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Meeresforsch. 33 (1991), 121-140  
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ISSN 0341-6836

## Increasing oxygen deficiency in Kiel Bay (Western Baltic) A paradigm of progressing coastal eutrophication

BRIGITTA BABENERD

*Institut für Meereskunde an der Universität Kiel, FRG*



*Ms. received 8.3.1988*

*Ms. accepted 4.7.1990*

### Abstract

Evidence is presented for an increasing oxygen deficiency in the water below the pycnocline in Kiel Bay (Western Baltic) over the past 30 years. Subpycnocline oxygen consumption rate in summer has increased by a factor of 2-3 since 1957. This development is considered to be related to a proportional increase in primary production in the entire transition area between the North Sea and the Baltic Sea as a consequence of progressing coastal eutrophication.

A simple box-model is presented which satisfactorily describes the variation of subpycnocline oxygen concentrations in the Bay during the summer months as a function of oxygen consumption rate and rate of effective vertical water exchange.

### Kurzfassung

*Zunehmender Sauerstoffmangel in der Kieler Bucht (westliche Ostsee) – Ein Beispiel fortschreitender Eutrophierung in Küstennähe*

Zunehmender Sauerstoffmangel im Wasser unter der Sprungschicht ist während der letzten 30 Jahre für die Kieler Bucht (Westliche Ostsee) zu verzeichnen. Die sommerliche Sauerstoffzehrungsrate in diesem Wasserkörper hat seit 1957 um das Zwei- bis Dreifache zugenommen. Diese Entwicklung hängt offenbar mit einer proportionalen Zunahme der Primärproduktion im gesamten Übergangsbereich zwischen Nord- und Ostsee als Folge wachsender Eutrophierung in Küstennähe zusammen.

Ein einfaches Boxmodell beschreibt die Veränderungen der sommerlichen Sauerstoffkonzentrationen unter der Sprungschicht in der Kieler Bucht als Funktion der Sauerstoffzehrungsrate und der effektiven vertikalen Wasseraustauschrate.

### Resumen

*Incremento de la deficiencia de oxígeno en la Bahía de Kiel (Mar Báltico Occidental) – un paradigma del aumento de la eutrofización costera*

Se presenta evidencias de un incremento en la deficiencia de oxígeno de las aguas por debajo de la pycnoclina en la Bahía de Kiel (Báltico occidental), durante los últimos 30 años.

La tasa de consumo de oxígeno en la sub-pycnoclina durante el verano se ha incrementado por un factor de 2-3 desde 1957. Se considera que este desarrollo esté en relación al incremento proporcional de la producción primaria en toda el área de transición, entre el Mar del Norte y el Mar Báltico, como consecuencia del progreso de la eutrofización costera.

Se presenta un modelo simple ("box-model"), que describe satisfactoriamente la variación de las concentraciones de oxígeno de la sub-pycnoclina en la bahía durante los meses de verano, como una función de la tasa de consumo de oxígeno y la tasa de intercambio vertical de agua efectiva.

### Introduction

Since 1980, exceptional plankton blooms and unexpectedly severe oxygen depletion with detrimental effects on benthic invertebrates and fish have been observed in the Belt Sea, in the Kattegat and in the German Bight (EHRHARDT and WENCK 1984; MILJØSTYRELSEN

1984; ROSENBERG 1984, 1985; DETHLEFSEN and v. WESTERNHAGEN 1983; RACHOR and ALBRECHT 1983; WEIGELT and RUMOHR 1986).

Public concern that the escalating occurrence of such ecological perturbations might be linked to an increasing impact of anthropogenic nutrient input has resulted in an enforced research on the ecological effects of eutrophication in the German coastal waters (GERLACH 1984a, 1984b).

As part of these research activities, the oxygen dynamics of Kiel Bay were studied more closely. Investigations included the determination of pelagic consumption rates required to complete budget calculations, and analysis of the oxygen data available since 1957. A simple box-model has been developed to describe the effect of oxygen supply by vertical water exchange on oxygen concentration in Kiel Bay during the summer months.

Most interesting was a highly significant decrease of the mean oxygen concentration in the deeper waters of the Bay. The trend suggests that primary production in summer has more than doubled during the past three decades, most probably as a result of progressing coastal eutrophication. The investigations reported here deal, in particular, with the oxygen conditions in the subpycnocline water of Kiel Bay during the time of summer stratification which usually extends from the middle of May to the middle of September.

#### Hydrography, stratification, and oxygen

Oxygen concentrations in the deeper parts of Kiel Bay are strongly influenced by complex hydrographical processes resulting from the water exchange between the brackish Baltic ( $\sim 8\text{‰ S}$ ) and the marine North Sea ( $\sim 34\text{‰ S}$ ) (Fig. 1).

Characteristically, there is a permanent surface outflow of low salinity (less dense) water from the Baltic towards the North Sea due to the general freshwater surplus in the Baltic catchment area (BROGMUS 1952). The outflow at the surface is compensated by a gradient-driven bottom inflow of high salinity (dense) water from the North Sea (Skagerrak) via the Kattegat to the Baltic proper. During their passage through the shallow transition area encompassing Kiel Bay, both water masses are subject to strongly fluctuating mixing processes. These depend on the large-scale pressure and wind field as well as on local weather conditions and bottom topography. The main routes of water exchange by which the mixed water masses enter Kiel Bay are the Fehmarn Belt in the east and the Great Belt in the north. Summer stratification usually develops by the beginning of May due to rapidly increasing solar radiation and ceasing wind activity. In May, the discharge of light Baltic surface water to the Kattegat-Skagerrak area is at its maximum, and surface salinity in the entire area is at its minimum (SIEDLER and HATJE 1974). As a consequence of reduced vertical mixing there is an increase in salinity of the bottom water inflow from the Skagerrak-Kattegat area (see Fig. 2a and b). Both effects cause a stratification with strong vertical density gradients lasting from mid-May to, at least, mid-September.

The average summer pycnocline depth in Kiel Bay is about 14 m (POLLEHNE 1986). It roughly corresponds with the bottom of the euphotic zone (SCHINKOWSKI 1971). An equal mean pycnocline depth is reported for the Kattegat area (GRANELI and SUNDBÄCK 1986). The actual pycnocline depth, however, may vary considerably. In addition, the surface and the bottom water layer in Kiel Bay are often subdivided into several layers by steep density gradients indicating under- and overlaying processes due to advection.

Although the thermohaline stratification is a permanent summer feature in Kiel Bay, some vertical exchange takes place between the water above and below the pycnocline as is indicated by gradual or intermittent downward transport of heat. This necessarily includes downward transfer of dissolved oxygen from the well oxygenated surface to the undersaturated subpycnocline layers. The mechanisms of this exchange are apparently partly due to shear current mixing and largely due to advective processes such as described by KRUG (1963).

