

## Annual variability in the seasonal cycles of chlorophyll, nutrients and zooplankton on the North-West European continental shelf

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### ABSTRACT

Seasonal cycles of salinity, nutrients, chlorophyll and zooplankton at 8 locations on the West-European shelf were analysed with respect to their timing and magnitude in the period 1980-1984. A late spring bloom with low chlorophyll values ( $2-4 \text{ mg.m}^{-3}$ ) is observed in the Irish Sea, off the Scottish east coast and the Channel entrance. An early spring bloom and relatively high chlorophyll values ( $7-12 \text{ mg.m}^{-3}$ ) are found in the southern Bight and the Skagerrak, whereas a late spring bloom with high chlorophyll concentrations ( $24 \text{ mg.m}^{-3}$ ) is found along the Dutch and Belgian coast. In contrast to the other regions, the peak of the phytoplankton cycle in the German Bight (Helgoland) occurs in the summer period instead of the spring period. The peak in the yearly abundance of copepods shifts from May-June in the south to July-August in the north of the shelf. In the Irish Sea and the Channel entrance two seasonal copepods peaks are observed. The January nitrate values in Irish Sea, the southern Bight and the Skagerrak are about 20 % higher than those in the Atlantic input signal in the Channel entrance and east off Scotland. The January DIP values in these regions are comparable to those of the input signal, but the Irish Sea forms an exception here the level is increased by 10-20%. If compared with the Atlantic input signal the January values for nitrate and DIP at the Dutch and Belgium coast are about 10 and 4, and in the German Bight

(Helgoland) 4 and 3 times higher, respectively. At most sites changes in the seasonal cycles of chlorophyll coincide with changes in nutrient concentrations, whereas the maximum level of the seasonal signal is related to the nutrient levels.

## 1 INTRODUCTION

Understanding long-term trends across different marine trophic levels is highly relevant for distinguishing between naturally and man induced changes in the marine environment (Aebischer *et al.*, 1990). Enhanced levels of phytoplankton abundance and primary production observed in north west European coastal seas have been attributed to enhanced nutrient inputs from the densely populated continent during past decades (*e.g.* Lancelot *et al.*, 1987, Gieskes & Schaub, 1990, Radach *et al.*, 1990, Rosenberg *et al.*, 1990, Cadée & Hegeman, 1993, Hickel *et al.*, 1993, Richardson & Heilmann, 1995). Johannessen & Dahl (1996) analysed oxygen concentrations in the coastal Skagerrak between 1927 and 1993 and observed a decline starting from the early sixties (see, however, also the comment of Gray & Abdullah, 1996). This decline is suggested to be caused by eutrophication and resulting structural changes in the pelagic community. Indeed, between the early sixties and the end of the seventies winter nitrate and phosphate concentrations have increased in the coastal areas of the Southern Bight of the North Sea, and this increase could be directly related to discharges from the river Rhine (Van Bennekom & Wetsteijn, 1990). In the same study these authors showed that the increase of inorganic nutrients in the Strait of Dover was due to inputs from the river Seine and the English coast, and similar increases in nutrient concentrations due to enhanced inputs were observed in the Kattegat area (Andersson & Rydberg, 1988). Although a causal relationship between enhanced dissolved nutrient concentrations observed during the winter months and higher annual primary production is appealing, it is not always as straightforward as it seems at first sight. Most stations for which long-term series on phytoplankton exist are at fixed locations (*e.g.* Marsdiep: Cadée & Hegeman, 1993, Helgoland Roads: Hickel *et al.*, 1993) and, as such, subject to variations in salinity due to changing freshwater runoff and open sea current patterns. Thus, variations observed may at least partly be due to changes in the relative contribution of river and ocean water to the local water masses. Precipitation leading to runoff as well as marine current patterns are strongly influenced by regional and global changes in weather and climate (Otto *et al.*, 1990, Turrell *et al.*, 1992, Hurrell, 1995). Consequently, effects related to eutrophication and climatic change may interfere in determining long-term signals of phytoplankton and other biological variables.

The concept of increased nutrient inputs yielding increased phytoplankton abundance and productivity ignores the role of other controls. Light availability puts important limits to phytoplankton growth particularly in the turbid coastal zones. Also, top-down control by zooplankton can constrain phytoplankton concentrations within certain levels (*e.g.* Reid *et al.*, 1990). It has been hypothesized that the strength of this control is related to eutrophication through feed-back mechanisms resulting in changed species composition of both the phytoplankton and the zooplankton communities (Riegman *et al.*, 1993). Even more complicated relationships may be expected when the potential role of sedimentation, cell lysis and viruses in structuring the pelagic food web and its dynamics are taken into account (Brussaard *et al.*, 1995, 1996). Thus, the effects of increased nutrient inputs on long-term phytoplankton dynamics may be obscured by the complexity of the trophic relationships and interactions involved.

Most studies on long-term trends are based on annual means, thus filtering out seasonal signals (*e.g.*

Dickson *et al.*, 1988, Aebischer *et al.*, 1990, Cadée & Hegeman, 1993, Richardson & Heilmann, 1995, Johannessen & Dahl, 1996). Nevertheless, the seasonal cycles of phytoplankton and zooplankton, forced by the availability of light and nutrients, represent probably one of the most obvious properties of the pelagic system. This cycle is characterized by a relatively high phytoplankton biomass peak during spring, a reduction during summer because of nutrient depletion and grazing by herbivores followed by a second bloom during the late summer when regenerated nutrients become available again (Mommaerts, 1980). However, local differences caused for example by the input of nutrients in coastal areas or by hydrodynamic circumstances may alter this cycle. The seasonal abundance of zooplankton is determined by the availability of phytoplankton and the onset of phytoplankton growth in combination with the rise of the seawater temperature during spring triggers zooplankton to reproduce. However, due to the small overwintering zooplankton stocks and temperature related long generation times of zooplankton, the phytoplankton spring bloom is largely under-exploited (Fransz & Gieskes, 1984). In the summer period the zooplankton is food limited because of the nutrient limited relative low biomass of phytoplankton. The zooplankton decline in autumn coincides with the phytoplankton decline.

Radach *et al.* (1990) observed increased summer blooms of mainly flagellates and a shifting and shortening of the nutrient depletion phase during the annual cycle in the German Bight, that seemed mainly due to anthropogenic eutrophication and not by large-scale climate change. Similarly, Greve (1991) shows a clear increase of small copepod density at Helgoland from 1974 to 1989 which is possibly related to the higher winter stocks which is supported by the increased abundance of flagellates during the winter months described by Radach *et al.* (1990).

Likewise, Cadée & Hegeman (1986a,b) observed increased phytoplankton cell numbers during the spring peak and in summer between the early seventies and the mid-eighties, but also a lengthening of the duration of the spring peak and the period that the flagellate *Phaeocystis pouchetii* occurred in the plankton. In the same period the average abundance of the successive developmental stages of the copepod *Temora longicornis* during spring increased by a factor between four and eight while at the same time the seasonal peak of this species extended into the summer months (Fransz *et al.*, 1992). Understanding these changes and their causes is important to predict future changes in the structure and functioning of the pelagic system.

