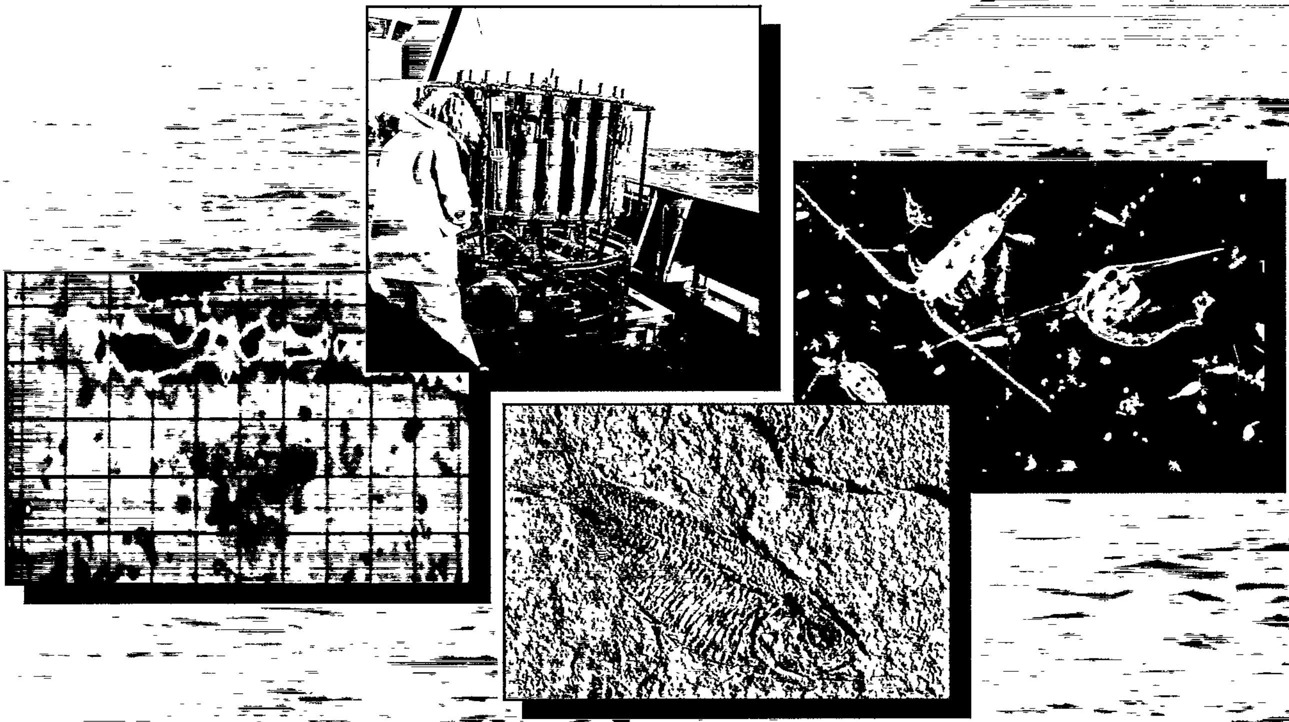
Southampton Oceanography Centre

Report



Natural Environment Research Council

University of Southampton

SOUTHAMPTON OCEANOGRAPHY CENTRE

REPORT No. 5

The biogeochemistry of nitrogen in the southern North Sea: the development of a mathematical model based on the results of the NERC-North Sea Programme surveys in 1988 and 1989

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1997

Final Report to the Department of the Environment

on

North Sea Nutrient Model
(Contract Reference Number: PECD 7/8/179)

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The Biogeochemistry of nitrogen in the southern North Sea: the development of a mathematical model based on the results of the NERC-North Sea Programme surveys of 1988 and 1989.

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ABSTRACT

We present a 2D hydrodynamic biogeochemical model of nitrogen dynamics in the southern North Sea. Eight variables are modelled (NO_3^-, NH_4^+, O_2, chlorophyll, and carbon and nitrogen in detrital and microplankton forms) on gridboxes approximately 35km square. Advection is forced by wind and tide residuals and dispersion by tidal amplitudes. NERC-NSP data are used to initialise, calibrate and validate the model and to provide reliable boundary values for solutes. External nutrient inputs are riverine, atmospheric and sedimentary. The water column is assumed to be well mixed and sediment processes are not modelled. The model reproduces the observed annual cycle of dissolved inorganic nitrogen ($r^2 = 0.88$) and supports the idea that the North Sea is a nitrogen sink. Nitrogen inputs to the southern North Sea are 590, 550, 330, 140 ktonnes N from rivers, sediments, ocean waters and the atmosphere respectively. Model estimates of average production in NSTF-ICES boxes 3b,4,5 and 7b are 120, 220, 140 and 150 gCm^{-2}, compared with observations of 79, 199, 261 and 119 gCm^{-2}. The decrease in production following a 50% reduction in river nutrient inputs would be 8,18,14 and 7% respectively in the four NSTF-ICES boxes.