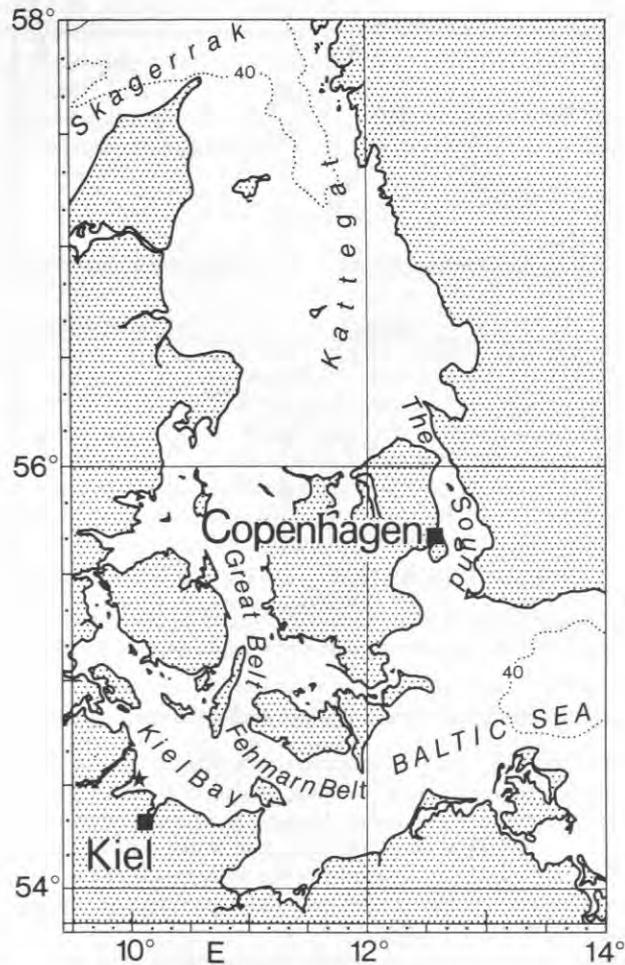


Fig. 1. Geographic location of Kiel Bay and sampling station (\*) within the transition area between the North Sea and the Baltic Sea

Summer stratification leads to an oxygen decrease below the pycnocline. Biological and chemical oxygen consumption exceed oxygen supply by vertical exchange and by lateral advection.

Though oxygen concentration in the productive surface layer usually remains close to saturation due to the exchange of oxygen with the atmosphere, the absolute amount of dissolved oxygen declines as a consequence of increasing water temperature.

Depletion of oxygen below the pycnocline layer usually culminates in mid-September. Subsequently stratification is reduced by progressive cooling and downward mixing of surface waters and by increasing influx of mixed Kattegat water of intermediate salinity in the deep.

Total reoxygenation of the water column may be a slow process, sometimes lasting through the entire winter, especially when ice formation inhibits the uptake of atmospheric oxygen. However, saturated oxygen levels are usually reached throughout most of the water column by March or April (see Fig. 2c and d).

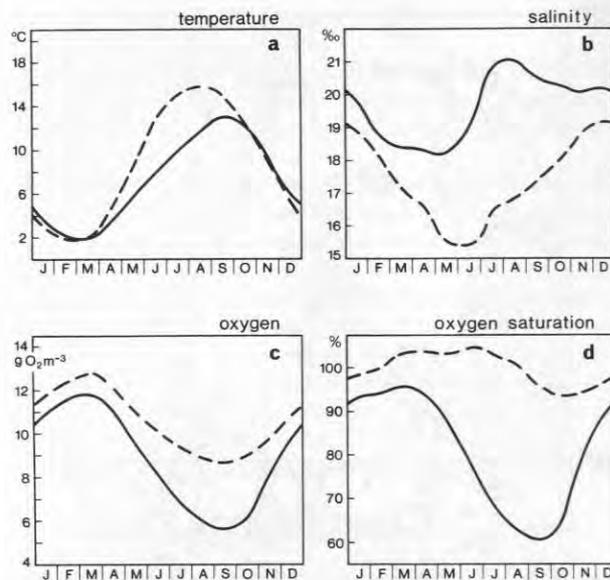


Fig. 2. Long-term annual course of temperature, salinity, and oxygen in Kiel Bay, 1957-1975, based on monthly observations. Solid line: mean values below 14 m; dashed line: mean values above 14 m

#### Oxygen budget of the water below the pycnocline during summer stratification

Changes of subpycnocline oxygen concentrations depend 1. on the rate of oxygen consumption through biological and chemical oxidation at the sediment-water interface and within the water column below the pycnocline, and 2. on the rate of net oxygen supply to the subpycnocline layer by vertical and advective water exchange including turbulence and diffusion. The latter can be estimated from the difference between the rate of change of actually observed oxygen concentrations and the experimentally obtained rate of total oxygen consumption (benthic + pelagic).

There is no other source of oxygen supply because insufficient light conditions do not allow substantial net production of oxygen by autotrophs in the deep layer. Irradiance measurements carried out in the Bay during 1985-1987 (J. LENZ and M. SOMMER, pers. comm.) showed that even in summer photosynthetically active radiation below 14 m is less than  $0.3-0.6 \text{ E m}^{-2} \text{ d}^{-1}$ , which is the assumed compensation level for microphytobenthos (GRANELI and SUNDBÄCK 1986) and phytoplankton growth (HARRIS 1978; RICHARDSON et al. 1983).

The subpycnocline oxygen budget presented here is based on own field observations in 1985 and 1986 and experimental work on pelagic consumption carried out in summer 1986, as well as on benthic consumption rates determined by POLLEHNE (1986) in summer 1984.

#### Study area

Investigations on oxygen dynamics were carried out at the long-term reference station BOKNIS ECK ( $54^{\circ} 32' \text{ N}$ ,  $10^{\circ} 03' \text{ E}$ ; depth 28 m) in the south-western part of Kiel Bay (Fig. 1). Although the station is not far from the coast, it is not under the direct influence of local sewage discharge or of freshwater run-off. Environmental conditions for production and decomposition of phytoplankton at the station are considered to be representative for the entire open Bay (v. BODUNGEN 1975; BABENERD 1980; SMETACEK et al. 1987).

The Bay covers an area of 2571 km<sup>2</sup> and holds a water volume of about 42 km<sup>3</sup> (BABENERD and GERLACH 1987). Mean water depth is 16–17 m; maximum depths in the channels and basins extend to about 30 m. As already mentioned, depth of the pycnocline is set to be 14 m.

The area below the pycnocline is 1.754 km<sup>2</sup> (= 68 % of the total) and the volume is 9.931 km<sup>3</sup> (= 24 % of the total). Average depth below the pycnocline is  $9.931 \times 10^6 \text{ m}^3 : 1.754 \times 10^6 \text{ m}^2 = 5.7 \text{ m}$ .

#### *Field observations*

Oxygen concentrations in the water column were measured monthly (1985) or bi-weekly (1986) at six standard depths: 0.5, 5, 10, 15, 20, and 26 m. In the water below the pycnocline, concentrations generally decline with depth. Mean concentrations for the total subpycnocline water body of Kiel Bay were calculated from concentrations observed at the standard depths in 15, 20 and 26 m taking into account the different volumes of corresponding depth layers according to the topography of Kiel Bay (BABENERD and GERLACH 1987). Data on oxygen, temperature and salinity used for trend analyses originate from KREY et al. (1978) and from ongoing research and monitoring programmes (H. HEUSER, unpubl. results; Baltic Monitoring Programme; own observations).

All oxygen analyses including experimental determination of consumption rates were performed by the WINKLER titration technique according to GRASSHOFF (1976).

#### *Oxygen consumption below the pycnocline*

##### *Consumption rate in the water column*

In situ pelagic oxygen consumption rates were measured for the first time in Kiel Bay over a period of 15 months from October 1985 to December 1986. Six of a total of 17 experiment series were run during the period of summer stratification in 1986. Water samples from the six standard depths were incubated in 120 ml WINKLER bottles immediately after sampling and kept in a water-bath in complete darkness at in situ temperatures. Incubation time was about 48 hours in order to obtain well-measurable oxygen differences. Oxygen content before and after incubation was determined in 2–5 parallels for each depth.

An effect of actual oxygen tension on the pelagic consumption rates could not be observed. This agrees with the results of ZOBELL (1940) and also with recent observations by GÖCKE (pers. comm.) showing that even extremely low oxygen tensions do not influence bacterial activity provided other physical, chemical, and nutritive properties of the substrate remain the same. Bacterial metabolism is assumed to be the main source of oxygen consumption in the water column.

The impact of bottle volume on consumption rates has not been studied. The mean rate of pelagic consumption for the total subpycnocline water of Kiel Bay amounts to 0.064 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup> (Tab. 1).

