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Climatological annual cycles of nutrients and chlorophyll in the North Sea

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Abstract

A large amount of nutrient and chlorophyll data from the North Sea were compiled and organised in a research data base to produce annual cycles on a relatively fine spatial resolution of 1° in each horizontal direction. The data originate from many different sources and were partly provided by the ECOMOD data base of the Institut für Meereskunde in Hamburg and partly by ICES in Copenhagen to cover the time range from 1950 to 1994. While the annual cycles of nutrients and chlorophyll derived for the continental coastal zone are representative for the decade 1984–1993 only, those for the remaining parts of the North Sea may be considered climatological annual cycles based on data from more than four decades. The composite data set of climatological annual cycles of medians and their climatological ranges is well suited to serve for validational and forcing purposes for ecosystem models of the North Sea, which have a resolution larger than or equal to 1° in both longitude and latitude. The annual cycles of the macronutrients and chlorophyll presented here for 1° × 1° squares in the North Sea show especially that sufficient observational data exist to provide initial, forcing and validational data for the simulations with the 130-box setup (ND130) of the ecosystem model ERSEM. The annual cycles presented give a clear picture for the whole of the North Sea. The highest concentrations occur at the continental coasts as a result of continued river input, which is added to the ongoing atmospheric input over the North Sea. Also, from the Atlantic Ocean water with relatively high nutrient concentrations enters the North Sea via the northern boundary. In the productive areas on and around the Dogger Bank nutrient concentrations are lower than in the other parts of the North Sea, even in winter. The areas with seasonal stratification have very different annual cycles in the upper (0–30 m) and lower layers (30 m–bottom). The shallow boxes are fully mixed and exhibit a relatively fast increase of nutrient concentrations caused by summer regeneration of nutrients.

Keywords: climatological annual cycles; nutrients; chlorophyll; North Sea, ecosystem model, ERSEM

1. Introduction

The ecosystem model ERSEM (European Regional Seas Ecosystem Model) has been developed during the last seven years (1990–1996) as a tool for understanding the functioning of the North Sea ecosystem. The details and achievements of the modelling activity have been presented in many papers. (For an introduction to ERSEM see Baretta et al. (1995), the ERSEM papers cited therein and the other papers in this issue.) One important aspect of modelling is how to get faith into the modelling results. The according procedure is called validation,

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for which many data of different kinds are needed. For testing and validating the model at least annual cycles of the main state variables are needed to enable a comparison of model outcome with observed system behaviour.

Also, for several other purposes such as initialising and forcing of the ecosystem model ERSEM data were needed in amounts that allow us to prescribe the initial situation within the North Sea and the temporally continuous forcing at the open boundaries of the simulation area (i.e. boundary conditions) by statistically meaningful data products. None of such comprehensive data sets existed before ERSEM. Generally speaking, validational data suitable for being compared with North Sea-wide ecological model simulations were lacking. Therefore such data sets had to be produced within the ERSEM project.

For most of the state variables included in ERSEM the available amount of data is insufficient, and — except for temperature and salinity — only for the nutrients and chlorophyll sufficient data were publicly available to form the necessary data products. As we intend to relate the simulation results to annual cycles, we have to define time series from the data which can serve this purpose. Inspection of the available data led us to the conclusion that sensible statistical quantities could be formed, after quality checking, on the basis of aggregating the data per month and per spatial box, disregarding the specific year. For most parts of the North Sea data from all years were used to define so-called 'climatological' monthly means within a specified box, and thus climatological annual cycles per box were created. In addition climatological ranges were derived from the data sets whenever possible. The term 'climatological' indicates that the means were formed over decades. This expression is commonly used for analogous data in meteorology (Hellermann and Rosenstein, 1983) and oceanography (Levitus, 1982; Damm, 1989).

For the continental coastal zone (CCZ), however, the procedure had to be modified, because variability of the concentrations occurs on periods longer than decades in this area of riverine influence. In the CCZ analysis has been restricted to the decade 1984–1993, and care has been taken that the data in this decade were adequately weighted to calculate representative annual cycles.

According to the rationale of validation, which is discussed later, we concentrated on the compilation of all available nutrient and chlorophyll data to describe climatological annual cycles, accepting the inhomogeneity of the data in space and time, but regarding possible long-term changes in the concentrations. We have tried to compile as many nutrient and chlorophyll data as possible from many different sources to obtain statistical reliability of the statistical estimates of the monthly means and the ranges of variability to the mean conditions, which we produced. Therefore, we restricted ourselves to the state variables phosphate, nitrate, ammonium, silicate and chlorophyll.

The nutrients phosphate, nitrate, ammonium and silicate are prognostic state variables in ERSEM, which can directly and without any conversion be compared to the observations. Chlorophyll is not a predictive variable in ERSEM, but a diagnostic state variable, which is calculated from phytoplankton carbon by applying different C/Chl-ratios to the different phytoplankton groups and then summing the resulting chlorophyll concentrations; this quantity can then be compared to the chlorophyll observations.

In the ERSEM project three different setups of the ecosystem model ERSEM were used for the whole North Sea. The 15-box setup, ND15, was used during the first phase of ERSEM (Baretta et al., 1995). The 130-box setup, ND130, was chosen as the standard setup during the second phase of the ERSEM project (1993–1996), when we started to apply ERSEM to the coastal areas where the 15-box setup did not satisfy the needs of spatial resolution to properly describe the pathway of river inputs from the estuaries along the continental coast into the central North Sea. The continental coastal application of ERSEM (COCOA) used an even finer spatial box resolution in the continental coastal zone (Lenhart et al., 1997). For each of the ERSEM setups suitable data sets of monthly means have been created (Radach et al., 1996a).

So far data products from the basic data sets have been used only for the 15-box ND15 setup of ERSEM (Radach and Lenhart, 1995; Lenhart et al., 1995) and for the three-dimensional primary production model ECOHAM1 of the North Sea (Moll, 1995, 1997) for validation and forcing of model simulations. The data base was also utilised for the refined coastal application COCOA (Lenhart et al., 1997). A detailed description of the data sets, together with the whole procedure of obtaining the climatological annual cycles from the original data sets, is given by Radach et al. (1996b) for the North Sea as a whole; in addition to the procedure outlined in the latter report a specific treatment of the CCZ is presented in this paper.

This paper is restricted to the presentation of annual cycles derived from observations for the ERSEM ND130 setup, for which the North Sea is divided into 130 spatial boxes; the boxes are mostly regular 1° × 1° squares. Although the annual cycles were produced especially for use in the modelling project ERSEM, they have a wider range of application.

2. Material and methods

2.1. The ERSEM model setup ND130

In the first phase of the ERSEM project a 15-box setup (ND15) was used. The rationale for the ND15 setup was given in detail by Lenhart et al. (1995). Although the gross features of the circulation and of the stratification were entering this setup, the ND15 setup was not suited to reproduce the dynamics of the continental coastal strip, where strong horizontal gradients prevail all year round (Radach and Lenhart, 1995). It became clear that the horizontal resolution had to be refined, and therefore the ND130 setup was constructed.

In the ND130 setup the concept of a two-layered system was maintained. During summer large areas of the North Sea are stratified, and during this period primary production is mostly confined to the upper layer. Although it is known that the thermocline depth varies in the North Sea in time and space (Tomczak and Goedecke, 1962; Otto et al., 1990), for the stratified areas the approach of a two-layered system, consisting of a productive upper layer and a non-productive lower layer, was deliberately kept for reasons of simplicity in modelled physics. The boxes were divided in the vertical at the depth of 30 m wherever stratification prevails during summer.