In the framework of the North West European Shelf Programme (NOWESP, Van Leussen *et al.*, 1996) existing biological, physical and chemical data are compiled with the final goal to study inter-annual variability, spatial variability and long term trends. The aim of this study is to characterise the seasonal cycles at different locations on the shelf in terms of the quantity and timing of plankton development and their relation with nutrients and local hydrodynamic features. To this end, eight areas were distinguished by both their differences in the magnitude of Atlantic and land-born influences and their position on the shelf. The seasonal cycles in these areas were analysed with respect to the possible effects of natural and anthropogenic nutrient levels.

## 2 MATERIAL AND METHODS

The analyses on seasonal cycles include chlorophyll, zooplankton and nutrient data (dissolved inorganic phosphate [DIP], nitrate and silicate) from seven areas on the shelf. These areas are the Irish Sea (5°00' -4

°.00'W; 53°25'-54°10'N), the entrance of the English Channel (5°00'-3°00'W; 49°00'-50°10'N), an area off the east coast of Scotland (2°00'-1°00' E; 56°00'-58°00'N), the southern Bight of the North Sea (3°18'-3°48'E; 52°22'-52°42' N), the south and north part of the Skagerrak, the combined data of two sites in the coastal zone (first 10 km) of Belgium and the Netherlands (approximately 2°25'-3°27' E; 51°00'-51°34'N and 4°08'-4°28'E; 52°02'-52°22'N; see Visser *et al.* this volume, for the exact location of sub-sites along the Belgium coast) and the German Bight (6°40'-8°00'E; 54°00'-54°45'N) as most of the data in this area originate from Helgoland Roads this side will be referred to as Helgoland). Only data from the upper 10 metres of the water column were taken into account as averaged monthly means. Missing values were interpolated by means of a log-linear regression method (McCullagh & Nelder, 1989). To compare the seasonal cycles at different sites and to detect shifts in the timing of the seasonal cycles, a reference period (1980-1984) was chosen. In this period data of the different parameters appear to overlap in almost all the areas studied. Because of insufficient data coverage this period could not be used for the area east off Scotland. Here the seasonal cycles are composed of all the data available between 1960 and 1990. In the data series from Helgoland no chlorophyll data is available in the reference period. Instead, we have employed data on phytoplankton carbon (PC; based on phytoplankton counts and subsequent conversion to carbon) to indicate the seasonal cycle of phytoplankton in this area.

The zooplankton analyses are based on 6 small sized copepod species or genera from the CPR (continuous plankton recorder) surveys. *Acartia* (almost always *Acartia clausii*), *Centropages typicus*, *Centropages hamatus*, *Temora longicornis*, *Para-pseudocalanus* group (contains *Paracalanus* and *Pseudocalanus* species) and *Corycaeus* (almost always *Corycaeus anglicus*). Together these species account for most of the abundance and biomass of zooplankton. For the southern Bight of the North Sea and the Belgian and Dutch coastal areas, no zooplankton data was included in the NOWESP data base. The time series of zooplankton show little overlap in time between the six areas studied, therefore the seasonal cycles are based on the periods indicated in Fig 1. The data used in the analysis are stored in the NOWESP research data base in Hamburg (Radach *et al.*, 1998).

The effects of trends in the characteristics of the annual cycle were indicated by the number of months nutrient concentrations drop below, and chlorophyll concentrations rise above, designated values. These values were determined by the concentrations in the seasonal cycles in the reference period. The data were not corrected for salinity. Due to insufficient data coverage no such analyses could be made in the area east off Scotland and with respect to chlorophyll in the entrance of the English Channel.

### 3 RESULTS AND DISCUSSION

The seasonal salinity values over the reference period 1980-1984 (Figure 1) show that, as may be expected, the Channel entrance and the area east off Scotland are not influenced by fresh water. These sites are located near the entrance of the residual current and hence the water is almost purely of Atlantic origin (Lee, 1980). In the Irish Sea and the Southern Bight of the North Sea some effect of land run-off is indicated by the slightly reduced mean salinities of 34 and 34.5 psu, respectively. Strictly speaking, however these locations are strongly affected by oceanic input. This in contrast to the situation at Helgoland and in the south part of the Skagerrak where the impact of freshwater inflow is manifested by reduced salinities (32 psu). In particular during the summer period when these areas are stratified

(Goedecke, 1968, Krause *et al.*, 1986, Kiørboe *et al.*, 1990). The salinity in the Belgian and Dutch coastal waters is relatively low. Here fresh water from the Seine, Scheldt and Rhine enters the North Sea and causes salinities of around 28 psu. The low salinity in the northern part of the Skagerrak is not directly related to the outflow of rivers. The greater part of the outflow of the Baltic Sea enters the North Sea via the Kattegat and off the Swedish coast into the Skagerrak. Due to this low saline Baltic outflow, layered on top of water from oceanic origin, the Skagerrak is stratified all year round (Richardson & Christoffersen, 1991).

The averaged seasonal characteristics of nutrients over the period 1980-1984 at eight areas on the shelf are shown in Figure 2. The January nutrient concentrations clearly show the differentiation between areas affected by river discharge and other areas. The January concentrations at the Belgian and Dutch coast are approximately a factor of eight (nitrate) to four (DIP) higher than those observed in offshore areas. Due to its location Helgoland is somewhat intermediate. The January concentrations of nitrate and, to a lesser extent, of DIP are somewhat higher than those in offshore areas, but the January concentration of silicate (about  $7 \mu\text{mol}\cdot\text{dm}^{-3}$ ) is hardly affected. One should keep in mind however, that the hydrography in the German Bight is complicated and variations in the outflow patterns of the river Elbe and related to this, fluctuations of relatively fresh, Elbe induced, water masses at Helgoland have a significant effect on measured values of nutrients (Berg & Radach, 1985, Körner & Weichart, 1992). These fluctuations might be the reason for the low silicate concentration in the reference period, as this time span greatly includes a period of low silicate concentrations (Figure 3).

In the offshore areas, the Southern Bight of the North Sea shows the highest January and summer nitrate concentrations, only after July the nitrate concentrations drop to lower values. This can be explained by the exchange with sediments and mineralization of organic material in this relatively shallow area. On the other hand, the rapid decrease of silicate in spring in the Southern Bight suggests that the spring bloom is silicate limited, leaving nitrate left.

Of interest are the relatively high January concentrations for DIP and silicate in the Irish Sea. These values drop during spring and summer but, compared to the other offshore areas they remain relatively high. This, in relation to the high salinity values in the Irish Sea might indicate a significant riverine input of these nutrients (see also Slinn, 1974). The Channel entrance and the area off the Scottish east coast show comparable January values of  $\sim 0.7 \mu\text{mol}$  for DIP,  $\sim 7 \mu\text{mol}\cdot\text{dm}^{-3}$  for nitrate and  $\sim 5 \mu\text{mol}\cdot\text{dm}^{-3}$  for silicate. These values are in line with the natural background values of water deriving from the Atlantic Ocean (Horwood, 1982).