##### *Consumption rate at the sediment-water interface*

Rates of oxygen uptake at the sediment-water interface were determined by several authors for different sediment types from different depths in western Kiel Bay between 1973 and 1984 (BOJE 1974, 1977; BALZER 1978, 1984; BALZER et al. 1983, 1986; POLLEHNE 1980, 1986). Since most of the published rates were obtained in April or early May when benthic consumption is comparatively high due to preceding sedimentation of the spring bloom, they do not cover the period of summer stratification when sedimentation and consumption rates are supposed to be small (SMETACEK et al. 1987).

However, POLLEHNE (1986) determined mean uptake rates for subpycnocline sediments near the reference station during the vegetation period in 1984. They were found to

Table 1. Mean daily rates (24 hours) of pelagic oxygen consumption at different depths below the pycnocline in Kiel Bay during summer stratification (1986)

Water depth	15 m	20 m	26 m
Mean rate (g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup> )	0.067	0.062	0.052
Stand. deviation	0.028	0.010	0.011
Range	0.036–0.103	0.049–0.076	0.037–0.064
Mean water temperature	7.0°C	5.4°C	4.7°C
Range	4–12°C	3–10°C	3–8°C

be 0.318 g O<sub>2</sub> m<sup>-2</sup>d<sup>-1</sup> for muddy sand in 18 m depth, and 0.284 g O<sub>2</sub> m<sup>-2</sup>d<sup>-1</sup> for mud in 28 m depth. Muddy sand and mud, and sandy mud as a mixture of both, are the predominant sediment types below 14 m in Kiel Bay (BABENERD and GERLACH 1987). As both uptake rates are similar, an average rate of 0.301 g O<sub>2</sub> m<sup>-2</sup>d<sup>-1</sup> has been used to calculate the mean rates of benthic oxygen uptake contributing to oxygen consumption in the total subpycnocline water body of the Bay. Since the mean subpycnocline depth is 5.7 m, this rate amounts to 0.053 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup>.

The total subpycnocline consumption rate (benthic + pelagic) adds up to 0.117 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup>. The rate is considered valid for summer conditions in both years, 1985 and 1986.

#### Present-day oxygen budget

As calculated from cruise observations, between May 15th and September 15th, in 1985 and 1986 subpycnocline oxygen concentrations in the Bay decreased at a mean rate of 0.053 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup> and 0.060 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup>, respectively. These rates of decrease represent the sum of total subpycnocline consumption rate minus the rate of net oxygen supply by advective and vertical exchange. Taking the mean consumption rate (0.117 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup>), the rate of oxygen supply could be calculated and the oxygen budget completed (Tab. 2).

Table 2. Mean daily rates of oxygen fluxes below the pycnocline in Kiel Bay during summer stratification

Oxygen consumption	1985	1986
In the water column	-0.064 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>	-0.064 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>
At the sediment-water interface	-0.053 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>	-0.053 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>
Total oxygen consumption	-0.117 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>	-0.117 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>
Observed oxygen decrease	-0.053 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>	-0.060 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>
Calculated oxygen supply by advective and vertical exchange	+0.064 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>	+0.057 g O <sub>2</sub> m <sup>-3</sup> d <sup>-1</sup>

#### Discussion

The question arises as to the significance of estimating the rate of total subpycnocline oxygen consumption. As there only are few data for comparisons, a preliminary estimate, e.g. for Laholm Bay (SE Kattegat), indicates a total subpycnocline consumption rate of 0.224 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup> from May to September (GRANELI and SUNDBÄCK 1986). This comparably high rate presupposes subpycnocline pelagic consumption in Laholm Bay to be about three times higher than in Kiel Bay, 0.171 g O<sub>2</sub> m<sup>-3</sup>d<sup>-1</sup> instead of 0.064 g O<sub>2</sub>

$\text{m}^{-3}\text{d}^{-1}$ . In Kiel Bay, similar high rates are only found in the surface waters above the pycnocline during summer (BABENERD, unpubl.) but would also be valid for a water body that was recently submerged to the subpycnocline layer.

However, subpycnocline consumption rate is closely linked to primary production and sedimentation which determine the amount of organic carbon supplied to the subpycnocline layer where it is decomposed. According to SMETACEK et al. (1987) the mean daily rate of primary production in Kiel Bay in summer is found to be  $0.569 \text{ g C m}^{-2}\text{d}^{-1}$ . During summer stratification, a constant portion of about 25 % =  $0.142 \text{ g C m}^{-2}\text{d}^{-1}$  is found to be transferred to the bottom layer where it is oxidized at the rate of  $0.447 \text{ g O}_2 \text{ m}^{-2}\text{d}^{-1}$  (assuming RQ = 0.85; i.e. 3.14 g of oxygen are used up to oxidize 1 g of organically bound carbon). Since the mean subpycnocline depth is 5.7 m, the per-volume-rate of total oxygen consumption in the subpycnocline water body amounts to  $0.078 \text{ g O}_2 \text{ m}^{-3}\text{d}^{-1}$ . This recalculated rate is based on investigations of primary production and sedimentation carried out in Kiel Bay with great temporal resolution in the period 1972–1974 by the former „Sonderforschungsbereich 95“ (SMETACEK et al. 1987). The rate corresponds well with the present finding of  $0.117 \text{ g O}_2 \text{ m}^{-3}\text{d}^{-1}$  estimated for the period 1984–1986. A very good fit is obtained when the trend, indicating that the consumption rate has more than doubled since 1957, is considered as a consequence to a proportional increase in primary production (see Chapter Evidence of a long-term decrease . . .).

#### Oxygen supply by exchange with surface water

The decrease of oxygen concentrations due to biological and chemical consumption in the deep water of Kiel Bay is more or less effectively counterbalanced by oxygen supply during the summer months. During 1985 and 1986 the potential decrease was counterbalanced to about 50 % (see Tab. 2) which possibly represents an average summer value for Kiel Bay. But this value is assumed to vary considerably. Clearly, variations in mean supply rate during the summer months, which depend on interannual differences of meteorological and hydrographical conditions, will largely influence the extent of annual late summer oxygen depletion in the Bay and elsewhere in the transition area. Moreover, short-term events during summer may also be of great significance.

Since the irradiance below 14 m is insufficient for photosynthetic oxygen production in Kiel Bay (J. LENZ and M. SOMMER, pers. comm.) and also in the adjacent areas (DERA et al. 1984), substantial net production of oxygen by autotrophs is not expected to occur below the pycnocline in the entire transition area (v. BODUNGEN 1975).

Primary production rate (to which consumption rate is assumed to be proportional) is believed to be of the same order of magnitude in the entire Belt Sea including Kiel Bay and Mecklenburg Bay and also in the south-western part of the Kattegat (SMETACEK 1985), where the bottom inflow to Kiel Bay is thought to have its origin (KRUG 1963). Uniformity of the region with respect to nutrient supply (in particular of airborne nitrogen, and mineral fertilizers introduced in by freshwater run-off) and consequently to primary production has also been demonstrated by BABENERD and ZEITZSCHEL (1985).

Oxygen measurements carried out in the Kattegat and in the Belt Sea, 1974–1981, as part of the Danish Belt Project (AERTEBJERG NIELSEN et al. 1981; JACOBSEN 1982) also indicate that subpycnocline consumption rates are largely uniform in the entire area. In the Danish waters, subpycnocline oxygen concentrations decrease, during summer, at a rate similar to that observed in Kiel Bay. Thus, mere replacement of stagnant bottom water in Kiel Bay through advection of stagnant bottom water from the north would not increase the mean subpycnocline oxygen concentration in the Bay, although water volume transported may be large with a significant change in salinity during summer.

Supply of oxygen to the subpycnocline water body in Kiel Bay is therefore assumed to be solely dependent on hydrographic exchange with surface water which has two principal

sources. One is advection of Kattegat and Great Belt surface water from the north admixed to the deep inflow such as described by KRUG (1963). The other is direct vertical mixing and entrainment within the Bay and along its margins which may be of significance as suggested by AERTEBJERG NIELSEN et al. (1981).

