Phytoplankton variability in the Marsdiep, The Netherlands

Gerhard C. Cadée

Phytoplankton has been sampled regularly in the Marsdiep, the westernmost tidal inlet of the Wadden Sea, since the early 1970s. During this period, *Phaeocystis* was numerically the most important species. Duration of blooms of non-diatoms, particularly of *Phaeocystis* (defined as periods with >1000 cells · ml⁻¹) have increased since the early 1970s from ~30 to >100 days. In the 1980s, duration of *Phaeocystis* blooms remained ~100 days, with highest values at the end of the decade (120-150 days), a continuing increase not observed in other non-diatom plankton. The duration of diatom blooms fluctuated considerably, but at the end of the 1980s they were the same as at the end of the 1960s. Average annual phytoplankton biomass (chlorophyll *a*) showed a good correlation with annual average Rhine runoff measured at Lobith. This indicates the importance of nutrients carried by Rhine water either reaching the Marsdiep via the River IJssel or Lake IJssel or with the residual coastal current along the Dutch coast. Enhanced leaching of nutrients particularly N from over-fertilized agricultural land during high rainfall seems the main cause of the observed correlation of phytoplankton biomass and algal blooms in the Dutch coastal waters.


Introduction

The knowledge of natural variability of the ecosystem is important when studying trends due to man-induced changes of the environment, e.g. eutrophication or global warming. Phytoplankton variability has been studied in a broad spectrum of scales ranging from tidal (e.g. Veldhuis et al., 1988), diurnal (e.g. Sournia, 1975), and neap-spring tidal cycles (Balch, 1986) to annual (e.g. Cadée, 1986a), and year-to-year scales (e.g. Tont, 1987).

One may question whether a time period of ten years (1980-1989), as chosen for this symposium, is long enough to illustrate long-term variability. It almost coincides with the 11-year cycle in sunspots: maximum sunspot activity coinciding with nice summers and more severe winters in our area. The sunspot cycle is prominent in tree-ring records (Zeuner, 1958). Ottestad (1942) could correlate cod catches with tree-ring width and thus sunspot cycle in northern Norway. Vibe (1967) observed 11-year sunspot cycles in among others drift-ice extension, cod landings, and numbers of polar bears, harp seals, and ptarmigans in Greenland. Colebrook and Taylor (1984) observed plankton periodicity with a wavelength of 10-12 years which, however, they did not relate to a particular process.

Variations in plankton with cycles of less than 10 years are known: cycles of about three years are present in the data of the Continuous Plankton Recorder (CPR) survey (Colebrook and Taylor, 1984; Colebrook, 1986). El Niño with its marked effects on plankton and fisheries off Peru, but also elsewhere, occurs about every four years. The interval between two successive events varies from 2 to 10 years (Barber and Chavez, 1983; Cane, 1983).

Long-term changes in climate of about 50 to 70 years' duration express themselves in periodic changes in wind strength and direction (Cushing, 1975). Cushing stresses the influence on marine phytoplankton production cycles and hence on the match or mismatch of fish larval production and consequently fish recruitment. The CPR survey data for the North Sea (since 1931) and for the Northwest Atlantic (e.g. Colebrook, 1986; Owens et al., 1989) and the so-called Russell cycle observed in plankton of the English Channel since 1924 (Southward, 1963; Russell, 1973) are the best data available for illustrating such long-term trends. The existence of such long-term cycles equaling the lifetime of a scientist makes the study of natural vs. man-induced variations in the sea no easier (Gillbricht, 1986). This implies that the debate whether changes observed in (phyto)plankton are due to climate or eutrophication will continue.
This paper summarizes data on phytoplankton variability in the Marsdiep, the westernmost tidal inlet of the Wadden Sea. Monitoring phytoplankton started in the 1970s and historical data going back to 1897–1899 (Cleve, 1898–1900; Cadée and Hegeman, 1991) can be used for comparison. Earlier reports on this data set have been presented (Cadée, 1986a, 1990b, 1992; Cadée and Hegeman, 1991). Phytoplankton changes observed in this coastal area are comparable to those found in the Rhine-influenced part of the Southern Bight, North Sea (Gieskes and Kraay, 1977), and in the Helgoland series (Radach et al., 1990): increase in non-diatom phytoplankton and no increase in diatoms. They are different from changes observed in the open North Sea (e.g. Owens et al., 1989), where climatic changes effective in the open North Sea are overridden by man-induced changes in nutrient (ratios) in the continental coastal North Sea waters (van Bennekom et al 1975); Cadée, 1990a; Riegman et al., 1992a,b).

