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Long-term simulation of the eutrophication of the North Sea: temporal development of nutrients, chlorophyll and primary production in comparison to observations

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Abstract

The ecosystem model ERSEM II has been used to hindcast the development of the ecosystem of the North Sea during the years 1955 to 1993. The simulation was driven by the box-aggregated output from a general circulation model of the North Sea of corresponding duration; radiation, river inputs, atmospheric input and boundary conditions at the borders to the Atlantic Ocean and to the Baltic Sea were applied as realistically as possible. The general features of the eutrophication process are reproduced in the hindcast: the coastal areas show strong changes in nutrient concentrations in the hindcast as well as in the observations. Eutrophication not only shows up in the nutrient concentrations, but also in primary production. The simulated spatial distributions of phosphate, nitrate and primary production compare well with the observed ones. In addition, the hindcast simulates considerable trend-like changes of the nutrients in the southern part of the North Sea, where the nutrients are transported from the continental coastal strip to the southern central North Sea. The line from the river Humber to southern Norway separates the region of noticeable anthropogenic influence of riverine and atmospheric input from the northern area, which is mainly influenced by the Atlantic nutrient inflow. The observed annual cycles in the central and northern North Sea are quite well reproduced by the hindcast. The comparison of the hindcast with the long-term observations at two sites in the continental coastal zone of the North Sea shows that the long-term behaviour of phosphate, nitrate and silicate is simulated well. Primary production is increased in summers during the main period of eutrophication, 1975 to 1989, in the hindcast and in the observations. The flagellates at Helgoland, however, experience much more pronounced annual cycles with much less interannual variability in the hindcast than in the observations. © 1997 Elsevier Science B.V. All rights reserved.

Keywords: eutrophication; long-term simulation; North Sea; nutrients; chlorophyll; primary production; ecosystem model; ERSEM

1. Introduction

In the 1980s it became clear that the continental coastal areas of the North Sea and parts of the Baltic

Sea were seriously eutrophicated (Gerlach, 1990). Nutrients enter the North Sea as riverine input of phosphorus and nitrogen in dissolved and particulate form and as atmospheric input of ammonium and nitroxides. For the German Bight the long time series obtained at Helgoland by the Biologische Anstalt Helgoland showed clearly how several ecosystem

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variables, especially the nutrients and the phytoplankton concentrations, had changed from 1962 onwards (Radach et al., 1990; Hickel et al., 1992, 1993, 1995). Similar changes in phytoplankton composition were observed by Cadée (1986, 1992) at the westernmost inlet of the Dutch Wadden Sea. Up to now it is not clear from observations to which degree the southern and central North Sea is affected by the nutrient input.

Nelissen and Stefels (1988) were the first to compile the existing facts on the eutrophication of the coastal as well as of the central North Sea. They provided budgets for the whole of the North Sea and for the continental coastal strip from France to Denmark, comparing inputs and outputs across the interfaces of these sea areas to the adjacent seas. They showed that the coastal regions are governed by the riverine inputs. Radach (1992) provided an update of their budgets. The percentage of river input of nitrogen (phosphorus) into the continental coastal strip related to all inputs increased from 20% (15%) in 1950 to 52% (52%) in 1980. The annual cycle of the N/P ratio and of the different groups of the phytoplankton were changed drastically (Cadée, 1986, 1992; Radach et al., 1990).

These facts were evaluated in the *Quality Status Report of the North Sea* (Anonymous, 1993), and, as a conclusion, it is stated that in most areas of the North Sea data are lacking to investigate trends (e.g., Dickson et al., 1988). Only the southern North Sea is considered to be an area where phosphate has increased. Data from the winter of 1986 differ by a factor of three to four along the continental coastal strip from the winter values of 1935 and 1936 (Weichart, 1986). The isopleth indicating a doubling of the concentrations corresponds to the 33 psu surface isohaline. A similar comparison for nitrate cannot be made, because no reliable data exist before 1960.

The status concerning eutrophication of the central and northern North Sea is still under debate. However, the causes of the eutrophication of the coastal areas are doubtless of anthropogenic origin, as was demonstrated by Radach et al. (1990) for the German Bight.

The eutrophication of the North Sea was subject of several modelling attempts during the last decade (Fransz et al., 1991). Earlier, Mommaerts et al. (1984) simulated the annual cycling of nitrogen

in the Belgian coastal waters. Fransz and Verhagen (1985) attempted to simulate the effect of eutrophication in the coastal areas off The Netherlands. They compared simulations for input conditions in 1930 and in 1980. They found an increase of primary production by a factor of two and a shift from a diatom to a flagellate community, as was observed in Dutch and German coastal waters (Cadée, 1986; Radach et al., 1990). These findings are supported by theoretical studies of the effects of the increase of the nutrient concentrations on the phytoplankton by Radach and Moll (1990), who showed that the increase of nutrient concentrations resulted in an increase of the spring bloom in a nonlinear response and a shift of production into summer, when the nutrients, which had not been utilised during spring, were consumed by algae.

Recently a model comparison was performed, in which existing models for the whole or for parts of the North Sea were used to simulate eutrophication during the year 1985 under natural and under reduced river input conditions (Anonymous, 1997a). The North Sea ecosystem box model ERSEM II described in this paper, the three-dimensional primary production model ECOHAM1 (Moll, 1995, 1997), the three-dimensional plankton model NORWECOM (Aksnes et al., 1995; Skogen et al., 1995), the continental shelf model DCM-NZB (Anonymous, 1997b) and the southern North Sea model DYMONNS (Hydes et al., 1997; Kelly-Gerreyn et al., 1997) and other models were compared in a validation exercise for the same year 1985, using several data sets for validation. It turned out that ERSEM II in its setup ND130 yields good to reasonable results in comparison with data and with other models for phosphate and chlorophyll, as measured by a cost function over the whole of the North Sea. A cost function gives a weighted root mean square of the mean quadratic distance between simulated and observed monthly means (rms), normalised by the standard deviation of observations (Anonymous, 1997a). The good correspondence with data encouraged us to report here about a simulation over a time span of decades.

ERSEM had been used so far for simulating one or two annual cycles, e.g. for the meteorological and hydrodynamical years 1988 and 1989 (Baretta et al., 1995; Radach and Lenhart, 1995). Here the attempt to hindcast the eutrophication of the North Sea with

ERSEM II during the last 40 years, from 1955 to 1993, is reported and the results are compared to long-term observations compiled in the MAST project NOWESP for several sites in the North Sea (Radach et al., 1996, 1997).

2. The model

For this study ERSEM II, i.e. ERSEM version 11 has been used. The earlier ERSEM I (version 5.2) has been described in detail by Baretta et al. (1995) and the papers referred to therein. Here the description of ERSEM will not be repeated, but changes in the model which occurred since then will be briefly mentioned.

2.1. The ecosystem model ERSEM II

Earlier, in the coarse spatial setup ND15, ten large surface boxes and five deep boxes in areas deeper than 30 m were used (Lenhart et al., 1995). In this study we describe results obtained with ERSEM II for the new standard setup ND130 (Radach and Pätsch, 1997). ND130 consists of 130 interior boxes, covering an area of 555 232 km². According to a method described by Lenhart and Pohlmann (1997), the 1° × 1° boxes in the model domain were differentiated into boxes which were predominantly mixed and those which were predominantly stratified during the year. The latter ones were divided into an upper box (0 to 30 m depth) and a deep box (30 m to bottom) to account for the consequences of thermal stratification. In this way 85 upper and 45 lower boxes were defined. The spatial structure of the model domain is shown in Fig. 1, together with the grid on which the general shelf seas circulation model HAMSOM runs (see Section 3.1). In addition to the interior boxes also boundary boxes were defined (boxes 131 to 155). These boxes serve to define boundary conditions. For the long-term simulation ERSEM II was extended with an option to introduce atmospheric nitrogen input.

The pelagic and benthic webs of interacting state variables for ERSEM I are given in Baretta et al. (1995) — their fig. 1. Apart from the finer spatial resolution in comparison to the setup ND15, the most important change in ERSEM II in relation to ERSEM I relates to the phytoplankton dynamics.

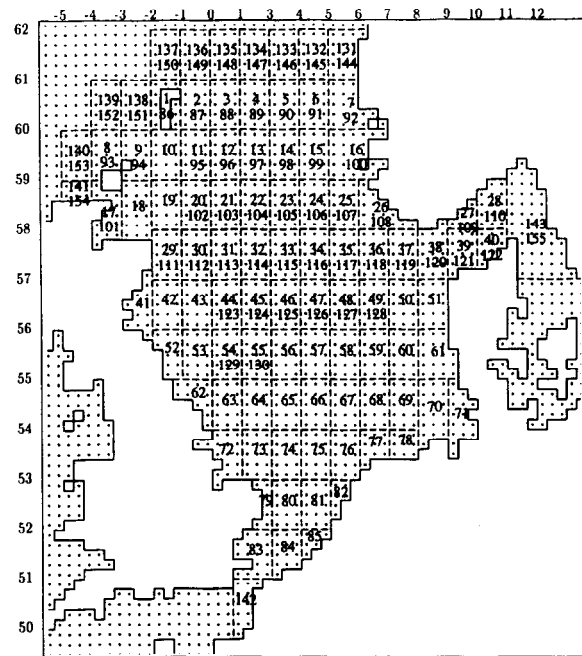


Fig. 1. Box structure of the North Sea for the ERSEM model version ND130 with 130 boxes plus 25 boundary boxes; the dots indicate the grid points of part of the domain of the general shelf seas circulation model HAMSOM. The rivers Rhine and Meuse enter box 85, the Elbe and Weser box 71, the Humber box 72, and the Firth-of-Forth box 17.

The carbon and nutrient dynamics are decoupled (Baretta-Bekker et al., 1997, 1998); the calculation of the underwater light and of the functional relation between the growth rate and the available light has been improved (Ebenhöh et al., 1997) and the number of phytoplankton functional groups has been expanded. There are now four groups for the phytoplankton, diatoms, flagellates, picophytoplankton and inedible phytoplankton. The latter group contains the genus *Phaeocystis*. The primary production module has been re-formulated accordingly (Ebenhöh et al., 1997).

The benthic biology and chemistry is coupled dynamically to the pelagic system. Therefore, interface conditions regulate the exchange of dissolved and particulate matter between water and sediment. The sediment chemistry was described in detail by Ruudij and Van Raaphorst (1995). As in the earlier version of the benthic module of ERSEM, the latest version does not include the burial of material in the sediment. The module simulating the benthos used

in the ERSEM version 5.2 (Ebenhöh et al., 1995) was modified meanwhile; the latest version of the benthic biology is described by Blackford (1997).

2.2. Initialisation

The long-term simulation was initialised by running the model for 29 years using post-war conditions (see below). The resulting system state after 29 years, i.e. January, 1 of the 30th year was used as the initial state for the 39 years of simulation of the long-term development of the North Sea ecosystem. The initial distributions of the nutrients phosphate, nitrate and silicate in the North Sea for 1955 are similar to those given by Johnston and Jones (1965).

3. The scenarios and the forcing

The long-term simulations with ERSEM are forced by several agents listed below:

- The hydrodynamical transports of matter by advection and diffusion are derived from a corresponding hydrodynamical simulation using a general shelf seas circulation model.
- Global radiation drives the primary production.
- The dissolved and particulate river loads and the atmospheric input of nitrogen provide nutrient input into the North Sea.
- Internal forcing was applied for closing the ecosystem towards the highest trophic levels. For this purpose the fish loads over the North Sea were prescribed.
- The boundary conditions at the open boundaries of the North Sea towards adjacent seas are called forcing in this context. At the open sea boundaries in the north of the North Sea and in the Channel and to the Baltic Sea time series were prescribed for nutrients and mesozooplankton.
- Light attenuation is influenced by suspended particulate matter, which is introduced as a time series derived from a simulation of the distribution of suspended particulate matter in the North Sea.

In this paper the long-term simulations for two scenarios are described, which differ solely in the forcing:

The hindcast for the years 1955 to 1993 (simulation H). A hindcast (simulation H) is intended to

represent the development that has really taken place from 1955 to 1993. The hindcast is driven by all the time-dependent forcing functions derived in this section. The forcing functions have been derived as realistically as possible, and time series of daily values for the four decades 1955 to 1993 have been calculated. The available data allow this to the extent presented in the following Sections 3.1–3.6. If not stated otherwise in the following sections, the forcing was prescribed as climatological forcing. The simulation started with horizontal nutrient distributions comparable to those given by Johnston and Jones (1965). The initial states of the other state variables were prescribed to correspond to the nutrient concentrations fields.

Continued post-war conditions (simulation N). As reference for the simulation for hindcasting the real development since 1955, the hypothetical continuation of the post-war conditions after 1955 (simulation N) has been simulated, under the hypothesis that the anthropogenically-caused nutrient input into the North Sea remained at the level observed in the mid-1950s, ten years after the Second World War. The initial conditions used are the same for the reference simulation and the hindcast. The hydrodynamical forcing has been kept unchanged for this simulation in comparison to the hindcast. Also, the time series of irradiance were the same as in the hindcast. However, the river input and the atmospheric input have been modified to maintain the input situation of 1955.

The boundary conditions for nutrients at the open boundaries had to be considered for each boundary separately. At the northern boundary to the Atlantic Ocean the same conditions as in the hindcast were used, because we consider these areas not to be anthropogenically influenced. Because eutrophication has been observed in the English Channel (Menesguen et al., 1995) and in the Baltic (Gerlach, 1990), the annual cycles for 1955 in the Strait of Dover and at the eastern boundary to the Baltic Sea were repeatedly prescribed.

The characteristics of the two scenarios are summarised in Table 1.

3.1. The hydrodynamic forcing

The hydrodynamical forcing was derived from a simulation run of the semi-baroclinic general shelf

Table 1
Characteristics of the two scenarios simulated

Condition	Hindcast (simulation H)	Post-war conditions (simulation N)
River input	time series for 1955–1993 (see Table 2)	annual cycles for 1955
Atmospheric input	linearly increasing input (Section 3.4)	annual input for 1955
Northern boundaries	time series of nutrient and mesozooplankton concentrations for 1955–1993	
Baltic boundary	time series of nutrient and mesozooplankton concentrations for 1955–1993	repeated climatological annual cycle of nutrient and mesozooplankton concentrations for 1955
English Channel boundary	time series of nutrient and mesozooplankton concentrations for 1955–1993	repeated climatological annual cycle of nutrient and mesozooplankton concentrations for 1955
Hydrodynamic forcing	time series of transport from HAMSOM simulation, 1955–1993	
Irradiance	time series from cloudiness data and radiation model 1955–1989, climatological annual cycle for 1990–1993	
Suspended matter	climatological annual cycle from SPM simulation model, using monthly means from 1986–1990	

seas circulation model HAMSOM (Backhaus et al., 1986) for the region of the northwest European shelf (47.68°N to 63.88°N; 15.08°W to 13.92°E). The simulation covers the period 1955 to 1993. The meteorological forcing for HAMSOM was derived from a large data set of meteorological weather data, spanning from 1955 to 1993 (Backhaus et al., 1985; Smith et al., 1996). Temperature fields were taken for the North Sea from Damm (1989) as climatological means over 18 years (1968–1985). The hydrodynamical simulation, which is utilised for deriving the forcing for ERSEM, is described in Pätsch (1997). Examples of the time series of transports through the vertical interfaces at the open sea boundaries of the ERSEM regions are also presented by Pätsch (1997). The high temporal variability in the inflow across the northwestern boundaries and in the outflow through the Norwegian Trench obviously causes high variability in the nutrient transports across these boundaries. The hydrodynamic simulation results are discussed in relation to the meteorological forcing in detail by Pätsch (1997).