KEYWORDS

KEYWORDS

ISSUING ORGANISATION

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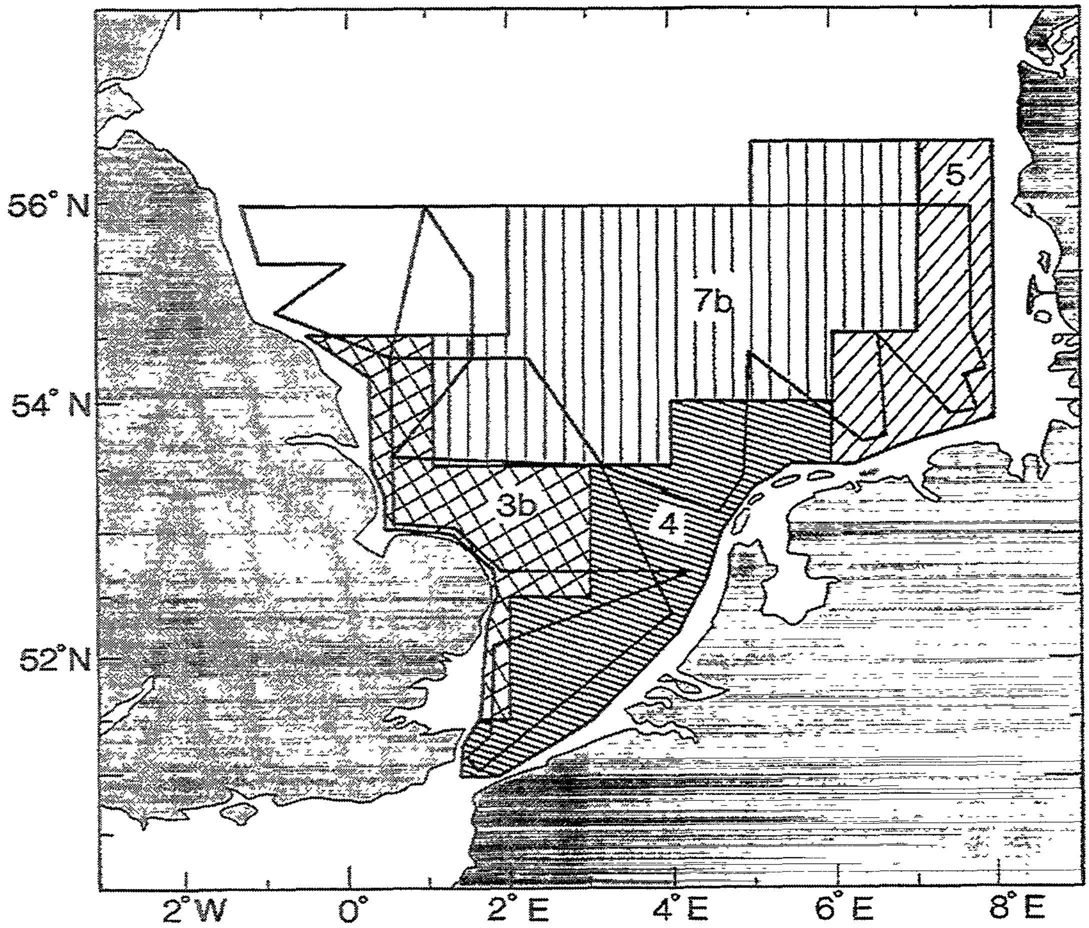


Map of the cruise track of the NERC North Sea Community Programme and the division of the North Sea into areas distinguishable hydrographically.

CONTENTS

EXECUTIVE SUMMARY

1. This project has developed a mathematical model of the processes involving dissolved nitrogen in the southern North Sea and analysed newly available data.
2. The model was used as an aid to understanding these processes and also to predict what would happen to the production of algae in the southern North Sea if inputs of nitrogen from human sources were reduced.
3. Data from the 1988-89 NERC North Sea Project were used in the model's construction.
4. It was shown that most of the variation in levels of nutrients throughout the year in the southern North Sea could be accounted for by a normal seasonal cycle, which the model accurately reproduced.
5. Using both model estimates and available field data, annual budgets for nitrogen and silicon in the southern North Sea were drawn up.
6. For most nutrients, maximum concentrations were confined to coastal regions.
7. On an annual basis the most significant sources of new nitrogen to the North Sea are from rivers and the atmosphere.
8. Budgets indicated that algal production depended more on the re-cycling of nutrients within the southern North Sea than on inputs from rivers and the Atlantic.
9. Recycling of nitrogen between water and plankton during a single growing season varied between 2 times off the UK coast and 5 times off the Dutch and German coasts. This is probably an the effect of relatively high turbidity caused by coastal erosion off the English coast. The availability of light energy is more important in limiting photosynthetic production in this area than the supply of nitrogen.
10. The model estimated that, if the input of nitrogen from rivers to the North Sea was cut by 50%, annual algal production would fall by up to 18%.
11. The model gave support to the idea that the North Sea is an overall sink for nitrogen.

