waters under appropriate hydrographical conditions, and at the right time, control summer blooms. When nitrogen is a limiting factor, phytoplankton production in general should increase with increasing atmospheric input of nitrogen.

5. The sedimentation of organic matter and the importance of the sediment for oxygen depletion events.

5.1. The effect of grazing

For Kieler Bucht a concept of plankton dynamics has been developed (Smetacek et al., 1984) which demonstrates the importance of herbivorous zooplankton for phytoplankton dynamics (Fig. 27). In summer phytoplankton is heavily grazed down by zooplankton (and suspension feeding macrobenthos). Nutrients incorporated in phytoplankton cells are quickly released to the water, in form of excretion products of zooplankton and macrobenthos. Organic carbon is largely mineralized in the water to carbon dioxide. Only rather small amounts of organic particles sink to the sea floor, and the oxygen demand to mineralize these particles at the sediment-water interface or in the sediment is small, compared with spring bloom situations.

If there is a balance between phytoplankton growth on the one hand, phytoplankton mortality by zooplankton grazing on the other, one can imagine that phytoplankton biomass increases in a period when zooplankton grazing, for whatever reason, declines so that fewer phytoplankton cells are eaten. Lindahl and Hernroth (1983) think that phytoplankton blooms could develop when zooplankton is reduced, provided that other factors remain stable and nutrients are available. Curl et al. (1979) call this "runaway growth". Herbivorous zooplankton is itself heavily grazed by the jellyfish _Aurelia_ in Kieler Bucht (Möller, 1979) and by the ctenophore _Pleurobrachia_ in the German Bight (Greve, 1981). These carnivores could control the herbivores, which again control the phytoplankton. Phytoplankton has generation times of days, herbivores have generation times of weeks, but _Aurelia_, in Kieler Bucht, develop just one generation per year. _Aurelia_ represent large biomass in mid-summer. _Aurelia_ biomass has to feed or to die, but cannot otherwise be adjusted to changes of food quantity. The biomass of _Aurelia_ depends on the survival of scyphostoma polype stages during the preceding winter and on the survival of small ephyra medusal stages in early summer. Survival depends on temperature and food. Aurelia in Kieler Bucht therefore shows large fluctuations from year to year. The grazing impact of Aurelia upon the herbivorous copepod populations should fluctuate accordingly. The relatively low zooplankton biomass in June - July (Fig. 27) might be explained by Aurelia grazing. There is much speculation in this scenario. But at least in theory it is possible that carnivorous populations control, to a certain extent, the quantity of organic matter which sinks to the sea floor and may cause oxygen depletion there.

5.2. The persistence of conditions in the sediment

In general, the concentration of degradable organic matter is higher in the sediment than in the water, and quite regularly oxygen depletion starts from the sediment and extends into the overlying water, as could be shown in experiments of the bell jar type (Fig. 16), which isolate a certain area of the sea floor and the overlying water. As long as oxygen concentrations in the overlying water are above about 1 ml/1, many macrofauna animals are able to persist and continue with their activities. They create water currents and bring water containing oxygen and food in contact with their gills and mouths. By their normal life activities they ventilate the sediment-water interface and stir the upper sediment layer. But when oxygen concentrations decrease below their tolerance level they die, the ventilation effects disappear, and immediately a considerable change towards complete oxygen depletion can be expected. Toxic hydrogen sulfide then spreads from the sediment into the overlaying waters (Jørgensen, 1980). Fig. 28 gives an example from an area in the western part of Kieler Bucht where oxygen depletion in the deep water occurs quite regularly, nearly every autumn. Macrofauna died in September-October. During the subsequent winter hydrogen sulfide was observed in the pore water of the sediment right up to the sediment-water interface, in spite of the fact that the near-bottom sea water was saturated with oxygen. Only in the early part of the following spring some macrofauna species recolonized the sea floor and were able to bioturbate the upper layer of the sediment, so that high concentrations of hydrogen sulfide were not encountered, then, in the upper 5 cm of the sediment. In September oxygen depletion occurred again, and hydrogen sulfide was measured in the overlying water. The macrofauna

died out again.
But what would have been the situation without macrofauna activity between February and August ? Or with an excessive phytoplankton bloom sedimenting between March and July ? More case studies of this type are necessary to understand the complex sediment-water system and the interchanges. It seems probable that the conditions in the sediment during winter predict, to some extent, the oxygen depletion potential of the following summer.

6. Eutrophication effects on higher links of the food chain.

In principle, higher biomass and higher production of phytoplankton can sustain more herbivorous zooplankton which, in turn, can feed more carnivorous fish and jellyfish. The increase in zooplankton productivity might be compensated by increased predation by fish and jellyfish on zooplankton, so that zooplankton biomass must not necessarily increase. But the higher productivity of fish should allow greater catches of commercial fish, and increasing populations of jellyfish should be noted. The long term variation of biomass and productivity of top carnivorous animals might reflect variations of the eutrophication status. Correlations have been proposed between eutrophication and catches of herring, sprot and cod in the Baltic (Nehring, 1981).
Increased phytoplankton populations provide increased amounts of food for benthic macrofauna, either directly for filter feeders or indirectly via sedimenting organic particles that can be used as food for bacteria and deposit feeders. Cederwall and Elmgren (1980) found that the macrozoobenthos of Baltic stations revisited after 50 years had significantly higher biomass. This might be the consequence of eutrophication and of higher concentrations of phytoplankton available as food. There are also observations from coastal areas of the Federal Republic of Germany which could point in the same direction:
A muddy sand station SSW of Helgoland showed a slight increase of benthic bivalves between 1969 and 1983. This might as well be correlated with an improved supply of particulate organic matter (see Box 10).
In the 9 - 13 m regions of Kieler Bucht macrozoobenthos 1982/83 had about 4 times higher biomass compared with evaluations of 20 years ago (1964/65); the populations which increased were mostly deposit feeding bivalves, worms and crustacea (Box 11).

continued on p. 69

Box 10

Report on Subproject: Macrozoobenthos in the German Bight 1969 to 1983: Trends in bivalve populations.