This depth was shown to be a reasonable approximation of the thermocline depth in the North Sea (Pohlmann, 1996). For deciding which of the boxes

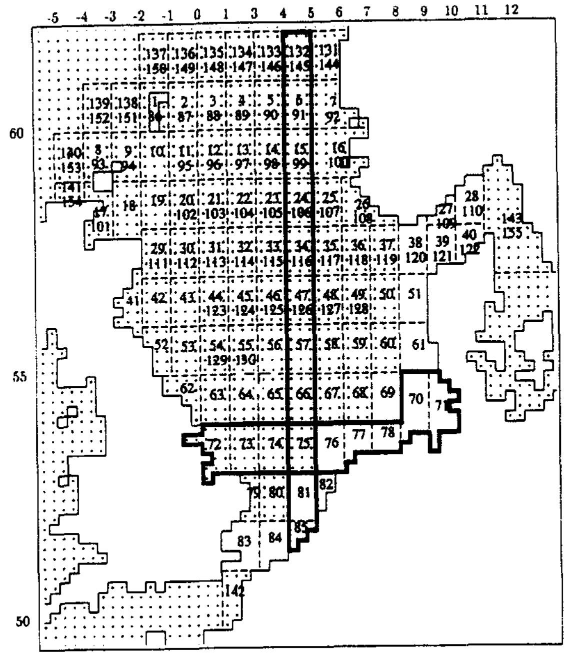

Fig. 1. Box structure of the North Sea for the ERSEM model version ND130 with 130 boxes plus 25 boundary boxes. The North Sea is separated into the North Sea without the CCZ (region A: boxes with grid points) and the continental coastal zone (region B: boxes without grid points); the south–north and west–east sections used in Figs. 6 and 7 are indicated; where two numbers are given, the upper number refers to the upper box (0–30 m), the lower number refers to the lower box (30 m–bottom).

had to be separated into an upper and a lower box, the results of the baroclinic shelf circulation were analysed according to a method applied by Lenhart et al. (1995) and Lenhart and Pohlmann (1996). This is because the model reproduces the available observations of the thermocline quite well and yields results everywhere in the North Sea, even in areas where no sufficient data exist. In this way 45 of the 85 water columns were separated into an upper and a lower box for the ND130 setup. In Fig. 1 two box numbers are given for the stratified 1° × 1° areas.

For defining the spatial structure for the ERSEM setup ND130 the HAMSOM grid was used. This is the numerical grid used for the hydrodynamical simulations that are utilised in ERSEM as forcing (Backhaus, 1989; Lenhart et al., 1995). The regular box size is 3 (east–west) by 5 (north–south) grid points, which corresponds approximately to 'rectangles' of 60 × 100 km side lengths. In addition to the interior boxes 1 to 130, boundary boxes 131 to 155 were defined, because they serve for defining boundary conditions for the model (see e.g. Radach and Lenhart, 1995). The northern North Sea is closed towards the Atlantic ocean by the boxes 131 to 141 (east to west) in the surface and by the boxes 144 to 154 in the deeper layers. The Skagerrak partly belongs to the interior of the model domain in ND130, and the eastern Skagerrak and northern Kattegat serve as boundary box 143 (surface) and box 155 (deep). In the Channel box 142 was added.

2.2. The data sets

This data analysis is based on two large data sets, which differ structurally from each other, (a) the ECOMOD data set of original observations and (b) an ICES data set of monthly statistics (mean values and ranges of variability).

The first data set consists of original observations compiled by means of the ECOMOD data base which was developed and installed at the Institut für Meereskunde in Hamburg in the department Mathematical Modelling of Marine Ecosystems. This data set contains many data from many sources, including observational data from ICES which were obtained before 1984. It does not contain double data.

The second data set originates from ICES and was ordered from ICES to have the ICES data of the years 1985 to 1994 included. As ICES, according to its data policy, cannot provide original data less than 10 years old without permission of the originators and because of the limited time available in the project, we had to work with the data products as provided by ICES rather than with the original data. Otherwise we would have had to wait for the permission of the numerous originators for using the original data of this period. The ICES data set of monthly statistics (means and ranges of variability) were compiled from all data which ICES holds for the area of the northwest European shelf, including the data up to 1994. As a consequence of this procedure, we cannot determine to which extent the ICES data set of monthly means is based on the same data, which are contained in the ECOMOD data set. This could cause problems, when forming a monthly mean using both data sets together. These problems were circumvented by forming a composite data set on a monthly basis, using either ECOMOD or ICES data for a specific month in a specific box. The two resulting data sets of monthly means (and ranges) have different intensities of coverage of the model area. Therefore a composite data set of monthly means (and ranges) was created, using either the ECOMOD monthly means (and ranges) or the ICES monthly means (and ranges), thus taking always the best monthly mean (and ranges). In our opinion this is the best data set obtainable from the two large data sets for the ERSEM model purposes.

2.2.1. The ECOMOD data sets of original observations

The ECOMOD data sets of original observations have been organised by using a relational data base (Radach et al., 1996a). The data products presented in Section 3 are partly derived from the data sets compiled during the last 15 years in our ECOMOD data base. The data set compiled in this data base is called the 'ECOMOD data set' in the following.

The ECOMOD data used for this analysis originate from many sources (Radach et al., 1996b). Part of the data were collected before the ERSEM project and part of it was compiled during the ERSEM project; further data sets were provided by the North-West European Shelf Seas Project NOWESP (Van Leussen et al., 1996, 1997; Radach et al., 1996b, 1997), from which we were able to include the public domain data. For nutrients and chlorophyll all of these data sets are included. The technical report by Radach et al. (1996a) gives the main data originators and the numbers of the data which they provided.

Quality control. All ECOMOD data sets of observations were uniformly treated. As the data sets for each of the above-mentioned five state variables stem from different sources, they may have had originally different units, which were unified before merging the data into one data set. Before the data were loaded into the data base, the data were quality-controlled with respect to obvious errors, e.g. negative values were eliminated, and the data were checked with respect to the basic information, like their information about the date, time, depth, co-ordinates, area (latitudes and longitudes), and their units.

The checks were made during the automatic conversion of the data sets from the format in which the data arrived, into the data base format which is equal for all types of data. Further checks are performed by visual inspection concerning the ship's or platform's name, the cruise number, the parameter code, the unit, and the originator of the data. If inconsistencies or errors were found, they were corrected by manually or automatically modifying the entries in the data base, mostly after contacting the data originator again. The data were then checked in order to exclude double data, which is important for correct statistics. The quality control procedure was reported in detail by Radach et al. (1996a).

Selection of data for determining climatological monthly statistics. For calculating the box-specific and month-specific data products, the original observational data were extracted from the data base ECOMOD according to a certain criterion, which ensures that the observation stems from the sea and not from rivers and their estuaries. As a spatial reference the grid cells of the HAMSOM grid were taken, which consists of so-called 'wet points' in water deeper than 10 m; these are the grid points where the hydrodynamic equations are solved. All the observations in HAMSOM grid cells, which belong to a specific box of the ND130 setup (Fig. 1) form the basis for calculating the statistical quantities on a monthly basis. As the estuaries are not covered by the HAMSOM grid, the high values originating from estuaries and rivers could mostly be excluded, when restricting the data selection to these 'wet point data'.

Although only 'wet grid points' were used for selecting the data to be included in calculating the data products, it turned out that extreme values still occurred in coastal boxes. These were considered to be 'outliers'. Therefore the upper 1% of the data was excluded to remove the 'outliers'. This procedure also eliminated the extreme values, which were left in the data set and were probably erroneous data that had escaped the standard quality control routines. The removal of the estuarine data and of the outliers had the advantage that neither relatively high estuarine nor erroneous nutrient and chlorophyll values entered the calculated statistical quantities and, therefore, could not bias these quantities. The disadvantage is that 1% less data are available in total, and that variability may be underestimated.