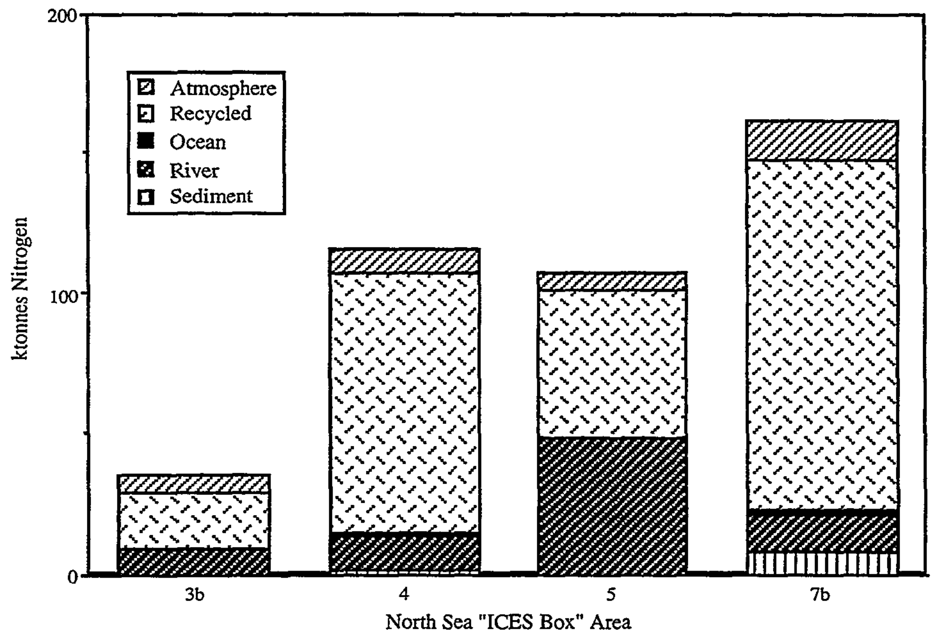
TECHNICAL SUMMARY

Mathematical models of the biogeochemical processes controlling the fate of nutrient elements in sea water are required to test and synthesise our understanding of the processes involved. A successful model should have a prognostic capability to predict the impact of changes in nutrient inputs on phytoplankton population levels, and their subsequent impact on water quality. During the UK-NERC's North Sea Community Research Programme (NSP) data were collected systematically over more than a full annual cycle. That database covering hydrological conditions, nutrient chemistry and phyto- and zooplankton populations has provided the first consistent data set which could be used to calibrate and validate, a model capable of predicting the likely impact of increased nutrient concentrations on plankton populations. The work involved in this contract has involved both quantitative analysis of observed data and the development of a biogeochemical model.

A simple mathematical and statistical analysis of the NSP data shows changes through the seasonal cycle can be described by a cosine wave. The mean concentrations and standard deviations over the whole area through time were salinity 34.26(±.74), ammonia 1.3(±1.0)μM, nitrate 4.9(±6.0)μM, nitrite 0.4(±0.5)μM, phosphate 0.5(±0.3)μM, silicate 2.5(±2.5)μM and suspended sediment 2.6(±3.5)mg/l. A seasonal cycle accounts for most of the variance in temperature and nutrients. The spatially-averaged seasonal amplitudes for both nitrate and silicate are approximately equal to their mean values - this is consistent with these being limiting nutrients. Maximum concentrations are confined to the coastal regions except for ammonium and nitrite for which they occur offshore. Spatial distributions of the anomalous (non-seasonal) components can be interpreted to indicate the effect of specific riverine and oceanic exchanges. Correlations between nitrate, nitrite and ammonium correspond to the inter conversion of these compounds.

NSP data enables a budget to be drawn up for the southern North Sea of the sources of dissolved inorganic nitrogen (DIN) and silicon contributing to the winter maxima in concentrations of nutrients. In contrast to previous ideas about shelf seas the major supply is shown to be from recycling (from sediments for silicon and within the water column for DIN) rather than inputs of "new" nutrients from rivers and ocean waters. An estimate of the relationship between the quantity of available DIN and the observed production indicates that the high productivity of the North Sea is also maintained by extensive recycling during the production period The recycling of nitrogen between water and plankton during the productive season varies between 2 times off the UK coast to 5 times off the Dutch and German coasts. The importance of the recycling term is indicated in the following figure. The derivation of the information in this figure is discussed in Section 1.3

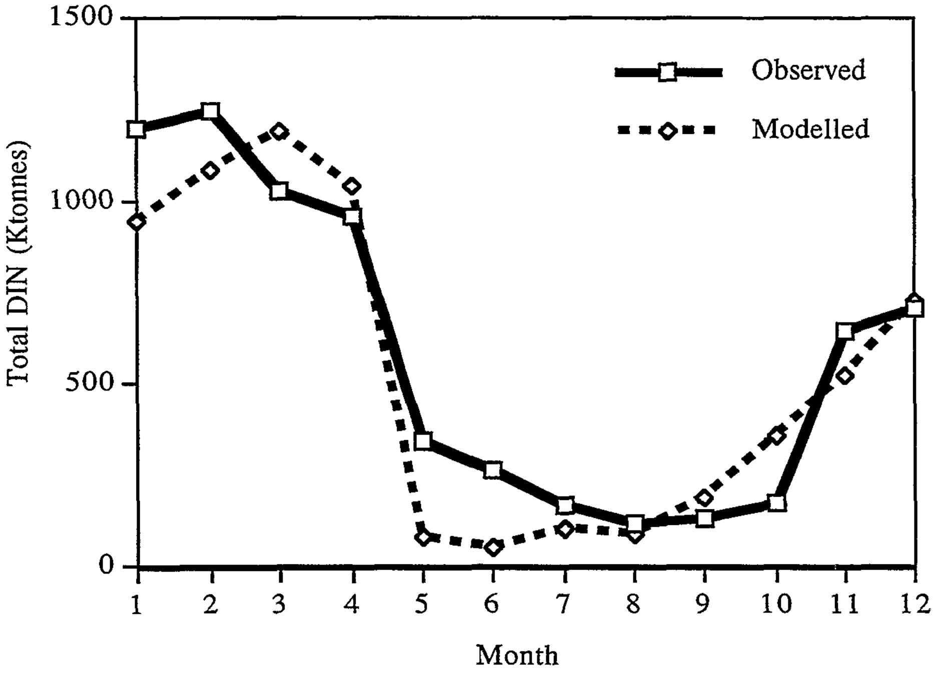
A stacked bar chart comparing contributions of different source terms to observed change in DIN load in different NSTF box areas of southern North Sea between November 1988 and January 1989, is shown below.