Methods
Methods are treated more in extenso in earlier papers (Cadée, 1986a, 1992; Cadée and Hegeman, 1974, 1979). The sampling locality is the NIOZ Marsdiep pier (A in Fig. 1), where weekly (more frequently during spring blooms, less frequently in winter) samples were taken with a bucket during high tide. Annual average values are based on monthly averages to compensate for this unequal sampling over the year. For chlorophyll-a measurements, 0.5 to 1 l water was filtered over MgCO_3 coated glass fibre filters (Whatmann GF/C); acetone extracts were measured following Lorenzen (1967). Phytoplankton was counted in Lugol preserved samples with the Utermöhl (1958) method using a Zeiss inverted microscope. Most larger species were identified to the species level, but many of the smaller flagellates had to be aggregated because of identification problems.

Results
Species composition
In Table 1 all dominant diatoms (occurring at least in one month between 1980 and 1990 in numbers exceeding 100 per ml) and *Phaeocystis* sp. have been enumerated. Species dominance and composition varies markedly from year to year. Only *Phaeocystis*, *Thalassiosira* sp., and *Skeletonema costatum* occurred in numbers >100 ml\(^{-1}\) in all years, albeit with marked differences in the number of months per year.

From Table 1 it is possible to list a Marsdiep phytoplankton top-ten. Below I give (in parentheses) the number of months the species was found (at least once) in numbers >100 ml\(^{-1}\). *Phaeocystis* (81, most probably *P. globosa*, see Cadée, 1991) is numerically the most important plankton species, its period of occurrence in numbers >100 cells ml\(^{-1}\) increased from 4–6 months in the early 1980s to 10–11 months in the late 1980s. The colonial *Chaeotoceros socialis* (51) and *Skeletonema costatum* (49) follow in importance. *Thalassiosira* sp. (25), *Plagiogramma brockmanni* (24), *Asterionella glacialis* (24), and *Rhiacosolenia delicatula* (24) are numbers 4 to 7; *Nitzschia seriata* (17) is number 8. *Melosira granulata* (16) number 9, is a freshwater species sluiced into the Wadden Sea from the Lake IJssel, particularly in winter and early spring. *Melosira sulcata* (10) and *Leptocylindrus minimus* (10) share 10th place. The latter species rapidly increases: it occurred for prolonged periods in numbers >100 ml\(^{-1}\) only in 1989 and 1990 and particularly in summer and autumn (Table 1).

Seasonal variation of Marsdiep phytoplankton
The seasonal variation for 1989 is given here as an example (Fig. 2). A diatom spring peak occurred early in April, followed by a *Phaeocystis* peak at the end of April. This is the usual sequence, the difference in time of the two peaks being on average two to three weeks (Cadée, 1990b; Cadée and Hegeman, 1991). The explanation for this peak sequence is that diatoms first deplete Si, leaving P and N in considerable amounts for algae not using Si (Bennekom et al., 1975). The large second peak of diatoms in late summer, mainly consisting of the small *Leptocylindrus minimus*, was not observed in earlier years, but in 1990 it was observed again. Other non-diatom plankton reached highest numbers after the *Phaeocystis* peak. The yearly occurring peak in chlorophyll a coincides with the *Phaeocystis* spring peak; the diatom peaks in spring and late summer cause less marked chlorophyll a peaks.

Year-to-year changes in duration of blooming periods
Blooming periods are defined here as periods with >1000 cells ml\(^{-1}\). The duration of these periods can easily be read from annual curves giving variation in cell numbers over the year. Figure 2 gives an example of such a curve for 1989; curves for earlier years were published in Cadée (1990b). To compare the different years, the length of this blooming period is in my experience the best parameter, better than, for instance, average or maximum cell numbers, values which are severely influenced by missing or sampling the peak values. For the period 1980 to 1990 it is difficult to discern trends, but if we include older data (Fig. 3) it appears that blooming periods of flagellates and *Phaeocystis* increased since the early 1970s. Diatom blooming periods varied considerably, increasing from short dura-
Table 1. Dominant phytoplankton algae (diatoms and Phaeocystis) for the period 1980-1990 occurring at least once in densities >100 per ml in the months indicated as numbers. Asterionella glacialis is synonym for A. japonica; Chaetoceros socialis includes C. radians and probably some other small Chaetoceros sp.; Chaetoceros sp. includes all larger species.