In the following an attempt is made, using a simple box-model, to describe the rate of effective vertical water exchange which is responsible for subpycnocline oxygen supply in Kiel Bay. This rate is estimated by numerical integration. The approach has the advantage that it is scale-independent and that it quantifies vertical transport without the need to introduce physical parameters such as horizontal and vertical gradients and shear stress. For the concept it is irrelevant at what locale the vertical transport actually took place since the transition area is considered an entity with respect to subpycnocline consumption rate and to oxygen concentration in the surface layer during summer.

The rate of effective vertical exchange does not fully correspond with the virtual water exchange, since in the calculation the vertical water exchange occurring during advection may be slightly overestimated. Nevertheless, the concept and resulting rate represent a tool which provide better understanding of the oxygen dynamics in the Bay during the time of summer stratification, in particular with respect to changing production and consumption rates.

*Estimate of rate of effective vertical water exchange during the time of summer stratification*

The effective vertical water exchange between May 15th and September 15th can be described as a dilution rate  $E$  where a constant volume of subpycnocline water  $V_{ex}$  is exchanged every day with surface water (directly and indirectly through advection):

$$E = V_{ex} \delta t^{-1} V_b^{-1} \quad (1)$$

$V_b$  is total subpycnocline volume.

Vertical transport of oxygen to the subpycnocline layer is proportional to the difference at time  $t$  of mean oxygen concentration in the surface layer,  $O_{s,t}$  ( $\text{g O}_2 \text{ m}^{-3}$ ) and in the subpycnocline layer,  $O_{b,t}$  ( $\text{g O}_2 \text{ m}^{-3}$ ). The index  $t$  indicates the time in days. Concentration of oxygen in the subpycnocline layer then changes at a rate which is set by total subpycnocline consumption  $R$  and the hydrographic exchange rate with surface water  $E$ :

$$\delta O_b \delta t^{-1} = -R + (O_{s,t} - O_{b,t}) E \quad (2)$$

Surface oxygen concentration,  $O_{s,t}$  is always found to be close to saturation due to oxygen produced by photosynthesis and exchange of oxygen with the atmosphere.  $O_{s,t}$  can therefore be assumed to be an independent variable.  $O_{s,t}$  decreases slowly during summer as a consequence of increasing water temperature and is described by the equation:

$$O_{s,t} = 2.68 e^{-0.021 t} + 8.5 \quad (3)$$

May 15th is set as  $t = 1$ , making September 15th,  $t = 124$ . The equation describes long-term mean conditions in Kiel Bay for the period 1957–1975 (BABENERD 1986).

The subpycnocline consumption rate  $R$  is determined by the experimentally obtained value of  $0.117 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$ ;  $O_{s,t}$  is entered into the calculation from the above equation (3).  $E$  can be approximated by adjusting it in such a way that numerical integration of  $O_{b,t}$  over time, starting with the known value on May 15th, will yield the known value on September 15th. Numerical integration was carried out with time steps of one day using initial and final  $O_{b,t}$  values averaged from observations obtained in 1985 and 1986.

The rate of effective vertical water exchange was found to be  $1.7\% \text{ d}^{-1}$ . As can be concluded from statistical analyses of long-term observations this rate probably represents an average summer value for Kiel Bay (see Chapter Evidence of a long-term decrease . . .). The results of numerical integration have been plotted along with oxygen observations

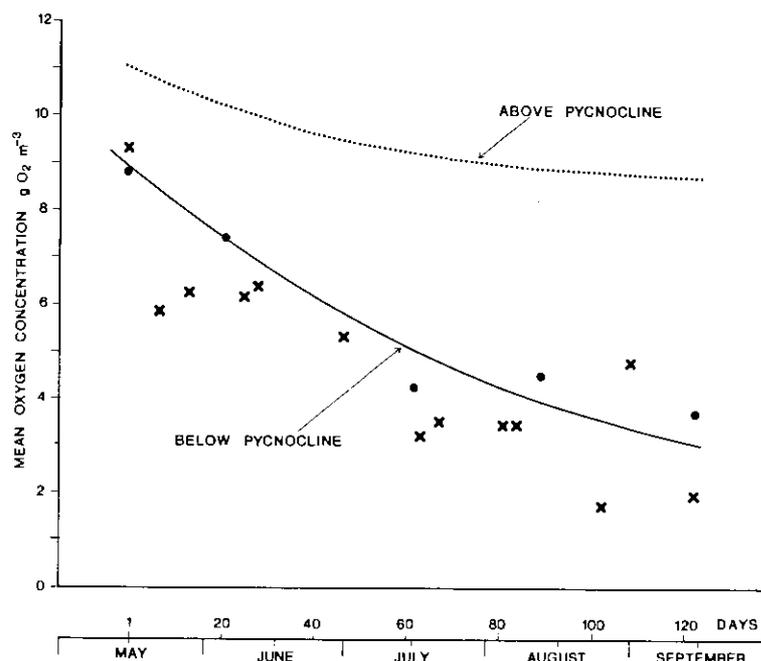


Fig. 3. Calculated and observed mean oxygen concentrations in Kiel Bay above and below the pycnocline during the summer months. Dotted line: long-term mean values for the layer above the pycnocline as calculated from equation (3); solid line: mean values below the pycnocline for 1985/1986 as calculated from equation (2) using mean rate of effective water exchange  $\bar{E} = 1.7\% \text{ d}^{-1}$ . Actually observed mean oxygen concentrations in the subpycnocline layer are marked by dots (1985) and by crosses (1986)

actually obtained in 1985 and 1986 (Fig. 3). Obviously, the calculations produce a satisfactory similarity with the observed values. Greater deviation of the actual values in 1986 may be due to the fact that the surface oxygen concentrations in this year were lower than usual, whereas in 1985 surface concentrations corresponded with the long-term means.

*Variation in extent of annual late summer oxygen depletion in Kiel Bay as a function of consumption rate and rate of effective vertical water exchange*

The extent of annual late summer oxygen depletion in Kiel Bay depends on the subpycnocline consumption rate, but can be modified (weakened) considerably by weather-dependent variations in the mean rate of vertical exchange with oxygenated surface water during the summer months. As already discussed, the first variable is closely linked to primary production in the area (SMETACEK et al. 1987). This in turn is assumed to have increased significantly during the past decades as a result of increased availability of plant nutrients in the coastal areas. Without doubt, man has contributed to a considerable degree and still is contributing to coastal eutrophication (LARSSON et al. 1985; BERG and RADACH 1985; GERLACH 1984a), resulting in an increased organic load and, consequently, an increased oxygen demand in the coastal waters.

The second variable (rate of vertical water exchange) depends on meteorologic and hydrographic conditions only and is in so far beyond the influence of man.

No trend has been found by testing long-term meteorological (GRASSL and STENGEL

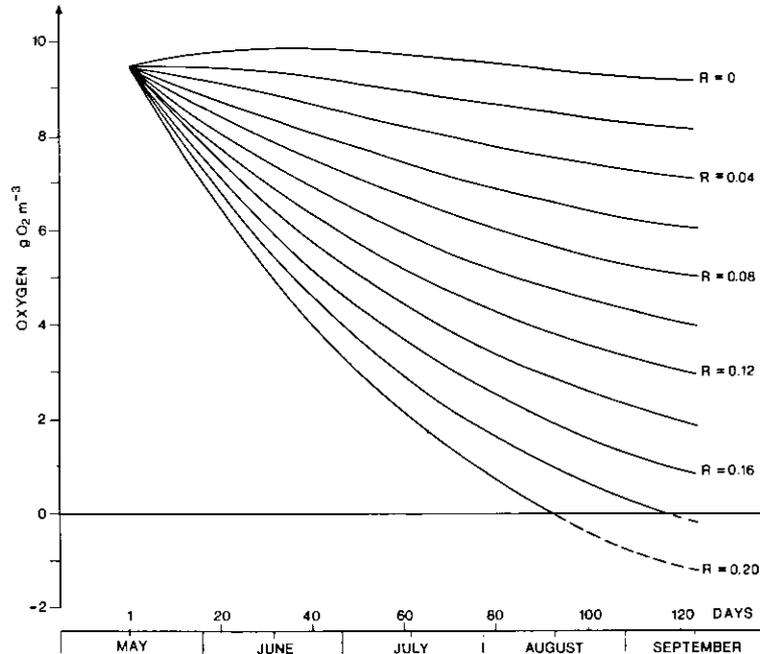


Fig. 4. The variation of subpycnocline oxygen concentrations in Kiel Bay during the summer months for a range of consumption rates  $R$  ( $\text{g O}_2 \text{ m}^{-3} \text{ d}^{-1}$ )

1985) and hydrographical data (FREY and BECKER 1986) collected at light-ship "Elbe I" in the German Bight, 1946–1983, and at light-ship "Fehmarnbelt" in the Western Baltic, 1948–1983. It can therefore be assumed that neither the mean rate nor the variability of vertical water exchange in the transition area have changed significantly during the past decades.