A depth-integrated coupled physical/biogeochemical model has been developed for the southern North Sea to examine the seasonal cycling of nitrogen (N). The model is a fusion of the advection/dispersion general purpose 2-D model produced by the Proudman Oceanographic Laboratory P.O.L. (PRANDLE 1984, HOWARTH *et al* 1993, HUTHNANCE *et al* 1993) and a 3 Layer Vertical and Microbiological Processes Model for Shelf Seas (TETT, 1990). Combining these two models enabled the development of a model which could simulate the seasonal cycle of the nitrogen containing nutrients nitrate and ammonia in the southern North Sea. The model also describes the impact of biological production and decay processes on the concentration of dissolved oxygen in the water.

The grid for this model is comprised of grid cells 1/2° longitude by 1/3° latitude, approximately 35km square, covering the shelf seas around Britain and Ireland from 47°N-64°N and 14°W-13°E. Each time step is of 6 hours with the net transport of water between adjacent cells and the associated concentrations calculated over this period. The driving forces for advection are tidal and meteorological residuals, and for dispersion, tidal amplitudes. The model code is modular which allows the insertion of specific processes without interfering with the original code. Productive and destructive microbiological processes are simulated in the model in response to changing light levels and degree of stratification of the water column. There is an oxygen air/sea gas exchange with the surface layer of water. Dissolved gas and particle exchanges are modelled across the sediment interface. The water column is modelled by a single mixed layer. Beneath is a sediment layer where tidally driven resuspension and aerobic remineralisation occur. Rate-limiting physical fluxes, which determine the transport of water or gas and associated entities, take place only at the boundaries between layers. A set of differential equations exist for each grid box describing the rate of change of the model's variables. The physical component predicts the inter-box exchanges and the biological component predicts the state variable changes within each box.

Analysis of the model output suggests a residence time for water in the North Sea of about a year similar to previous estimates. The model reproduces the annual cycle in dissolved inorganic nitrogen with an r^2 value of 0.88 when modelled and observed monthly values of nitrogen tonnages are compared. The comparison of the observed cycle and the modelled cycled is shown in the figure below.

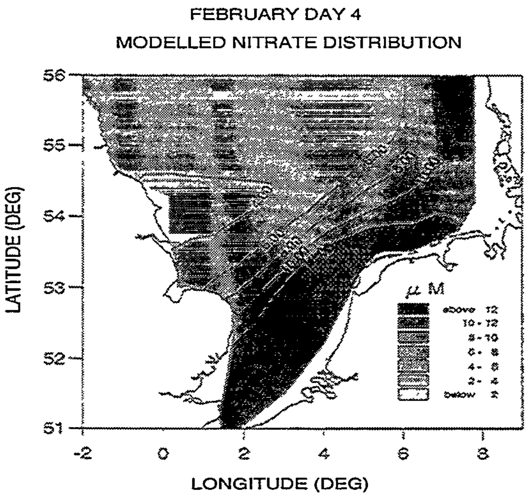


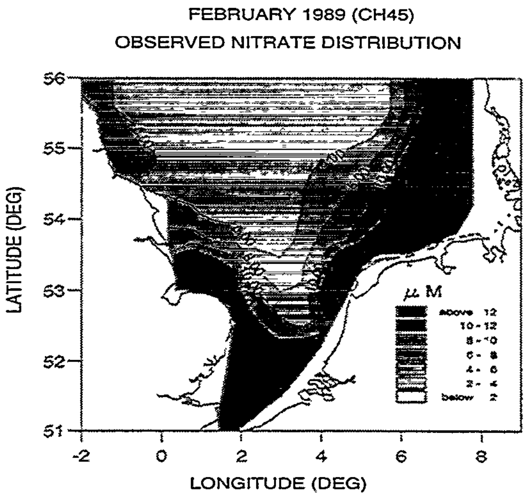
Budgeting of the supply terms of nitrogen suggests that the North Sea is a sink for dissolved nitrogen. Nitrogen is retained in the sediments or converted into biomass in higher tropic levels than plankton. In the modelled year the nitrogen inputs to the southern North Sea supporting production are estimated as 590, 550, 330, 140 ktonnes N from rivers, sea bed sediments, ocean waters and the atmosphere respectively. Estimates of average production from the model in NSTF-ICES boxes 3",4,5 and 7" give values of 120, 220, 140 and 150 gCm-2, compared with estimates based on the NSP observations of 79, 199, 261 and 119 gCm-2. The model estimates that annual primary productivity would fall by up to 18% for a 50% reduction in the input of riverine nitrogen.