The data sets selected are presented in a condensed form in figs. 2–6 of the technical report by Radach et al. (1996a). These data sets form the basis for all calculations. The data are then reduced by spatial selection described above and by the selection according to the criteria given below. The data comprise the data holdings from 1950 to 1994.

Spatial and temporal coverage of the North Sea with data. The distribution in space and time is not the same for all the basic data sets of state variables for the North Sea in total (see figs. 2–6 of Radach et al., 1996a).

Phosphate, nitrate and silicate observations cover the North Sea and adjacent areas quite well. The annual cycle of phosphate is fully covered, with nearly equal intensity over the year. Variability of the phosphate observations is similar throughout the year. The bulk of the values lies below 1.7 mmol m^{-3}.

The annual cycle of nitrate is also covered well, but there are weeks with only few data (e.g. weeks 1–2, 25–26, 36, 40) as well as with many data (weeks 44–49). Most values are below 10 mmol m^{-3}. There are no data before 1960.

Observations of ammonium are fairly restricted to certain areas in the North Sea. The German Bight and some Scottish, English, Dutch and Belgian coastal waters are best monitored. In addition sections off Denmark, in the Skagerrak and across the northern North Sea give valuable information. There are no data before 1960. The annual cycle is covered unevenly well; weeks 1–2, 9, 25–26, and 50–52 contain only few data. The bulk of the data are below 15 mmol m^{-3}.

Silicate shows varying variability over the year, with a minimum between weeks 28 and 39; there seems to occur a strong increase in the availability of high silicate concentrations from 1974 to 1975. The coverage of silicate is best during weeks 45–49, but less so during weeks 1–4, 13–14, 25–26, 29–36, 40 and 51. The bulk of the values lies below 10 mmol m^{-3}.

Chlorophyll data are mostly coastal data in the southern North Sea, along the Scottish, English, Belgian, Dutch and German coasts. In the northern North Sea the observations cover the area north of 57°N quite well, especially on the British side. The central North Sea between 53°N and 57°N is sparsely covered. In the annual cycle of chlorophyll observations the spring bloom can be recognised. The spatial sampling frequency is highest in a few squares close to the English coast and in the southern central North Sea. The bulk of the values is below 4 mg Chl m^{-3}. The frequency of observations is irregularly distributed over the year. Clearly, less observations are available in winter (weeks 1–8, 44–52) but also during summer in weeks 25–29.

2.2.2. The ICES data sets of monthly statistics

In addition to the original data from ECOMOD we have access to a data product which was produced for this project by ICES. ICES calculated the statistics for 1°×1° boxes. This spatial resolution is largely identical to that of the ND130 setup for ERSEM. A few coastal ERSEM boxes are larger or smaller than the respective 1° × 1° box to include coastal areas which are not suited to form boxes on their own (boxes 7/92, 16/100, 17/101, 26/108, 38/120, 41, 61, 62, 70, 71, 72, 83, 131/144, 142, 143/155).

For each 1°×1° box a data set of the 16.6%-, 50%- and 83.3%-quantiles for every month from 1960 to 1994 has been obtained, for the state variables phosphate, nitrate, ammonium, silicate and chlorophyll. ICES provided us also with climatological monthly medians plus 16.6%- and 83.3%-quantiles for the 1° × 1°-squares. The numbers of observations behind the ICES data products are given in Radach et al. (1996b).

2.2.3. Statistical analysis of the data in the North Sea and especially in the continental coastal zone

As the derivation of climatological annual cycles presupposes that the annual cycles are periodically stationary time series of the concentrations, this assumption had to be checked. It was found that the data outside the continental coastal zone (CCZ) — called area A here — obey this condition, but that the data in the CCZ — called area B here — (Fig. 1) show in their majority trend-like evolutions. Therefore an additional analysis for the data from the CCZ has been performed.

Analysis for the North Sea, except for the CCZ. Inspection of the data in area A of the North Sea (Fig. 1) gave no indications of non-stationarity of the annual cycles. In case of the whole North Sea except for the CCZ all selected data were used to calculate the medians and the ranges of variability (method A). The annual cycles obtained may therefore be regarded as climatological, being representative for the whole time span investigated. Our ranges give the full natural variability during the years 1950–1994.

Analysis for the continental coastal zone. In the continental coastal zone (area B in Fig. 1) it was not possible to apply the same procedure as in area A, because the time series of concentrations were not periodically stationary, but exhibit long-term changes in the majority of the boxes in the CCZ. Therefore the analysis was restricted to the decade 1984 to 1993, in which most of the data lie and where a fairly even temporal coverage with data can be assured. The analysis was based on the following criteria. Only data from 1984–1993 are considered. And, for calculating a monthly mean the condition has to be fulfilled that in each of the three time ranges 1984–1986, 1987–1989 and 1990–1993 at least one observation has to be available.

Instead of applying method A (which uses all data) method B was used, which is as follows. For each year of the three time ranges monthly medians were calculated from ECOMOD data and by ICES, if possible. From these monthly medians a monthly mean value is calculated for each time range, and from these monthly means the final monthly mean is calculated (as an arithmetic mean). This procedure ensures that temporal accumulations of data do not bias the monthly mean. However, this procedure abandons the strict rule of working with medians only.

To check the effects of the different aggregation methods A and B the annual cycles obtained by the method have been compared with those of method A for the boxes from the CCZ only. In general, data from the decade 1984–1993 results in higher monthly means from method B than from the simpler procedure including all available data. The comparison for chlorophyll is shown in Fig. 2. For ammonium (box 70) and silicate (boxes 83, 84), however, the values according to method B became lower than those obtained by applying method A (not shown).

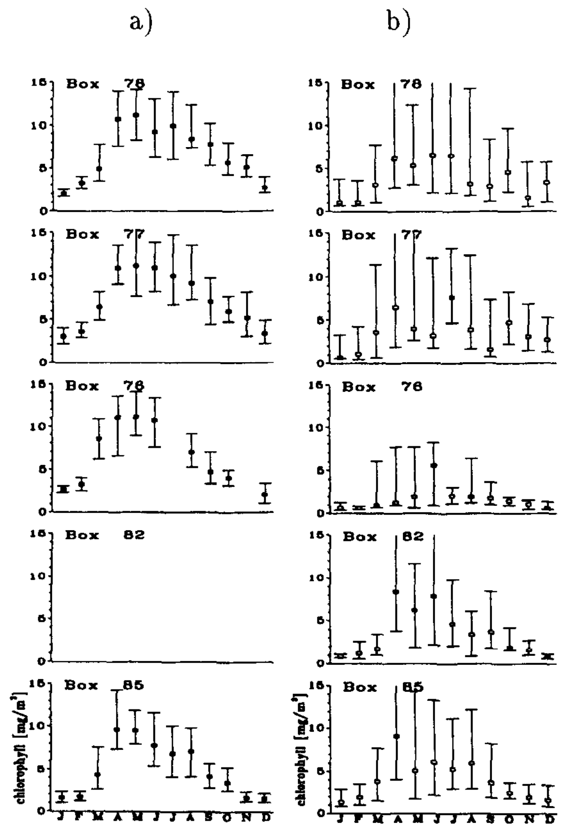

Fig. 2. Comparison of the annual cycles for chlorophyll in boxes of region B, (a) obtained by using method B, (b) obtained by using method A. For symbols see Table 1.

2.2.4. *Composite data sets of climatological monthly statistics for the North Sea*

The monthly means in the CCZ which result for the decade 1984–1993 when applying method B can be joined with the climatological monthly means for the area A of the North Sea to form a consistent data set for the decade 1984–1993, because we found periodical stationarity outside the CCZ. These annual cycles form an adequate validational data set for the ERSEM simulations of the years 1988 and 1989.