Eike Rachor

Institut für Meeresforschung Bremerhaven

Trends are different at the two stations analyzed. The mud station at 23 m water depth is situated between the Elbe estuary and Helgoland, a sedimentation area for silt and mud material including organic matter (Rachor, 1980). During the entire period 1969 - 1983, only about 4 bivalve species per sample were found; species number shows no trend. One dominant species is _Abra alba_ which fluctuates from year to year. _Nucula nitidosa_ and _Mysella bidentata_ declined in abundance, and _Abra nitida_ was found only a few times after 1976. It seems that life conditions in this area are declining. The muddy sand station lies about 10 nautical miles to the west, between Helgoland and Spiekeroog at 34 m water depth. Species number per sample is much higher and showed an increasing trend from 10 to about 13 between 1969 and 1983. Abundance of _Abra alba_ and _Nucula nitidosa_ increased during this period, and it seems that life conditions for bivalves did improve in this area. An explanation might be that due to eutrophication macrofauna found better food conditions at the muddy sand, while the mud station with its high content of organic material is overburdened by any additional input.

Reference:

Rachor, E. (1980): The inner German Bight - an ecologically sensitive area as indicated by the bottom fauna. Helgoländer Meeresunters. 33: 522 - 530

Box 11

Report on Subproject: Increase of macrozoobenthos in Kieler Bucht above the halocline, comparing the 1960s with the 1980s

Thomas Brey, Heye Rumohr and Sebastian A. Gerlach
Institut für Meereskunde Kiel

In 1982/83 macrozoobenthos abundance and biomass were investigated at 16 stations from sandy sediments 9-13 m deep (that is above the halocline) in Kieler Bucht (Brey, 1983). In 1961 - 1964 Kühlmorgen-Hille (1965), sampled 4 stations - among others - which can be compared, though the localities are not identical. Abundance and biomass of the main taxa of macrozoobenthos were significantly higher in 1982/83 (10 652 ind/m^2, 260.1 g wet weight/m^2) compared with 1964/65 (1108 ind./m^2, 64.7 g wet weight/m^2). The main difference is caused by increased populations of deposit feeding macrofauna: the bivalves Corbula gibba and Macoma baltica, the worm Pygospio elegans and the crustacea Phoxocephalus holboelli (Brey, in press).

There are different possible explanations for these findings. One is that benthic populations fluctuate from year to year. It may be by chance that in 1964/65 a trough, in 1982/83 a peak was encountered. Unfortunately no other material is available to fill the time gap between the two sampling periods. The second explanation is that the increase in macrozoobenthos reflects a trend which is correlated with a better food supply from phytoplankton, which was stimulated by anthropogenic plant nutrient input (eutrophication). This is the argument brought forward by Cederwall and Elmgren (1980) to explain increased macrozoobenthos above the halocline at the West Coast of Sweden and around Gotland and Öland.

A third explanation may be climatic: subsequent years with calm weather and without strong gales, which could sweep away fine particles from sandy sediments, may be the reason for higher than usual concentrations of organic particles in the surficial layers of sandy sediments of Kieler Bucht. Macrozoobenthos animals which feed on such particles may have the benefit of such a situation, and their populations might increase.

References:

Brey, T. (1984): Gemeinschaftsstrukturen, Abundanz, Biomasse und Produktion des Makrozoobenthos sandiger Böden der Kieler Bucht in 5 - 15 m Wassertiefe. Ber. Inst. Meereskunde, 123, 1 - 124

Kühlmorgen-Hille (1965): Quantitative Untersuchungen der Bodenfauna in der Kieler Bucht und ihre jahreszeitlichen Veränderungen. Kieler Meeresforsch. 19, 42 - 66

Cederwall, H. and R. Elmgren (1980): Biomass increase of benthic macrofauna demonstrates eutrophication of the Baltic Sea. Ophelia Suppl. 1, 287 - 304

Brey, T. (1984): Increase in macrozoobenthos above the halocline in Kiel Bay, comparing the 1960s with the 1980s. (in press)

Box 12

Report on Subproject: Documentation of oxygen deficiency events in Kieler Bucht since the end of last century

Heye Rumohr

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Oxygen measurements done with hydrographic routine suffer from the fact that water depth is measured from the surface. However, there is a strong gradient between the sediment surface and in the overlying water column. Measurements therefore should be done at a fixed distance from the sediment surface, otherwise they are of little meaning. For example, at the station "Boknis Eck 26 m water depth" (Krey et al., 1978) the deepest samples were collected 25 m below the water surface; this in reality was 0.5 to 5 m above the seabed. The variation is caused by wind-induced changes of the water level in Kieler Bucht and by inaccuracies of position finding.