On the basis of timing and magnitude of the seasonal chlorophyll cycles the regions in this study can roughly be divided into three groups. A late spring bloom (April and May) with low chlorophyll values ( $2\text{--}4 \text{mg}\cdot\text{m}^{-3}$ ) is observed in the Irish Sea, the area off the Scottish east coast and the Channel entrance. The second group constitute the Southern Bight of the North Sea and the Skagerrak data. These locations are characterized by an early (March -April) spring bloom with relatively high chlorophyll values ( $7\text{--}12 \text{mg}\cdot\text{m}^{-3}$ ) and, finally the third group located in the Dutch and Belgium coastal zone where the spring bloom is late (May) with high chlorophyll concentrations ( $20\text{--}25 \text{mg}\cdot\text{m}^{-3}$ ). The phytoplankton carbon (PC) data from Helgoland cannot directly be used in this classification, but from chlorophyll measurements in the 1960s and early 1970s collected at this location, it can be concluded that the average concentration of chlorophyll at the peak of the spring bloom (between April and May) was about  $4 \text{mg}\cdot\text{m}^{-3}$  (data not shown). Richardson & Christoffersen (1992) reported highest values of  $10 \text{mg}\cdot\text{m}^{-3}$  in the offshore areas of the German

bight. This would mean that on the basis of the chlorophyll cycle Helgoland is again intermediate. However, one should be aware that after the 1970s significant changes in nutrient concentrations and phytoplankton dynamics have occurred at this station (see Visser *et al.* this volume, Radach & Bohle-Carbonell, 1990). The areas clustered in the first group are characterised by deep water and, at least in spring, not stratified, so that the low average light intensities over the water column probably causes the late onset of the phytoplankton spring bloom. Another characteristic of the areas in group 1 are the N/P ratio's which remain under 10 during the growing season, indicating a relative shortness of nitrogen. This in combination with the light regime may be the main reason why, despite the potential for higher values as shown by the January nutrient concentrations, only a modest phytoplankton spring bloom occurs. In group 3, the Dutch and Belgian coast, the development of the phytoplankton spring bloom is delayed because of reduced light availability, but this time caused by high concentrations of suspended matter, especially during winter and early spring (van Raaphorst *et al.*). The early spring bloom in the Skagerrak is the result of the permanent haline stratification which keeps the phytoplankton at a shallow depth with on average high light levels (Rick, 1990). The same can be postulated for the relatively shallow waters in the central southern North Sea where light availability triggers a relatively early spring bloom. In the Irish Sea, the Southern Bight and the Dutch and Belgian coastal area the chlorophyll concentrations remain in comparison with the spring bloom values, relatively high during summer. At the entrance of the Channel, off the east coast of Scotland and in the Skagerrak, chlorophyll concentrations drop to almost zero during the summer followed by an autumn bloom in September and October. The phytoplankton carbon data from Helgoland constitute an exception to the pattern of spring bloom values dominating summer values. Here the values in July and August are an order of magnitude higher than those observed during the spring bloom. The underlying mechanism for this unusual seasonal cycle is not clearly understood but there are a number of possibilities. Possibly there is a relation with the high N/P values found during the spring bloom (Figure 2), which may prevent the further development of diatoms and trigger the growth of flagellates during summer. Alternatively, the high phytoplankton values during the summer might also be the result of stratification or driven by advective transport of nutrients during summer. Another possibility is the effect of grazing. As shown in Figure 2, copepods develop early and in large numbers in the German Bight, but after June the number is reduced to relatively low levels. Consequently, the grazing pressure of copepods on the summer phytoplankton is reduced.

With respect to the seasonal cycle of zooplankton, it appears that there is a shift from the south to the north in the period with the highest seasonal abundance of copepods. The highest seasonal numbers are observed at Helgoland in June, in the Skagerrak in July and off the Scottish east coast in August. At two stations copepod abundance shows two seasonal peaks in the period studied (May and September in the Irish Sea and June and September in the Channel entrance). Besides the observed differences in timing and seasonal behaviour of copepods there is also a spatial shift in species composition. Copepods in the Skagerrak are dominated by the *Para-pseudocalanus* group, at Helgoland by the *Acartia* and the *Para-pseudocalanus* group, the Channel entrance and the area east off Scotland by *Acartia* and in the Irish Sea by *Temora* and the *Para-pseudocalanus* group. One should keep in mind however, that the CPR surveys are taken at about 10 metres depth only. In the deeper areas of the shelf almost all copepods are found below 10 metres during winter and spring and hence not covered by CPR data.

In Figure 3 possible trends in the characteristics of seasonal cycles are indicated by the number of months nutrient concentrations drop below a designated value and chlorophyll concentration rises above a



designated value during the summer period. The time series show that during the whole year the N/P ratio in the Irish Sea and the Channel entrance remains under 16 (except for sometimes a few months in the Channel entrance). This indicates a relative shortness of nitrogen. Note, that ammonium and nitrite are not taken into the account here. The biological role of rapid recycling of ammonium may be important (Riegman *et al.*, 1990). Ammonium data, however, was not sufficiently available. In the other areas the period of N/P ratios below 16, approximately spans the 6-8 months following the phytoplankton spring bloom. In the Skagerrak and at Helgoland changes in the length of periods with ratios below 16 show an opposite trend. In the Skagerrak there is a shift from about 6 months per year in the early 1980s to 10-12 months in the early 1990s, while at Helgoland there is a sharp decrease from about 6 months per year before 1980 to about 1 month at the end of the 1980s, indicating an increase of the periods with a relative shortness of DIP. This is caused by a reduction of the DIP concentration in the 1980s and, at the same time, an increase of the nitrate concentration (see Visser *et al.*, this volume).

In the Irish Sea there is a discrete reduction of the yearly period with a DIP concentration below  $0.2 \mu\text{mol}\cdot\text{dm}^{-3}$ . Before the end of the 1960s this period spans 3-4 months per year, after 1967 the period is reduced to 0-2 months per year. Only at the end of the time series (1994) there is an indication of a return to the situation in the 1960s. A more or less similar behaviour shows up from the annual periods of silicate concentrations below  $2 \mu\text{mol}\cdot\text{dm}^{-3}$ , a reduction at the end of the 1960s which persists in the 1970s and a return to the situation of the 1960s in the early 1990s. Changes in the annual periods with nitrate concentration below  $2 \mu\text{mol}\cdot\text{dm}^{-3}$  appear to be more gradual, they decrease from about 5-6 months in the 1960s to about three months in the 1990s. Notwithstanding the low N/P ratio's in the Irish Sea, it has a shorter period of low nitrate concentrations than observed in other regions of the shelf (Figure 3).