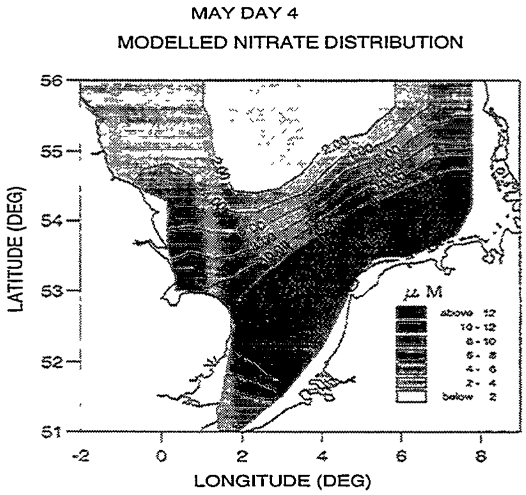
The accuracy of the present formulation of the model is limited by a number of approximations which have been made to achieve a working model at an early stage of development. Firstly sediment processes are not modelled but driven by the observed NSP data. In an area like the North Sea which is flushed in about one year by ocean water, the incorporation of material in sediments is the only way that high inputs in one year can be stored within the system to have an effect in subsequent years. Estimates of water flow between different areas can be improved by increasing the resolution of the model, and driving the model with winds which correspond to weather patterns rather than climatic means. Productivity estimates from the model agree well with observations in the more river impacted areas as these are well mixed. The agreement is less good in deeper waters because the model does not reproduce the stratification that occurs in these areas.

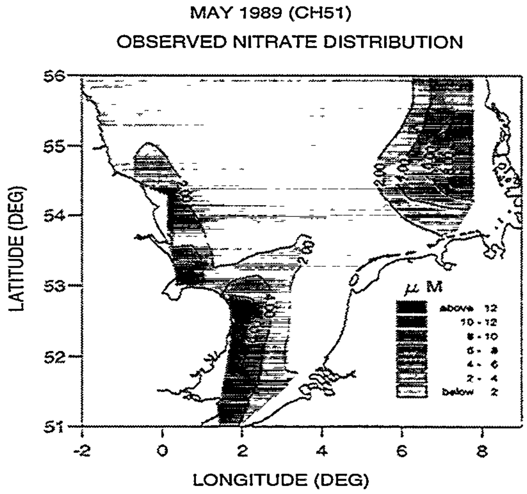
MAPS

On following pages maps are presented which enable a comparison to be made between the output of the model and the observed distributions of dissolved nitrate, ammonia and oxygen and the chlorophyll concentration in the water.