Fish kills or other symptoms of oxygen deficiency at the sediment-water interface have been reported for 1875, 1913, 1926, 1931 and 1936-37 occurring in Eckernförde Bay, the region east of Lightvessel Kiel, at Schönberger Strand and in Hohwacht Bay. Such anecdotic evidence does not mean that the oxygen situation in all the other years was good. However, a situation as bad as 1981 has never been reported in the past 100 years.

Reference:

Krey, J., B. Babenerd and J. Lenz: Beobachtungen zur Produktionsbiologie des Planktons in der Kieler Bucht: 1957 - 1975. 1. Datenband. Ber. Inst. Meereskunde Kiel 54: 1 - 113

Box 13

Report on Subproject: Historic oxygen depletion events and past concomitant nutrient patterns recorded in sediment cores of Kieler Bucht.

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Geologisch-Palaeontologisches Institut und Museum
Universität Kiel

In a 3.5 m sediment core from 26 m water depth east of Bredgrund and in a 5 m sediment core from 22 m water depth in Marstal Bay not bioturbed silt and sand layers have been found which could indicate past periods without the occurrence of such macrozoobenthos which bioturbates the sediment. These were possibly periods of oxygen depletion which prevailed over many subsequent summers. However, the age determination of discrete layers of the core has not been done yet.

One 1 m core from 29 m water depth in Eckernförde Bay was investigated with regard to saturation characters. The idea is to identify the early diagenesis of minerals containing phosphorus. It seems plausible that a large fraction of the phosphorus introduced with waste water into Kieler Bucht should be found bound within phosphorus minerals in the sediment. However, up to now no elevated phosphorus concentrations could be found in the upper sediment layer. The fate of the large amounts of phosphorus introduced into Kieler Bucht, therefore, at present remains mysterious.

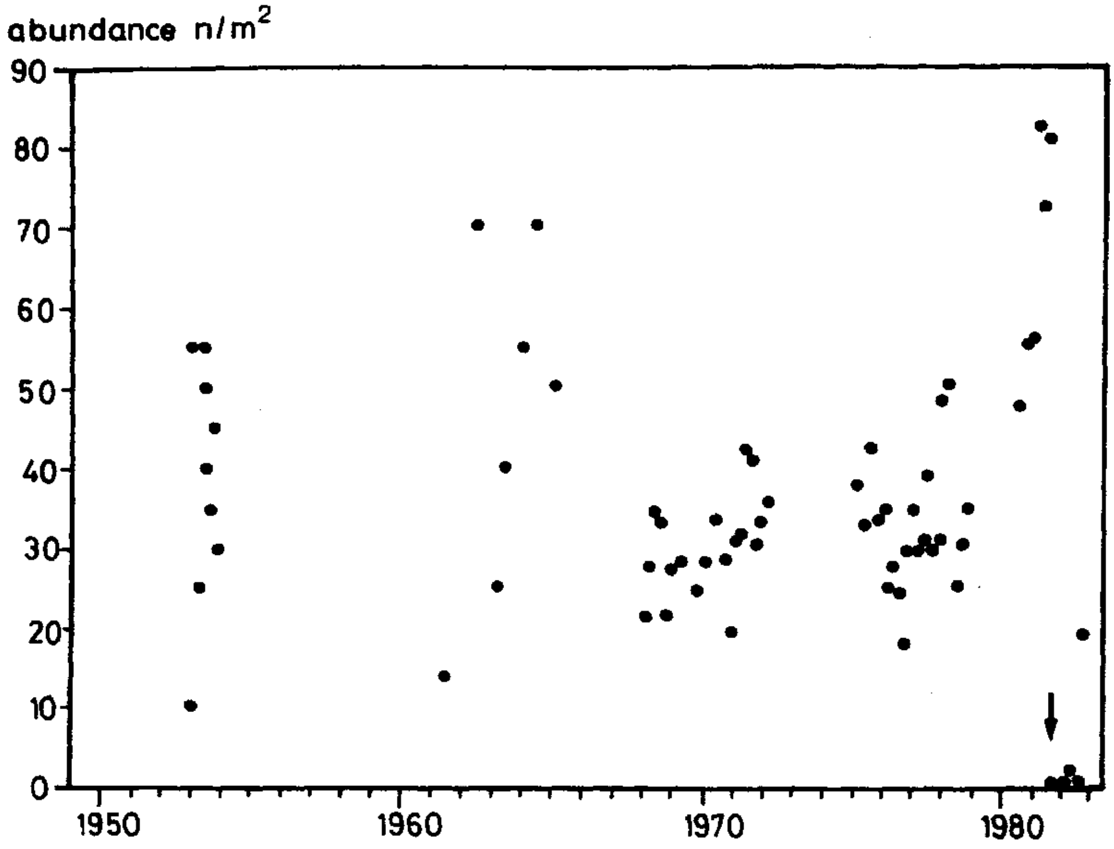

Fig. 29: Abundance of the polychaete worm *Nephtys* in samples collected between 1953 and 1983 in the region Millionenviertel-Süderfahrt, central part of Kieler Bucht. Note that this member of benthic macrofauna was found with 1o - 8o ind./m^2 in every sample collected (no data from years without points!). The only exception is 1982 - 1983, following the 1981 oxygen depletion catastrophe, when samples were without *Nephtys* (arrow).
Unpublished data kindly provided by Dr. H. Rumohr, Institut für Meereskunde, Kiel.

continued from p. 62

7. Historic evidence of oxygen depletion

Marine science in Kieler Bucht and in the German Bight is more than one hundred years old. Unfortunately, events of oxygen deficiency in the near-bottom water and at the sediment-water interface are evident only for scientists looking specifically either for oxygen or hydrogen sulfide in the water column, or for redox conditions in the sediment, or for benthic animals. If at all, the public only gets notice of such events when demersal fisheries is concerned or when upwelling of water poor in oxygen causes fish kills.