The impact of the first variable (potentially influenced by man) on the variation of oxygen concentrations during the summer months has been studied by numerical integration as described above for a range of values of consumption rates  $R$  using the calculated mean rate of effective water exchange  $E = 1.7\% \text{ d}^{-1}$ . Subpycnocline oxygen concentration in May was kept constant, as was surface oxygen development during summer according to equation (3). The results are depicted in Fig. 4.

Oxygen concentrations in summer proved to be linearly dependent on the consumption rates. The relationship of the mean subpycnocline concentrations in mid-September ( $O_{b,\text{Sept.}}$ ) on consumption rate  $R$  was found to be:

$$O_{b,\text{Sept.}} (\text{g O}_2 \text{ m}^{-3}) = 9.14 - 51.68 R \quad (4)$$

For instance, an increase of the consumption rate by  $0.04 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$ , as is expected to have occurred between 1973 and 1985/1986, accounts for a decrease of subpycnocline oxygen concentration in mid-September of about  $2.0 \text{ g O}_2 \text{ m}^{-3}$ . It also accounts for a 50% increase in primary production during the summer months since 1973. The consumption rate in 1973 was estimated to be  $0.078 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$  (as discussed in Chapter Oxygen budget of the water . . .). This result is based on the assumption of a close quantitative relationship between rates of carbon production, sedimentation, and decomposition as suggested by SMETACEK et al. (1987). It therefore appears to be realistic to recalculate the primary production rate from the consumption rate by using the given proportions. Since the consumption rate was  $0.078 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$  as derived from a production rate of  $70 \text{ g C m}^{-2}$

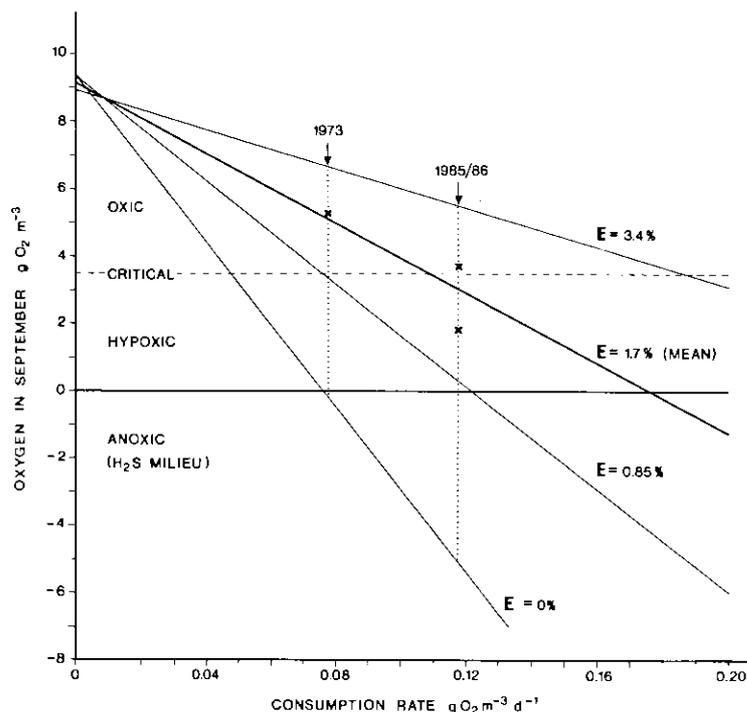


Fig. 5. Subpycnocline oxygen concentrations in Kiel Bay in September as a function of consumption rate  $R$  and rate of effective vertical water exchange  $E$ .

for the period May–September in 1973, the consumption rate of  $0.117 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$  will result in a primary production rate of about  $105 \text{ g C m}^{-2}$  for the same period in 1985 and 1986. Unfortunately, there are, except for the rate determined by v. BODUNGEN for 1973 (v. BODUNGEN 1975), no other reliable summer primary production rates in Kiel Bay available for comparison.

Fig. 4 shows that at very low consumption rates ( $R < 0.020 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$ ), the oxygen input by vertical exchange dominates over the oxygen consumption during May and June, as is indicated by a slight increase of the subpycnocline oxygen concentration during these months.

At hypothetical mean consumption rates higher than  $0.170 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$ , the mean subpycnocline oxygen concentrations will reach values below zero in late summer. That means, considerable amounts of hydrogen sulphide ( $\text{H}_2\text{S}$ ) will be present in the deeper part of the water column, originating from anaerobic metabolism taking the place of aerobic metabolism. Nevertheless, degradation of organic matter continues at about the same rate as during oxidic conditions (GÖCKE, pers. comm.) but, of course, an oxygen debt is built up where 1 mole  $\text{H}_2\text{S}$  is equal to two moles  $\text{O}_2$ . The oxidation of ammonia will require additional oxygen. This oxygen debt will be balanced after a time delay by chemical oxidation (chemical consumption) when free oxygen is supplied to the subpycnocline layer by intensified vertical water exchange.

The impact of the second (the physical) variable on the variation of subpycnocline minimum oxygen concentrations in mid-September has been studied by carrying out similar integrations for a range of values of both consumption rates  $R$  and rates of apparent vertical water exchange  $E$ . The results are depicted in Fig. 5.

The diagram clearly demonstrates how sensitive late summer oxygen concentrations

may be to variations of  $E$ . Sensitivity or range of variability increases with increasing rates of consumption. If  $E$  is allowed to vary between zero and double the mean daily water exchange rate of 1.7%, present-day (1985/1986) mean subpycnocline oxygen concentrations in September are calculated to vary from moderately oxic ( $5.5 \text{ g O}_2 \text{ m}^{-3}$ ) to completely anoxic conditions (hydrogen sulphide milieu). Actual mean concentrations in mid-September were determined to have been  $3.8 \text{ g O}_2 \text{ m}^{-3}$  in 1985 and  $2.0 \text{ g O}_2 \text{ m}^{-3}$  in 1986. Water exchange rates were favourable since they approximated natural mean rates in both years. However, hypoxic conditions of less than  $3\text{--}4 \text{ g O}_2 \text{ m}^{-3}$  will already cause severe damage to fish and zoobenthos (SWANSON et al. 1979). In fact, episodes of hydrogen sulphide formation were observed in the near-bottom water of the Bay in August and again in October 1986. Subpycnocline water exchange with surface water takes place predominantly at the pycnocline and is expected to be reduced with depth. Supply of oxygenated surface water to the near-bottom layer in the Bay, thus, may be extremely slow when there are additional steep density gradients in the subpycnocline water body resulting from inflow of stagnant Kattegat bottom water of especially high salinity in early summer. Conditions such as these are sometimes observed in the Bay (WEIGELT 1987).

Consumption rates are comparatively higher at the sediment-water interface. They depend on sedimentation rate and on additional input of organic matter through lateral transport (e.g. of macrophytobenthic material). Local bottom anoxic conditions, therefore, are likely to occur sporadically in the deep basins of the Bay, where such material accumulates, at overall consumption rates considerably lower than those calculated for 1985/1986 and 1973.