In the entrance of the Channel no general trend is visible in the length of periods with low nutrient concentrations. In the southern Bight the periods of DIP concentrations below  $0.2 \mu\text{mol}\cdot\text{dm}^{-3}$  reduced from about 4 months to 1-2 months in the early 1980s, but after 1987 the length of the periods are comparable again to those in observed the 1970s. This shift coincides with a temporary increase of 20% in the DIP concentration in the first part of the 1980s (Visser *et al.*; this volume). The DIP concentrations in the Belgian and Dutch coastal zone reach their highest values in the same period but, the idea of transport from the near coastal zone to the more offshore areas is falsified by the fact that less than 10% of the salinity variance in this area can be explained by variance in the coastal waters (Laane *et al.*, 1996, Visser *et al.*, this volume). Moreover, no significant signal resulted from cross-correlations between the DIP data sets (Visser *et al.*, this volume). A comparable picture, but less pronounced and 3 to 5 years later, can be seen in the change of the periods of nitrate concentrations below  $2 \mu\text{mol}\cdot\text{dm}^{-3}$  in the Southern Bight.

In both the northern as southern part of the Skagerrak the period with DIP concentrations below  $0.2 \mu\text{mol}\cdot\text{dm}^{-3}$  remains at approximately 6 months per year. With respect to nitrate there is a gradual shift from about 5 months per year in the early 1980s to 7 months in the 1990s. Underlining the earlier mentioned change in N/P ratio's. An exceptional year is 1987. During this year the nitrate concentrations in the northern part of the Skagerrak remained under  $2 \mu\text{mol}\cdot\text{dm}^{-3}$ . The seasonal chlorophyll profile in this year however, was not unusual (Danielsen, pers. comm.).

Along the Belgian and Dutch coast and at Helgoland changes in the length of the periods with low nutrient concentrations are more pronounced. The number of months with nitrate concentrations below  $20 \mu\text{mol}\cdot\text{dm}^{-3}$  in the Belgian and Dutch coastal zone is almost zero during the last part of the 1970s and the early part of the 1980s. From 1987 onwards the period gradually increased to about 4 months in the 1990s.

In the period before 1980 the average period of nitrate concentration below  $20 \mu\text{mol.dm}^{-3}$  at Helgoland was about 11 months. This period drops quite rapidly to about 6 months per year in the 1980s. After 1987 a gradual upward trend seems to follow the trend observed along the Belgian and Dutch coast. Due to a lack of data no complete time series on DIP along the Belgian and Dutch coast is available, but sporadic data from the 1960s show a decrease of the period with DIP concentrations below  $1 \mu\text{mol.dm}^{-3}$  from about 9 months in the early 1960s to 3 months in the late 1960s and to zero months in the late 1970s and early 1980s. From 1982 onwards there is a gradual increase to about 5 months in the early 1990s. A similar trend is observed at Helgoland, a reduction from about 11 months in the middle 1960s to about 5 months in the early 1980s. After the strong increase in 1987 the length of the periods with relatively low DIP concentrations again are comparable to those observed in the 1960s. A comparison between the Dutch and Belgian coast and Helgoland for periods with relatively low silicate concentrations is interesting. In the middle of the 1970s the length of periods with silicate concentrations below  $5 \mu\text{mol. dm}^{-3}$  seem to be almost similar, about 6 months. Later the two time series diverge from each other. There is a small decrease of the length of the period at the Belgian and Dutch coast and, particularly in the early 1980s, a strong increase of the periods (to 12 months in 1982 and 1985) at Helgoland. After 1985 the situation is reversed, at the Belgium and Dutch coast the periods remain almost constant at 3-5 months but, at Helgoland the length of the periods decrease to almost zero in the late 1980s. It is tempting to relate the observed changes in the length of relatively low concentrations at Helgoland for the different nutrients. The increase in the length of periods with low silicate concentrations in the early 1980 coincides with a reduction of the length of the periods with low nitrate concentration. The reduction of the period of low silicate concentrations to almost zero in 1987 coincides with an elongation of the period with low DIP concentration. The possible relation of these changes in the availability and summer depletion of nutrients and their ratio's to shifts in phytoplankton composition is not clear. From the 1960s onwards the total phytoplankton biomass at Helgoland increased by a factor of 3-4 (Hickel *et al.*, 1992). In 1960s and 1970s predominantly caused by an increase in diatoms abundance and, around 1980 by a pronounced increase of flagellate biomass (Berg & Radach, 1985). However, these trends are covered with a great extent of inter-annual variability.

Changes in the length of the spring bloom period are compiled in Figure 3. Periods characterized by a noticeable increase of chlorophyll in the Irish Sea (around 1980 and in the early 1990s; see Visser *et al.*, this volume) are also manifested by an increase of the length of periods with relatively high chlorophyll concentrations. This means that both the peak values as well as an increase of the bloom period contributed to the up-going trend. Because of the inter-annual variations in the southern Bight no change in the length of the spring bloom can be concluded.

Notwithstanding the early and short spring bloom in the Skagerrak (Figure 2) the reduction of the average annual chlorophyll concentration in the early 1990s (see Visser *et al.*, this volume) is manifested by a marked shortening of the annual period with chlorophyll concentrations higher than  $3 \text{mg.m}^{-3}$ . Particularly in the southern part of the Skagerrak where this period decreased from 3-4 months in the early 1980s to only one month in the 1990s.

The inter-annual variation in chlorophyll maxima along the Belgian and Dutch coast lies between 10 and  $60 \text{mg.m}^{-3}$  (data not shown). The low values are represented by the years in which no months with concentrations above  $15 \text{mg.m}^{-3}$  occur (Figure 3). However, despite the large variation in the spring bloom maxima the length of the spring bloom is more or less constant. The spring bloom period of three months



as shown by two years in the time series is due to a divergence in the timing of the bloom between the Belgian and Dutch coast which is translated in a longer period of high chlorophyll concentrations in the averaged data sets. The phytoplankton carbon data from Helgoland are displayed as changes in the length of spring bloom and of summer bloom, respectively (Figure 3). The data show no general trend in the length of the summer bloom, but around 1980 the period of phytoplankton carbon concentrations above  $40 \text{ mg.m}^{-3}$  in spring increased by on average one month. Apparently, the length of the spring bloom is more subjected to variation than the length of the summer bloom. The rising trend of the phytoplankton biomass at Helgoland shows two periods of steep increase (Hickel *et al.*, 1993), one at the end of the 1960s (mainly caused by diatoms) and one around 1980 (mainly caused by an increase of flagellates). The latter increase coincides with the observed lengthening of the spring bloom and a reduction of the period with low nitrate concentrations (Figure 3), and suggests a shift from nitrogen limitation in the 1960s and 1970s to enhanced nitrogen availability in the 1980s. Moreover, this idea is also underlined by the rising trend of the N/P ratio from 1980 onwards (Visser *et al.*; this volume) and the reduction (to almost zero) of the number of months with N/P ratios above 16. Apparently, the increased phytoplankton biomass at Helgoland is not only determined by higher maximum values but also by an increase of the length of the spring bloom.