Historic cases of oxygen depletion are reported from Danish waters (Miljøstyrelsen, 1984) and from Kieler Bucht (Box 12). An oxygen depletion event of such a dimension as 1981 has never been described before. Since 1953, more regularly since 1968 there are records of benthic macrofauna living in the central part of Kieler Bucht below 20 m water depth (area of Millionenviertel - Süderfahrt). In all previous samples there were 10 - 80 individuals per m^2 of the large polychaet worm Nephtys. It seems that this population disappeared for the first time after the oxygen depletion catastrophe 1981 (Fig. 29), and recovered in subsequent years (see Box 2). There is some hope that the investigation of sediment cores may provide evidence whether long lasting periods with oxygen deficiency occurred in past centuries (see Box 13).

8. Weather effects on water stratification and on the current pattern

Bell jar experiments demonstrate what happens if the sea floor and the near-bottom water are isolated from the adjacent water masses (Fig. 16): the oxygen concentrations decrease due to the oxygen demand of animals and bacteria. When oxygen is near zero, hydrogen sulfide is released from the sediment, mostly generated by the reduction of sulfate due to the activity of specialized anaerobic bacteria. The same process occurs in the sea if a thermocline or halocline prevents contact of the bottom water with the upper compartment of the stratified water. Such conditions were observed during 1980 - 1983 in various regions of the North Sea and the Belt Sea, with different degrees of oxygen depletion. In previous chapters it has been analyzed that increased phytoplankton growth may be one factor leading to oxygen depletion. But what about the weather conditions which influence water stratification ?

Unfortunately, existing North Sea models at present do not integrate actual situations of water stratification, but work with average conditions. These models have to be developed further before they can be used to predict water stratification, for instance in the German Bight, as a consequence of preceding weather influence. A first attempt to tackle the problem of oxygen depletion with an existing dynamic North Sea model was performed with a simulation of wind-stress induced currents 1955 to 1980 (see Box 14). The surprising result is that the general picture of the dominant circulation is quite often disturbed. The dominant picture is a current which transports Rhine water into the inner German Bight and which turns north after the waters from Weser and Elbe are added. This current situation provides a good flushing of the inner German Bight and a dilution of any river load, including nutrients. It works with the predominant winds from SSE over S and W to WNW. Winds blowing several days from other directions, however, cause either a reversal of the current system, or a decrease in water transport (Fig. 30). During winters 1968/69, 1973/74 and 1975/76 flushing was reduced compared with normal conditions. Further analysis of summer conditions and analysis of the years 1981-1983 will be done.

Obviously calm weather promotes water stratification because wind induced turbulence of the upper water masses is reduced. Further, during summer a sky with little cloud cover promotes water stratification because sun energy can warm up the upper water layers. Weather data 1929 to 1983 have been analyzed for periods of calm and sunny weather, of strong wind and cloudy sky, and of storms (see Box 15).

It is a striking fact that the year 1981 is not an extreme year, and that summers 1959, 1969, 1972, 1974, 1979 and 1983 had a higher potential for water stratification than summer 1981, when large scale oxygen deficiency was observed in many regions of the North Sea and the Baltic (Fig. 31). However, there might be a general trend towards calm and sunny summers from 1957 to 1983.

It seems necessary to investigate other meteorological factors which could influence water stratification. One is wind stress which induces upwelling and an horizontal exchange of deep water. The other factor is rain which influences freshwater runoff.

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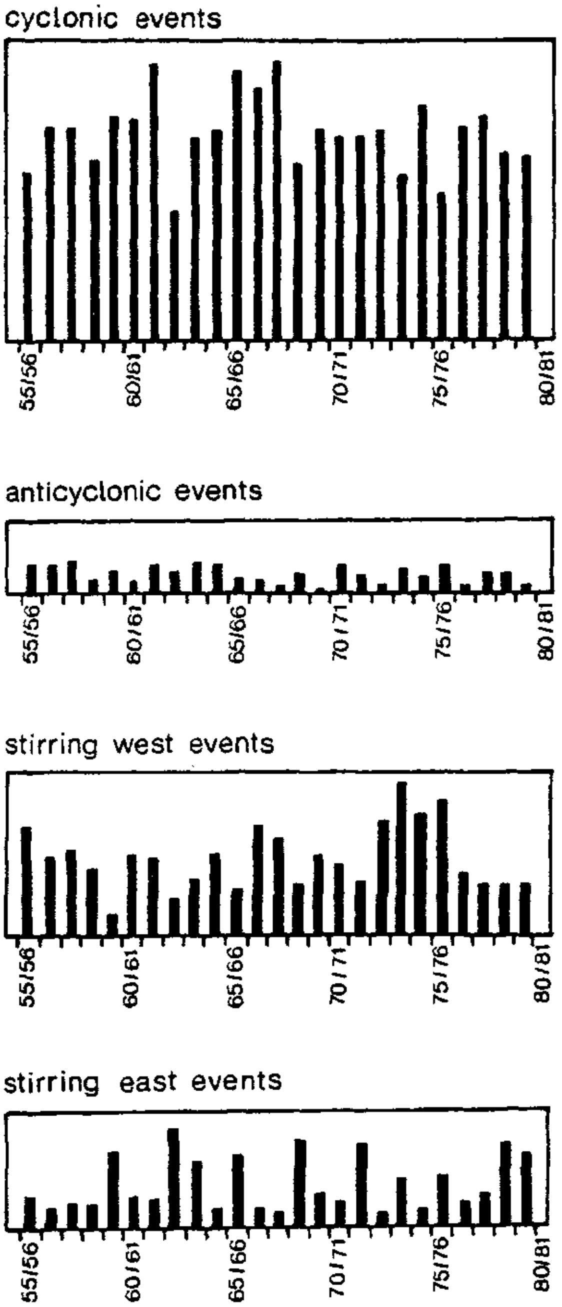