3.2. Solar irradiance and underwater light

The solar irradiance was calculated from monthly cloudiness distributions and the radiation model by Dobson and Smith (1988). The cloudiness data consist of frequency distributions of cloudiness in octas (i.e. cloud cover of sky in eights) for every month

during the period from 1955 to 1989 on a spatial resolution of $1^\circ \times 2^\circ$ in the region of the North Sea and the Baltic Sea. The model by Dobson and Smith (1988) was tested for its applicability to the North Sea by Moll and Radach (1991). The method which we used here to derive the actual daily solar radiation at the sea surface was described in detail by Pätsch (1994). The results of this procedure have been compared with direct measurements of solar radiation at light vessels and islands in the North Sea and also with forecasts of irradiance by the European Weather Forecasting Centre in Reading, England. The comparisons gave confidence in using the procedure for this long-term simulation exercise (Pätsch, 1994). Daily values of global irradiance (W m^{-2}) were simulated for each of the $1^\circ \times 1^\circ$ ERSEM boxes from 1 January 1955 to 31 December 1989. For the remaining time, from 1990 to 1993, climatological cloudiness data were used. The time series of monthly means of solar energy for the southern North Sea (average for the boxes 70 to 85) and the northern North Sea (averages for the boxes 1 to 21) exhibit regional differences in the amount of solar energy received; the long-term mean daily solar energy input is 109 W m^{-2} in the southern and 83 W m^{-2} in the northern North Sea, i.e. they differ by about 24% on average (Pätsch, 1997). This is not only the consequence of the different solar angle due to latitude, but also of the different cloud cover.

Suspended particulate matter (SPM) distributions were simulated for the North Sea by Pohlmann and Puls (1994) for 1986–1990. Their results were condensed and adapted to observed SPM levels (Lenhart et al., 1997) to yield monthly mean values for each of the boxes. The monthly means were then introduced into the formulation for underwater light attenuation to simulate the actual light conditions.

3.3. River inputs

River loads for the continental rivers were compiled for the time period from 1977 to 1993. The observed time series of discharges and of concentrations, which had gaps, were used to interpolate time series of daily load values for these rivers (Lenhart et al., 1996). For the other rivers entering the North Sea loads were taken as derived for the year 1985 from reports (Anonymous, 1992, 1993); these values were prescribed for the years 1977 to 1993. For the time before 1977 assumptions had to be made about the increase from post-war conditions to the load estimates for 1977. An overview of the assumptions about the temporal development of the different river input parameters is given in Table 2. The annual cycles of the river inputs for the nine state variables were extrapolated into the past according to literature values and plausible guesses (Pätsch, 1997). In Fig. 2 the annual nutrient loads of the European rivers entering the North Sea are presented cumulatively for dissolved and particulate phosphorus and nitrogen as time series of total nutrient loads per year during 1955–1993.

3.4. Atmospheric input

The atmospheric input of nitrogen into the North Sea is considerable and cannot be neglected. It has to be included as forcing when aiming at the reproduction of the observed development of the nutrients in the North Sea. For this study we took the figures given in the *Quality Status Report* (QSR; Anonymous, 1993). For the area of the North Sea up to 59°N, including Kattegat and Skagerrak, of 525 000 km² the QSR gives 330 kt a⁻¹ as a minimum value and 520 kt a⁻¹ as a maximum value for the atmospheric nitrogen input, which is assumed to consist of equal amounts of nitrate and ammonium (Beddig et al., 1997). We have used the maximum value of 520 kt N a⁻¹, resulting in a flux of 990.47 kg km⁻² a⁻¹, i.e. 71 mmol N m⁻² a⁻¹. We assume that the atmospheric nitrogen input into the model area has increased linearly from 274.97 kt in 1955 to 549.94 kt in 1993 and that it is evenly distributed over the North Sea.

The atmospheric phosphorus input is not known, but is believed to be small; the QSR (Anonymous, 1993) did not give numbers as for nitrogen because of the lack of importance.

3.5. Boundary conditions

The model simulations need all state variables to be prescribed at the open boundaries of the model domain. However, only for a few of them sufficient amounts of data exist to derive boundary conditions. The necessary amounts of data only do exist for the

Table 2

Extrapolation of river loads into the past by assuming different factors of increase for different time ranges and nine state variables, which are needed for ERSEM

State variable	1955–1970 16 years	1971–1976 6 years	1977–1993 17 years
Phosphate	increase by factor 3	increase by factor 3	actual time series
Particulate P	increase by factor 3	increase by factor 3	actual time series
Nitrate	increase by factor 2	increase by factor 2	actual time series
Nitrite	increase by factor 2	increase by factor 2	annual cycle of 1985
Ammonium	mean annual cycle of 1977–1979		actual time series
Particulate N	increase by factor 2	increase by factor 2	actual time series
Silicate	mean annual cycle of 1977–1979		actual time series
Particulate Si	mean annual cycle of 1977–1979		actual time series
Particulate C	increase by factor 2		annual cycle of 1985

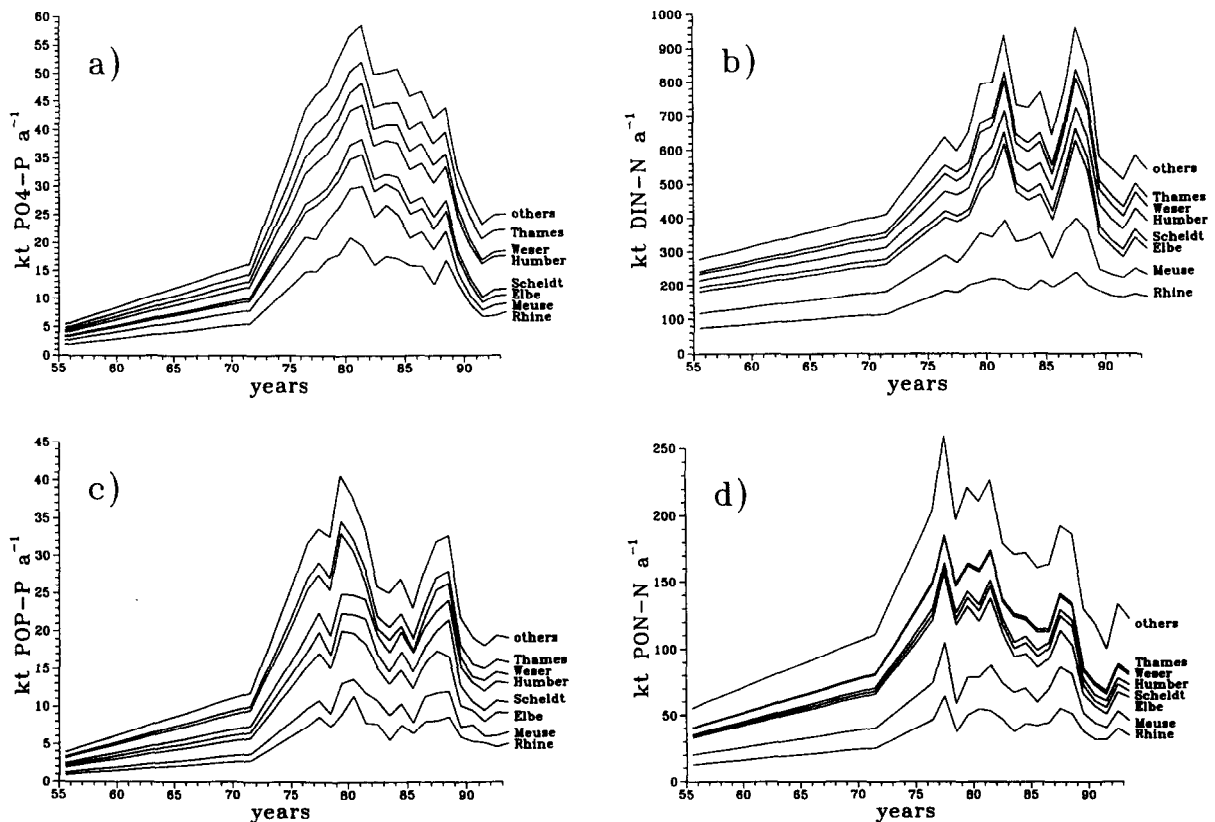


Fig. 2. Time series of annual nutrient inputs, cumulated for all the rivers entering the North Sea for (a) dissolved phosphate; (b) dissolved inorganic nitrogen; (c) particulate phosphorus, and (d) particulate nitrogen.

nutrients, chlorophyll and for mesozooplankton, but also in these cases interpolation and extrapolation schemes have to be used for creating time series without gaps. As chlorophyll is a diagnostic variable, no boundary conditions have to be defined for chlorophyll. From the continuous plankton recorder survey (CPR) mesozooplankton data are available (Broekhuizen et al., 1995). Thus, only nutrients and mesozooplankton boundary conditions can be defined. Monthly means for all nutrients and for mesozooplankton have been calculated for all boundaries for all years; the method has been described by Pätsch (1997).

3.5.1. Open sea boundary conditions for nutrients

The boundary conditions at the open boundaries of the North Sea were prescribed by long time series of nutrient concentrations. These time series were constructed by utilizing all available observations in

the vicinity of the boundaries. As continuous long time series of concentrations or transports of matter do not exist at the open boundaries of the North Sea, firstly, the nutrient data close to the boundaries were used to establish climatological annual cycles for the boundary boxes. Secondly, where monthly means for the actual months during 1955 to 1993 could be calculated, the deviation from the climatological mean was determined; where no monthly mean was obtainable, the deviation was set to zero. Thirdly, the matrix of deviations was then asymmetrically interpolated, favouring the similarity between the same month of consecutive years as opposed to preceding and following months in the same year. By this interpolation deviations of value zero were replaced by probable deviations. Finally, the matrix of complemented deviations was added to the matrix of climatological monthly means to yield the nutrient time series for the time 1955 to 1993 without any

gaps. In this way the available observations were used to close the gaps in the observed time series on the basis of monthly means.

The resultant nutrient forcing in nine areas at the boundaries for phosphate for each month during 1955 to 1993 is projected into the boundary boxes 131 to 155 for driving the simulation. The resultant time series generally show a picture which is consistent with our knowledge. In a few cases the annual cycle might perhaps be prescribed more smoothly; the data, however, do not confirm this.

3.5.2. Open sea boundary conditions for mesozooplankton

The zooplankton data from the CPR were provided by Broekhuizen et al. (1995) as monthly mean values for the boundary boxes of the ERSEM setup ND15 (see Radach and Pätsch, 1997). At the northern boundary data were provided for the boxes 17, 18, 20 and 21 of the setup ND15 from 1958 to 1991. The transition from the coarse boundary boxes of the setup ND15 to the boundary boxes of the setup ND130 was achieved by regional projection. Also, the distribution of the mesozooplankton over upper and lower boxes had to be determined. It was assumed that the concentrations in the lower boxes are equal to 30% of the concentrations in the upper boxes (Bryant, pers. comm.).

The data represent two categories, the 'small copepods' and the '*Calanus* copepodites V and VI'; they are taken together to be identified with the ERSEM state variable 'omnivorous mesozooplankton'. Although the data were provided as time series, a few gaps in time and space had to be closed. The same procedure as described for the nutrients (Section 3.5.1) was applied. The missing years in the beginning (1955–1957) and at the end (1992–1993) of the simulation period were filled by the climatological annual cycles. Then the time series of zooplankton used as forcing in the areas of the Norwegian Trench, the open northern boundary, the area around the Orkneys, the area of the English Channel and the area of the Skagerrak appear to be consistent.

3.6. Internal forcing

Fixed predation rates by fish on the lower levels were taken from Bryant et al. (1995). They were

estimated from consumption rates of fish and the biomasses of their prey. The consumption rates were estimated for the ten ERSEM North Sea areas of the setup ND15 (Radach et al., 1995), which were then mapped onto the boxes of the setup ND130. Four guilds of fish (pelagic planktivores, pelagic piscivores, demersal piscivores and demersal benthivores) were taken into account. The prey was categorized according to the functional groups in ERSEM to estimate the carbon consumption rates for each of the feeding links.

4. The simulation results

Three aspects have been considered. First, the spreading of the nutrients and of the primary production into the North Sea is considered on decadal time intervals. Second, an analysis of a few boxes in the southeastern to central North Sea is given on a monthly basis. Third, the hindcast is compared to a few of the long time series of nutrients and chlorophyll, which are available from the NOWESP project for the continental coastal areas of the North Sea (Radach et al., 1997).

The results of the hindcast simulation H will be related in the following to the results of the reference simulation N. Therefore, the simulation N is evaluated briefly first to provide a background for the comparison with the hindcast. The obvious result of the reference simulation is the constancy of the annual cycles during the temporal development of all state variables over the decades, overlaid with a variability induced by the hydrodynamic forcing and by the irradiance. In this post-war simulation the annual cycles of nutrients are comparable to those illustrated by Johnston and Jones (1965). The final spatial distributions of the nutrients do not differ markedly from the initial state in 1955 (Fig. 3a and Fig. 4a). Further results of this reference run will be presented when discussing the hindcast.

4.1. Decadal development of the spatial patterns of nutrients and primary production in the North Sea

Nutrient concentrations in winter indicate the degree to which the nutrient input from rivers and atmosphere have changed nutrient availability in the North Sea; they form the basis for the potential pri-

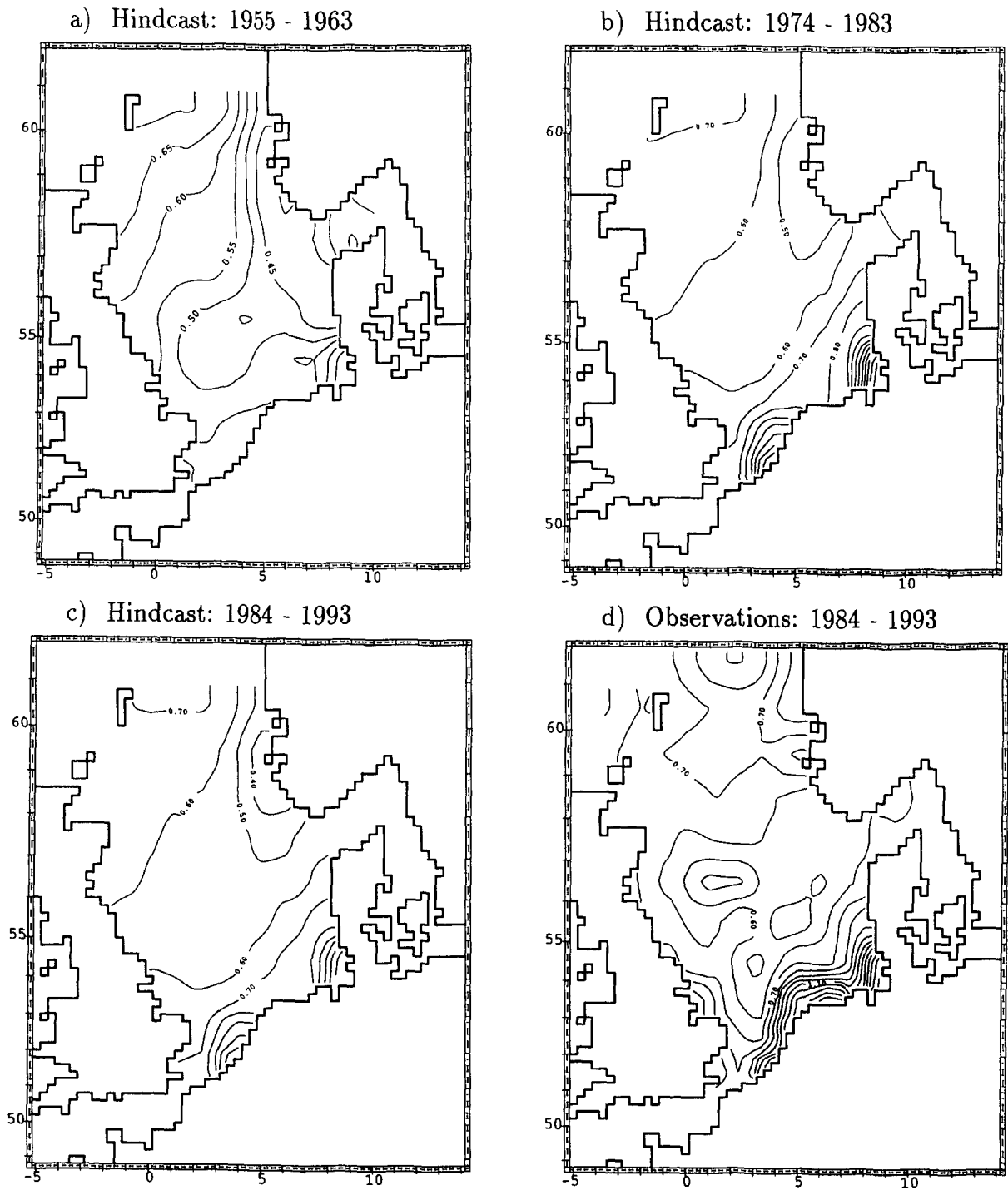


Fig. 3. Horizontal distributions in the surface waters (0–30 m) for simulated phosphate in mmol m^{-3} in winter (December, January, February) for the decades (a) 1955–1963; (b) 1974–1983; (c) 1984–1993), and (d) for observed phosphate in winter in the decade 1984–1993.