## CONCLUSIONS

Over the North West European shelf eight different locations were analysed on aspects of seasonal changes. With regard to the timing and size of the chlorophyll spring bloom the locations can be subdivided into different groups. One group is formed by the external regions on the shelf (the Channel entrance, the Irish Sea and off the east coast of Scotland), but with respect to the size of the bloom also includes Helgoland. These regions are characterized by a relatively late spring bloom and chlorophyll peak values of about  $2\text{-}4 \text{ mg.m}^{-3}$ . The other group includes the regions in the Southern Bight of the North Sea and the Skagerrak with an early spring bloom and maxima of about  $8\text{-}10 \text{ mg.m}^{-3}$ . The Belgian and Dutch coastal areas are characterized by a relatively late spring bloom and high chlorophyll values. The above mentioned subdivision can (except for the coastal regions) not directly be related to the January nutrients concentrations, indicating that other factors play an important role. The availability of light over the water column is mentioned in this respect, but also nutrient ratios may play a role. For example the low N/P values observed in the external regions of the shelf may prevent a further development of the spring bloom.

Going from the north to the south of the shelf, the difference between the month with the highest chlorophyll concentration and the month with the highest abundance of copepods elongates from 0-1 month to 4 months. In the southern part of the shelf (the Irish Sea and the entrance and of the Channel) a second copepod peak is observed in the autumn.

A distinct decline of the annual number of months with low DIP was observed in the Irish Sea at the end of the 1960's which coincides with an increase of nutrient concentration and chlorophyll. In the southern Bight the seasonal cycles of nutrients and chlorophyll hardly changed during the period studied and in the Dutch and Belgian coastal zone the recent reduction of nutrients is manifested in an elongation of the annual length of relatively low nutrient concentrations. No such change was observed for chlorophyll. This

in contrast to the Skagerrak were the annual period of chlorophyll concentrations above a certain level reduced in connection with nutrient (mainly nitrate) reduction. The large variations in the annual length of periods with a low concentration of nutrients at Helgoland is probably due to the variable hydrodynamic conditions in this area.

### Acknowledgements

This study has been performed in the NOWESP project in the Marine Science and Technology programme (MAST): MAS2-CT93-0067

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Figure 1. Seasonal changes in salinity averaged over the period 1980-1984.

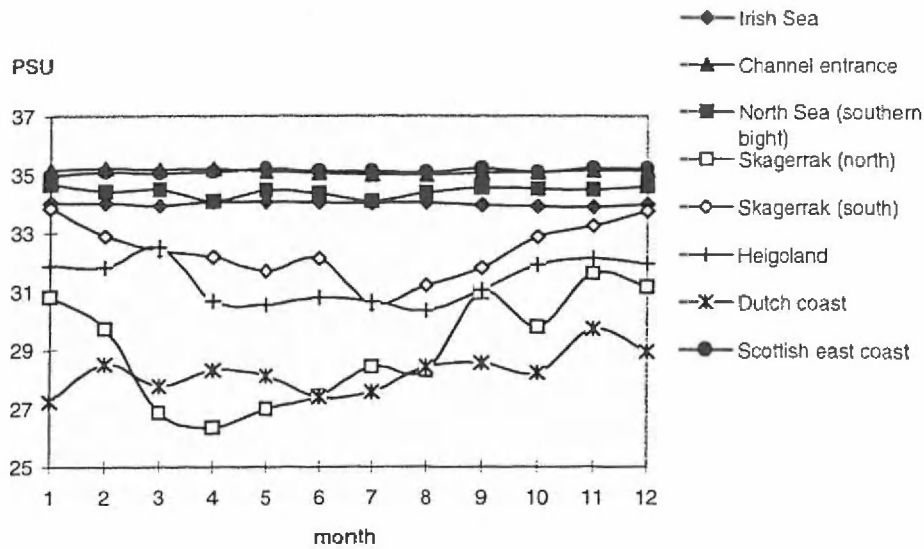


Figure 2. Seasonal cycles of nutrients, chlorophyll (PC Helgoland) and zooplankton in the period 1980-1984 at eight localities on the North-west European shelf. Zooplankton data at Helgoland spans the period 1970-1974 and zooplankton data at the south part of the Skagerrak spans the period 1965-1969.