cyclonic events

anticyclonic events

stirring west events

stirring east events

Fig. 3o: Cumulative yearly energy (in arbitrary units) of weather events which produce cyclonal, anticyclonal, stirring west and stirring east situations in the current system of the German Bight.
Unpublished figure kindly provided by M.Boehlich and Dr.J.Backhaus, Institut für Meereskunde, Universität Hamburg.

Box 14

Report on Subproject: Simulation of wind induced currents in the system North Sea - Baltic Sea to interpret biological and chemical processes which influence eutrophication effects in the German Bight

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An existing North Sea model with a grid of about 20 km was modified to investigate the influence of a wind of 10 m/s (about 20 knots) blowing for 6 days from various directions. The result is: the circulation in the North Sea reacts very sensitive to wind direction, and within 1 - 3 days quasistationary conditions are reached in the simulations.

With wind from 150° - 290° (SSE over S to WNW) circulation is cyclonal. Atlantic water enters the North Sea, flows south along the British coast, flows east along the Dutch coast (together with water from the Channel), flows north to the Skagerrak and further with the Norwegian coastal current. In the long term, this is the most frequent wind and current situation, and German Bight water is quickly renewed by such "flushing".

With wind from 345° - 100° (NNW over N to ESE) circulation is anticyclonal. The Norwegian coastal current reverses and runs southward, and its water enters the German Bight together with Baltic water from the Kattegat; it leaves the North Sea either via the Channel or northward. Wind speeds are generally lower compared with cyclonal conditions. Nevertheless flushing times are rather short.

With wind from 100° - 150 ° (ESE to SSE) no large-scale circulation occurs, and there is nearly no exchange with Atlantic water. This situation is termed "Stirring East".

With wind from 290 - 345° (WNW to NNW) there is no circulation either. This situation is termed "Stirring West".

Nutrients which reach the German Bight from Elbe and Weser rivers during seasons with predominant "stirring" conditions may become concentrated in this area, and the situation is completely different compared with "flushing" conditions (cyclonal or anticyclonal).
Atmospheric pressure data 1955 - 1980 from Norsk Meteorologisk Institutt, available every 6 hours on a 150 km grid, were transformed into data of wind stress, and these were filtered with a cutoff of 6.5 days, because the analysis is restricted to large scale, quasistationary conditions. 25 winter situations in box German Bight were analysed for one of the four characteristic weather situations described. The result is an extreme variability from winter to winter, resulting in just as variable circulation patterns. It seems useless to operate with "average winter conditions", each winter is characterized by an individual sequence of weather events. Winters 1962/63, 1968/69, 1973/74 and 1975/76 had a minimum of events which provide "flushing", and winters 1968/69, 1973/74 and 1975/76 in addition had many "stirring" events. If events in winter should have an inpact upon "eutrophication effects" in summer, such summers could have been 1969, 1974 and 1976.

Box 15

Report on Subproject: Analysis of weather conditions which could be important for chemical and biological processes in coastal waters of the Federal Republic of Germany

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Institut für Meereskunde Kiel

Mean daily data on cloud cover, relative humidity, difference between air and water temperature and wind speed 1929 - 1983, from lightvessels Elbe 1 and Fehmarnbelt, were analyzed. The assumption was that days with calm and sunny weather (wind below 10 knots, less than 7/8 cloud cover) should promote water stratification, and that wind above 20 knots should prevent, storm above 25 knots should break up stratification.

A comparison of 1965, known to be a "cold and windy summer", with 1981, known to be a "calm and sunny summer", did not however reveal significant differences in wind and storm days, and since 1957 there had been 15 summers with fewer storm days than 1981, plus 10 summers with storm days like 1981. However, there are 7 years without summer storms in this period (one was 1983). The period 1967 to 1977 is remarkable for the low number of summer storms. There is a difference in the number of days with calm weather (below 10 knots) between 1965 (43 days) and 1981 (70 days per year). However, if one analyzes days with wind below 10 knots plus cloud cover less than 7/8, from 1957 to 1983, then there might be a slight trend towards calmer and brighter summers in recent years, but 1981 is no extreme. Summers 1959, 1969, 1972, 1974, 1979 and 1983 had more potential for increased water stratification.

From this first analysis of weather data 1957 - 1983 one cannot conclude that oxygen depletion as observed in 1980 - 1983 is caused by weather conditions very different from weather of preceding decades.