Summing up, both factors – consumption rate (which is assumed to be proportional to primary production) and water exchange rate – may vary within a natural range, large enough to produce sporadically critical oxygen conditions in the near-bottom water of the Bay and anoxia at the sediment-water interface.

However, the long-term increase of primary production rates, which has apparently taken place during the past decades, has significantly increased the danger of the occurrence, duration, and intensity of hypoxia and anoxia in Kiel Bay.

#### Evidence of a long-term decrease of subpycnocline oxygen content during the period of summer stratification

The calculations presented so far were speculative. In the following, however, evidence is given for a long-term decline of average subpycnocline oxygen content in Kiel Bay during summer. The trend is independent of the physical variables and can thus be regarded to reflect long-term changes due to increasing coastal eutrophication.

#### Data base

The data base used covers three decades of monthly observations (1957–1986) at the permanent reference station BOKNIS ECK described earlier in this paper. It consists of data collected by KREY from 1957 to 1975 (KREY et al. 1978) and recent, yet unpublished data from ongoing research and monitoring programmes (H. HEUSER, unpubl. results; Baltic Monitoring Programme; own observations). Unfortunately, no comparable data were available for the periods 1976–1978 and 1982–1984 due to changes in the research programmes.

#### Results of trend evaluation

Mean oxygen concentrations were calculated for May 15th, June 15th, July 15th, August 15th and September 15th of each year. The period between May 15th and September 15th is considered the time of annual summer stratification when the water below the pycno-

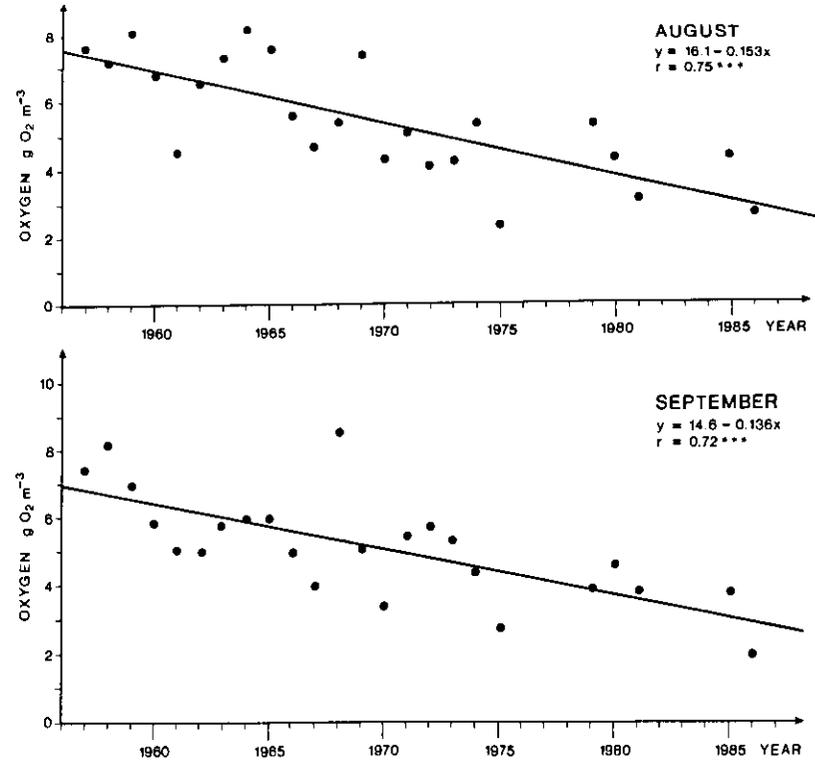
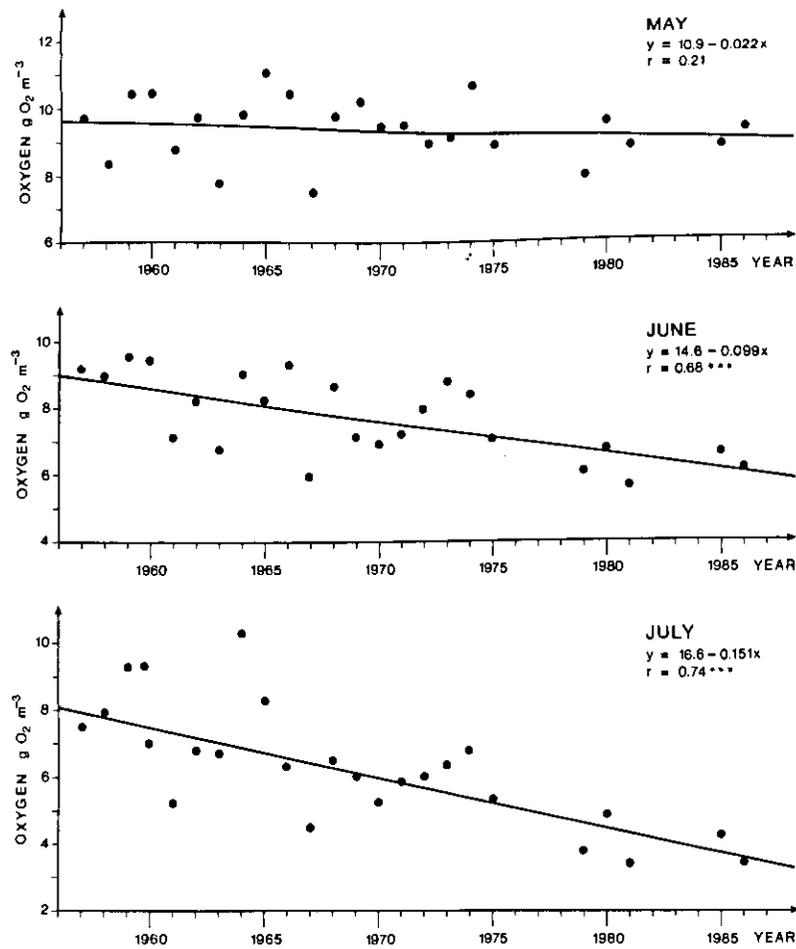


Fig. 6. Mean oxygen concentrations of the water below the pycnocline in Kiel Bay during the summer months, 1957-1986. Significance at a confidence level of 0.001 = \*\*\*, (In the regressions  $x = \text{actual years} - 1900$ )