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tion in the early 1970s to long blooming periods in the mid-1980s, but in the late 1980s they decreased again to a length similar to that in the late 1960s (Fig. 3a).

Year-to-year changes in chlorophyll $a$

Annual average chlorophyll $a$ (Fig. 4) showed variations in the period 1980–1990, and again, adding older data, we can discern an increase in the late 1970s up to the mid-1980s comparable to the increase in the duration of blooming periods of non-diatoms. After the mid-1980s the average chlorophyll $a$ content drops again, but remains above the values for the early 1970s.
Figure 2. Seasonal phytoplankton cycle at the Marsdiep sampling station in 1989. A = diatoms, B = *Phaeocystis*, C = other non-diatoms (note differences in vertical scale), D = chlorophyll $a$.

Figure 3. Length of "algal blooming periods" (days with cell numbers exceeding 1000 cells·ml$^{-1}$) in the Marsdiep for the different years. A = diatoms, B = all non-diatoms, C = non-diatoms minus *Phaeocystis*, and D = only *Phaeocystis* and including historical data of Cleve (1898–1900).
Figure 4. Year-to-year variation in annual phytoplankton biomass in the Marsdiep measured as annual average chlorophyll a.

Discussion

Eutrophication

Changes observed in phytoplankton: increase up to the mid-1980s in blooming periods, in biomass (chlorophyll a) and in primary production (Cadée, 1986b, 1992), have been attributed to eutrophication (Cadée, 1986b; Beukema and Cadée, 1988; de Jonge, 1990). The higher inputs of nutrients from the rivers, particularly the Rhine, are held responsible. However, increase in nutrient concentrations in the Rhine started much earlier, around 1950 (van Bennekom et al., 1975; van Bennekom and Salomons, 1980). Part of the Rhine input enters the Wadden Sea via Lake IJssel, and van der Veer et al. (1989) have argued that the late response of Marsdiep phytoplankton to eutrophication (only in the 1970s, whereas rapid increase in nutrients from the Rhine as measured near Lobith started 20 years earlier and stabilized in the 1980s) was due to storage of nutrients (P) in the bottom sediments of Lake IJssel. When these sediments were saturated they became a source themselves for nutrients, which resulted in higher nutrient loadings from Lake IJssel to the Wadden Sea in the late 1970s (Raaphorst and van der Veer, 1990). Rieger et al. (1992a,b) point to the role of the building of the Houtribdam in 1975, disconnecting the southern part of Lake IJssel where muds with high binding capacity for P occurred and thus leading to increased nutrient discharges to the Wadden Sea after 1975. Van der Veer (1990) hypothesized that the introduction of an extensive mussel culture in the western Wadden Sea in 1950–1960 (whereas since 1960 the area used for mussel culture remained constant) might have counteracted earlier effects of eutrophication on phytoplankton. Cadée and Hegeman (1974) actually observed lowering of phytoplankton biomass and primary production in summer above a mussel culture area in the western Wadden Sea. In conclusion, a number of causes might explain a retarded influence of eutrophication on the Wadden Sea/Marsdiep area.

The eutrophication by (large) rivers of the ocean in front of the rivermouth leading to areas in the plume of higher phytoplankton biomass and primary production has been found repeatedly (e.g. Hobson, 1966; Cadée, 1975, 1978; Revelante and Gilmartin, 1976; Sklar and Turner, 1981; Ning et al., 1988; Lohrenz et al., 1990). Szekielda (1982, 1983) and Szekielda and McGinnis (1991) note that the area of eutrophication is of vital importance for the coastal ecosystem and may play a more important role than thought in the past; its presence and spatial variability can be studied best by using satellite observations. This eutrophication may lead to large algal blooms and subsequent anoxia with mass mortalities of benthos and fish if river inputs of nutrients are increased too much due to the activity of men. The Roumanian coast along the Black Sea influenced by the Danube (Gomoiu, 1983, 1987) and the northern Adriatic influenced by the River Po (Marchetti et al., 1988, 1989) are good examples.