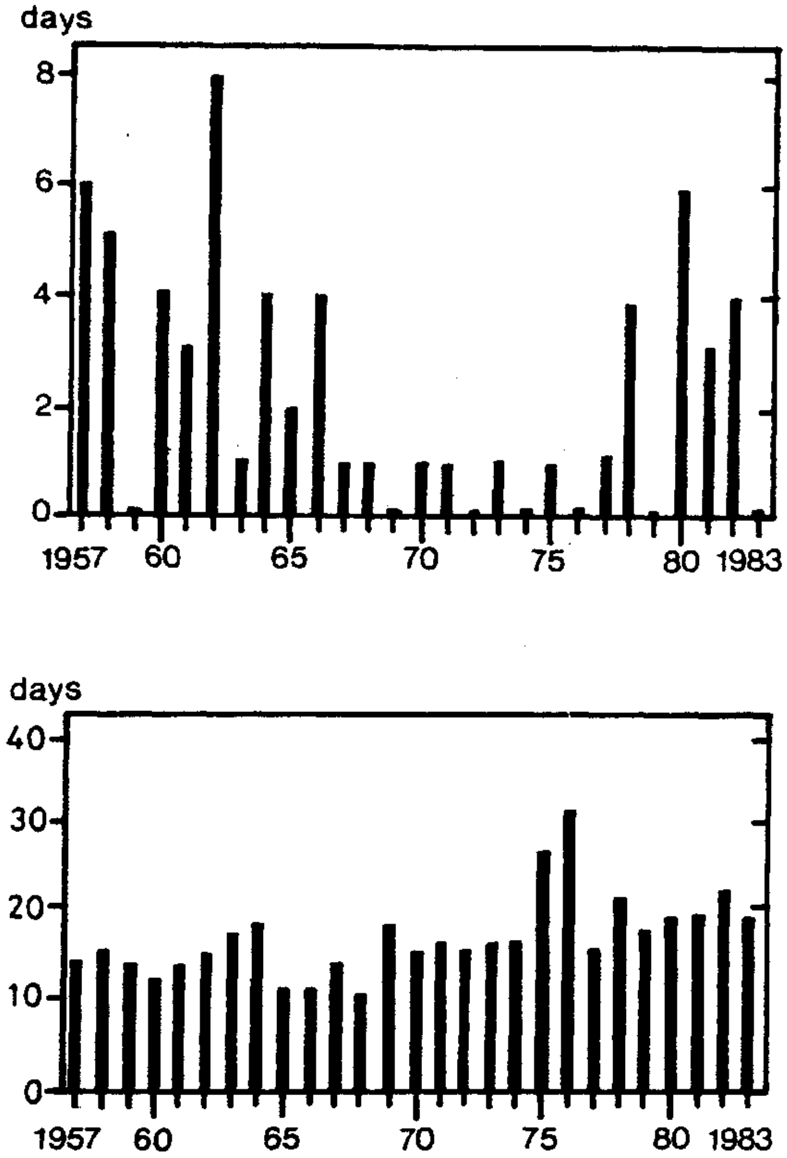

Fig. 31: Number of summer days with storm above 25 knots (upper figure), and number of days per year with average wind velocity below lo knots and with clouds less than 7/8 (figure below) 1957 - 1982. Lightvessel Elbe 1. Unpublished figure kindly provided by Prof.Dr. H.Graßl, J.-A.Falke and M.Stengel, Abteilung Maritime Meteorologie, Institut für Meereskunde, Kiel.

continued from p. 70

9. Conclusions and recommendations (which will be further discussed in the working group)

a) There are numerous open questions regarding origin, ways of distribution, deposition and effects of phosphorus and nitrogen compounds in the German Bight, Kieler Bucht and Mecklenburger Bucht. Therefore, for the time being, only limited conclusions are possible.

b) According to investigations carried out so far it is likely that phosphorus concentrations in the German Bight increased as a consequence of anthroprogenous input.

c) The main inputs of phosphorus into the German Bight are via the rivers (Elbe, Weser, Ems and contributions from the Rhine by coastal currents). In the catchment area of the North Sea sewage plants, for anticipatory reasons, might be equipped and operated with facilities for the elimination of phosphates.

d) The causal connection between increased phosphorus concentrations in the waters of the inner German Bight and oxygen depletion events is not clearly established. Further research is necessary to define the effects which phosphate elimination might have.

e) Phosphate elimination has the advantage that many inorganic and organic contaminants to a certain degree will co-precipitate and are thus prevented from being introduced into inland waters as well as into the sea.

f) There is less evidence for an anthropogenous cause of increased phosphorus concentrations in Kieler Bucht and Mecklenburger Bucht. Eutrophication problems in some landlocked fjord situations like Flensburg, Schleswig, Eckernförde, Travemünde-Lübeck might be counteracted by means of phosphate elimination, but these questions were not topics of the working group.

g) It seems that nitrogen more often than phosphorus is the limiting factor in controlling summer phytoplankton blooms in coastal waters.

h) The input of nitrogen compounds into the sea should be reduced as far as possible by reducing nitrogen emissions to the atmosphere, by reducing untimely and surplus application of mineral fertilizers and liquid manure in agriculture, and by appropriate measures (nitrification, denitrification) in sewage plants.

i) However, nitrogen-fixing Cyanophyta (Cyanobacteria, blue-greens) bloom at zero nitrogen concentrations in the water. Further research is necessary to assess the risk that such blooms may occur in coastal waters of the Federal Republic of Germany.

j) Whatever measures will be taken, due to the complex situation in the North Sea and the Baltic positive effects may only be expected after many years.

k) For an assessment of trends, for the control of measures carried out and, if necessary, for the preparation of further measures appropriate monitoring programmes are indispensable.