For the whole of the North Sea monthly means for 1° × 1° boxes were calculated, which can be identified with the interior and the boundary boxes of the ND130 setup of ERSEM. However, depending on the number of data available for calculating the monthly means, the statistical significance of the means varies. Applying a fairly strict condition, as e.g. condition (C1) (see below) would leave us with many cases where we would be unable to give any information on significant monthly means. We decided to give the available information also in cases where less strict conditions are fulfilled. In the figures care has been taken that the statistical significance can be recognised. Three conditions have been introduced, and it has been indicated which of these conditions is fulfilled for each of the monthly mean values given. The three conditions are the following:

(C1) Condition 1. More than 15 data are available in the specific box for the specific month under consideration. This condition ensures that the statistical measures make sense.

(C2) Condition 2. The absolute difference between the median m and the arithmetic mean μ is less or equal to 15% of the mean value of median and arithmetic mean:

$$|m - \mu| \leq 0.15 \times (m + \mu)/2$$

This condition demands that median and arithmetic mean are lying closely together, i.e. that the data are nearly normally distributed.

(C3) Condition 3: The confidence limits of the estimate of the arithmetic mean are small compared to the mean μ, i.e. they are less than 15% of the estimate for the mean:

$$2.58 \times \sigma/\sqrt{N} \leq 0.15\mu,$$

where σ is the standard deviation and N the number of data.

This condition ensures that the arithmetic mean of the ensemble, μ^*, and our estimate for the arithmetic mean of the sample, μ, are lying closely together, i.e.

$$|\mu^* - \mu| \leq 0.15\mu.$$

In Table 1 the degree to which the conditions are fulfilled are ranked by attributing case numbers. The best case (0) occurs when all conditions are fulfilled, the worst case (8) occurs when no data are available. In between we rank the data availability and goodness of the statistical measures. The case numbers are combined with symbols used in the figures to indicate the statistical reliability of the mean value shown.

The data sets which were finally used in ERSEM were the composite data sets which result when

Table 1
Ranking the quality of the calculated climatological means and their ranges

Case	Conditions which are (not) fulfilled	Symbol in the figures
0	all fulfilled	filled square plus range
1	not C3	empty square plus range
2	not C2	empty square plus range
3	not C2, C3	empty square plus range
4	not C1	empty square
5	not C1, C3	empty square
6	not C1, C2	empty square
7	not C1, C2, C3	empty square
8	no data	no symbol

For explanation of conditions see text.

merging the two data sets of monthly medians and quantiles together (from ECOMOD and from ICES), taking into account the quality of the monthly medians according to the criteria given above. Whenever a monthly mean value is available from both, the ECOMOD and the ICES data sets, and when the same case number (Table 1) is attributed to both means, the one obtained from more original data is chosen. Whenever a monthly mean value is available from one data set with a higher ranking case number than from the other data set, this monthly mean is taken. If the ICES means appear to include estuarine data in the coastal boxes, the monthly means from the ECOMOD data set are preferred.

In this way nearly complete mean annual cycles for the North Sea on a monthly basis can be obtained. For region A the report by Radach et al. (1996a) indicates the origin of the mean and the ranges (either ECOMOD or ICES) in their table 10.

The criteria (C1)–(C3) are applied to both the annual cycles obtained for the boxes in region A and in region B, and the figures show means of different statistical quality. In the figures we also give climatological ranges around the means. When plotting the medians we add the range between the 16.6%- and the 83.3%-quantiles.

3. Results

The numbers of the available monthly medians of the climatological year, separated according to their statistical significance, are given for the five state

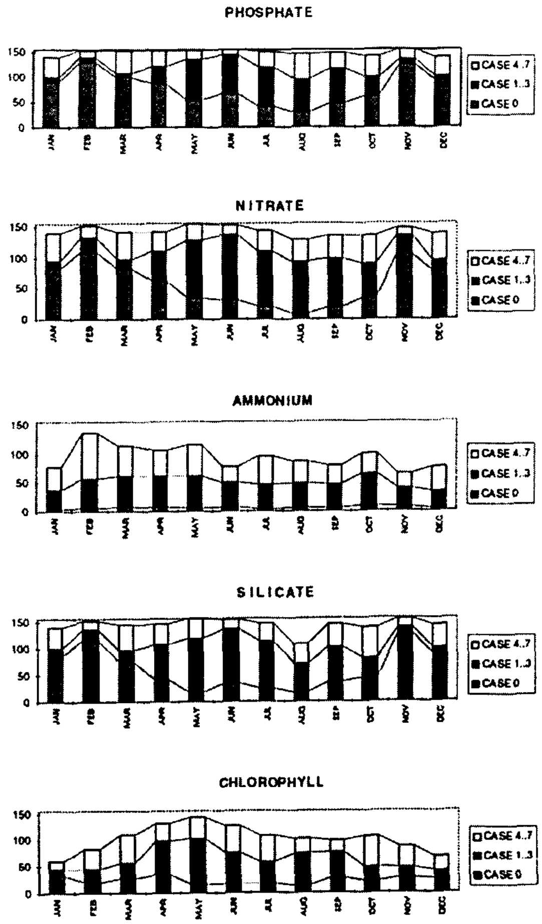

Fig. 3. Numbers of available monthly medians of the climatological annual cycles for the five state variables phosphate, nitrate, ammonia, silicate and chlorophyll for the 155 boxes, separated according to their statistical significance (see Table 1). Cases 0 to 7 sum all categories; the maximum number of boxes is 155; the gap between case 4–7 and the upper line at 155 denotes the number of missing monthly means.

variables in Fig. 3. For phosphate the coverage of the annual cycles is >86% for all months; for nitrate the coverage is lower during July to October and December to January, but still >78%. The situation is similar for silicate, in several months as for phosphate, but August is less well covered (66%). For chlorophyll the available information is very different from month to month, ranging from 53 median values in January to 138 in May. The most solid statistical measures (case 0 to 3), including ranges of variability, are in the majority during most of the months for all state variables. For ammonium relatively few such values are available.

The results for the ND130 setup are illustrated by examples only. Initial conditions on a 1° × 1°-grid are given in Fig. 4. For the annual cycles we give the information in Fig. 5 (boundary boxes) and in Figs. 6 and 7 (interior boxes). The figures contain the 16.6%-, 50%- and 83.3%-quantiles, when available. Quantiles are considered to give the most robust statistical description.

3.1. Winter distributions for 1° × 1° squares

For all simulation runs one needs, amongst others, to specify the initial conditions for all state variables. As there was no internally consistent set of data available to initialize all state variables in ERSEM, certainly not at a 1° × 1° spatial resolution, ERSEM was run for a 30-year period, using perpetual annual cycles for boundary forcing, to obtain numerically stabilised, repeating annual cycles. The state variable values at the end of this run were used to initialise the simulation with specific-year forcing. For ERSEM this procedure was chosen, when working with the 15-box setup, ND15, (Radach and Lenhart, 1995), with the 130-box setup, ND130, (Pätsch and Radach, 1997) and with the continental coastal application COCOA (Lenhart et al., 1998).

Another possibility is to define initial conditions by evaluating data, and the results of such a procedure will be presented here for 1° × 1° squares, to give other modellers the opportunity to use initial fields for the North Sea, which may be called mean winter conditions for the decade 1984–1993. It has to be kept in mind that these initial fields for which data exist cover only a small number of state variables in ERSEM.

The winter conditions are presented for the spatial resolution of 1° in both directions, north–south and east–west. All data from December, January and February from the composite data set have been compiled. The spatial distributions of the concentrations are shown for the nutrients in Fig. 4. The influence of nutrient-rich river water in the CCZ and Atlantic water in the north is obvious. Squares for which no data are available are left blank.