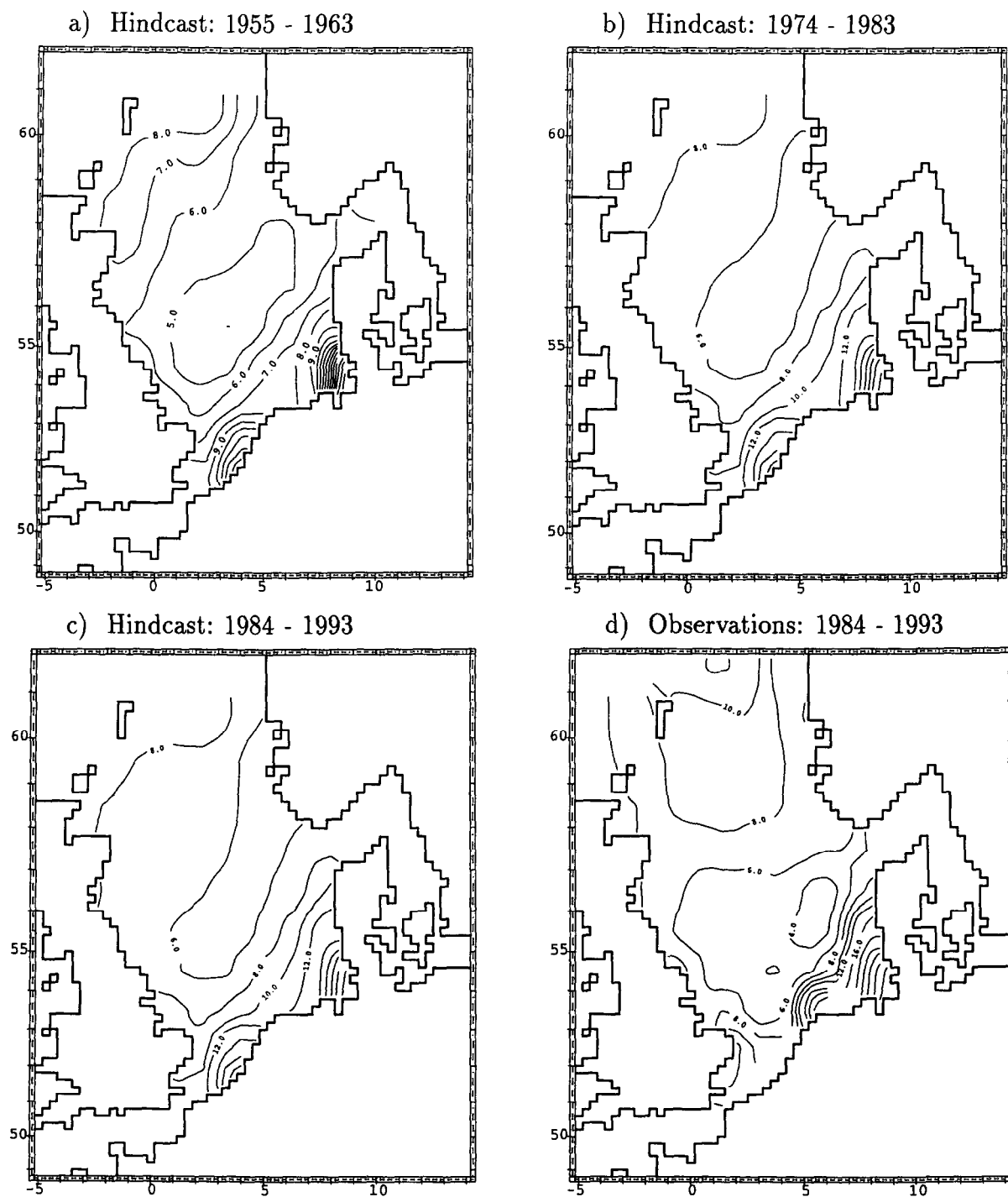


Fig. 4. Horizontal distributions in the surface waters (0–30 m) for simulated nitrate in mmol m^{-3} in winter (December, January, February) for the decades (a) 1955–1963, (b) 1974–1983, (c) 1984–1993, and (d) for observed nitrate in winter in the decade 1984–1993.

mary production. Fig. 3b,c shows phosphate concentrations during winter (December–February) from the hindcast simulation, averaged for the decades 1974–1983 and 1984–1993 and Fig. 4b,c shows the corresponding concentrations for nitrate. The map for the decade 1955–1963 is similar to that showing the initial conditions (Fig. 3a and Fig. 4a). For the decade 1964–1973 no large changes occurred. For the last decade observed spatial distributions for the nutrients phosphate (Fig. 3d) and nitrate (Fig. 4d) are available and will be used for a comparison. Fig. 5 shows simulated annual primary production for the four decades. For primary production only sporadic measurements were available.

The Atlantic influence is recognisable by the relatively high phosphate and nitrate concentrations in the vicinity of the northern boundaries in all four decades. Although time-varying boundary conditions have been applied, the isopleths of 0.6 and 0.7 mmol m⁻³ for phosphate in the southeastern North Sea (Fig. 3b,c) have not changed position over the decades. The same is valid for the isopleth of 8 mmol m⁻³ for nitrate (Fig. 4b,c). This reflects the finding by Pätsch (1997) that the northern boundary conditions exhibit interannual variability, rather than trends over decades.

The southern North Sea has, however, experienced changes during the decades. The nutrient concentrations increase from 1955–1963 to 1974–1983 in a strip parallel to the continental coast, and they are obviously strongly determined by the river inputs from the rivers Rhine, Meuse and Elbe. The last decade, however, shows a decrease of the simulated horizontal nutrient distributions close to the coast; the maximum simulated values for phosphate and nitrate in the German Bight are 1.4 mmol m⁻³ and 25.4 mmol m⁻³, respectively. Compared to the foregoing decade the isopleth of 0.7 mmol m⁻³ for phosphate has slightly altered its position in the southeastern North Sea from the third to the last decade, running from Norfolk/East England to mid-Jutland instead of the northern tip of Denmark. For nitrate the development is different; the isopleth of 8 mmol m⁻³ runs from the mouth of the Humber to northern Jutland during the last two decades. In the last decade the area around the outflow of the rivers Rhine and Meuse shows the same concentrations as in the preceding decade, while the German Bight exhibits

slightly decreased nitrate. The concentrations of both nutrients are, however, still high, i.e. about 150% of the level of the decade 1964–1973 for phosphate and about 120% for nitrate.

For the observed horizontal phosphate and nitrate distributions in winter comparable figures exist; they are taken from Radach and Pätsch (1997), where maps of 1° × 1° rectangles are given (their Fig. 3a,b). The same data are presented here as isopleth plots and give a comparable distribution valid for the decade 1984–1993 and can thus be compared to the simulated distribution in the last decade. The observed phosphate (Fig. 3d) is similar to the simulated distribution in wide parts of the North Sea, outside the continental coastal zone of about 100 km (up to the isopleth 0.7 mmol PO₄-P m⁻³). The observed tongue of Atlantic water reaches further down into the North Sea than in the simulation. The data show small areas of less than 0.5 mmol P m⁻³ in the central North Sea, which have no correspondence in the simulated distribution. The isopleth of 0.7 mmol P m⁻³ is reproduced well in the simulation. The English coastal waters, however, have higher observed concentrations than simulated. Southeast of this zone close to the continental coast the observations give higher concentrations than simulated, which can be seen e.g. in the isopleth of 1.7 mmol P m⁻³ instead of 1.2 mmol P m⁻³ in the inner German Bight. The observed distribution resembles more the situation in the foregoing decade, and even between the maxima off the river mouths we find high concentrations close to the Frisian coast; such values are not simulated. The model simulation may disperse phosphate too quickly. Another possible reason may be the exchange of nutrients between the sediment and the overlying water, which cannot be checked against observations. Also the diffusive, non-point sources of nutrients along the continental coastal zone are not represented in the simulation.

As for phosphate, the tongue of Atlantic nitrate concentrations reaches deeper into the North Sea than simulated. For the rivers Rhine and Meuse outflow area and for the eastern Frisian coastal waters nitrate data are lacking unfortunately (Fig. 4d). The simulated horizontal distribution yields a river influence on the southeastern North Sea, which reaches further to the northwest than in the observations. The isopleth of 8 mmol N m⁻³ runs from south

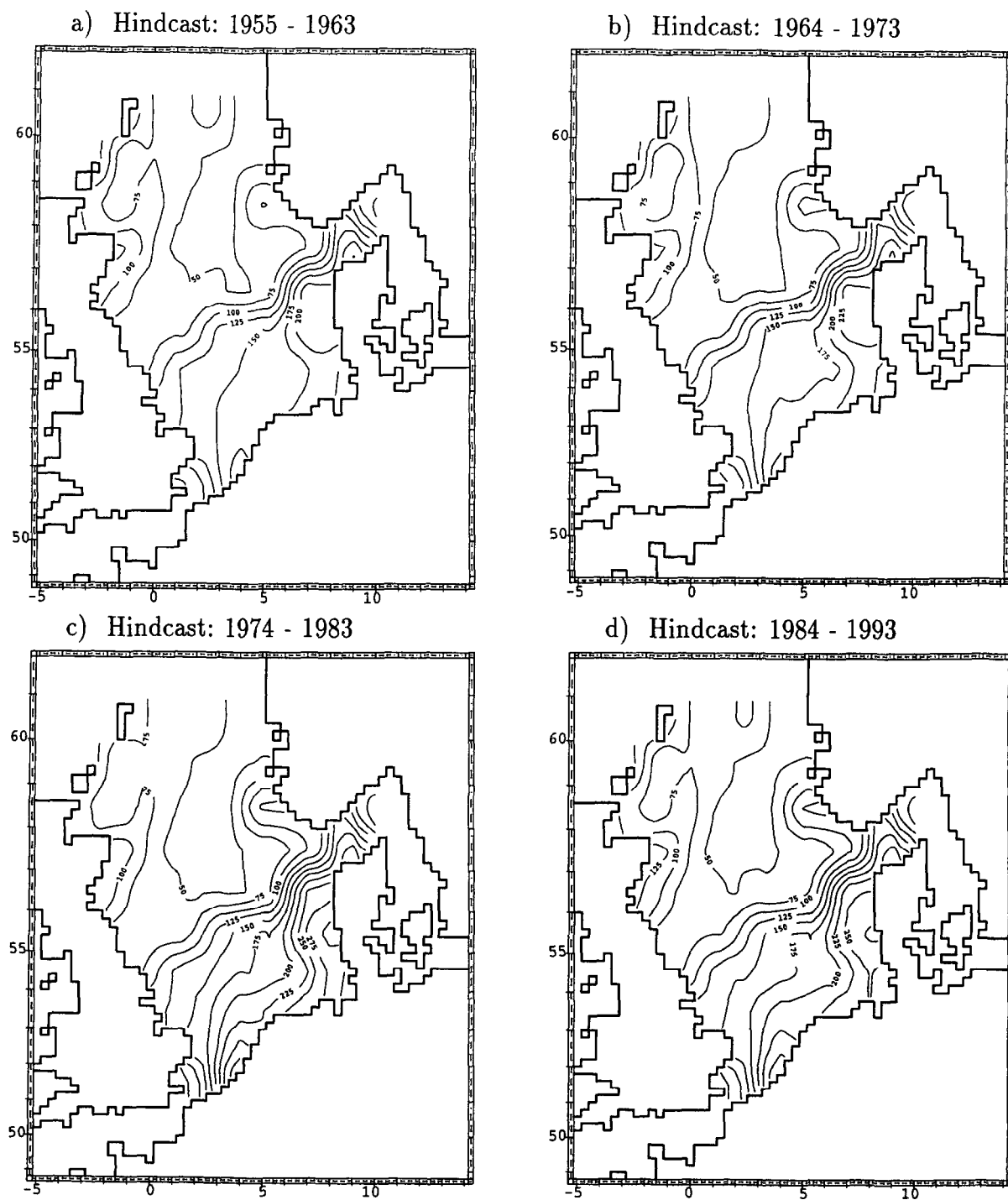


Fig. 5. Horizontal distributions for simulated annual primary production in the North Sea in $\text{g C m}^{-2} \text{a}^{-1}$ for the periods (a) 1955–1963, (b) 1964–1973, (c) 1974–1983 and (d) 1984–1993.

of the Wash to northern Jutland in the map from observations (Fig. 4d), but from north of the river Humber to northern Jutland in the map of the simulation (Fig. 4c). Clearly the region of influence of the rivers in the North Sea is slightly overestimated in the simulation. As for phosphate, the observed concentrations in the continental coastal zone during 1984–1993 are considerably higher than simulated, especially close to the coast.

Generally, the net annual primary production decreases in northwesterly direction and reaches regionally varying values of 75 to 100 g C m⁻² a⁻¹ in the central North Sea (Fig. 5). This spatial pattern persists through the decades. The minimum values of primary production are simulated around the Fladen-ground area in the northwestern North Sea, with values of <50 g C m⁻² a⁻¹. Towards the North Atlantic and the Scottish coast net annual primary production increases up to values between 75 and 100 g C m⁻² a⁻¹; it increases about 25 g C m⁻² a⁻¹ during the last decade off the eastern Scottish coast around the Firth of Forth. Net annual primary production sensitively shows the spatial extent to which the riverine and atmospheric inputs influence the North Sea. In the first decade the isopleth of 100 g C m⁻² a⁻¹ goes from north of the river Humber to southern Norway, and increases towards the continental coast up to 150–175 g C m⁻² a⁻¹. Off the rivers Rhine/Meuse and Elbe and west of Jutland (Denmark) the annual amount of >200 g C m⁻² a⁻¹ is reached. In the second decade the southeastern North Sea has become more productive, and values over 175 g C m⁻² a⁻¹ prevail. During the period of strongest eutrophication in the coastal area, e.g. in the third decade, net annual primary production reached maxima of nearly 300 g C m⁻² a⁻¹ off the rivers Rhine/Meuse and Elbe (Fig. 5). From the third to the last decade primary production has decreased by about 10% in the area south of the line from the river Humber to southern Norway. During all decades primary production per m² and year decreased from the outer German Bight (box 70) towards the inner German Bight (box 71) to lower values. This can be explained by the relatively small depth of box 71.