10. Problems of monitoring

10.1. How oxygen depletion can be detected

First information about reduced oxygen concentration in the deeper water layer of the German Bight 1980 - 1983 came from biological studies. First information about hydrogen sulfide in the deep water of Kieler Bucht 1981 came from marine chemistry work; it was subsequently confirmed by one of the cruises done 4 times per year by Deutsches Hydrographisches Institut in the framework of the Baltic Monitoring Programme (Deutsches Hydrographisches Institut, 1983).

With the knowledge gained from 1980 - 1983 we can conclude that oxygen deficiency starts at the sediment-water interface in such localized coastal areas where the water mass below the pycnocline is not exchanged early enough by water rich in oxygen. We can indicate sensitive localities where the oxygen situation should be monitored. We further know that oxygen depletion is an event that lasts just for days or weeks, and usually occurs in the holiday season. Therefore continuous recording of the oxygen situation is essential, supplemented by macrofauna surveys. Among the macrofauna living in the sediment are species which are very vulnerable to oxygen deficiency. Macrobenthos surveys, done once during the winter period, give a good picture of how the oxygen situation was during the preceding summer.

First recommendation:

Select sensitive stations and monitor continuously the temperature and salinity profile (for density structure) of the water masses and the oxygen concentration at a fixed distance from the sea floor. Organize special missions to investigate actual cases of oxygen depletion. Monitor in winter macrofauna on transects from sensitive areas to areas above the normal depth of the pycnocline to assess the regional extension of possible benthic mortality.

10.2. How the oxygen depletion may be explained: the decaying plant approach

Oxygen depletion may occur when large quantities of degradable organic substance reach the sea floor. The quantity and quality of sedimenting phytoplankton can be monitored with sedimentation traps moored on the sea floor. Unfortunately at present there are no methods available to measure the input of decaying macroalgae, eelgrass and other detritus from shallower into deeper coastal areas via horizontal transport down the coastal slope.

Second recommendation:

Monitor the sedimentation of degradable organic substances with sedimentation traps and develop a better understanding of horizontal advection of organic substances on slopes of the shore.

10.3. What is the origin of decaying plant material ?

Phytoplankton and phytobenthos are the sources of decaying plant material. Unfortunately there is no continuous method available for phytoplankton productivity measurements. If these measurements are done at long intervals, one might miss many peaks of short lived blooms. If they are done according to the calendar one might not distinguish years with early and with late ontset of blooms. Biomass data may help when connected with light data. Chlorophyll measurements can be done continuously.

As plankton is distributed in patches, continuous recording will yield better data than discrete sampling. Particle analysis may be an additional tool in the future. Additional information on the size of algae and on species composition of the phytoplankton is essential for conclusions from biomass to production. Taxonomic work is gaining in importance, from the public health point of view, because for a couple of years blooms of toxic or possibly toxic dinoflagellates have been observed in the North Sea and in the Belt Sea. If such blooms occur the public must be warned not to eat mussels and oysters.

Third recommendation:

Monitor phytoplankton and light conditions in the water continuously, as far as technically possible. Get additional information on species composition during blooms, and develop better means to assess phytoplankton and phytobenthos production.

10.4. Grazing may control phytoplankton production

In summer, zooplankton grazing is supposed to be a master factor that regulates phytoplankton populations and keeps them at a low level. Zooplankton speeds up the decomposition of organic matter produced by primary production, and the rapid circulation of phosphorus and nitrogen in the upper water masses, so that only small amounts of degradable organic matter sink into the deeper water masses. Phytoplankton blooms may be explained as "runaway growth" and occur when zooplankton grazing is not effective enough to keep phytoplankton biomass at a low level (Lindahl and Hernroth, 1985). Herbivorous zooplankton is controlled by carnivorous macrozooplankton, and pelagic fish.

Forth recommendation:

Monitor zooplankton and jellyfish abundance, collect fisheries data and try to correlate results with phytoplankton data.

10.5. Nutrients control primary production in spring

The sea water concentrations of phosphorus and nitrogen at the end of the turbulent winter period determine the amount of primary production during the spring phytoplankton bloom. For the assessment of long term trends in nutrient concentrations in sea water, the most appropriate strategy is the monitoring of winter concentrations when an equilibrium between sediment and water has been achieved.

Fifth recommendation:

Monitor nutrient concentrations in sea water at the end of the winter period, before the spring phytoplankton bloom starts.

10.6. Conditions that control primary production in summer

During summer and autumn, primary production in principle depends, like in spring, on the availability of plant nutrients, even if dinoflagellates are able to store, in their plasma, enough phosphorus for some generations and therefore may bloom, during a limited period, in waters with low nutrient concentrations. Cyanobacteria can bloom in waters with low nitrogen concentrations because they are able to fix atmospheric nitrogen. Controversy surrounds the question whether phosphorus or nitrogen are more important as limiting factors. There are regional differences. Nutrients get lost from the upper water layer due to the sedimentation of particles. To explain blooms by nutrients, one should know the processes which bring nutrients back into contact with phytoplankton: input with freshwater, and input from deep water by turbulent mixing, caused by waves or currents, by upwelling due to offshore winds or anticlockwise eddies, by vertical lifting of the pycnocline due to cooling, or due to the advection of water masses with higher salinity, etc.. Some algae can swim up and down and possibly by this behavior come into contact with nutrients.

Sixth recommendation:

Interdisciplinary studies of phytoplankton dynamics are necessary which include local knowledge of nutrient inputs and water mass dynamics. They should rely on monitoring data from fixed stations, on data from moored instruments and from research vessel cruises, on satellite information and on numerical models.