3.2. Boundary data sets for 1° × 1° squares

The composite climatological annual cycles for the boundary boxes are much more complete than the ones obtained solely from the ECOMOD data base or from the ICES data set. It turned out that the ICES data set is especially useful for defining the boundary conditions for the ecosystem model ERSEM. Fig. 5 shows the monthly means for the macronutrients and chlorophyll for the surface boundary boxes obtained from the composite data set.

The climatological annual cycles for phosphate (Fig. 5a) are fairly complete. Those for nitrate (Fig. 5b) are less well covered. The data base for ammonium is thin (no figure). The annual cycles for silicate (Fig. 5c) are fairly well covered. The annual cycles for chlorophyll (Fig. 5d) are also only sparsely represented by the data products.

Thus, for the boundary boxes, problems still remain. The lack of chlorophyll data for the deep boxes 144 to 155 (not shown) is not so severe, because we may assume very low chlorophyll values below the thermocline for most of the year. Although the ICES data set did help much concerning the boundary boxes of the ND130 setup, for the problematic boxes the annual cycles from the ND15 setup have been used (Radach and Lenhart, 1995; Radach et al., 1996a).

3.3. Validational data sets for 1° × 1° squares

The validational data sets are used for the comparison of simulation results with observations in the form of monthly medians, together with ranges of the observations (16.6%- and 83.3%-quantiles). The detailed statistical information for the boxes in region A of the North Sea is given in tables 5 and 8 of Radach et al. (1996a).

It is not possible to comment here on all boxes of the ND130 setup. In Figs. 6 and 7 two sections through the North Sea on the basis of the composite data set have been given.

The north–south section is well covered with phosphate data (Fig. 6a). Starting in box 85 with winter values of 1.6–1.8 mmol m^{-3}; during the decade 1984–1993 data coverage in box 81 is statistically unsatisfactory. The winter concentrations drop down to 0.6 mmol m^{-3} already in box 75.

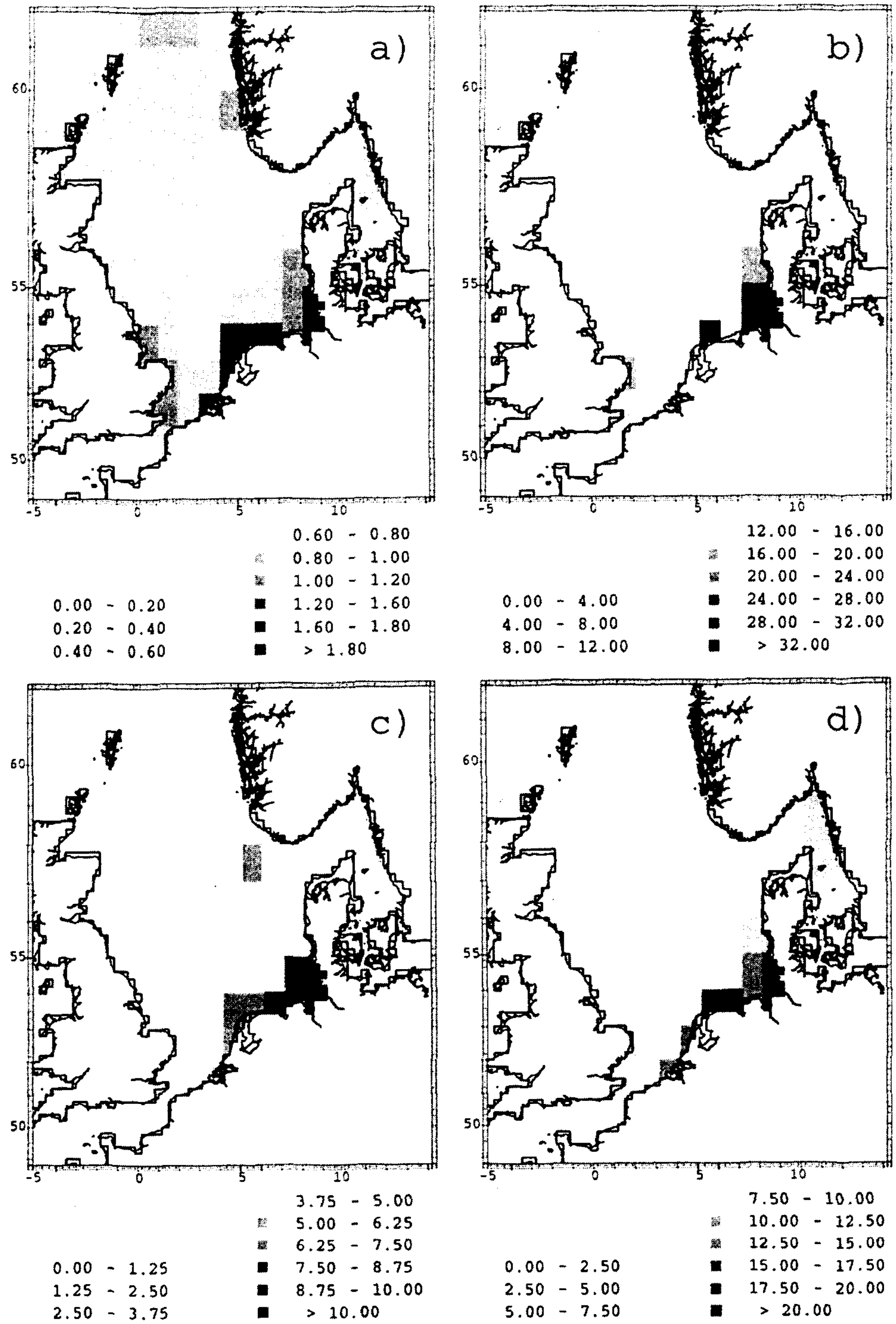

Fig. 4. Horizontal distribution of concentrations of (a) phosphate, (b) nitrate, (c) ammonium, and (d) silicate (all in mmol m^{-3}) in the North Sea in winter (December–February) for 1° × 1° boxes from the composite data set, 0–30 m. The scales are given for each panel separately.