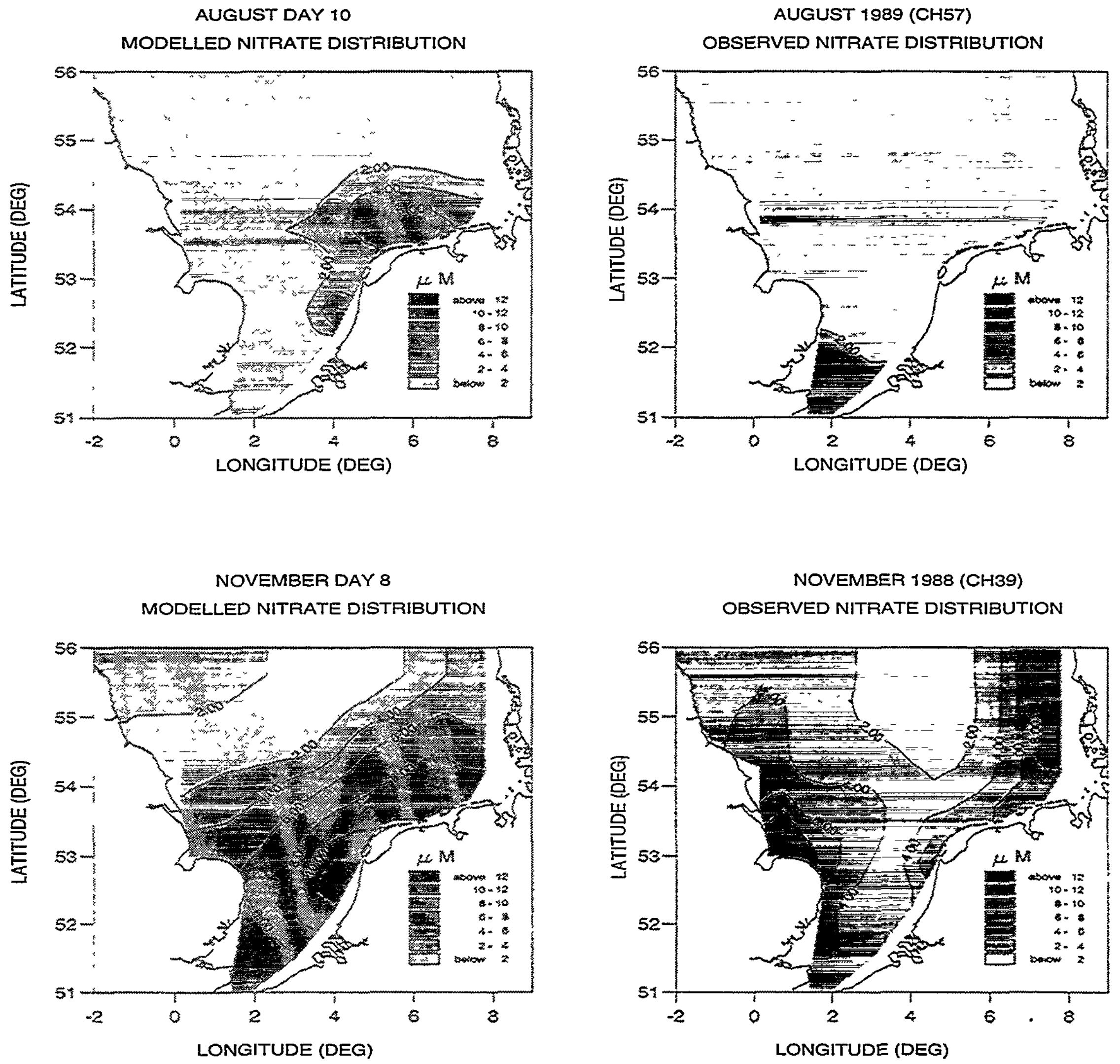






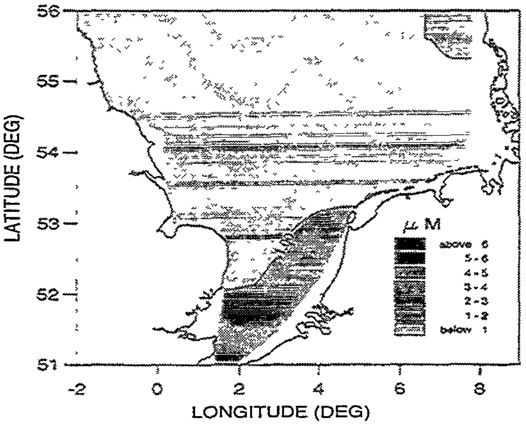


Modelled and observed nitrate concentrations are close to their maximum values in February. Model values are dominated by input from the river Rhine and the clockwise circulation pattern in the North Sea. Observed values off the UK coast are higher than model values. This may be due higher discharges than in the model estimates or due to the actual circulation being more influenced by easterly winds than during the NSP. A climatic average wind field is used in the model. The spring bloom occurred in May, removing nitrate from solution.

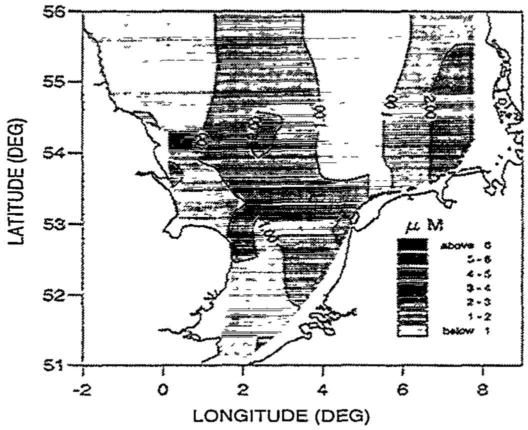


In both model and observations concentrations of nitrate remain low through the summer months. Because of the shallowness of the water, NSP observations could not be made close enough to the Dutch and German coasts to sample the main plume of water from the rivers which is held relative close to the coast in a density driven flow. The model does not resolve such flows and artificially allows fresh water to disperse more rapidly into the interior of the North Sea than it does in reality.