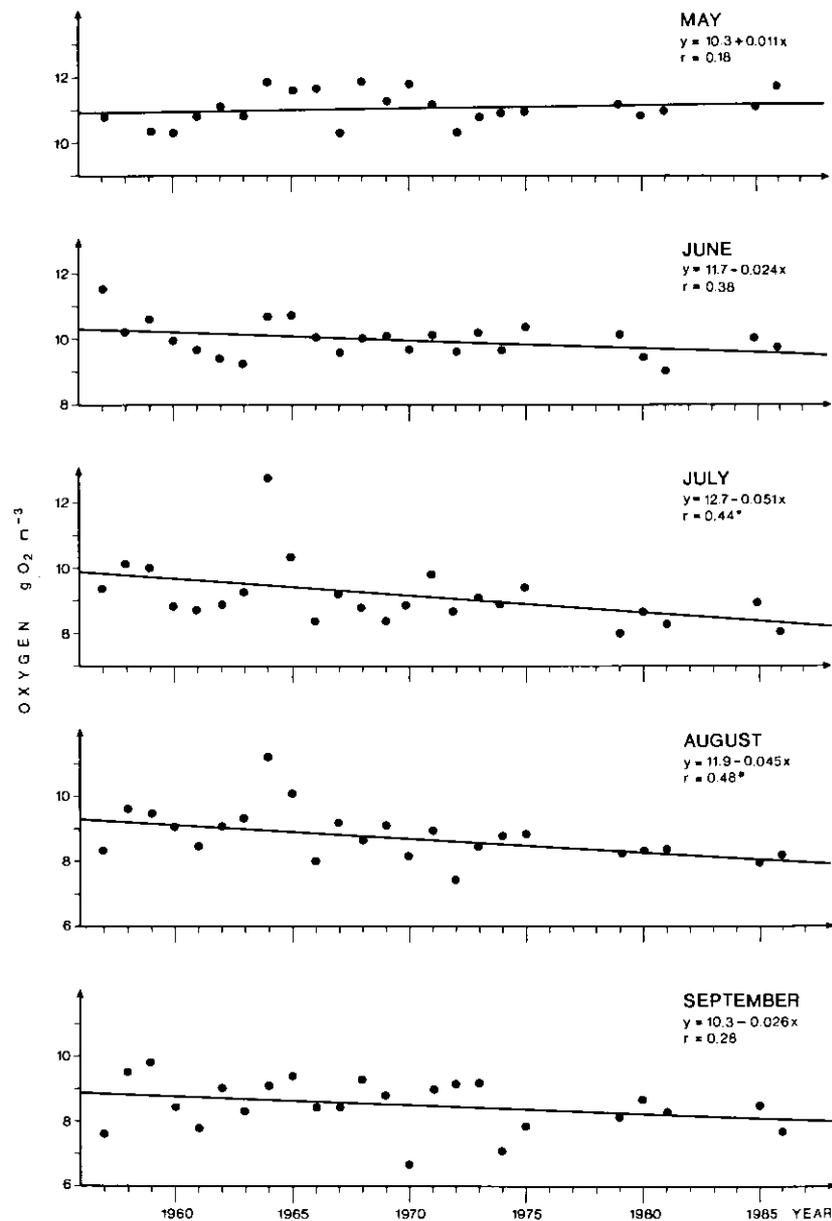


Fig. 7. Mean oxygen concentrations of the water above the pycnocline in Kiel Bay in the summer months, 1957–1986. Significance at a confidence level of 0.05 = \*. (In the regressions  $x$  = actual years – 1900)

cline in the Bay regularly show an oxygen deficiency. When no data were available for these specific dates, values were obtained by interpolation over time between adjacent data pairs. The trend analyses were carried out by linear regression, testing the concentrations calculated for each date against time. The regression parameters are presented in Fig. 6 and 7.

#### Dramatic decrease of subpycnocline oxygen content in summer

The results of the trend analyses for the subpycnocline oxygen content in summer are depicted in Fig. 6. Except for the values in May, which show a tendency but not a clear trend, a dramatic decrease is found for the subpycnocline oxygen concentrations in summer over the last 30 years. As recalculated from regressions, between 1957 and 1986 average oxygen concentration decreased by  $2.9 \text{ g O}_2 \text{ m}^{-3}$  in June, by  $4.4 \text{ g O}_2 \text{ m}^{-3}$  in July and August, and by  $3.9 \text{ g O}_2 \text{ m}^{-3}$  in September. Values in May decreased by  $0.7 \text{ g O}_2 \text{ m}^{-3}$ , but the trend is not statistically significant.

Curious, that these remarkable oxygen trends have not been detected before. However, as is evident from the diagrams, the trends are considerably masked by the weather-dependent variations in water exchange (oxygen supply) discussed in the previous chapter. Furthermore the systematic changes in the oxygen content had not been expected to occur in the Bay. For instance, the long-term development of inorganic nutrient levels in winter in Kiel Bay is obviously not indicative of substantial changes in primary production during spring (v. BODUNGEN 1986; GERLACH 1986, 1988). As pointed out by GERLACH (1988), however, assessment of winter water nutrient concentrations alone may not be sufficient for the evaluation of the production in Kiel Bay in summer since it is strongly influenced by water exchange with the adjacent sea areas.

#### No significant changes respectively weak trends in surface oxygen content in summer

The results of the trend analyses for the mean oxygen concentrations in the surface layer are depicted in Fig. 7. As yet, no significant trends can be observed for May, June, and September. Weak trends are found for July and August. The tendencies outlined in the diagrams indicate that the mean oxygen content in summer will decrease systematically, also in the surface layer. This means that exchange with surface water will be less effective in the future with respect to oxygen supply to the subpycnocline layer, and deterioration of oxygen conditions in the deep water will possibly accelerate, if eutrophication continues.

#### No concomitant trends in the physical variables

Concomitantly sampled temperature and salinity values in the Bay were subjected to the same statistical treatment as the oxygen data. But neither parameter showed any statistically significant trend. This agrees with the results of GRASSL and STENGEL (1985) that no significant meteorological trend can be found for the Western Baltic or the German Bight over the last 30 years. The decrease in the oxygen content in the Bay is therefore most likely the result of increasing oxygen demand due to increasing organic load in the waters of the entire transition area between the Kattegat and the Baltic.

#### *The results of the trend analyses as compared with the results of the theoretical approach by numerical integration*

In order to demonstrate more clearly the decrease in oxygen content over the past 30 years, oxygen concentrations in May, June, July, August, and September were recalculated from the respective regressions for the years 1957 and 1986, and also for 1973. The results are summarized in Fig. 8.

The annual variation over time during the summer months, demonstrated in Fig. 8, can now be directly compared with the curves resulting from numerical integrations presented in Fig. 4.

Experimentally obtained consumption rate  $R$  was  $0.117 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$  in 1985/1986 (see Chapter Oxygen budget of the water . . .);  $R$  in 1973 was recalculated to be  $0.078 \text{ g O}_2 \text{ m}^{-3} \text{ d}^{-1}$  using the proportions given by SMETACEK et al. (1987). Since subpycnocline oxygen concentrations in mid-September ( $O_{b, \text{Sept.}}$ ) are linearly dependent on consumption rates

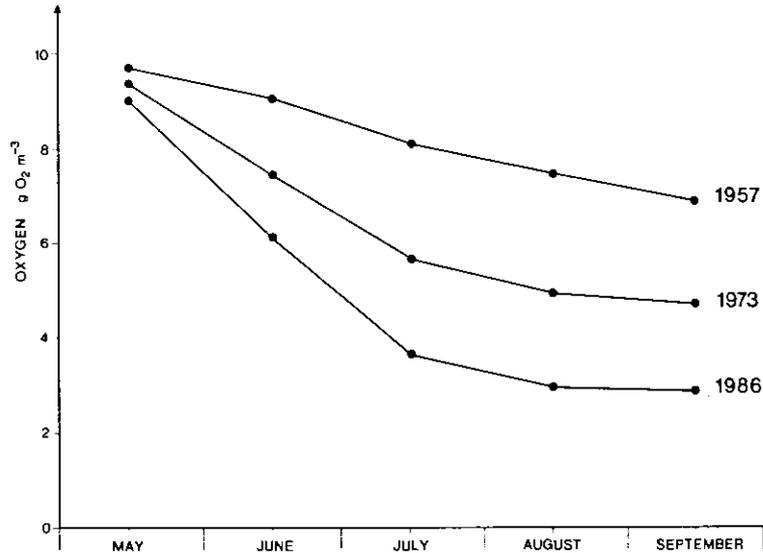


Fig. 8. Changes of subpycnocline oxygen concentrations in Kiel Bay in summer between 1957 and 1986 as calculated from the regressions given in Fig. 6

according to equation (4), respective consumption rates can be recalculated for each year between 1957 and 1986 from the regression given in Fig. 6 for oxygen concentrations in September. For instance:

$$\begin{aligned} O_{b, \text{Sept. (1957)}} &= 6.85 \text{ g O}_2 \text{ m}^{-3}; R_{(1957)} = 0.044 \text{ g O}_2 \text{ m}^{-3} \text{d}^{-1} \\ O_{b, \text{Sept. (1973)}} &= 4.67 \text{ g O}_2 \text{ m}^{-3}; R_{(1973)} = 0.086 \text{ g O}_2 \text{ m}^{-3} \text{d}^{-1} \\ O_{b, \text{Sept. (1986)}} &= 2.90 \text{ g O}_2 \text{ m}^{-3}; R_{(1986)} = 0.121 \text{ g O}_2 \text{ m}^{-3} \text{d}^{-1} \end{aligned}$$

Comparing the results in Fig. 4 and Fig. 8, there is an almost perfect congruence of the concentrations obtained theoretically with those recalculated for 1957 from the regressions presented in Fig. 6, when entering  $R_{(1957)} = 0.044 \text{ g O}_2 \text{ m}^{-3} \text{d}^{-1}$  in the numerical integration. Hence, during the course of the years the oxygen concentrations in June, July, and August, as derived from the trend analyses, evidently tend to deviate increasingly from the concentrations resulting from numerical integration using the respective values of  $R$ , i.e. they are significantly lower. The cause for this development is most probably that in Kiel Bay not only summer subpycnocline but also mean surface layer oxygen concentrations have decreased over the past 30 years.