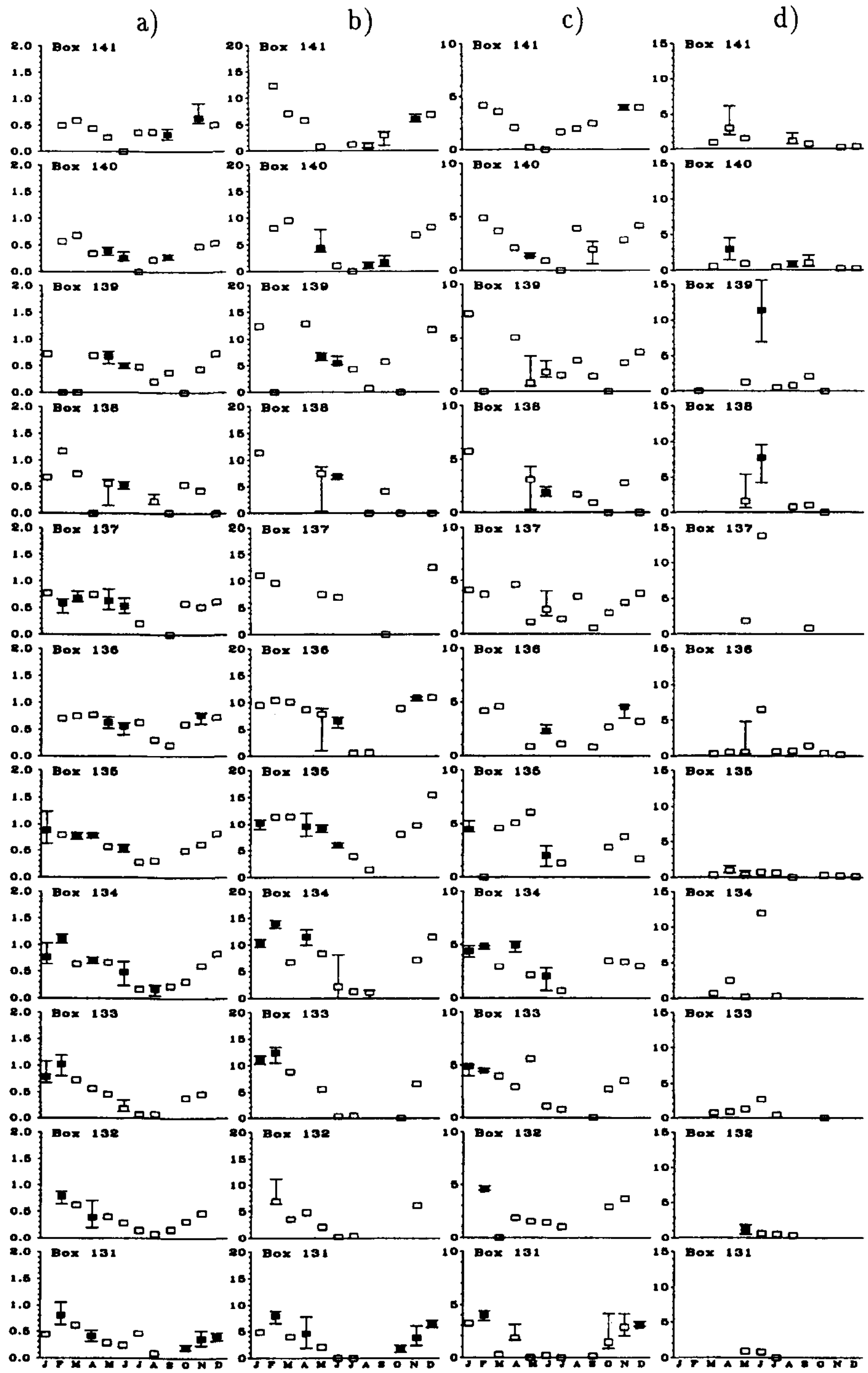

Fig. 5. Climatological annual cycles of (a) phosphate, (b) nitrate, (c) silicate (all in mmol m^{-3}), and (d) chlorophyll (mg m^{-3}) in the surface boundary boxes at the northern boundary (boxes 131–141) of the North Sea for the ND130 setup, using the composite data sets of ECOMOD and ICES. Monthly means are given together with the 16.6%- and 83.3%-quantil of the data available for each month during 1963–1993. For symbols see Table 1.

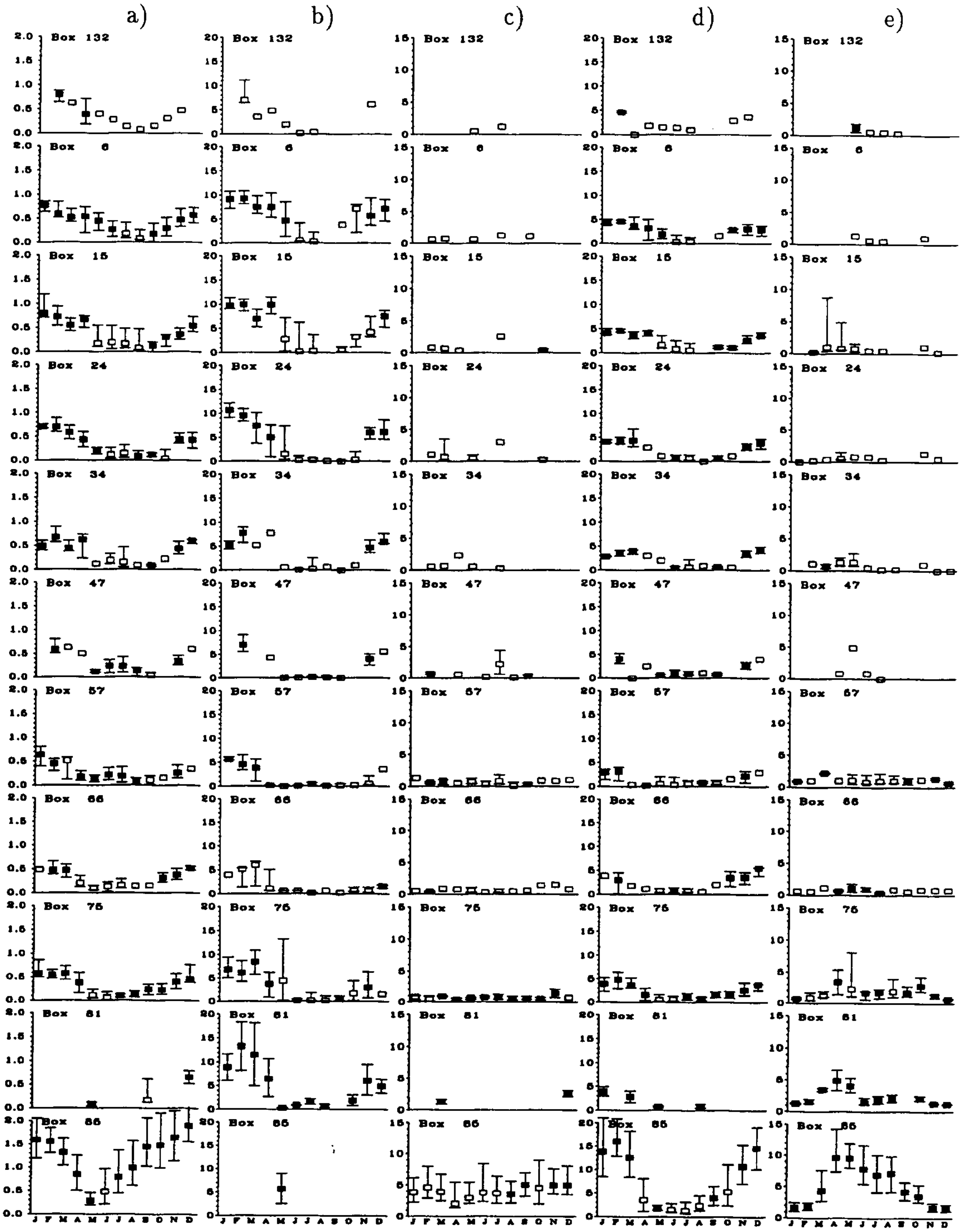

Fig. 6. Climatological annual cycles of (a) phosphate, (b) nitrate, (c) ammonium, (d) silicate (all in mmol m^{-3}), and (e) chlorophyll (mg m^{-3}) compiled from the composite data sets of ECOMOD and ICES for the boxes of the ND130 setup on a selected north–south section (boxes 132 to 85; see Fig. 1). Monthly medians are given together with the 16.6%- and 83.3%-quantil of the data available for each month during 1963–1993. For symbols see Table 1.