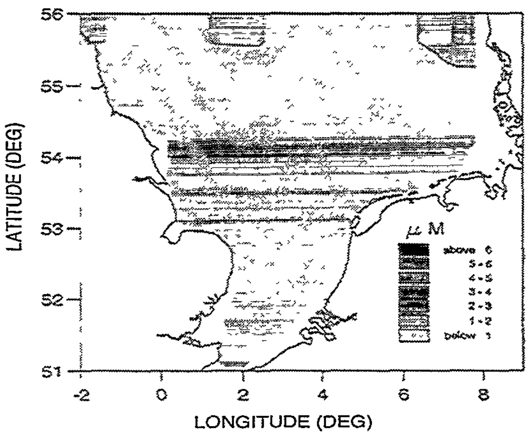
FEBRUARY DAY 4
MODELLED AMMONIUM DISTRIBUTION



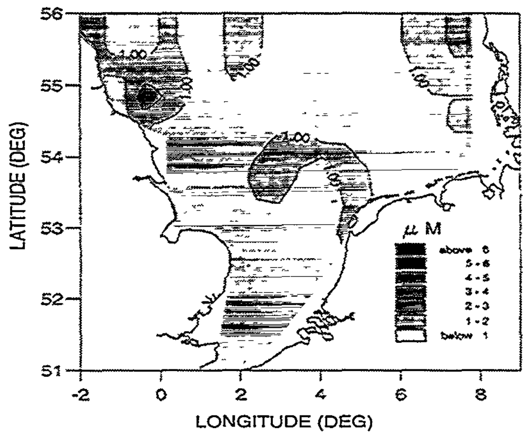
FEBRUARY 1989 (CH45)
OBSERVED AMMONIUM DISTRIBUTION



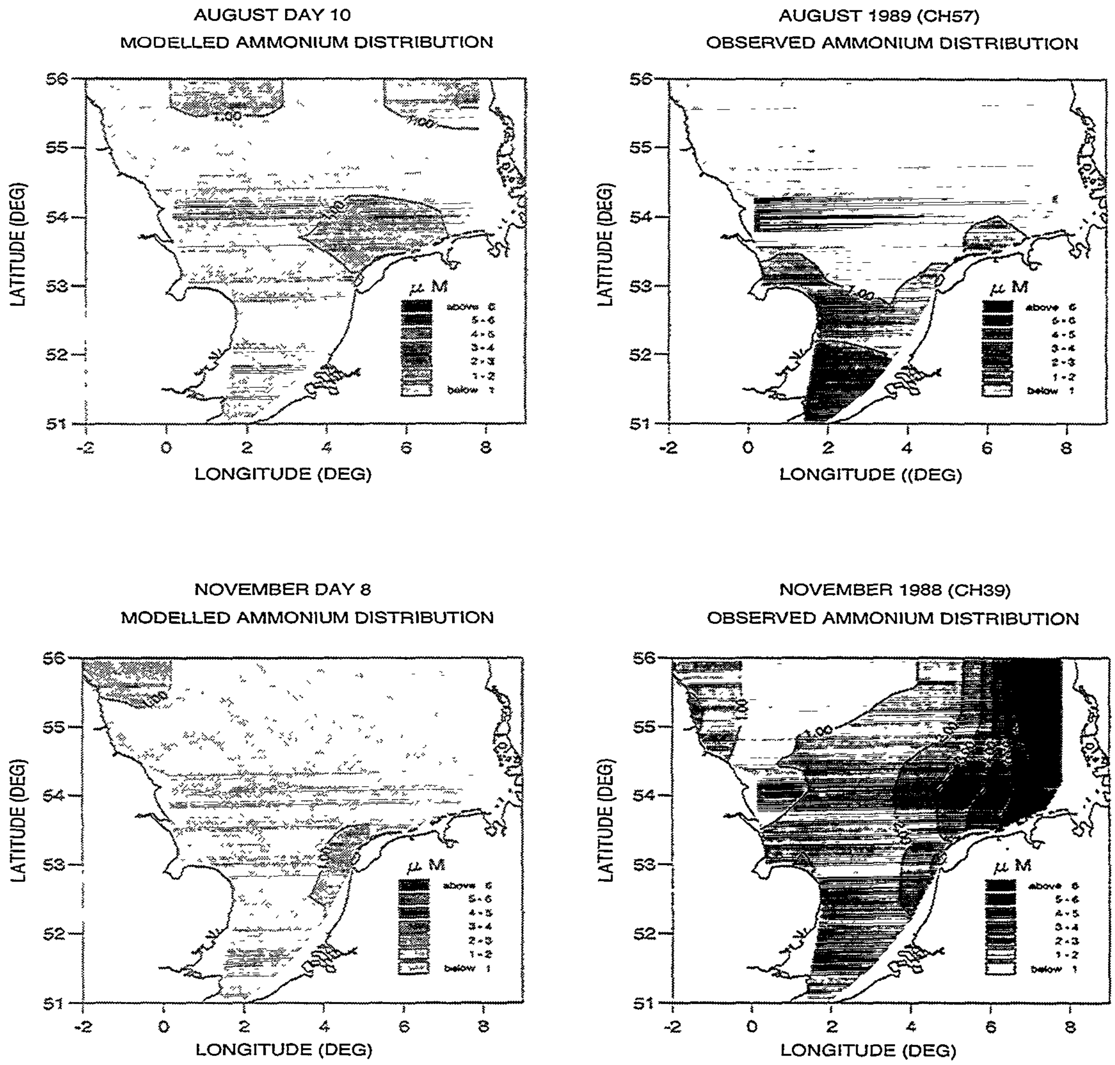
MAY DAY 4
MODELLED AMMONIUM DISTRIBUTION



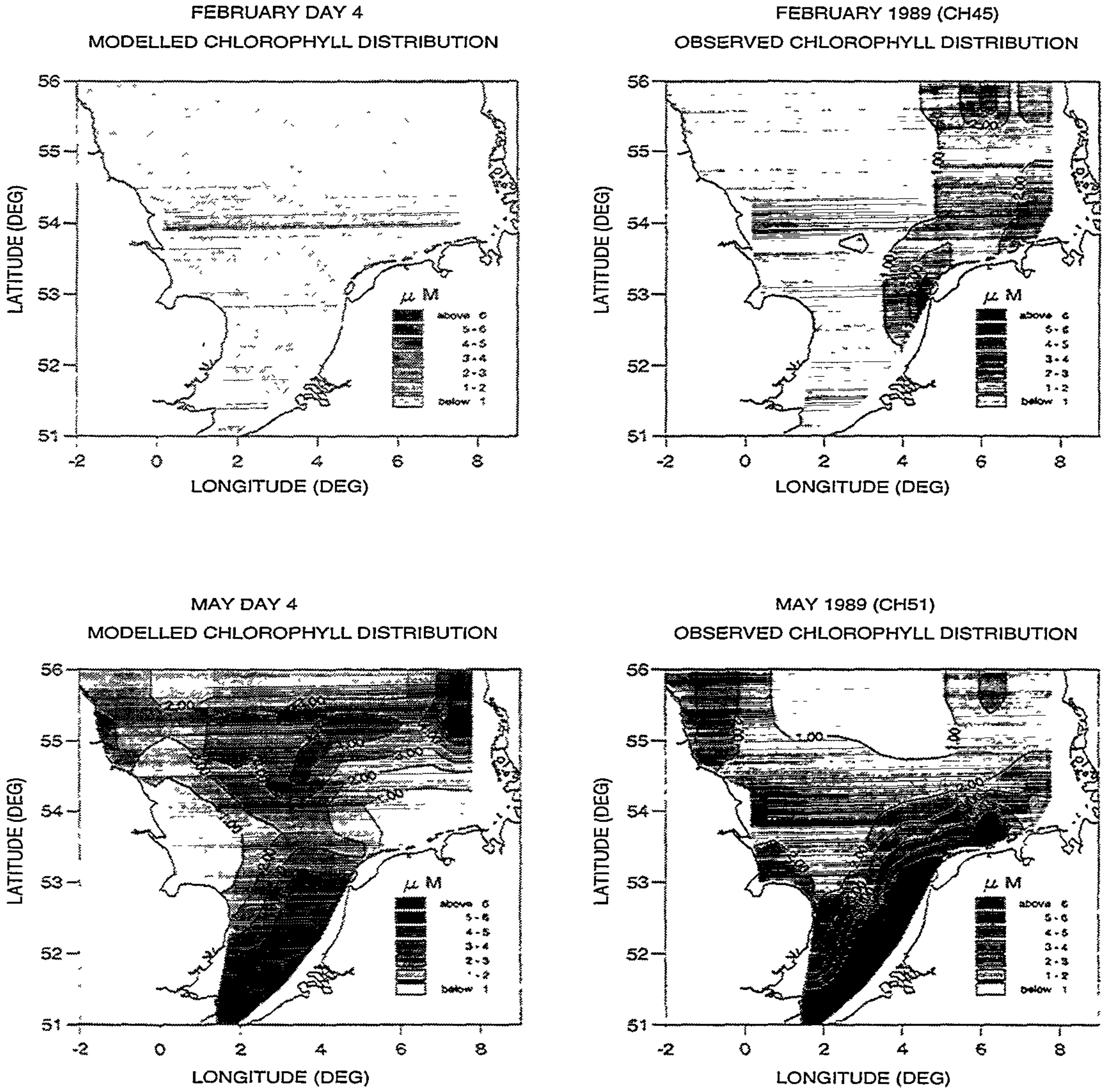
MAY 1989 (CH51)
OBSERVED AMMONIUM DISTRIBUTION



Modelled and observed concentrations of ammonia tend to be of similar concentration. Modelled concentrations tend to be lower. We feel this may in part be due to present estimates of nitrification rates being too high. The high values of dissolved ammonia observed in the Jutland current in November 1989 are not reproduced in the model.

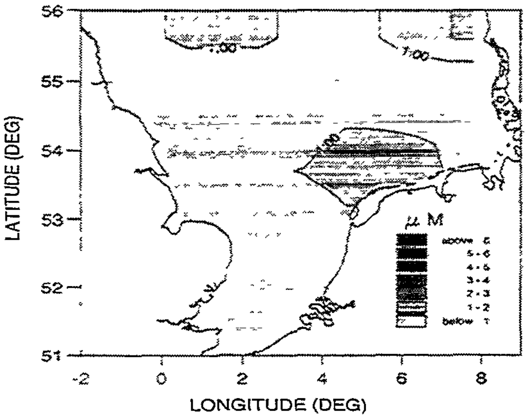


The model uses observed river water concentrations. For the elevated ammonia to cover such a wide area river inputs would have needed