Estimates of annual primary production based on measurements of primary production have been compiled by Van Beusekom and Diel-Christiansen (1994). The estimates are sparse and do not cover all

areas of the North Sea, as can be seen in Table 3, where the available estimates are sorted according to the corresponding decades for which the spatial distributions of annual primary production are presented in Fig. 5. For the Dutch coastal waters the estimates for the near-shore areas and Marsdiep have been summarized into a range in Table 3. Annual values of about 370–385 g C m⁻² a⁻¹ (Cadée and Hegeman, 1993) are considered to be influenced by the Wadden Sea, which is not represented in the model domain. In the northern North Sea the very few estimates from observations are higher than the simulated ones. In all other areas the estimates from observations and from the simulation have to be considered as compatible. It is interesting to note that the maximum production in the southern North Sea occurs west of southern Denmark, north of the German Bight. This feature was confirmed by the ZISCH cruise in spring 1986 (Brockmann et al., 1994).

Compared to the reference simulation N, primary production has not increased in the northwestern part of the North Sea. But about half the area of the North Sea, i.e. the area east of the line from the river Humber to southern Norway shows effects of the eutrophication in terms of primary production, ranging from 10% (in the northwestern part) to more than 80% increase of the post-war primary production along the continental coast, especially in the areas where the rivers Rhine/Meuse (>80%) and Elbe (>100%) discharge their nutrient loads. The 50%-isopleth stays close to the coast, extending from Belgium to Denmark (not illustrated). These results indicate that eutrophication has increased primary production in large parts of the North Sea. But the increase is nowhere proportional to anthropogenic input of nutrients via rivers (Table 2) and atmosphere. Over the last decade net primary production in the southeastern half of the North Sea is nearly down to a level somewhere between the decadal means of the second and third decade, with elevated primary production east of the Dogger Bank and in the continental coastal zone compared to the second decade, especially close to the river mouth of the rivers Rhine and Meuse and in the German Bight (Fig. 5). In the northern North Sea the regional pattern remained the same for the first three decades, and only in the last decade increased primary production is apparent in the area around the Firth of Forth.

Table 3

Simulated and estimated annual primary production with year of measurement (if stated in the source) in various areas of the North Sea, for the following periods (a) 1955–1963, (b) 1964–1973, (c) 1974–1983 and (d) 1984–1993

Area	Surface box numbers			Annual primary production (g C m ⁻² a ⁻¹)		
	ERSEM ND130	ERSEM ND15	ICES	simulated	estimated from measurements	year(s) of observation
Northern central North Sea	2–5, 11–14, 21–23	1	1	a. 50–75 b. 50–75 c. 50–75 d. 50–75	c. 100 ^c 125 ^b	1981 –
Northwestern central North Sea	10, 19–23, 30–32	2	2	a. 50–75 b. 50–75 c. 50–75 d. 50–75	c. 100 ^c 125 ^b	1981 –
Norwegian coastal waters	6, 7, 15–16, 24–26, 35–37	3	6	a. 50–175 b. 50–200 c. 50–200 d. 50–200		
Central North Sea	33–35, 43–49, 54–55	4	7a	a. 50–125 b. 50–150 c. 50–175 d. 50–150	d. 100 ^d	1988/89
Southern central North Sea	58–60, 64–69, 73–75	5	7	ba. 125–150 b. 125–175 c. 125–200 d. 100–200	c. 200–250 ^a d. 119 ^d ; 92 ⁱ ; 135 ⁱ	1988/89; 89; 90
Scottish coastal waters	9, 17–18, 29, 41–42, 52–53, 62	6	3a	a. 75–125 b. 75–125 c. 75–100 d. 75–125	d. 75 ^d	1988/89
English coastal waters	62–63, 72–73, 79–80, 83	7	3b	a. 75–150 b. 75–150 c. 75–175 d. 75–175	c. 40 ^c d. 79 ^d	1976 1988/89
Belgian coastal waters	84, 85	8	4	a. 150–175 b. 150–200 c. 175–275 d. 175–250	c. 170 ^f d. 199 ^d	1971/75 1988/89
Dutch coastal waters	81, 82, 85, 75–78	8	4	a. 150–175 b. 175–200 c. 200–275 d. 200–250	offshore: c. 250 ^c ; 210 ^g ; 170 ^h d. 199 ^d ; 92; 212 ⁱ ; 149, 191 ⁱ nearshore: d. 185–144 ^b	1971/81; 74; 75 1988/89; 89; 90 1985/92
German Bight	61, 69–71, 78	9	5	a. 175–200 b. ≈225 c. 225–300 d. 225–300	d. 261 ^d	1988/89

Table 3 (continued)

Area	Surface box numbers			Annual primary production ($\text{g C m}^{-2} \text{a}^{-1}$)		
	ERSEM ND130	ERSEM ND15	ICES	simulated	estimated from measurements	year(s) of observation
Danish west coast	50–51	10	5	a. ≈ 200 b. ≈ 225 c. 250–300 d. 225–275	d. 200–300 ^j	1988/89

Sources: ^a Gieskes and Kraay, 1984; ^b Van Beusekom and Diel-Christiansen, 1994; ^c Fransz and Gieskes, 1984; ^d Joint and Pomroy, 1992; ^e Horwood, 1982; ^f Joiris et al., 1982; ^g Gieskes and Kraay, 1975; ^h Gieskes and Kraay, 1977; ⁱ Peeters et al., 1991; ^j Howarth et al., 1994.

Summarising, the hindcast reproduces the observed distributions of phosphate and nitrate during the last decade to a large extent. The results of the simulation H compared to those of the simulation N indicate an increased transport of nutrients out of the continental coastal zone, especially out of the German Bight. It is important to note that the simulation is capable to reproduce the position, e.g., of the observed isopleth of $0.7 \text{ mmol PO}_4\text{-P m}^{-3}$ quite well. The isopleth of 8 mmol m^{-3} of nitrate, separating the northwestern, central North Sea from the southeastern, coastal North Sea, lies only about 60 km northwest of the observed one. An explanation could be that the benthic nutrient regeneration and the resultant diffusion into the overlying water may be overestimated due to the coarse vertical resolution in the model, resulting in a systematic underestimate of the retention time of the nutrients in the sediment, favouring the wash-out. An alternative cause could be an under-estimated inflow from the Channel.

4.2. Long-term development of simulated nutrients, chlorophyll and primary production at specific sites in the southeastern North Sea

The long-term development of the nutrients, chlorophyll and primary production in the ecosystem is exemplified here for a few boxes only. First we discuss the eutrophication effects in the regions of freshwater influence, i.e. the boxes 85 and 71, where rivers Rhine and Meuse and river Elbe enter, respectively. Then we leave the German Bight towards the northwest into the central North Sea to discuss decreasing of the eutrophication effects with distance from the coast, as shown on decadal time

scale in Figs. 3–5, on the basis of monthly means of the simulation results.

The Rhine and Meuse outflow enters box 85. The strong increase of phosphate and nitrate concentrations in the hindcast starts around 1975, and a clear decrease can be observed in the hindcast since 1989 (Fig. 6a). Maximum values are $>2 \text{ mmol m}^{-3}$ for phosphate and $>60 \text{ mmol m}^{-3}$ for nitrate. The increase is a clear effect of increased river (and atmospheric) input, as can be seen from the comparison to the reference simulation, where no nutrient increase over the years occurs, and also from the correspondence between river loads (Fig. 2) and nutrient concentrations in the sea. Also, ammonium (not illustrated here) shows increased values with maxima of over 12 mmol m^{-3} during these years, but in summer and autumn instead of winter and spring, as a result of increased regeneration by heterotrophs. Silicate concentrations (not shown) are not anthropogenically influenced, but changes in the dynamics of diatoms (see below) affect silicate concentrations. The largest changes occur when the depletion phase starts and ends, thus indicating a certain phase shift of the dynamics of diatoms during the hindcast. During summer the silicate concentrations in the hindcast are lower than in the reference simulation, as a consequence of the higher availability of the other nutrients.

Diatom biomasses are only moderately affected. It is, however, interesting to note that during the phase of medium eutrophication between 1962 and 1974 the difference of diatom concentrations between runs H and N increased from May to October up to about 50% as a consequence of abundant nutrients; thereafter the differences only intermittently show

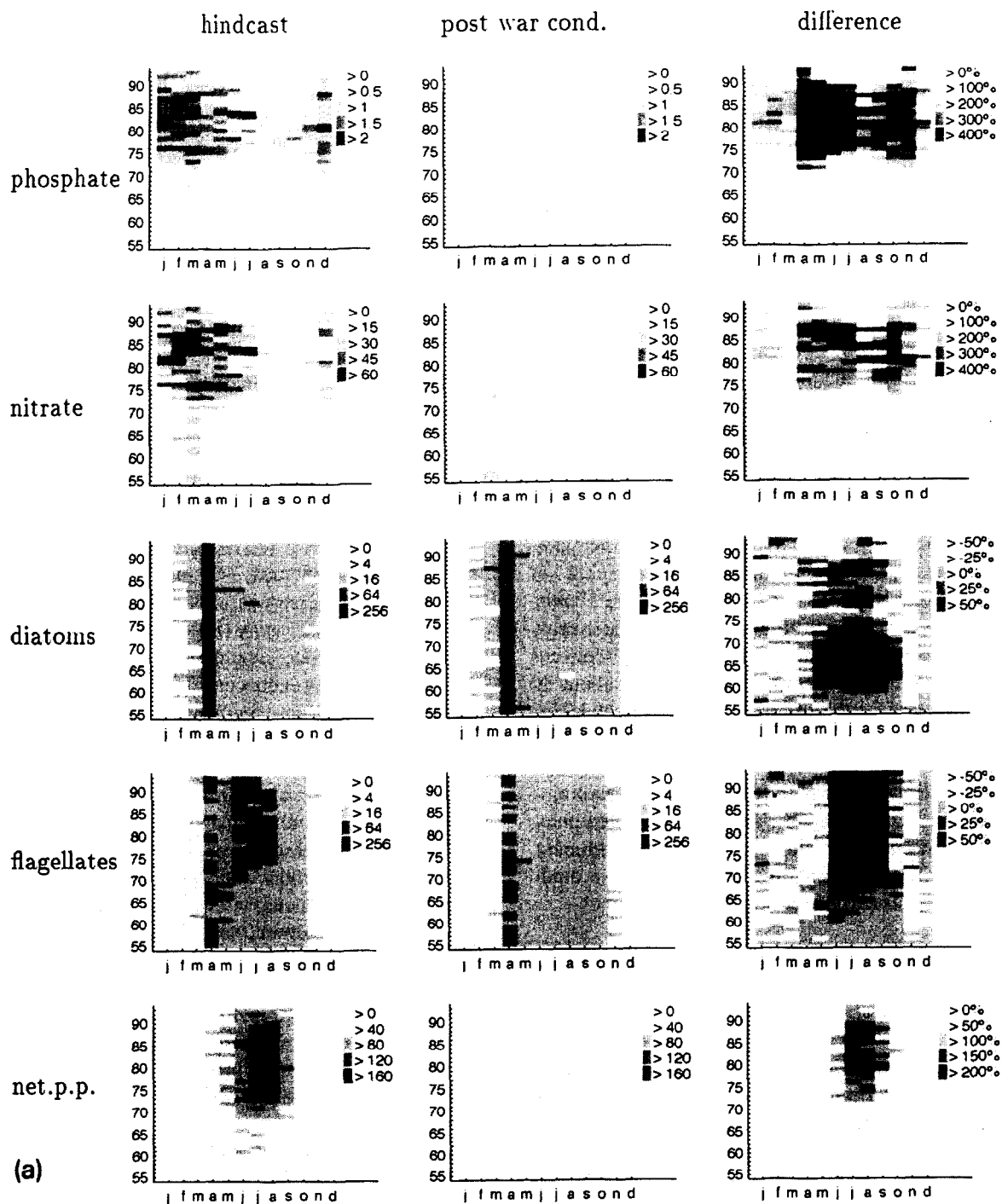


Fig. 6. Temporal development of phosphate, nitrate (both in mmol m^{-3}), diatoms, flagellates (both in mg C m^{-3}) and net primary production ($\text{mg C m}^{-3} \text{ d}^{-1}$) in (a) box 85, (b) box 71, and (c) box 58. The monthly mean values derived from the simulation for the specific boxes are given as consecutive annual cycles (horizontal axis): for the years 1955–1993 (vertical axis) for the hindcast in the first column, for the run with post-war conditions in the second column, and for their relative differences in the third column. Note the different scales for better contrasts of the differences.

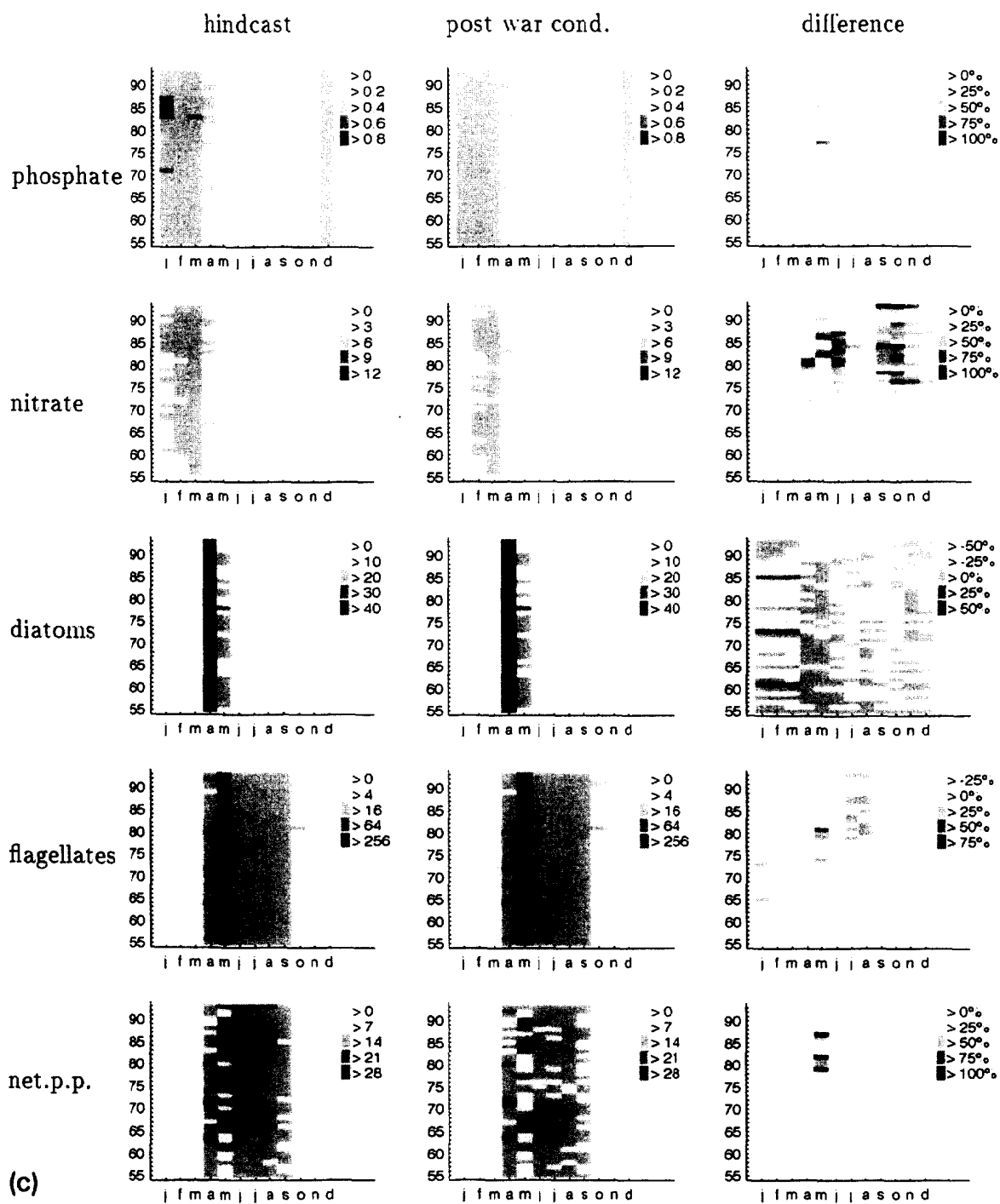


Fig. 6 (continued).