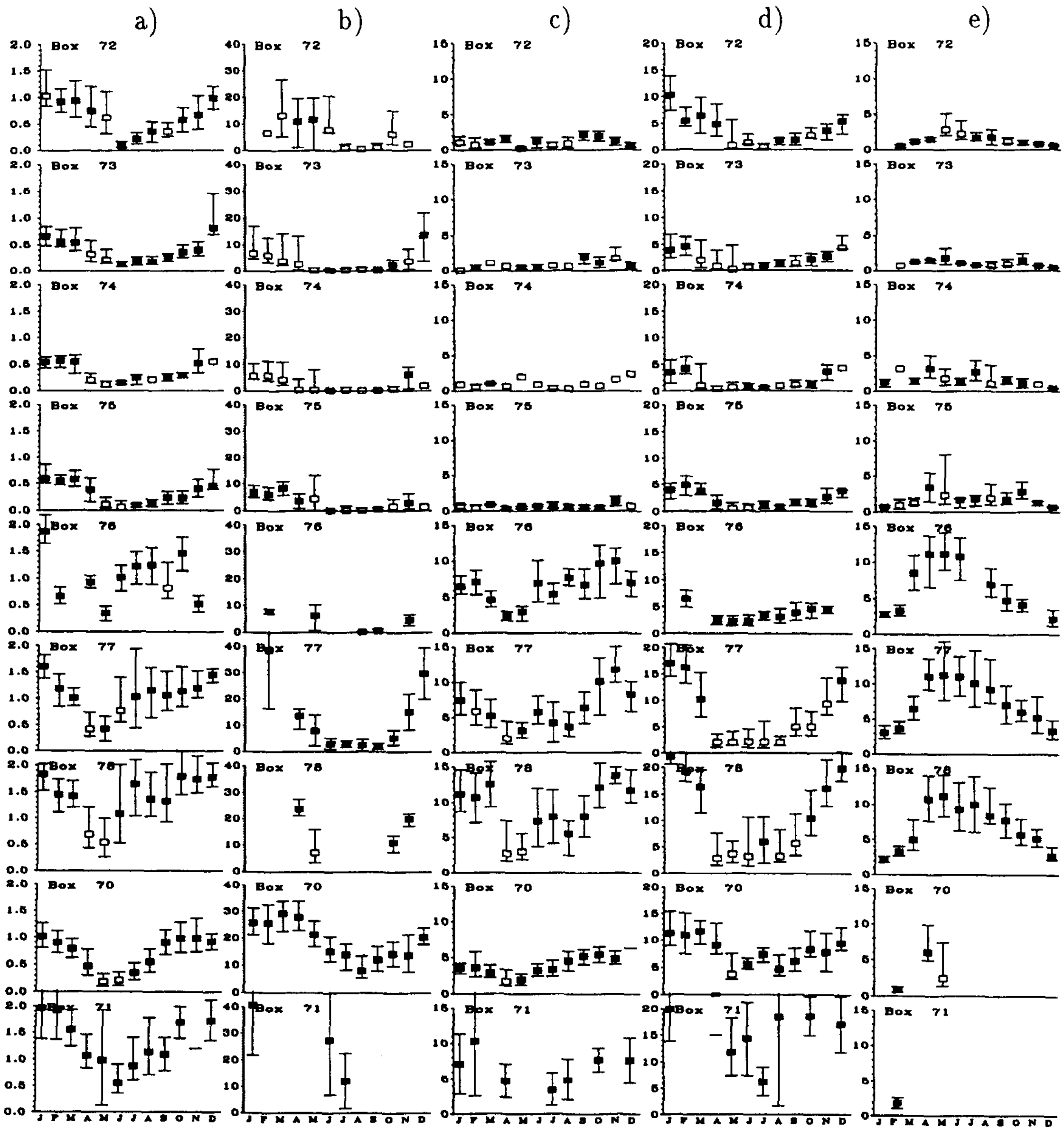

Fig. 7. Climatological annual cycles of (a) phosphate, (b) nitrate, (c) ammonium, (d) silicate (all in mmol m^{-3}), and (e) chlorophyll (mg m^{-3}) compiled from the composite data sets of ECOMOD and ICES for the boxes of the ND130 setup on a selected west–east section (boxes 72 to 71; see Fig. 1). Monthly means are given together with the 16.6%- and 83.3%-quantil of the data available for each month during 1963–1993. For symbols see Table 1.

Levels increase from box 24 northwards. Only the northern end (box 132) is not represented well by a full annual cycle. Off the Norwegian coast winter values of 0.7–0.8 mmol m^{-3} occur. There is summer depletion everywhere except for the very south.

For nitrate the data coverage is not so good (Fig. 6b), but the overall appearance is as for phosphate. Winter levels of 8–14 mmol m^{-3} in box 81 drop to about 5–6 mmol m^{-3} until box 34, from where they increase northwards to 10 mmol m^{-3}

(boxes 24, 15, 6). A summer depletion occurs from April or May until September in boxes 75, 15 and 6, and until November in boxes 81, 66 and 57.

For ammonium (Fig. 6c) everywhere except for box 85 the concentrations are below 2 mmol m^{-3}; however, in the northern boxes the data coverage is not good. In the southern box 85 there is a fairly constant level of about 3 to 5 mmol m^{-3}, with a minimum in April.

For silicate (Fig. 6d) the same discrimination between coastal boxes (85) and open North Sea boxes (all other boxes) is obvious. In winter the open North Sea level is 3–5 mmol m^{-3}, while the coastal values are 14–17 mmol m^{-3}. The coastal box shows a very strong depletion, down to 1–2 mmol m^{-3}, as do all other boxes.

Chlorophyll (Fig. 6e) shows a relatively gappy data coverage in several of the boxes of this section. The central (box 47) and northern (boxes 6, 132) North Sea are not well covered, but nevertheless it can clearly be seen that the biomass decreases from south (up to 10 mg m^{-3}) to north (up to 1 mg m^{-3}) and that the spring bloom occurs in April in the south and may occur already in March along the Norwegian coast, but on much lower levels than in the continental coastal areas.

The east–west section from the Wash and Tyne river (box 72) to the German Bight (boxes 70, 71) gives the following results. The annual cycles of phosphate for the ND130 setup show very clearly different signals on this section (Fig. 7a). While the western English box 72 shows an annual cycle similar to the northwestern North Sea, but on a higher level with winter values of 1.0 mmol m^{-3} and a strong summer depletion, the more the central southern North Sea is approached, the smaller the winter values (0.5–0.7 mmol m^{-3} in boxes 73, 74 and 75) are; they also exhibit strong summer depletion. Further east the concentrations rise and the phase of depletion (if there is any) is becoming shorter (two months in boxes 77 and 78). There is also only temporary depletion during summer in the German Bight (boxes 70, 71). The annual cycle in box 70 resembles the one in the English box 72, with winter levels of 1 mmol m^{-3}. The regeneration in summer starts earlier the more eastern we go. The section from west (box 72) to east (box 71) is characterised by high variability along the coasts, except for the more interior boxes in the Southern Bight (boxes 73–75) (Fig. 7a). The same holds for nitrate (Fig. 7b).

Nitrate (Fig. 7b) is not so well represented by the available data, and it is difficult to give an accurate description of the full annual cycles in the boxes 72, 76, 78 and 71. The annual cycles in boxes 73–75 show open North Sea conditions, starting with 6 mmol m^{-3} in January and depletion during April/May. Regeneration starting in October brings the winter conditions back. The annual cycles in the boxes 77, 78, 70 and 71 are different in that they show much higher winter values between 20 and 35 mmol m^{-3}, respectively. The depletion phase occurs later in the year (June–October) than for phosphate (boxes 77 and 70).

For ammonium (Fig. 7c) we find low values throughout the year from the west to the central Southern Bight (boxes 72–75) around 1–2 mmol m^{-3}. Boxes 76–78 are totally different, with mean values of 2–5 mmol m^{-3} in summer and 6–12 mmol m^{-3} in winter, but the seasonal cycle is not very pronounced. In box 70 (German Bight) monthly mean values around 2–6 mmol m^{-3} are observed; box 71 lacks data, but shows a cycle similar to box 78.

For silicate (Fig. 7d), as for nitrate, boxes 73–75 show open North Sea conditions, while boxes 72 and 77, 78, 70, 71 show coastal conditions, with winter values of 10–15 mmol m^{-3} and more. A depletion phase occurs from April to August in boxes 73–78♦, and one month later, from May to September, in boxes 70 and 72.