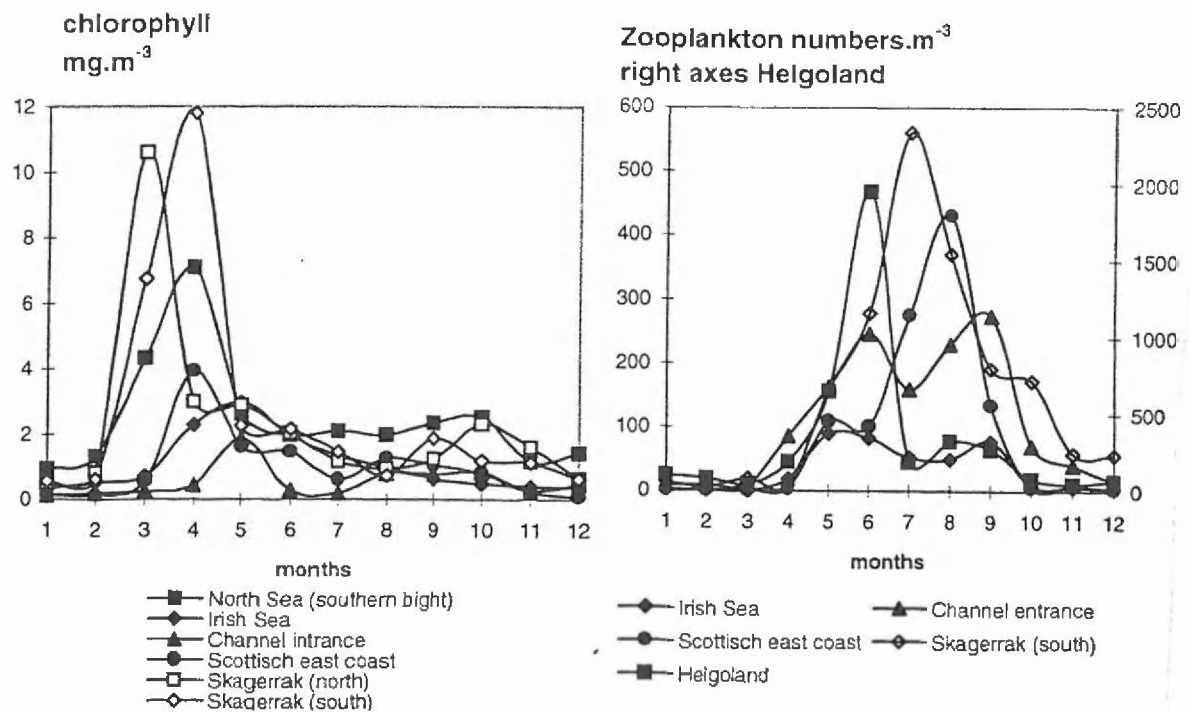


Figure 2. Cont'd

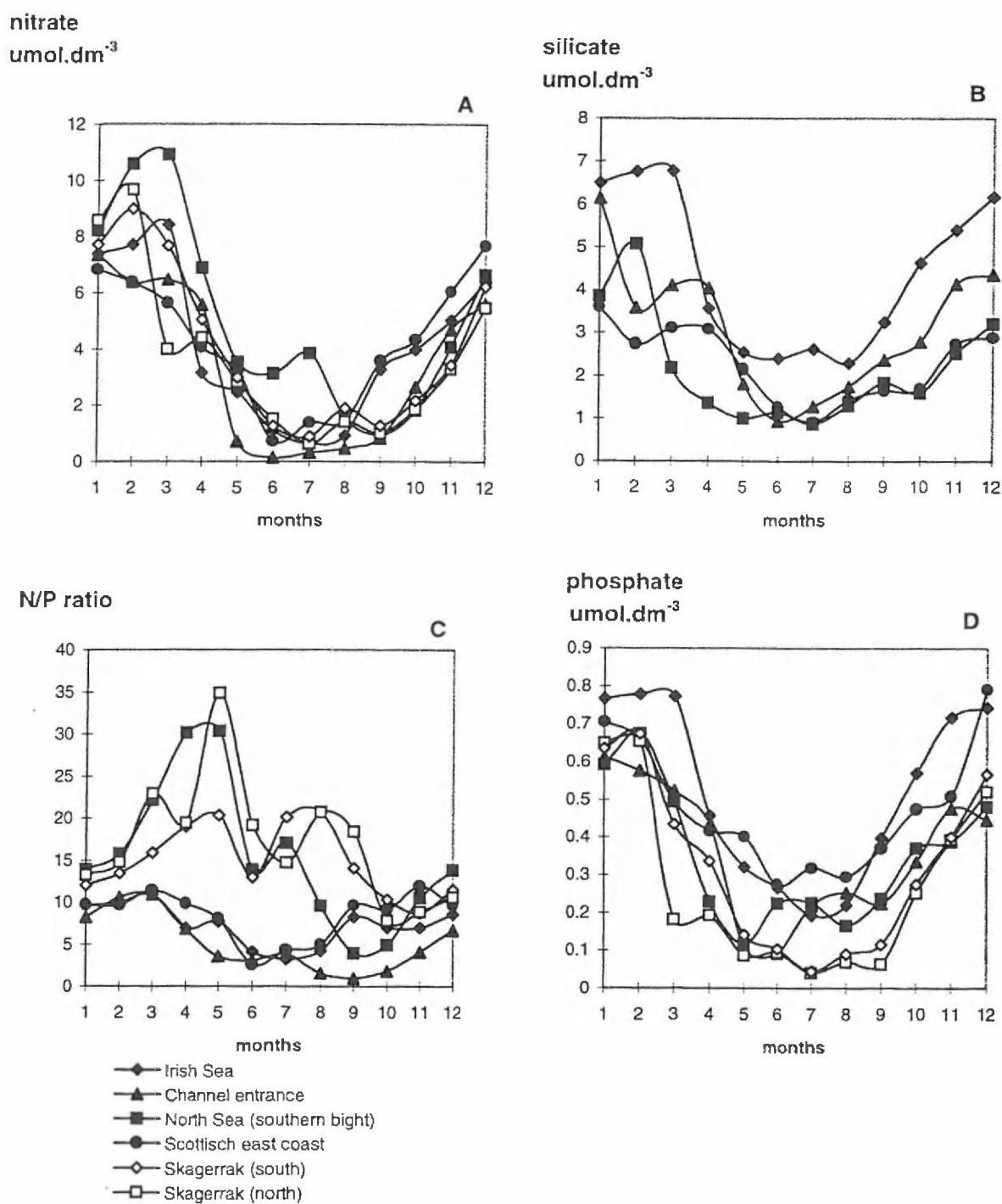
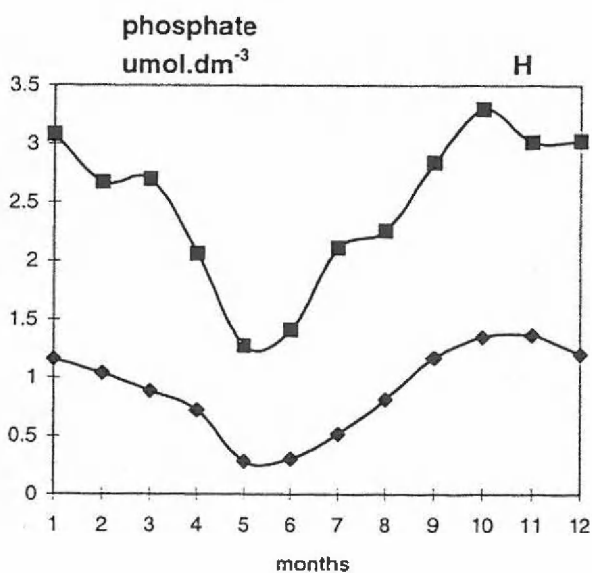
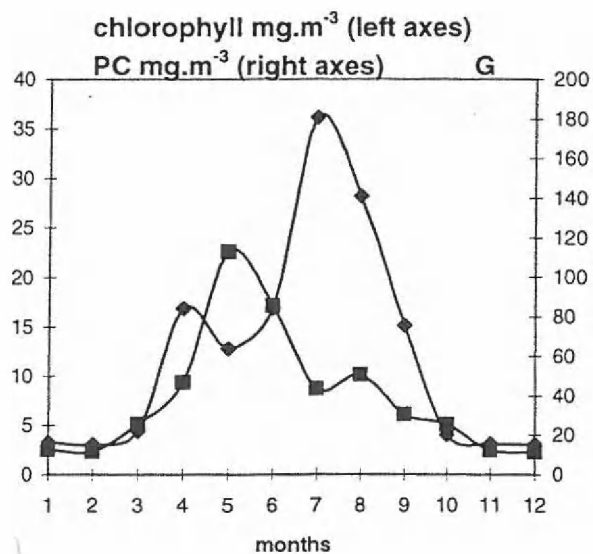
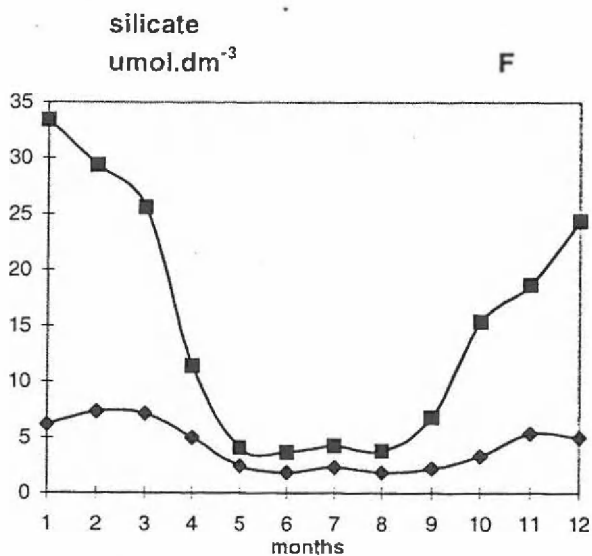
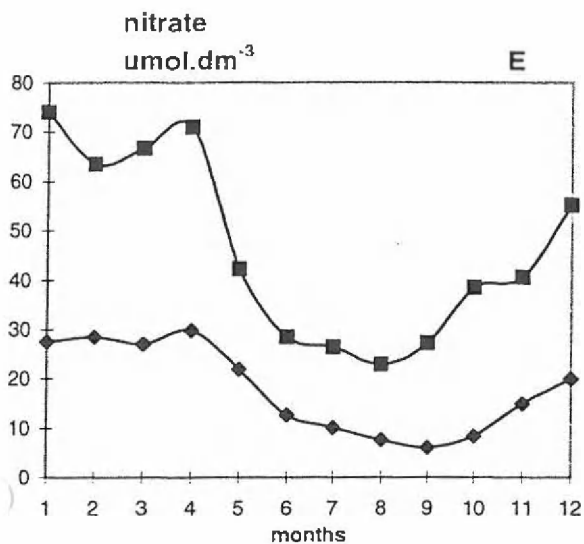