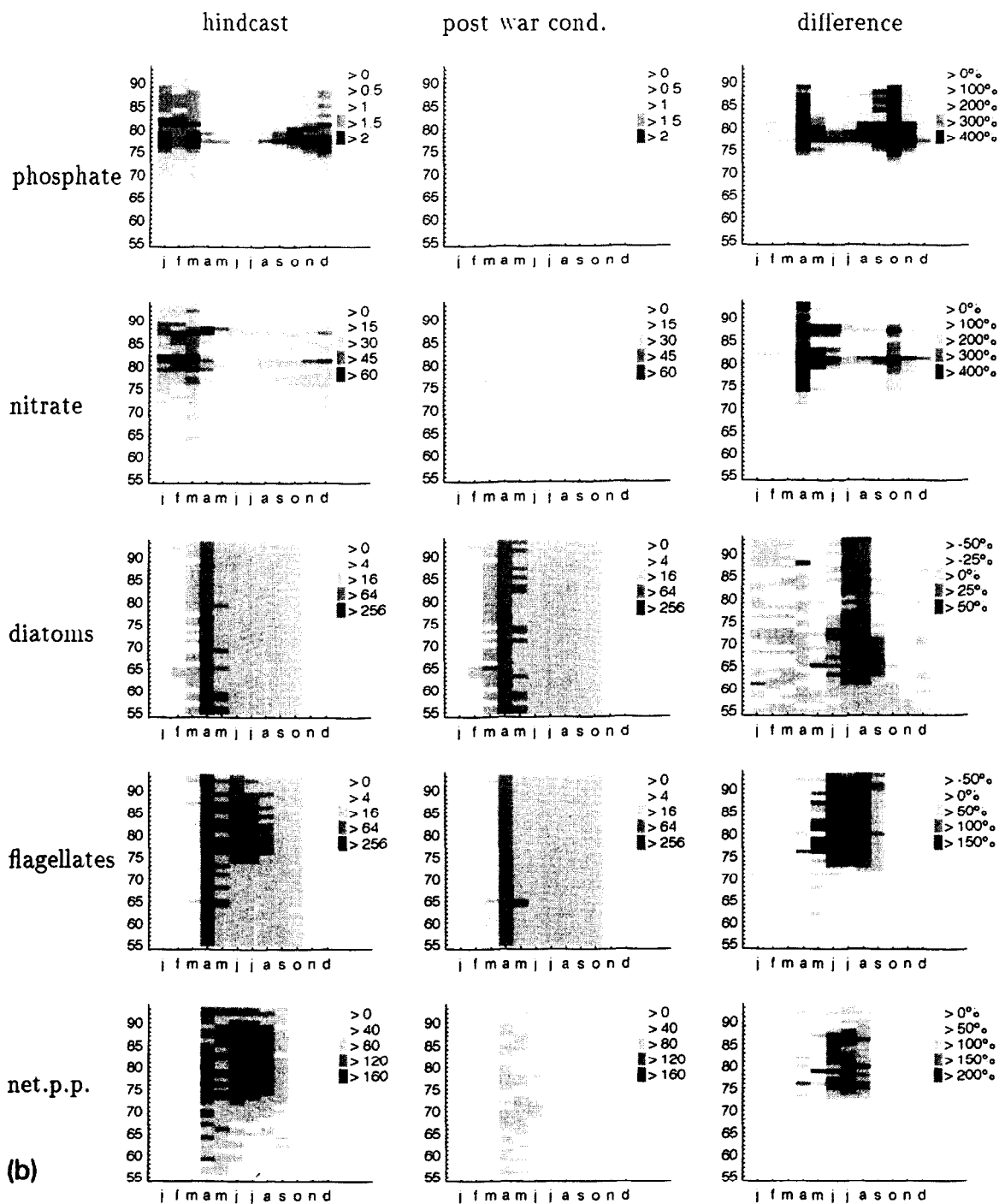


Fig. 6 (continued).

bursts of higher values, and during the 1990s even events of decreasing biomass in April and May compared to the reference by up to 50% happen.

The development of flagellates is very different; they increase from 1972 (>50%) compared to the reference during July and August, while the biomass decreases in most of the other months. Net primary production develops accordingly, mapping the strong activity mostly of the flagellates and picophytoplankton (not shown). The increase of primary production starts in the mid-1960s due to increased abundance of diatoms and reaches more than 100% of the corresponding values of the reference situation during the years 1975 to 1989 in July and August, coinciding with the maximum increase of flagellates.

The long-term development of winter concentrations of phosphate in box 85 over the four decades is strongly related to river input, without noticeable time shift (Pätsch, 1997). The river loads of nitrate and phosphate in the beginning of the 1990s again reach a level, which was observed in the mid-1970s or early 1970s, respectively (Lenhart et al., 1996; Pätsch, 1997). This is reproduced in the hindcast.

The rivers Elbe and Weser discharge into box 71 in our model domain. The phosphate concentrations in the hindcast are high all year from 1977 to 1979 (Fig. 6b). This is a result of the maximum phosphorus inputs by the river Elbe of 6 kt a^{-1} in 1977 (Fig. 2; Lenhart et al., 1996). The differences compared to the reference simulation are restricted mainly to April and September/October from 1975 to 1990, during which large changes occur, and to the summers of 1976–1983. There appears an overall increase of the basic phosphate level from 1974 to 1990. Winter values are twice the reference values from 1976 to 1989.

Elevated nitrate concentrations extend over a longer time period, from the mid-1970s into the 1990s, with two maxima, one in winter 1981/1982 and one in 1986/1987. These maxima can be explained by extraordinary nitrate loads during these years (Fig. 2; Lenhart et al., 1996). The largest differences compared to the reference occur from 1975 to 1993 in April and during 1977 to 1988 in October, nearly as for phosphate. Ammonium, silicate and diatoms behave similarly in boxes 71 and 85. But in box 71 the changes of diatoms compared to the reference are restricted mostly to July and August.

Flagellates reach biomasses $>400 \text{ mg C m}^{-3}$ (e.g., in April 1976), which is much more than in the Rhine outflow area. These values occur mostly during the 1980s. The differences compared to the reference simulation start to be strong intermittently in May, they occur regularly from June to September, i.e. one month earlier than in the Rhine outflow area (box 85). This feature has its counterpart in the pattern of the net primary production, which exhibits the main difference compared to the reference in April and from June to September from 1973 onwards. The maximum occurs in June 1977 ($>235 \text{ mg C m}^{-3} \text{ d}^{-1}$). While primary production occurs in the reference run with values $>40 \text{ mg C m}^{-3} \text{ d}^{-1}$ only during April and May, in the hindcast primary production attains such values during seven months, from April to October, from the early 1970s onwards.

In the mid-1980s the nutrient increase reversed. Also flagellate biomass and primary production decrease in the early 1990s, and the levels in 1993 are comparable to those in early 1970s for phosphate and to those in the mid-1970s for flagellates and primary production.

Moving from box 71 towards the northwest, perpendicular to the coast, with steps of about 100 km to boxes 69, 58 and 46, conditions appear to be less and less eutrophic.

The effect of eutrophication, as increased levels of nutrients, is noticeable from the mid-1970s and decreases from a clear effect in box 69, to a moderate effect in box 58 (Fig. 6c), to no effect in box 46. In box 58 the effects are noticeable only during the growing season (Fig. 6c). The effects for nitrate are in general much larger than for phosphate. The largest differences in nitrate in box 58 occur during 1976 to 1993 between April and November; they seem no longer directly related to the river inputs, and may be related to atmospheric input. Nitrate changes during several months by more than 100% compared to the reference.

The development of diatoms is much the same for both simulations in the boxes 69, 58 and 46. Also, the flagellates do not seem to profit much; in box 69 and 58 there are increases by up to 75% during May in the 1990s, but also decreases of more than 25% during April, June and September from 1975 to 1988, and sporadically also during other months. However, net primary production, which is about

20 mg C m⁻³ d⁻¹ in June, is obviously increasing, especially in May (intermittently >50%), compared to the reference, starting in the early 1970s, continuing by >25% increase until August/September. This is caused by increased picophytoplankton, which utilises the ammonium being excreted by the increased zooplankton.

The dynamics on the gradient from box 85, 80, 65, 46 are similar to those on the gradient 71, 69, 58, 46, but this more southerly region is somewhat more productive and since the mid-1970s the changes compared to the reference occur here from February to March and from May to September thus over the whole growing season. To show how far the river-induced eutrophication penetrates into the central North Sea the annual differences of primary production between the hindcast and the reference simulation were plotted against the corresponding increments of annual river inputs of phosphate and dissolved inorganic nitrogen for areas ranging from

the continental coast to the central North Sea (Fig. 7). Except for the central North Sea (box 46), nonlinear relations can be established as far into the North Sea as to box 58, although — of course — with decreasing effects in the amounts of primary production. The relations show steep increases of additional primary production for small increments of river inputs. The increments of primary production level off for large increments of river input, especially in the German Bight (box 71), indicating that primary production increases cannot cope with increasing river inputs because the carrying capacity — though driven high by the nutrient inputs — is reached. For the Rhine area (box 85) this is not valid for phosphate; very large input increments cause correspondingly (large) primary production increments. Overall, a clear influence of eutrophication is revealed even for the southeastern central North Sea (box 58).

The change of the phytoplankton dynamics with distance from the continental coast can be partly ex-

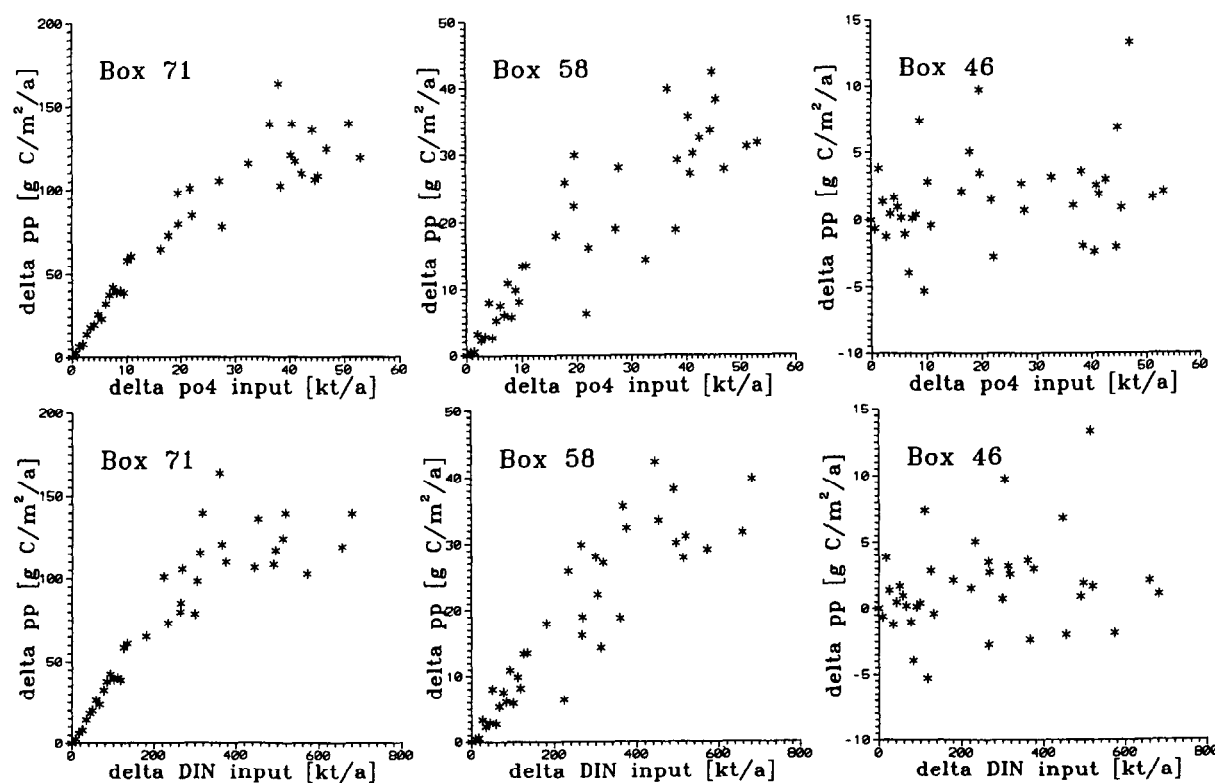
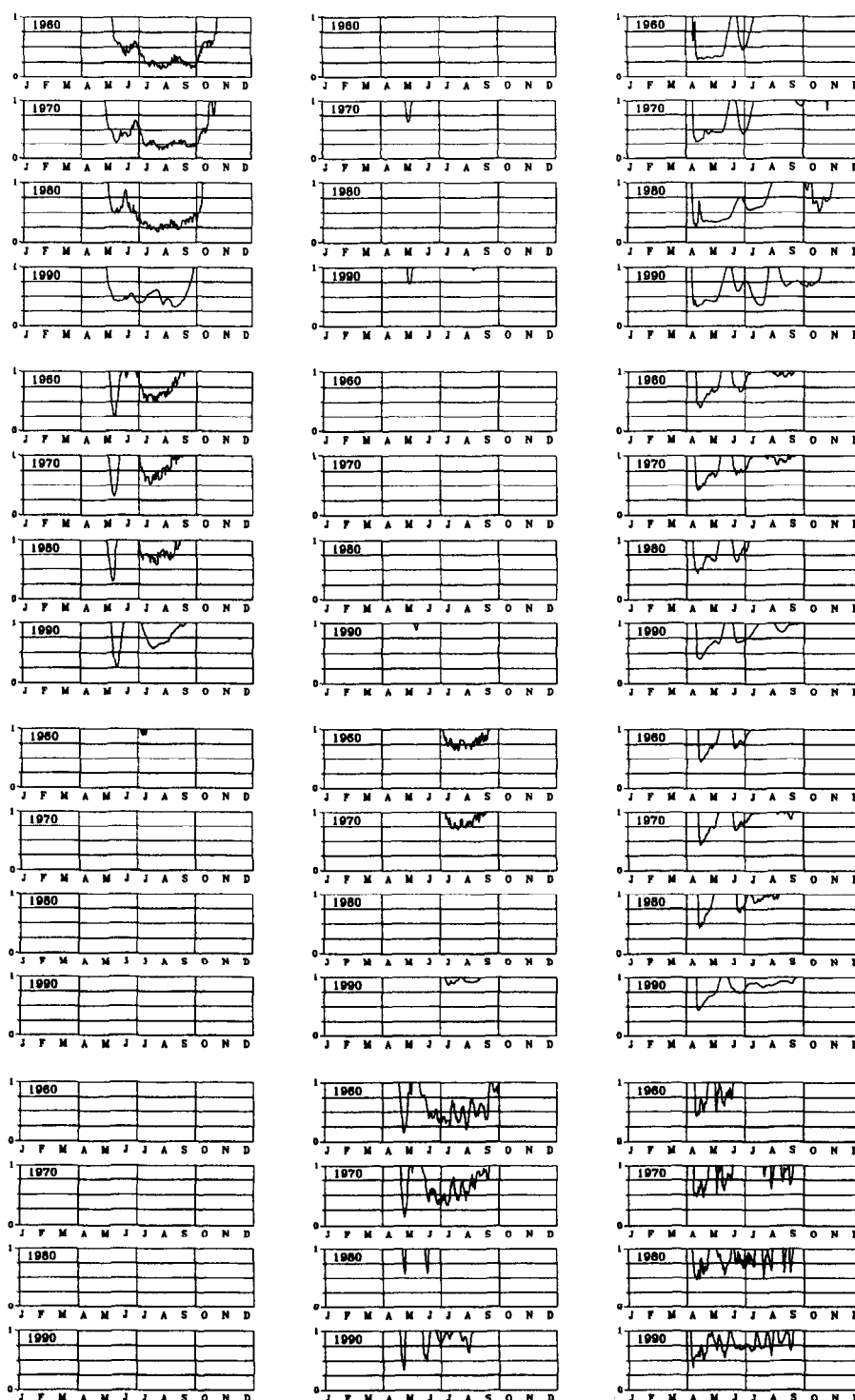


Fig. 7. Relations of simulated annual increase of primary production (delta pp) versus the annual increase of river inputs (in comparison to the reference simulation N) for 39 years of simulation, for phosphate (delta PO₄; upper panel) and dissolved inorganic nitrogen (delta DIN; lower panel) in the boxes 71 (inner German Bight), 58 and 46 (central North Sea).