The annual cycles of chlorophyll (Fig. 7e) show increasing mean spring and summer concentrations from west (4 mg Chl-*a* m^{-3} in boxes 72–75) to east (5–15 mg Chl-*a* m^{-3} in boxes 76–78). The annual cycle in the central Southern Bight (boxes 73–75) is similar to that of the English coastal waters (box 72). It is interesting that chlorophyll close to the English coast exhibits the same appearance as in the southern central area (boxes 73), with a slight spring bloom peak in May. Approaching the continental coast the spring peak increases in height (boxes 76–78) off the Netherlands. The highest and most variable values are occurring west of the German Bight (boxes 77 and 78). For the German Bight not enough data are available for the procedure applied.

4. Discussion

4.1. Comparison to earlier nutrient and chlorophyll distributions in the North Sea

The earliest attempts to map the surface distributions of the nutrients concentrations in the whole of the North Sea were performed by Laevastu (1963) and by Johnston and Jones (1965). While Laevastu (1963) distinguished water types with fixed characteristics, Johnston and Jones (1965) took the gradients between the water masses into account and presented bimonthly maps for phosphate, silicate, nitrate and — for the southern North Sea only — also for nitrite. Since the publication of the above papers more than thirty years have passed, and many more observations are available now. However, except for the atlas by Johnston and Jones (1965), no information about annual cycles for the whole of the North Sea seems available in the literature. Information on annual cycles is restricted either to sites, where long time series were created from monitoring data (e.g. for the Dutch coastal zone see Bot et al. (1996), for Helgoland Roads see Radach et al., 1990), or to regions of the North Sea, where intensive field work was performed over longer time ranges up to a few years (e.g. during the NERC North Sea Programme, see Howarth et al. (1993)).

In the North Sea Quality Status Report (Anonymous, 1993), for example usually only winter values (and sometimes also summer values) of the nutrient concentrations are reported for the ICES subregions of the North Sea; these regions usually contain several of the $1° \times 1°$ boxes which is the spatial unit here. Several larger data sets have been evaluated before with respect to annual cycles. The data obtained during the NERC North Sea Programme comprise the nutrients phosphate, nitrate, nitrite, ammonium, and silicate, chlorophyll and primary production, among other variables, over 15 months in the area south of 55°40′N. Howarth et al. (1993) presented annual cycles derived from this data set. At Helgoland Roads (54°11.3′N 7°54.0′E), which is situated in box 70, a continuing time series of nutrient concentrations have been obtained per work-day since 1962 (Hickel et al., 1993, 1995); they were analysed with respect to the annual cycles by Radach and Berg (1986), Radach et al. (1990) and Hickel et al. (1993, 1995). Off the Dutch coast an extensive monitoring programme provided several long time series at various distances from the coast since 1975; the sites fall into our boxes 81, 82, 84, and 85. In the Skagerrak the section between Torungen and Hirtshals was covered regularly from 1980 to 1994, and from the 13-year long data record the annual cycles and their interannual variation were derived (Danielssen et al., 1996). For the northwestern North Sea the Marine Laboratory in Aberdeen has compiled a large data set of nutrients and chlorophyll. The northeastern North Sea is well covered by nutrient observations obtained by the Institute of Marine Research in Bergen (Norway).

The NOWESP data set (Radach et al., 1997) comprises most of these data; its public domain data have also been utilised in our study. The NOWESP data have further been utilised to create the spatial distribution of the annual cycles of the nutrients and of other variables on a monthly basis by a different approach, which is similar to the approach taken by Johnston and Jones (1965) and which constitutes a complementary effort to describe the annual nutrient cycles in the North Sea (Radach and Gekeler, 1997).

All these data sets are contained in our composite data set (Radach et al., 1996a). The available long time series determine the annual cycles in the respective boxes, and their measures of variance are the most reliable ones. In our study we derived the annual cycles from all available observations for the larger region A of the North Sea, where no trend-like changes were found. However, in the continental coastal zone (region B) the temporal developments of the concentrations over the last decades map the drastic changes which have occurred due to increased (and later partly reduced) river input of nutrients. For this region our analysis followed a different approach which utilised only data from the decade 1984–1993.

The climatological and decadal annual cycles presented give a clear picture for the whole of the North Sea for the decade 1984–1993. The highest concentrations occur at the continental coasts as a result of continued river input, which is added to the ongoing atmospheric input over the North Sea. Also from the Atlantic Ocean water with relatively high nutrient concentrations enters the North Sea via the northern boundary. In the productive areas on and around the

Dogger Bank nutrient concentrations are lower even in winter.

The areas in which seasonal stratification takes place have a very different annual cycle in the upper layer (0–30 m) and lower layer (30 m–bottom). In most deep boxes there occurs no nutrient decrease or depletion during summer, but an increase of the concentrations in late summer and fall. In the upper boxes usually a summer depletion is observed. The shallow boxes are fully mixed and exhibit a relatively fast increase of nutrient concentrations caused by summer regeneration of nutrients.

When comparing the calculated mean values to the earlier distributions given by Johnston and Jones (1965) different mean values especially in the coastal areas are expected. The winter values (January/February) in both studies coincide for phosphate and nitrate in the northern boxes (e.g. 0.7–0.8 mmol PO_4-P m^{-3} and 9–10 mmol NO_3-N in boxes 1 to 5), while in the coastal boxes the values by Johnston and Jones (1965) are lower for phosphate (e.g. our mean values of 1.5–1.7 mmol PO_4-P m^{-3} in boxes 82 and 85 off River Rhine compared to their mean values of 0.8–1.0 mmol PO_4-P m^{-3} and 1.0–2.0 mmol PO_4-P m^{-3} compared to their mean values of 0.7–0.8 mmol PO_4-P m^{-3} in boxes 70 and 71 off the River Elbe). For nitrate concentrations off River Rhine it appears that the values given by Johnston and Jones (1965) may even be higher than ours, probably due to using a subset of relatively high values. However, it also appears — without having done a sound statistical analysis yet — that the concentrations of phosphate and nitrate are not significantly different in the central southern North Sea (boxes 74 and 75).

4.2. *What kind of data sets exist for the validation of ERSEM?*

When simulating an annual cycle of physical quantities, the forcing should not be climatological, because it is known that climatological forcing results in less variability than actual data with fine temporal resolution would exhibit (Ridderinkhof, 1991). This is even more true for biological and chemical variables than for physical ones, because the former are strongly influenced by the latter (Radach and Moll, 1993). Mean forcing fields cannot activate the full potential of reactions of the ecosystem. However, even if the actual forcing functions were known for one year, the field data for validation would not be available due to a lack of observational resources.

The strategy for the validation of ERSEM has its impact on the data products needed, and this demand can be fulfilled only to a certain degree by the available observations. The final data products presented in this paper constitute, as we see it, the result of a compromise between needs and abilities. We have to consolidate ourselves with measures of the reactive potential of the system. Such measures are given by the climatological and decadal means and the ranges of observations indicated, e.g., by special quantiles or extreme values. The climatological and decadal monthly means and ranges given here serve this purpose. Certainly they provide only a weak measure of validity of the simulation; they do not provide more than a range, in which the simulated system's behaviour should remain. This philosophy is discussed in some more detail by Radach and Moll (1993).

The composite data set of climatological and decadal annual cycles of medians and its ranges is suitable for validational and forcing purposes for ecosystem models of the North Sea, which have a resolution larger than or equal to 1° in both longitude and latitude. The results presented show clearly that for most of the ERSEM boxes sufficient observational data exist to provide initial, forcing and validational data for the simulations with the ND130 setup of the ecosystem model ERSEM. For the boundary boxes problems still remain. Although the ICES data set did help much concerning the boundary boxes of the ND130 setup, there still exist boxes where the annual cycles from the ND15 setup have to be used.

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