The Rhine influence

Reid et al. (1983, 1990) stress the importance of river influence on coastal North Sea phytoplankton. Increased river discharges add extra nutrients and may stabilize the water column, thus reducing vertical mixing and helping phytoplankton to stay in the euphotic zone. Gieskes and Schaub (1990) and Schaub and Gieskes (1991) observed a correlation between Rhine discharge in spring and summer and phytoplankton biomass in the Dutch coastal zone in the same periods. Nutrient loads (kg/sec) in the Rhine entering The Netherlands have stabilized in the 1980s (nitrogen), and even a decrease in the discharge of total dissolved P occurred due to measures like better wastewater treatment in Germany, which might influence fish production negatively (Bodeke and Hagel, 1991).

Increased water discharge gives lower total P concentrations (mg l⁻¹) at Lobith (Fig. 5a, r = 0.85, p < 0.0005; see also Gieskes and Schaub, 1990: fig. 6) due to dilution, and there is no significant increase in P discharge (kg sec⁻¹) with increased water discharge (Fig. 5b, r = −0.07). Gieskes and Schaub (1990) argue that increase in rainfall enhances nutrient leaching from the nutrient-saturated soils in The Netherlands and higher current velocities during high river discharge enhance exchange of nutrients from interstitial water in the Dutch part of the river Rhine. As a result, more nutrients should be added to the Dutch part of the catchment area of the Rhine during high water discharges and consequently more nutrients are carried to the North Sea. Nitrogen data not used by Gieskes and
Figure 5. Comparison of average annual Rhine discharge at Lobith (1970 to 1988, data RWS) with: A - average annual total P concentration (mg·l⁻¹), B - average annual total P discharge (kg·s⁻¹), C - average annual total N concentration (mg·l⁻¹), D - average annual total N discharge (kg·s⁻¹).
Schaub illustrate this process also for the German part of the catchment area of the Rhine: there is some dilution of total-N with higher river discharge (Fig. 5c), but there is a highly significant positive correlation between N-load (kg sec⁻¹) and Rhine discharge (Fig. 5d). In order to estimate the total input of nutrients by the Rhine we have to add to those discharged at Lobith those contributed in The Netherlands. Certainly, years with high rainfall (and thus high Rhine discharge) will also be years with high N-leaching from Dutch overfertilized agricultural soils. However, because of the spreading of Rhine water over different tributaries in The Netherlands this is more difficult to evaluate.

In order to test the hypothesis of Gieskes and Schaub (1990) of a causal positive correlation between Rhine discharge and Dutch coastal phytoplankton, which was based on a data set limited to the period 1977–1982, I compared quarterly and annual chlorophyll a values for the Marsdiep with Rhine discharge data for the period 1974–1990. A good correlation was found between annual discharge of the Rhine (Lobith) and the annual average chlorophyll a content of the Marsdiep (Figure 6, \( r = 0.61, p = 0.01 \)). The relatively low chlorophyll a data for the early 1970s can be explained by low Rhine discharge values. The highest annual chlorophyll a value (1981) corresponds with the highest Rhine discharge value.

Average values for Rhine discharge and Marsdiep chlorophyll a for the separate quarters of the year did not show a correlation. Gieskes and Schaub (1990) found positive correlations during the 2nd and 3rd quarters, i.e. during the growing season of phyto-

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Figure 6. Comparison of annual average chlorophyll a of the Marsdiep and Rhine runoff at Lobith. A = year-to-year variation, B = correlation.
plankton. This indicates a direct influence of Rhine discharge of the coastal area near the Rhine mouth, also observed in 1977 by Reid et al. (1983). The Marsdiep, farther away from the Rhine mouth, is influenced less directly. Water transport from the Rhine mouth to the Marsdiep takes one month on average (van Bennekom et al., 1974: fig. 5). Moreover, the Marsdiep area is also influenced by Rhine discharges via the river IJssel and Lake IJssel; this is a longer way with a flushing time of Lake IJssel in the order of 0.5 year (van Bennekom et al., 1974: fig. 5). Van der Veer et al. (1989), de Jonge (1990), and Riegman et al. (1991, 1992) deal in more detail with the importance of Lake IJssel hydrography and dike construction on the amounts and ratios of nutrients introduced into the western Wadden Sea and influencing also the Marsdiep area.

Conclusion

Marsdiep data corroborate observations by Gieskes and Schaub (1990); high Rhine discharges are correlated with higher phytoplankton biomass in the Dutch coastal zone. An increase in discharge leads to an increase in nutrient discharge, particularly of N. The increased nutrient inputs leading to these higher phytoplankton biomasses must partly originate from the Dutch part of the catchment area of the Rhine. For the Marsdiep area they will arrive via Lake IJssel, too.

Acknowledgments

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