10.7. How the sediment influences oxygen and nutrients in the overlying water mass

The sediment acts as a sink for sedimenting organic matter and for oxygen, and as a source for nutrients in the water. As long as enough oxygen is available at the sediment-water interface and in the upper layer of the sediment, organic matter will be quickly mineralized. Mineralized phosphorus is released into the overlaying water. Mineralized nitrogen is partly removed from the system by microbial denitrification, partly released into the overlaying water by microbial nitrification.

These processes are largely controlled by the presence or absence of available oxygen, or by chemocline situations at the border of oxic and anoxic conditions in the sediment. Even if a lot of progress has been made during the past decade in understanding the complex interactions, it seems fair to state that at present no coherent picture is available which allows, for a definite coastal area, to model the processes for the different depth ranges, the different sediment qualitites, the different seasons of the year. This lack of scientific knowledge is deplorable, because the nitrogen balance for larger bodies of water is influenced in the same order of magnitude by nitrogen fixing, by denitrification, and by man made input.

The sediment seems to be the memory of the sea: in the sediment an image of past processes is conserved. When due to oxygen depletion the macrofauna in the sediment is killed and no bioturbation occurs, the anoxic sulfide regime in the sediment may be close to the sediment-water interface during the winter which follows a summer with oxygen depletion. The spring phytoplankton bloom then is not properly mineralized and adds to the oxygen deficit in the sediment, which results in an increased probability for oxygen depletion during the subsequent summer.

Seventh recommendation:

Promote research activities in the field of sediment chemistry, sediment microbiology and benthic organism activity, including studies on sedimentation, resuspension, bioturbation and related effects.

10.8. Stratification, hydrography and the weather

Stratification of the water masses is a key factor for oxygen depletion at the sea floor and in the lower compartment of stratified waters, just by the "bell jar effect", the prevention of oxygen advection. Stratification is a key factor for phytoplankton dynamics too. A pycnocline prevents phytoplankton cells from being transported, by turbulence, into the deep water where light is not sufficient for photosynthesis. Better knowledge of the actual density structure in coastal waters should be gained from fixed monitoring stations (first recommendation) and from surveys during phytoplankton blooms and during events of oxygen deficiency The basic question, however, is the correlation between weather (wind, sunlight, precipitation) and water stratification.

Eight recommendation:

Develop better regional knowledge of the effects of weather upon water mass dynamics. Develop better models to simulate transport and mixing processes in different water layers of the German Bight and the Belt Sea.

10.9. Input of nutrients

Air pollution with ammonium and nitrogen oxides has increased during past decades, but there is little knowledge of direct input via the air-sea interface. Nutrient runoff from forest and from other land has increased due to "acid rain", nutrient runoff from agricultural land has increased due to mineral fertilizer and liquid manure.

Ninth recommendation:

Authorities should provide better data on inputs of nutrients from land. Better methods should be developed to measure directly the input from the atmosphere to the sea.

11. Monitoring and marine science

Oxygen depletion in the lower compartment of stratified coastal waters is caused by at least the following factors:

1) inition and persistence of water stratification,
2) persistence in the sediment of conditions triggering oxygen depletion,
3) input of degradable organic substance from phytoplankton production which depends on the
4) inition and persistence of water stratification (see 1), and on the
5) light regime in the water, on the
6) intensity of zooplankton grazing, and on the
7) availability of nutrients. Nutrient concentrations in the upper water layers depend on
8) overall nutrient concentrations in water and sediments,
9) physical processes which transport nutrients into the upper water layers during periods of water stratification,
10) man made atmospheric input, and
11) man made input via land runoff, rivers and sewage.

Each of these factors can be a key factor resulting in oxygen depletion, even if concurrent factors are in their normal range. Man can control only a few of the factors. A monitoring programme restricted to controllable factors will not result in the overall picture which is necessary to gain a comprehensive understanding of the regional situation.

Regional marine science work is needed in a rather broad sense, including most chapters of a marine science textbook. If one follows this argument and reads the recommendations for monitoring and for research to be done, one will come to the conclusion that only such a broad approach can, if at all, give the answers to the questions which the catastrophes of oxygen depletion formulate for us.

Eutrophication effects are caused by many factors which work isolated or in conjunction, and are much influenced by regional situations. A final goal might be to understand them all to simulate effects in an ecosystem model. However, the state of our knowledge at present is far from being good enough for such a goal. At present, comparing time series of different factors and events seems to be the most promising approach. In the future, such time series will be the only source of information to assess conditions and to verify simulations of causes and effects.

We need "environment stations" in the same way as a hundred years ago we needed "weather stations" for long-term data collection. They are not "monitoring stations" in the sense that their prime task is to warn, but as in the case of weather stations, without the assessment of their data no warning is possible.

The word "to monitor" is now used in all languages, including German. The root is Latin "monere", which became "monieren" (to complain) in German, "to admonish" in English. A monitor's task was to control the behaviour of adolescent youth. "To monitor" is not a nice word from the linguistic point of view; it means "to act like a warner" but normal people would say "to warn".

We have a lot of warning systems against hurricanes, storm floods, icebergs but we did not use the word monitoring in this context. The Common Commission of IOC and SCOR for Changes in Climate and Ocean (CCCO) recommends the use of the term "monitoring" for "any open ended time series of oceanic or atmospheric observations that is maintained on a routine and regular basis." Other authors confine "monitoring" to "measurement of a pollutant or its effects" (Cole, 1983). Both is necessary. In 20 years, mankind will need time series of environmental parameters and of biological data even more urgently than now. One should make a start.

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