Box 46

Box 58

Box 69

Box 71

Fig. 8. Simulated limitation functions for diatoms for the boxes 46 (central North Sea), 58, 69, and 71 (inner German Bight), for the years 1960, 1970, 1980 and 1990. The limitation functions for nitrogen (left), phosphate (middle), and for silicate (right) are given. 1 = no limitation, 0 = total limitation.

plained during all decades by the limitation functions for diatoms and flagellates during the years 1960, 1970, 1980 and 1990 (Fig. 8). When comparing the regional differences with increasing distance from the coast, the most striking feature is that diatoms as well as flagellates (not shown) are not limited by nitrogen close to the coast (box 71), but by phosphate (at least in the inner German Bight); but both taxa are limited by nitrogen and (nearly) not by phosphate in the more distant areas of the central North Sea (boxes 58, 46). This is valid for all decades. For diatoms phosphate limitation in the German Bight was strongest during the 1960s and 1970s, disappeared in the 1980s and reappeared in the 1990s. In box 69 phosphate limitation occurs only in the 1960s and 1970s. Silicate limitation is, however, important in all areas during the four decades (Fig. 8), everywhere increasing continuously over the decades. For flagellates the extent of nitrogen limitation increases towards the central North Sea, until it covers the period from May to October in box 46.

The examples given here demonstrate that the regional dynamics differ on scales of 50 to 100 km in the southern and central North Sea. Eutrophication affects the lower trophic levels as far off the continental coast as the southeastern central North Sea (box 58), although only little change can be detected in the nutrient concentrations. Compared to the reference run the hindcast clearly shows the influence of atmospheric and riverine input on the North Sea as far as about 300 km perpendicular from the continental coast.

4.3. Comparison of annual cycles of nutrients and chlorophyll in the central and northern North Sea

In the central and northern North Sea the two runs differ only little, and the annual cycles during the hindcast mostly do not change. We compare therefore a mean annual cycle and its variability, derived from the simulation for the years 1955 to 1993, in different boxes to corresponding climatological annual cycles obtained from observations during 1960 to 1994 (Radach et al., 1995; Radach and Pätsch, 1997). We have used the same statistical approach for both the data and the model simulation.

For the comparison we have chosen five boxes, i.e. the boxes 69, 58, 46 and 31, that stretch out to the

northwestern North Sea from the German Bight to 58° N, and box 65, that is situated halfway between the boxes 46 (56°–57° N) and 85 in the southern central North Sea, where the rivers Rhine and Meuse enter. These are areas, where we expect less and less influence of eutrophication with distance from the continental coast. The simulated annual cycles of the nutrients phosphate, nitrate, ammonium and silicate, and of chlorophyll compare to the observed annual cycles quite differently.

The winter levels of phosphate are well met, but the simulation predicts a stronger and longer depletion phase than observed (Fig. 9a) in all of the boxes, although a basic concentration still remains. In box 69 the late summer increase is simulated too late by two months. Nitrate, however, shows a good coincidence between simulation and observations (Fig. 9b). The observed silicate concentrations are higher in summer than simulated, and the regeneration occurs one or two months earlier than in the simulation (Fig. 9c). Although the chlorophyll observations are sparse in boxes 46 and 69, it seems that the predicted order of magnitude is correct, whereas the observed spring blooms are much smaller than simulated. The simulated summer stocks meet the order of magnitude of the observations in all boxes considered (Fig. 9d). Also, the autumn bloom in the central North Sea box 31 is reproduced. The discrepancy between simulation and observation can be explained for chlorophyll by the fact that phytoplankton blooms occur on relatively small space scales (1–10 km), while the averaging has been performed over areas of 100 km by 50 km; then local blooms are averaged and the result appears to yield small spring blooms. The problem is that the model does not resolve the spatial scales of plankton blooms.

Summarising, the coincidence of observed and simulated mean annual cycles is satisfactory for phosphate, silicate, chlorophyll and ammonium, and it is good for nitrate.

4.4. Comparison of simulated long-term developments with observations in the Dutch and German coastal zones

The simulated long-term development of nutrients and chlorophyll or phytoplankton are compared

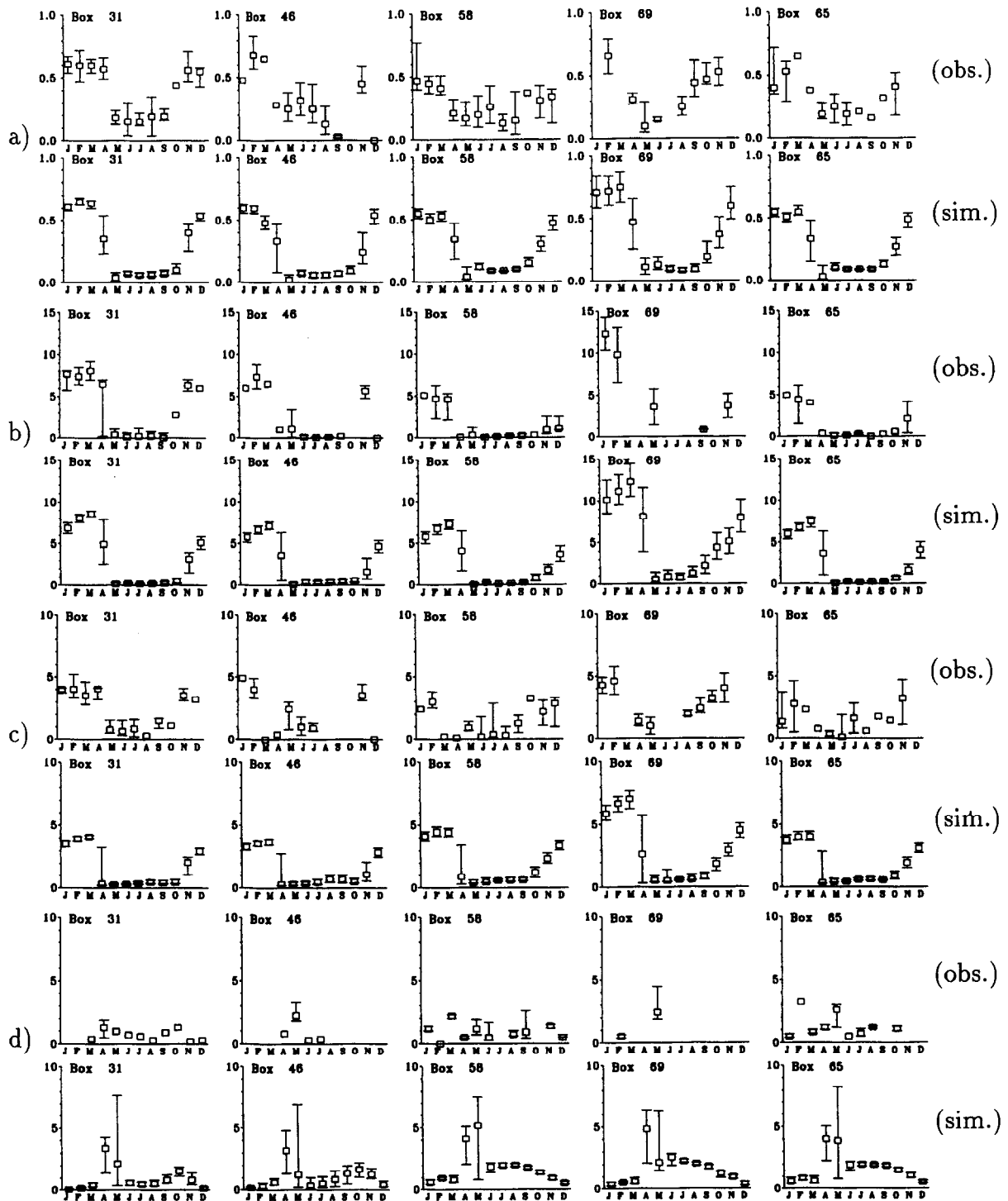


Fig. 9. Hindcast of the years 1955–1993: Observed and simulated climatological annual cycles of (a) phosphate, (b) nitrate, (c) silicate in mmol m^{-3} , and (d) chlorophyll in mg Chl m^{-3} in the boxes 31, 46, 58, 69 and 65.

to long time series on the basis of monthly means at two sites where the comparison between simulation and observed time series at specific stations promise to be fruitful. In the MAST project NOWESP time series have been compiled for temperature, salinity, nutrients, chlorophyll, suspended matter and plankton at several sites in the North Sea (Radach et al., 1996, 1997). Only the sites 4 to 6 are suitable for a comparison, because at those sites relevant time series are available and because they are situated in the continental coastal zone well away from boundaries of the model domain, but within the zone of strong influence of rivers Rhine/Meuse and Elbe and thus of strong gradients prevailing perpendicular to the coast. We restrict the examples here to NOWESP sites 5-2 and 5-3 (Dutch coastal waters) and 6 (Inner German Bight).

As the ERSEM boxes of the setup ND130 resolve the steep gradients in the coastal zone only on a spatial scale of 50–100 km, we face problems resulting from the model setup, when comparing the simulated time series to observations at single points or in small boxes of scales <50 km. The NOWESP sites do not coincide with the $1^\circ \times 1^\circ$ ERSEM boxes, which usually cover — at least partly — these NOWESP sites. In Table 4 the corresponding numbers of the overlapping ERSEM boxes are given. For our comparison the results from the box model are artificially refined by mapping the box concentrations onto the hydrodynamic grid (20 km by 20 km) and by smoothing the box results on that grid two-dimensionally to create a smooth gradient rather than steps on the scale of the hydrodynamic grid. The state variables in the $1^\circ \times 1^\circ$ ERSEM boxes are weighted according to Table 4 to enable a comparison between model results and observations. The weights are determined by re-

lating the overlapping areas of the ERSEM boxes to the areas of the NOWESP sites and to the smoothing procedure (Pätsch, 1997). At the chosen sites we will demonstrate how well observed time series can be reproduced by the ecosystem model ERSEM. We will consider the nutrients at site 5-2, but chlorophyll is lacking at site 5-2, and therefore the chlorophyll observations from site 5-3 are used. Chlorophyll is included in the comparison, although it is a diagnostic variable in ERSEM, calculated from the four groups of phytoplankton by applying a C/Chl ratio of 50 to flagellates, picophytoplankton and inedible phytoplankton and of 25 to diatoms.

In addition to the graphical presentation of the time series we provide statistical measures of the coincidence of simulation and observations (Tables 5 and 6), separately for all months, for winter (December–February) and for summer (April–September). The long-term mean and standard deviation are given for both the simulation results and the observations. N is the number of months included in the analysis. The entity rms (q) is the root mean square of the mean quadratic distance between simulated and observed monthly means, normalised by the standard deviation of observations. The correlation coefficient (c) is given together with 1% and 5% significance levels for the correlation.

4.4.1. Comparison with Dutch monitoring data (NOWESP site 5-2)

Site 5-2 is situated in front of the Rhine estuary, about 30 km offshore, in the middle of the gradient area in the coastal zone and represents average coastal zone conditions. Nutrient data are used from 1976 to 1988. For our comparison we show chlorophyll at NOWESP site 5-3, situated 20 km north

Table 4

Correspondence of NOWESP sites (with geographical positions) and ERSEM boxes, and interpolation weights for comparison of simulation results and NOWESP time series of the given state variables

NOWESP site	Position	ERSEM ND130 box numbers	Weights >0.02 (rounded)	Data source	State variables
5-2	3°48' E–4°08' E, 52°12' N–52°32' N	81, 82, 85	0.71, 0.23, 0.06	RWS, The Hague, NL	PO ₄ , NO ₃ , SiO ₄
5-3	3°18' E–3°48' E, 52°22' N–52°42' N	74, 75, 80, 81, 82	0.14, 0.05, 0.14, 0.65, 0.13	RWS, The Hague, NL	PO ₄ , NO ₃ , SiO ₄ , Chl
6	6°40' E–8° E, 54°N–54°45' N	70, 71	0.64, 0.36	BAH, Hamburg, DE	PO ₄ , NO ₃ , NH ₄ , SiO ₄ , Chl, diatoms, flagellates

Table 5

Statistical analysis of coincidence of simulated and observed time series for nutrients at NOWESP site 5-2 and for chlorophyll observations at NOWESP site 5-3 (Dutch coastal waters)

	State variable											
	Phosphate			Nitrate			Silicate			Chlorophyll		
	All months	Winter	Summer	All months	Winter	Summer	All months	Winter	Summer	All months	Winter	Summer
Mean												
sim	0.69	1.15	0.37	12.91	20.20	8.09	4.50	10.44	0.60	2.09	0.65	3.13
obs	0.70	1.10	0.41	16.29	26.16	10.47	4.11	8.97	1.30	2.19	1.21	2.55
Standard deviation												
sim	0.41	0.16	0.18	7.73	4.64	4.88	4.73	1.99	0.14	1.24	0.12	0.81
obs	0.42	0.33	0.29	13.07	10.70	10.49	4.73	4.77	1.08	1.67	0.65	1.80
Further statistical properties												
N	144	36	72	204	51	102	144	36	72	192	48	96
rms	0.81	0.89	1.23	0.70	1.03	0.77	0.72	0.86	1.21	0.95	1.28	0.92
corr	0.66	0.45	−0.08	0.78	0.49	0.73	0.74	0.62	−0.12	0.43	0.22	0.50
5%	yes	yes	no	yes	yes	yes	yes	yes	no	yes	no	yes
1%	yes	yes	no	yes	yes	yes	yes	yes	no	yes	no	yes

The means and standard deviations are given for the simulation results (sim) and the observations (obs) for phosphate, nitrate, silicate and chlorophyll for the whole year (all months), winter (December to February) and summer (April to September). In the lowest panel further statistical measures are given: *N* is the number of available data, the root mean square error (rms) and correlation (corr) between simulation and observations is given together with the 5% and 1% confidence limit of the correlation.

of site 5-2, because chlorophyll is available there as continuous time series of monthly means from 1976 to 1992 (Radach et al., 1997), which is not the case at site 5-2. The long time series from Marsdiep (Cadée, 1986, 1992) originate from the border of the Wadden

Sea to the North Sea, which is excluded from the simulation area, and are therefore not considered here.