Figure 2. Cont'd



N/P ratio

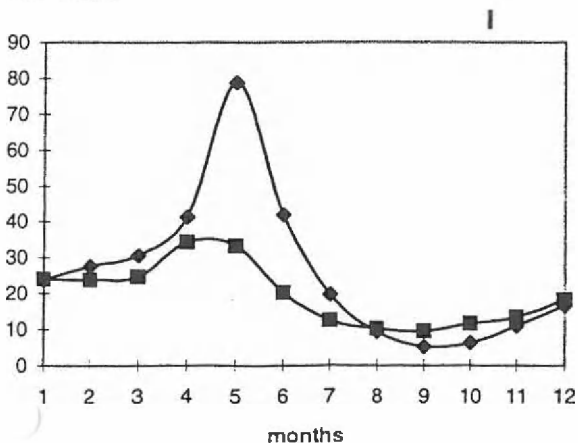


Figure 3. Changes in the number of months nutrient concentrations drop below the designated value and chlorophyll concentration rise above the designated value.

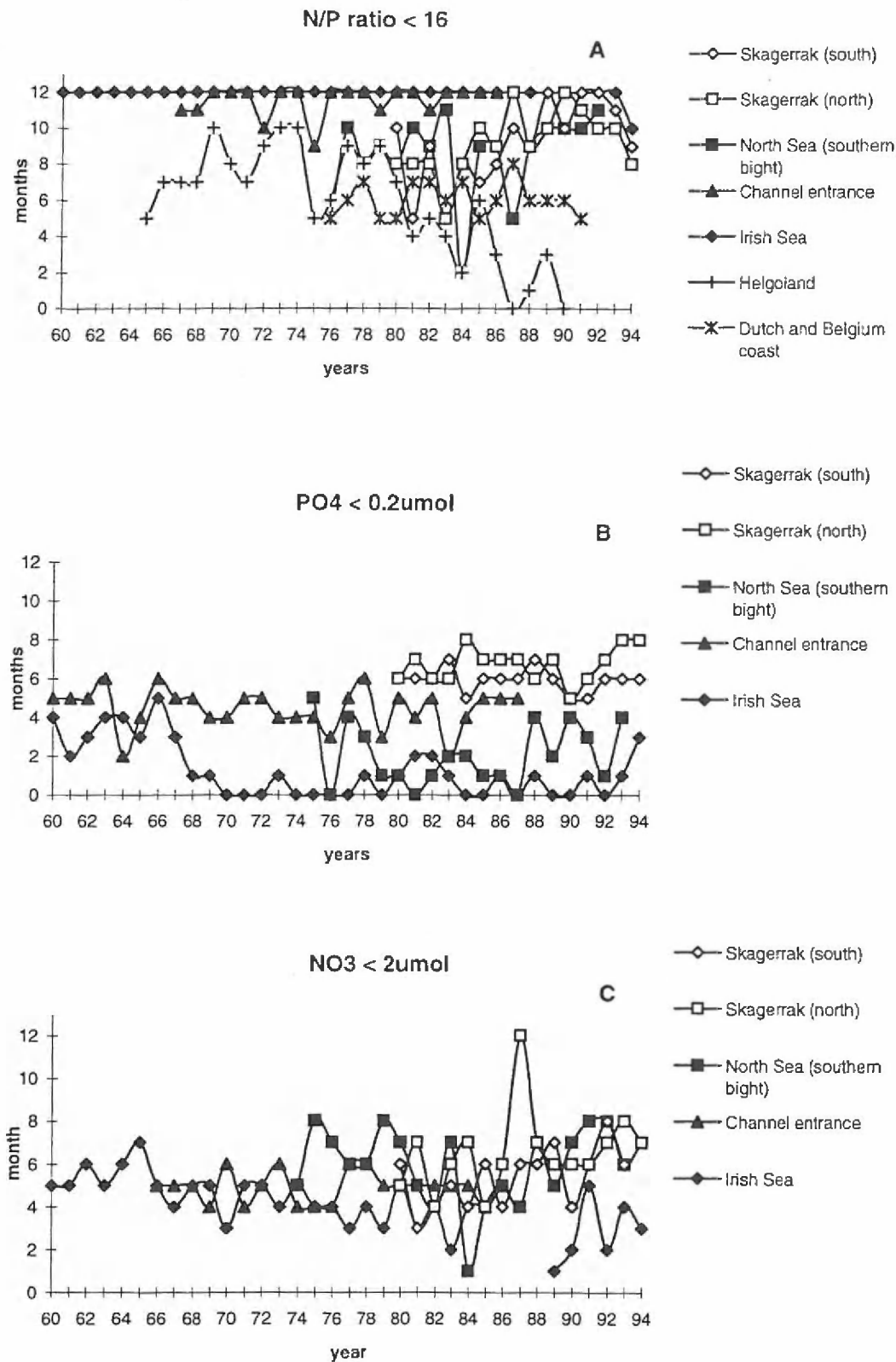


Figure 3. Cont'd

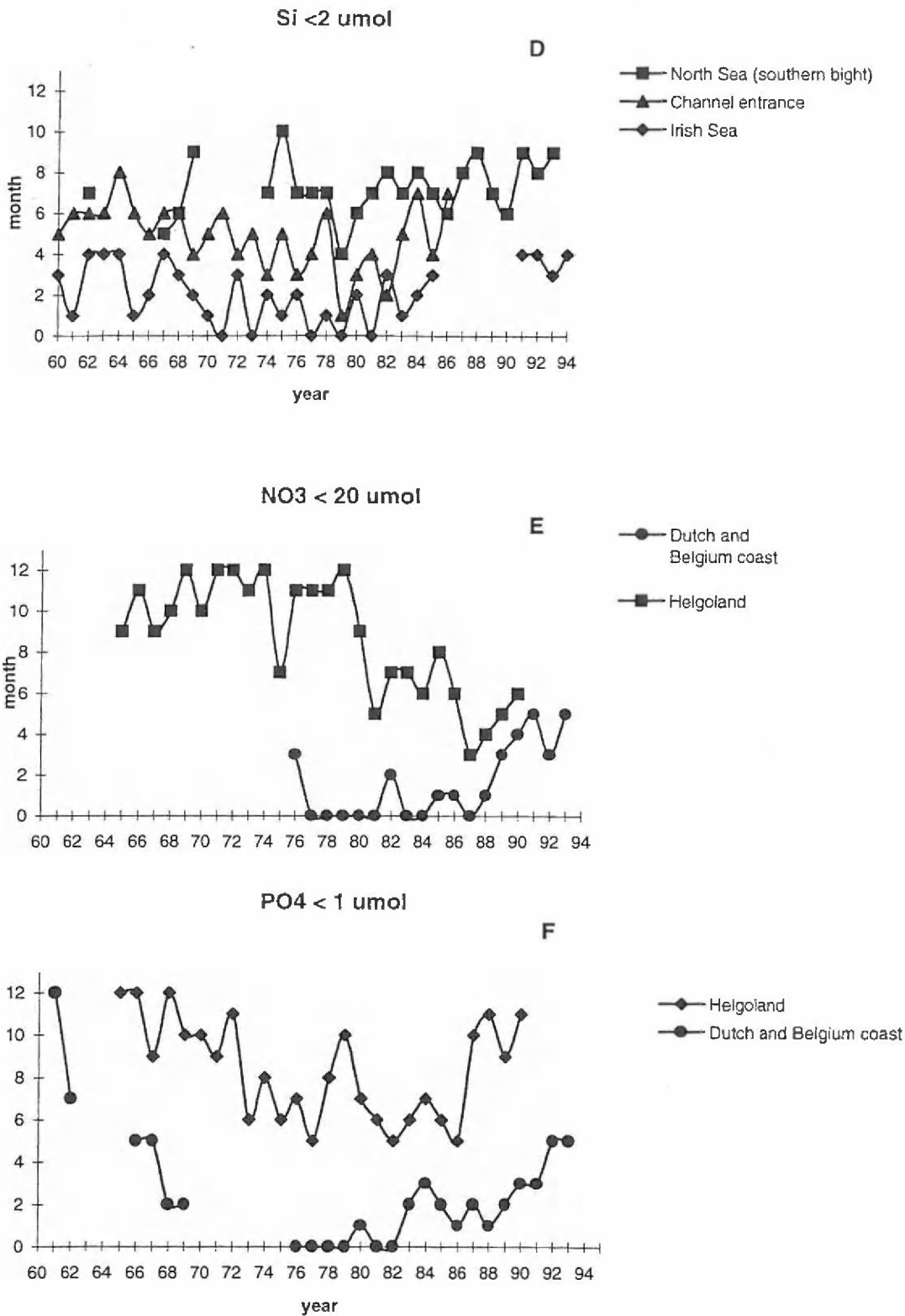


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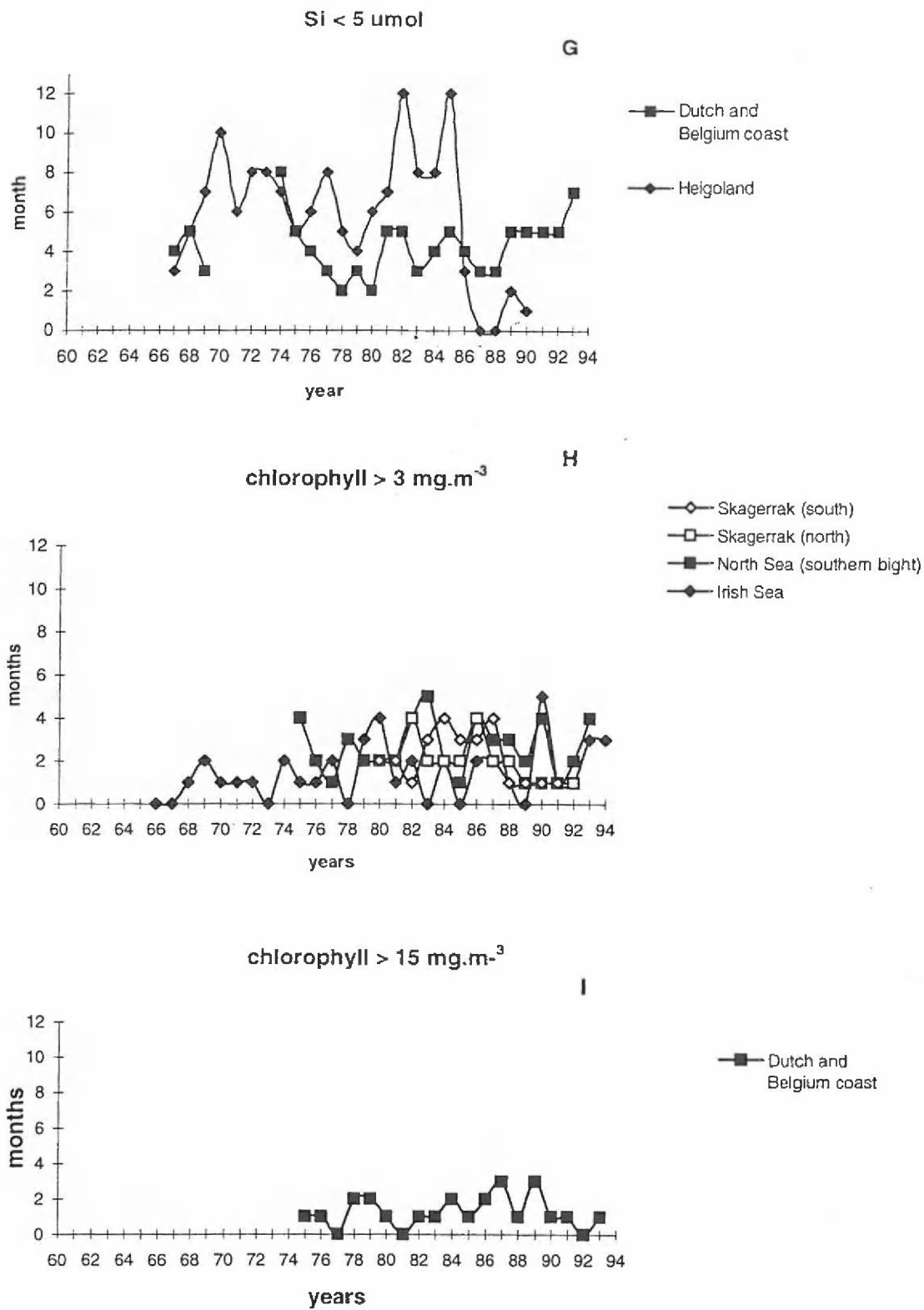


Figure 3. Cont'd