Equation (3), which is set to describe surface oxygen concentrations in summer as an independent variable, was derived from mean values for the period 1957–1975. Apparently, the assumption that this equation was constant over time is not valid for the more recent years (see Fig. 7).

#### Causes of the increased oxygen deficiency

According to present knowledge there are no statistically significant trends in meteorology and hydrography which could have been the cause of a reduced vertical exchange with surface water in the transition area and thus diminution of annual oxygen supply to the bottom layer in Kiel Bay in summer.

The increased oxygen deficiency, therefore, must be due to an increased oxygen

demand as a result of increased supply of organic matter (carbon and ammonia) to the subpycnocline layer in the Bay.

A comparison of the magnitude of annual phytoplankton production – about 400 000 tons of carbon per year, according to v. BODUNGEN (1975) – and supply of organic matter to the Bay through rivers and sewage outlets – about 6000 tons of carbon per year as recalculated from BOD<sub>5</sub> values given by BABENERD and ZEITZSCHEL (1985) – shows that the latter comprises only 1–2 percent of the former and is therefore not likely to explain the observed changes in consumption. Both values refer to investigations carried out in 1972–1974 (v. BODUNGEN 1975; BRANDT 1977) and to the areal extent of Kiel Bay as determined by BABENERD and GERLACH (1987). Since biological sewage treatment has largely expanded during the past decades the biological oxygen demand (BOD) and the chemical oxygen demand (COD) of waste water discharged to the sea has decreased rather than increased.

Another possible cause may be the significant restructuring of the pelagic food chain which has taken place during the past three decades, resulting in an increasingly greater fraction of the primary production which sediments to the subpycnocline layer in summer. The answer to this question must be left open, but such a development seems unlikely to occur without any changes in primary production.

This leaves two explanations for the increased oxygen demand. The first is that the load of oxidizable material in the subpycnocline waters entering Kiel Bay from the Kattegat and ultimately originating from the North Sea has increased. This could be the result of increased primary production in the Kattegat and in the Belt Sea and subsequent transport of particulate and dissolved organic matter into Kiel Bay. The second is a proportional increase in pelagic primary production in summer also within Kiel Bay. This hypothesis is supported by the close temporal coupling between benthic heterotrophic activity and the flux of organic material to the bottom (GRAF 1982, 1983).

However, as already discussed in the previous chapters, the southern Kattegat and the Belt Sea area, including Kiel Bay, are considered uniform with respect to primary production and consumption rates.

Subpycnocline consumption rates in the Bay in summer proved to have more than doubled since 1957. The close relationship to primary production leads to the conclusion that primary production in summer has also more than doubled in the area over the last 30 years.

This increase is most likely the result of enhanced supply of inorganic nutrients to the euphotic zone during the summer months. This hypothesis is supported by the following aspects: primary production is nutrient-limited during summer, and no accumulation of nutrients is observed in the euphotic zone during summer despite a drastic increase in runoff and atmospheric input of all major nutrients except silicate over the past decades. It can be concluded that the decreased subpycnocline oxygen concentrations in summer in Kiel Bay and in the adjacent transitional areas of similarly stratified regime are directly linked to the increased supply rate of inorganic nutrients during the same period.

Several sources possibly contribute to an increased nutrient supply in the Belt Sea and adjacent areas in summer. One major component may be the increased load of nutrients, especially nitrogen, observed in the deep layers of the northern Kattegat. This water ultimately originates from the coastal areas of the southern Skagerrak and the southeastern parts of the North Sea and is carried to the Kattegat by the Jutland Current. Part of this water mass constitutes the deep inflow to the Baltic. During its passage through the shallow transition area this deep water mixes to a certain degree with surface water. Nitrate concentrations in the bottom water of NE Kattegat were found to have increased gradually by a factor of 3 within the period 1968–1984 (AERTEBJERG NIELSEN 1985) in winter as well as in summer. Since nitrogen is indicated to be the limiting nutrient in the Western Baltic during summer (FONSELIUS 1978) an increased nitrogen supply to the euphotic zone is likely to stimulate an increase in primary production in the transition area.

Moreover, surface water from either the Baltic or the northern Kattegat is nutrient-depleted in summer and, therefore, unlikely to contribute directly to nutrient supply in the Belt Sea during the summer months.

Another likely source of increased nutrient supply in summer is the increased run-off from agricultural areas. Whilst phosphorus fertilizing did not change very much during the past decades, the use of nitrogen fertilizers in the Federal Republic of Germany and in Denmark has increased by a factor of more than 3 since 1960 (BABENERD and ZEITZSCHEL 1985; GERLACH 1986).

The same increase has been documented for air-borne input of nitrogen which at the present accounts for at least  $2 \text{ g N m}^{-2} \text{ yr}^{-1}$  (BABENERD and ZEITZSCHEL 1985).

When oxic conditions change to anoxic conditions at the sediment-water interface, the flux of nutrients from the sea-bottom into the water column is considerably intensified. Large amounts of iron-bound phosphate are remobilized and released from the anoxic sediments together with ammonia-nitrogen (BALZER 1984). Both nutrients can be used directly by the autotrophs to build up proteins, provided there is adequate light. On the other hand, nitrate and nitrite are increasingly eliminated from the bottom water by the process of denitrification (BALZER 1984).

Hence, the consequence of the more frequent and extended oxygen depletions has been that periodically abnormal amounts of phosphate and ammonia are supplied to the bottom waters in summer, thus creating the potential for increased primary production. This in turn may be the cause for a new episode of bottom anoxia. This vicious circle of self-sustaining nutrient supply and production makes it difficult to evaluate the direct impact of man in this process.

As has been discussed, critical oxygen levels in the near-bottom water and local bottom anoxia are likely to occur sporadically within the natural range of normal (i.e. not anthropogenic) production and consumption when vertical water exchange is extremely reduced in the transition area. This fact most probably accounts for the oxygen depletions in the Bay reported by RUMOHR (1986) for the period 1875–1939.

However, the progressing decrease of the subpycnocline oxygen content in the Bay in summer over the past 30 years evidenced in this study is quite another process. In my opinion this long-term decrease conclusively reflects the gradually progressing process of coastal eutrophication in the entire area.

Without doubt the increased availability of plant nutrients had significantly amplified the potential risk for increasing near-bottom oxygen deficiencies and local anoxia in the stratified shallow coastal areas, such as the transition area between the North Sea and the Baltic Sea, that are recipients of annually growing anthropogenic nutrient freights via rivers, coastal currents and atmospheric input.

#### Acknowledgements

I would like to thank Dr. E. BÄUERLE, Prof. S. A. GERLACH, Prof. J. LENZ and Prof. B. ZEITZSCHEL for helpful comments and Dr. H. MASKE for cooperation with the model concept.

Financial support was provided by the UMWELTBUNDESAMT (Wasser 102 04 215/19) and by the Bundesminister für Forschung und Technologie (NFE 0536 5).

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*Author's address:* Dr. BRIGITTA BABENERD, Institut für Meereskunde an der Universität, Düsterbrookweg 20, W-2300 Kiel, FRG