After a long-term increase during the 1970s, a slight long-term decrease of phosphate is simulated

Table 6

Statistical analysis of coincidence of simulated and observed time series at NOWESP site 6 (German Bight)

	State variables														
	Phosphate			Nitrate			Diatoms			Flagellates			Silicate		
	All months	Winter	Summer	All months	Winter	Summer	All months	Winter	Summer	All months	Winter	Summer	All months	Winter	Summer
Mean															
sim	0.54	1.00	0.22	13.42	21.76	7.69	28.67	4.09	44.73	39.07	3.41	69.94	6.40	15.30	0.70
obs	0.74	0.96	0.51	14.27	17.15	12.80	24.48	1.83	45.47	23.97	8.63	38.43	7.19	9.77	5.01
Standard deviation															
sim	0.43	0.27	0.17	8.91	6.76	4.94	33.19	3.64	39.25	53.48	1.77	61.46	6.91	2.79	0.46
obs	0.35	0.21	0.28	11.49	11.21	10.85	38.75	1.80	45.69	40.71	6.39	53.43	5.81	5.21	5.46
Further statistical properties															
N	382	96	190	381	95	190	384	96	192	384	96	192	316	78	159
rms	1.10	1.00	1.42	0.91	0.92	0.96	1.08	2.70	1.26	1.63	1.28	1.75	1.23	1.51	1.28
corr	0.66	0.65	0.36	0.50	0.56	0.55	0.33	−0.17	0.09	0.07	0.17	−0.18	0.39	0.11	−0.11
5%	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	no	yes	no	no
1%	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	no	yes	no	no

See further footnote to Table 5.

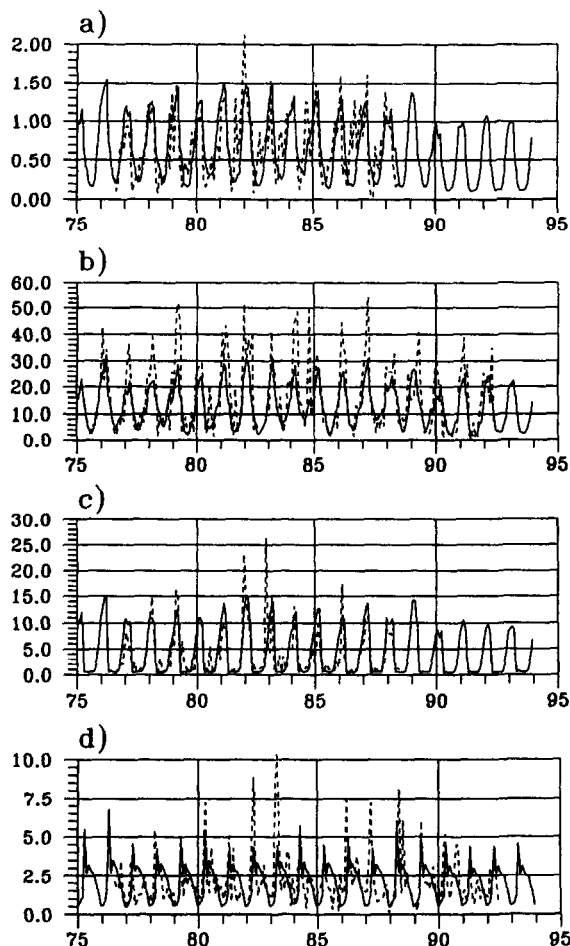


Fig. 10. Hindcast of the years 1975–1993: Temporal development of simulated (full line) and observed (broken line) nutrients (in mmol m^{-3}) at NOWESP site 5-2 and chlorophyll (in mg Chl m^{-3}) at NOWESP site 5-3 in the North Sea, using the indicated weighting (Table 4), for (a) phosphate, (b) nitrate, (c) silicate, and (d) chlorophyll.

and observed after the mid-1980s at site 5-2 (Visser et al., 1996). For phosphate there is a good coincidence for the winter concentrations (Fig. 10a). During the most eutrophicated years several relative maxima during summer are not reproduced by the simulation which yield an rms distance of $q = 1.23 > 1$ and fails in the correlation (Table 5). However, winter values are well correlated, and the decrease after winter is well simulated. The simulated annual cycles are shifted at site 5-2 by about one month in spring and by about several months in summer and fall towards the end of the year. Dur-

ing summer observations and simulation are not in phase, nutrient depletion is overestimated and recovery of higher concentrations occurs too late in the year.

The overall appearance for nitrate (Fig. 10b) is better than for phosphate, judging from the correlations, which are significant for all three cases. Mean levels of observations are rather close to the simulated ones. However, the observed standard deviations are all larger by a factor of two than simulated (Table 5). The mean rms deviation is acceptable for 'all months' and for the summer months; the winter concentrations are strongly underestimated in nearly every year, as expressed by the relatively high value of q . The positive appearance is due to the good coincidence in phase. The depletion during summer is usually simulated well.

Silicate observations are simulated well; the start of depletion and the autumn increase are simulated, which can be seen both from the curves (Fig. 10c) and from the statistical measures (Table 5). The overall correlation is good ($c = 0.74$); deviations originate from sporadically occurring very high silicate concentrations in winters 1981/82 and 1982/83, yielding a high standard deviation. The variability of the winter values including the interannual winter variability is, however, well simulated ($c = 0.62$). During summer the simulated concentrations are very low ($\mu_s = 0.60$), while in the observations frequently relative maxima occur, causing a higher mean ($\mu_o = 1.30$) and a higher standard deviation ($\sigma_o = 1.08$); this difference also yields the high rms error and the lack of a correlation. During the simulation the length of the depletion phase increases, suggesting an increasing period of silicate limitation for diatoms in this area.

The agreement of simulated and observed chlorophyll is satisfactory for all months and for summer (Fig. 10d). The mean values for all months are lying closely together, the mean deviation and the correlation coefficient are satisfactory (Table 5). The winter level and the variance for all time intervals are too low in the simulation. The simulation generally underestimates the maxima of chlorophyll, with the exception of a few years (Fig. 10d). Also, for summer the statistics are satisfactory. The spring bloom maximum occurs in April for simulation and observations; the second simulated maximum is, however,

always in June, different from observations, where the flagellate bloom occurs later in the year, sometimes as multiple maxima (e.g., 1983), sometimes as a strong summer maximum (e.g., 1977, 1990, 1991). The first maximum is caused by the diatom bloom, which is suggested on this monthly time scale by the coincidence of high chlorophyll with high silicate concentrations in 1982 and 1983. The simulation, however, does not reach the high observed maximum values of chlorophyll.

4.4.2. Comparison with Helgoland Roads time series (NOWESP site 6)

The observations at Helgoland are strongly influenced by the discharges of the river Elbe, which combine with the coastal currents (Radach and Bohle-Carbonell, 1990). The time-dependent discharge of freshwater does not enter the hydrodynamic simulation. We expect therefore that the simulation cannot reproduce the consequences of these features in the observations. When comparing, e.g., the Helgoland time series to the simulation results, we have to take into account again that strong gradients occur in the German Bight which are not resolved by the setup ND130. The nutrient concentrations in box 71 are considerably larger than those in box 70. When comparing the simulations to the observations, we compare a weighted sum of the simulated time series in boxes 70 and 71 (Table 4), because Helgoland is situated close to the eastern border of box 70. At Helgoland Roads time series of nutrients and phytoplankton biomass (diatoms, flagellates) are available from 1962 to 1993. The time series derived for NOWESP site 6 are compiled to a large degree from the Helgoland time series. This data set allows us to make statements about the period before the strongly eutrophic period starting around 1975. At this station the data series are about twice as long as the Dutch monitoring data.

The simulated phosphate concentrations (Fig. 11a) follow the observed decadal change, increasing until the late 1970s, stagnating and then decreasing during the 1980s and the 1990s. In the 1990s the concentration reaches the level of the late 1960s again. While the mean for 'all months' is higher in the observations, the standard deviation of the observations is lower than simulated (Table 6). The simulated winter maxima are slightly underes-

timated during the period before 1976; thereafter the river loads of phosphorus are given by measurements, and the maxima in the concentrations show a better agreement between simulation and observations. The spring decrease of the concentrations is well simulated during the period 1975 to 1989. Before this period the simulated decay occurs too early in the year and too strongly.

The statistics for winter phosphate are good; means and standard deviations are similar, the rms distance is $q = 1$, and the correlation is significant. During the strongest river input in 1977 (Lenhart et al., 1996) the simulation overestimates the observed concentration. While the simulated depletion phase in summer shows too low values in the summers before 1975, the coincidence is improved thereafter, but the increase of concentrations in summer occurs too late in the simulation by about two months, probably due to retarded benthic regeneration of phosphate. It appears that the initial conditions and the river input from the Elbe for phosphate were set too low, causing too low maxima and minima in the concentrations before 1975.

The mean observed and simulated concentration levels of nitrate during all months are fairly similar, but the winter means are overestimated and the summer means are underestimated (Table 6). The simulated nitrate concentration is close to observations during two periods, from 1966 to 1969 and from 1981 to early 1987; both curves are well in phase during these periods (Fig. 11b). The appearance of the single years is very different. The observed standard deviations during all months as well as during winters and summers are larger than the simulated ones (Table 6). The maxima in 1981 and 1987 were simulated; however, the short-term variability can only partly be reproduced. The simulated annual cycles appear to have shorter phases of low nitrate concentration. At no time a depletion of nitrate is simulated, where observations indicate possibly a depletion by low concentration values (1964, 1967–1969, 1973, 1976). For nitrate the times of greatest concentration changes occur too early (for phosphate too late), especially after summer. Large simulated concentrations occur in the winters 1981/82 and 1986/87, but not in the data in 1981/82. During these winters the German Bight suffered large river inputs of dissolved inorganic nitrogen (Fig. 2b). The high

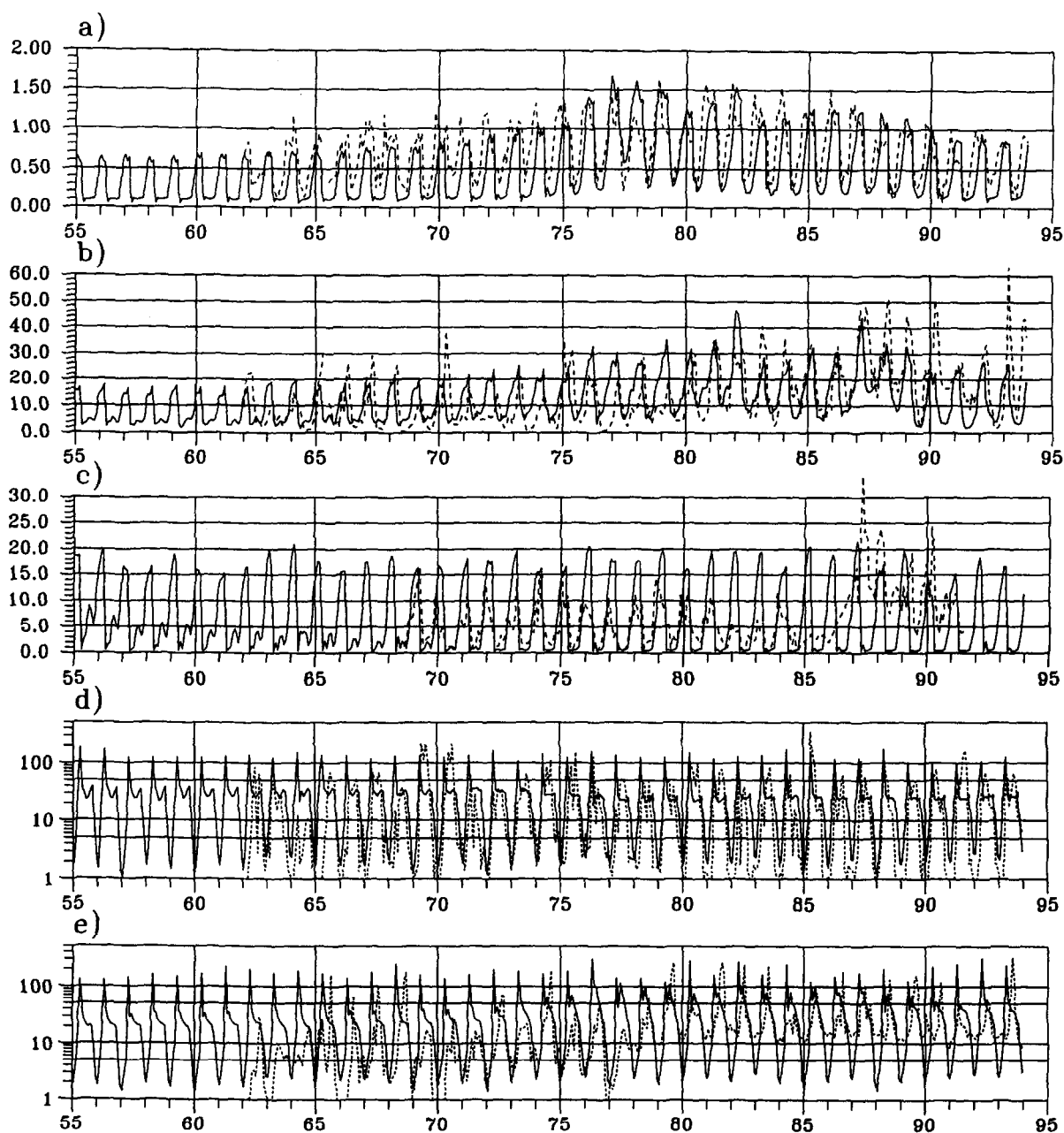


Fig. 11. Hindcast of the years 1955–1993: Temporal development of simulated (full line) and observed (broken line) nutrients (in mmol m^{-3}) and phytoplankton (in mg C m^{-3}) at NOWESP site 6 in the North Sea, using the indicated weighting (Table 4), for (a) phosphate, (b) nitrate, (c) silicate, (d) diatoms, and (e) flagellates.

observed nitrate concentrations in the years 1988–1990 and 1993–1994 are not hindcasted. In 1993 no corresponding river input was observed. While the observed concentrations increase during the late

1980s and occasionally during the 1990s, the simulated concentrations seem to decay.

Silicate is grossly overestimated in the winters, but underestimated in summers (Table 6). Therefore,

are mainly determined by the meteorological forcing and its variability. The ecosystem model ERSEM is thus driven with a rather realistic time- and depth-dependent circulation pattern that is condensed from a grid resolution of $\frac{1}{5}^\circ$ by $\frac{1}{3}^\circ$ to a spatial resolution of $1^\circ \times 1^\circ$ in the version ND130 of ERSEM.

It is, however, not only the circulation, i.e. the flow pattern, that influences the development of the ecosystem in nature. Vertical mixing and stratification have a decisive influence on the phytoplankton dynamics (Radach and Moll, 1993; Eigenheer et al., 1996). In ERSEM these features are represented by relatively coarse parametrisations. The chosen box structure of an upper layer of maximum 30 m thickness, separated in regions of deeper than 30 m from a deep layer (30 m–bottom), forbids a finer resolution of the vertical gradients and of the vertical diffusion on scales <30 m, and the upper 30 m are treated as a well-mixed layer without any vertical structure. Vertical turbulent diffusion acts across the interface between the two layers and serves for realistic transport rates as long as the mean concentrations in the layers are justified. Also, horizontal turbulent diffusion acts on the concentration fields. As shown by Lenhart and Pohlmann (1997) the parameterisations for horizontal diffusion can be (and were) adapted to yield results for the dispersion of passive material by the transports that resemble those of a finely resolved (about 20 km) transport model.

Third, there are problems related to the scales resolved for the distributions of chemical and biological state variables, mostly in space, but also in time as a consequence of the former. Even in the setup ND130 for ERSEM the gradients in the coastal zone are not well enough resolved. This hampers a solid comparison of model results and observations (see below). The horizontal resolution of the coastal zone is not sufficient to resolve the strong gradients in this area well enough for such a comparison. This applies already to the hydrodynamic simulation, because it does not take into account freshwater discharge of the rivers and therefore is not able to simulate the meso-scale stratification features due to temperature and salinity, which are typical in the areas in front of estuaries. These physical meso-scale structures have strong effects on the plankton dynamics (Hickel et al., 1992). As the mesoscale has neither been resolved in the physical model nor by the eco-

logical model ERSEM, one cannot expect that the simulations will reproduce the observed small- and meso-scale features. One can expect, however, the reproduction of the general spatial appearance and temporal development of the process of eutrophication, as was demonstrated.

It was necessary to use partly climatological annual cycles instead of actual time series for different forcing functions, because actual data were lacking. Although great care was taken in deriving the boundary conditions at the open sea boundaries, the forcing functions result from interpolation of partly sparse data. This situation cannot be changed for the past and will also occur in the future, because the capability to obtain the necessary observations will never be adequate to the demands of such a modelling enterprise. Therefore, the uncertainty connected to the boundary conditions and the forcing will carry over in an unknown manner into an uncertainty of the resulting concentrations. Simulations should be carried out to quantify this uncertainty.

The shaping of the limited trophic resolution in ERSEM has been discussed and rationalized elsewhere. With respect to the long-term simulations the general problem of comparing model state variables to observations appears in an intensified form.

5.2. Problems in comparing simulation results and observations

The uncertain correspondence between state variables in the model and measured quantities gives rise to problems in the comparison, both from the point of view of spatial resolution and of trophic resolution. For instance, in the area where the best data sets are available and where the gradient perpendicular to the coast is resolved by the observations, the spatial resolution of the model does not allow us to compare the observed time series directly to a box-specific time series. Each of the coastal ERSEM boxes contains an area, which exhibits a strong spatial gradient. The NOWESP sites 4-1, 4-2, 4-3 and also sites 5-1, 5-2, 5-3 line up along the gradients, but do not lie in the same box; therefore a comparison with these data necessitates the averaging of the observed time series, levelling off their spatial characteristics. This shows that any averaging of the model results for different boxes and of the obser-

also the standard deviations are grossly underestimated in the simulation, especially in summer. However, the large observed standard deviations are influenced by the unexplained (Hickel et al., 1995) jump from very low concentrations in 1985 to the highest observed silicate concentrations in 1988 (Fig. 11c). The statistical measures of rms deviations and the correlation coefficients are not satisfactory, although the phase differences between the simulated and observed concentrations are mostly small.

The similarity between simulated and observed diatoms is satisfactory. The timing of the spring bloom is well met; however, the diatom bloom occurs about one month earlier during many years in the simulations compared to observations (Fig. 11d). The observed and simulated concentration mean in summer is nearly equal; also, the observed standard deviations are well simulated (Table 6). However, from May to September the simulated concentrations are about 30 mg C m^{-3} and thus lower than observed during summer (up to 200 mg C m^{-3}). The duration of higher observed values is shorter than in the simulation, thus compensating the effects in the mean. Measured winter concentrations become very small from 1980 to 1993; although the shape of the annual variation is simulated, the magnitude of the small values is not reproduced. The lacking correlation during the summer period indicates that the long-term changes are not clearly simulated.

The comparison between observations and the simulation of flagellates is not satisfactory. No correlation occurs for all three cases (Table 6). The means and the standard deviations of the flagellates are larger in the simulation than in the observations during all months and during summers (Table 6). While the observations exhibit large variations in the shape of the annual cycles, the simulation does not (Fig. 11e). The maximum of the flagellates occurs in spring, as for diatoms, which is different from observations, where the maximum occurs in summer. The simulation is not capable to reproduce the summer blooming of flagellates. However, it yields a broad peak over the season when adding all non-diatom phytoplankton together (not shown).

At Helgoland in the years of strongest eutrophication, i.e. 1979, 1981–1983, and 1993, the observed flagellates reach highest concentrations with values $>200 \text{ mg C m}^{-3}$; also in the simulation higher con-

centrations are reached, but not only during this period. In the simulation the period of the occurrence of high concentrations covers the periods 1972 to 1976, 1980 to 1984, and 1990 to 1993. Although the concentrations of flagellates are not met, the model is capable of reproducing elevated levels of flagellate biomass from the nutrient inputs during summer. This becomes clear, when the averaged summer values from June to September are correlated with the corresponding observations (not shown).

5. Discussion and conclusions

5.1. General intrinsic problems of the model formulation

There are a number of intrinsic problems related to the technical realization of the ecosystem model ERSEM as well as to the physical and biological simplifications which were made.

The intrinsic technical restrictions limit the working with the model ERSEM over long time spans. The complex ecosystem model ERSEM needs 14 days of computer time on a workstation SUN Sparc 10 for forty years of simulation. This restricts the number of numerical experiments which can be performed. For instance, a thorough sensitivity analysis concerning the long-term driving mechanisms is hardly possible. The simulations presented in this paper are the final ones of a series of about twenty simulations, including long-term test runs.

The second kind of limitations pertinent to the long-term runs result from the different simplifications necessary in the modelling process, which inevitably cause certain shortcomings. This relates to the physical system as well as to the representation of the biological system.

The general circulation pattern on the shelf obtained with the general shelf seas circulation model HAMSOM (Backhaus et al., 1986; Backhaus, 1989) does not yield fully baroclinic conditions, because the density field is prescribed in the hydrodynamical model for the 39 years by one diagnostically determined climatological annual cycle of monthly density fields for each of the different depth levels. However, as was shown earlier by Backhaus et al. (1986), the model simulates the main features of the circulation of the North Sea and its variability, because both

variations for a comparison remains problematic, but without such an approach the simulated time series differ systematically from the observed ones.

The comparability of biological quantities from simulation and observations is not self-evident. The ecosystem model ERSEM has grouped biological entities according to their functions (Baretta et al., 1995). Phytoplankton is represented in ERSEM by four functional groups, the diatoms, flagellates, pico-phytoplankton and inedibles (including *Phaeocystis*). This grouping is certainly artificial, especially with respect to observations, because the observed quantities do not correspond exactly with the simulated groups. For instance, the groups of diatoms and non-diatoms observed at Helgoland are counted under the Utermöhl microscope and thus the small forms are not counted quantitatively. This is true in spite of the fact that diatoms were simulated relatively well. When lumping the non-diatoms into the functional group 'flagellates', one tends to identify the flagellates in the model with the observed quantity, which is only partly justified. One should not be surprised when the simulated group called flagellates does not coincide with the observed concentrations of the group of flagellates, and perhaps one should compare the observed flagellates with the sum of simulated groups of non-diatoms. Having done this, however, one may conclude that this did not improve the coincidence of observed and simulated phytoplankton. For any comparison the most reliable quantity characterising phytoplankton biomass (possibly chlorophyll) should be used, and reliable procedures should be developed to derive this quantity from the abundances of the observed taxa.

5.3. Changes in the North Sea and their causes

During the last decade variability due to natural and anthropogenic causes has obtained increased attention (Gerlach, 1990; Dickson et al., 1992; Lindeboom et al., 1996). From our model simulation variability on scales from days to four decades can be investigated, and despite the problems mentioned, a few interesting results were obtained which may fuel the ongoing discussion about the importance of natural (climatic) versus anthropogenic causes for observed changes. The changes in the North Sea may principally originate from natural causes,

such as climate change, and/or from anthropogenic causes, such as increases in river and atmospheric inputs. From the two simulations performed indications can be derived as to which changes may be expected from which causes. Here the achievements of the long-term simulation in reproducing the eutrophication during 39 years (1955–1993) are shortly summarized, and the model results are discussed in the light of the existing literature with respect to their coincidence with observations focusing on variability in several frequency bands. The results of the long-term simulations for natural, unperturbed conditions (N) and for the hindcast, i.e. perturbed conditions (H) may be characterized as follows.

5.3.1. Changes in the northern and central North Sea and their causes

The northwestern and northern central North Sea is not affected by river-induced eutrophication. In most parts of the northern and central North Sea the nutrient concentrations have not changed significantly by anthropogenic activity during the last four decades. The variability in the nutrient concentrations in this area occurs predominantly as a consequence of the variable Atlantic nutrient inflow from the north and northwest. The water and nutrient flow across the northern boundaries of the North Sea give no indications of any trend-like changes over the four decades investigated. Neither do the results of the hindcast yield any remarkable changes of the plankton over the forty years in the northern North Sea. Therefore, the hypothesis put forward by Lindeboom et al. (1996) that the inflowing water from the Atlantic has changed its composition and thus caused major changes in the North Sea ecosystem cannot be substantiated by the investigations about the inflow across the northern boundaries of the North Sea. It must be admitted, however, that the nutrient inflow was modelled in both runs N and H on the basis of sparse nutrient data distributed over four decades in this region, and the variability contains much uncertainty not only on the nutrient concentrations, but also on the variability of the water flow at the northern boundaries.

The overall pattern of the nutrient concentrations in the North Sea along a line from the English coast at 54°N to northern Denmark has remained constant. But there appears to be a penetration of

nutrients into the central North Sea from the south, when comparing the simulation H with observations. The North Sea south of the line from the English coast at 54° N to northern Denmark is increasingly affected by eutrophication as one nears the continental coast. The simulation suggests that the southern North Sea continuously filled up with nutrients until the 1980s (Fig. 3). Observations until 1986 do not allow significant regressions to conclude this (Dickson et al., 1988). Compiled North Sea data (Radach et al., 1995), however, show that the winter distributions of phosphate and nitrate exhibit elevated levels in the southeastern part of the North Sea, decreasing to the northwest, which resemble the corresponding simulated ones. In the western part of the southern North Sea, along the English coast, simulated phosphate reaches less, simulated nitrate more intensively northwards. The Danish coastal waters and the Skagerrak show increased nutrient concentrations caused by the continental coastal current and the Baltic outflow. The southwestern Norwegian coast does exhibit changes in the simulated nutrient concentrations of about $0.1 \text{ mmol PO}_4\text{-P m}^{-3}$ and of $1\text{--}2 \text{ mmol NO}_3\text{-N m}^{-3}$ over the four decades; this may be caused by the boundary condition applied at the border to the Baltic. The English coastal waters, however, are obviously influenced by the inflows from the river Tyne, the Wash and the Thames and show increased nutrient concentrations.

5.3.2. *Changes in the southern North Sea and especially in the continental coastal zone and their causes*

The long-term hindcast (simulation H) reproduces main features of the process of eutrophication of the southern North Sea during the last four decades, which was mainly caused by the river input of dissolved and particulate nutrients. After the culmination of river inputs of phosphate in the late 1970s and 1980s (Fig. 2) also the simulated phosphate concentrations decrease especially in the areas which directly take up the river loads; the effect occurs in the continental coastal zone without retardation. The changes in the outer German Bight (box 70) are much smaller (25%) than the changes in the inner German Bight (box 71). The nutrient concentrations in the continental coastal waters are obviously determined by the inflows from rivers Rhine and Meuse

and river Elbe; the large effects of the river discharge are restricted to a narrow area around the estuaries.

From the simulation H, when compared with run N, one may also conclude that the increased nutrient concentrations caused an increased primary production in the continental coastal waters, which reached twice the amount of primary production observed in the early years; this result was also obtained by the early simulation by Fransz and Verhagen (1985). It is important to note that the carrying capacity was reached in wide parts of this area, and primary production of flagellates and diatoms were limited by light limitation together with phosphate limitation; for diatoms predominantly silicate limitation stopped a further increase of primary production, although plenty of nitrogen nutrients were still available (Fig. 8). During the years of greatest eutrophication zooplankton grazing on phytoplankton also limits primary production (Pätsch, 1997). All these results indicate that eutrophication did increase primary production in major parts of the North Sea, but the increase is not simply proportional to anthropogenic input of nutrients via rivers (Fig. 7) in the continental coastal zone.

The detailed analysis of the simulated annual dynamics in the continental coastal areas has shown that the annual cycles were drastically changed by the eutrophication (Fig. 6). This is especially impressing in the areas off the rivers Rhine/Meuse and Elbe, and can best be seen in the nutrient cycles, which change from the early 1970s onwards (Fig. 6a,b). The disappearance and the reappearance of the depletion phase in summer is the most prominent feature, both for phosphate and nitrate, which was observed also (Radach et al., 1990). Also, the simulated shift of the uptake of nutrients by the algae into summer is an observed feature; the nutrients are utilized, which could not be used in spring, e.g. due to light and silicate limitation. The simulated diatoms increase during summer between 1960 and 1975 and decrease later to levels before the 1960s; this was also observed at Helgoland (Radach et al., 1990). There is clear evidence of increased biomass of non-diatoms in the simulation H, as was observed in the continental coastal zone (Cadée, 1992; Radach et al., 1990; Hickel et al., 1992), and a corresponding increase of net primary production (Fig. 6) occurred during that period (1970–1993).

It is noteworthy that the details in the outflow areas of river Rhine and Meuse and of the Elbe are different from each other, and the different interplay of the several agents in both areas is clearly recognisable. In the Rhine outflow area elevated phosphate and nitrate concentrations persist into July and exhibit large differences to the reference simulation N from April to November, whereas in the German Bight the differences to the reference run N are restricted to April and August–November; changes in primary production extend in the Rhine outflow area from July to September, but in the German Bight over a much longer period from April to September. The period of increased flagellate biomass starts earlier in the Elbe area. This may be caused by the higher excess nitrogen input by the river Elbe, showing up in much higher N/P ratios for the river Elbe (Lenhart et al., 1996), compared to the nutrient input of river Rhine.

A feature which is not reproduced in the simulation is the blooming of non-diatoms in summer and a corresponding shift of the main production from spring (diatoms) to summer and autumn (non-diatoms) (Radach et al., 1990).

The other areas which we considered in the south-eastern North Sea show in essence similar features, which are decreasing with increasing distance from the continental coast.

From the comparison of the simulated time series of run H with the observations at NOWESP sites 5-2 (Dutch coast) and 6 (German Bight) several conclusions may be drawn. The mean conditions are reproduced in the Dutch coastal waters for phosphate, silicate and chlorophyll. The simulation does not reach the observed nitrate mean value. The mean observed values in the German Bight are reproduced for nitrate and diatom concentrations, but not for phosphate (which is underestimated) and flagellates (which are overestimated).

The overall variability is characterised by the standard deviations of all monthly mean values. It is estimated well for phosphate and silicate in the Dutch coastal waters, but the observed variability of nitrate and chlorophyll is higher than the simulated variability. At Helgoland the variability of nitrate and diatoms is reproduced, but the simulated variability of phosphate and flagellates is higher than observed.

Both in the Dutch coastal waters and at Hel-

goland the long-term changes in the observations are reproduced qualitatively by the simulation. This is shown for nutrients by the significant correlations between observed and simulated winter values (Tables 5 and 6). The long-term variations are not simulated quantitatively well, but satisfactorily. The chlorophyll in the Dutch waters shows a good coincidence with simulated values. However, at Helgoland the simulated diatoms exhibit no trend or anomaly, in contrast to observations during the 1960s (Radach et al., 1990). The long-term increase of the biomass of flagellates in summer is reproduced qualitatively during the eutrophication phase (Fig. 6a,b).

The interannual variability is measured here by the standard deviations of winter means for nutrients and of summer means for biological state variables. This approach guarantees that no intra-annual variation is incorporated in the standard deviation. The interannual variability is generally underestimated by the model, except for phosphate at Helgoland. The interannual variability in the nutrient observations is about twice as large as the simulated one. For chlorophyll in Dutch waters and diatoms at Helgoland the underestimate is even more severe (about six times larger observed variability). Also, the simulated variability of the flagellates at Helgoland is three times smaller than the observed variability. The causes of the underestimation of the interannual variability may lie in the use of climatological annual cycles of temperature and salinity, on which the hydrodynamic simulation is based. Also, a mean annual cycle for particulate suspended matter was prescribed, which influences attenuation strongly. A higher variability would certainly be obtained in the simulation, if these parameters would be treated prognostically or prescribed time-dependently.

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