to be high for a longer period than is possible given the frequency of sampling. One possibility is input of ammonia from sediments continuing into the autumn for longer than primary production. Plankton growth in the summer and autumn quickly remove ammonia from solution. Estimates of ammonia fluxes in the model are based on NSP observations and so probably underestimate the flux from coastal sediments.

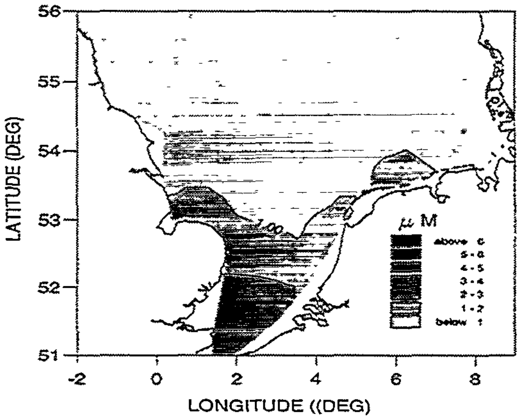


Observed levels of chlorophyll suggest that a low level of production does continue through the winter in shallow areas of the North Sea such as over the Dogger Bank and off the Danish Coast. This production is limited to specific species and is not reproduced well by the model which considers the plankton as an mixed population.

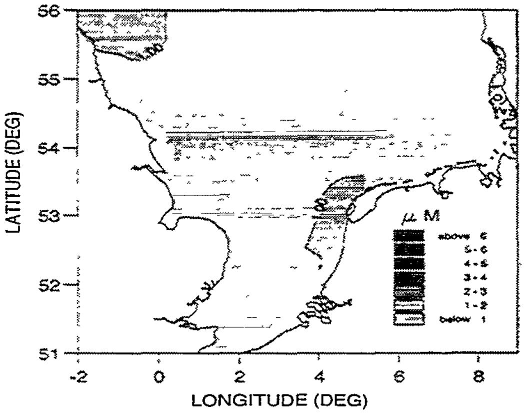
AUGUST DAY 10
MODELLED AMMONIUM DISTRIBUTION



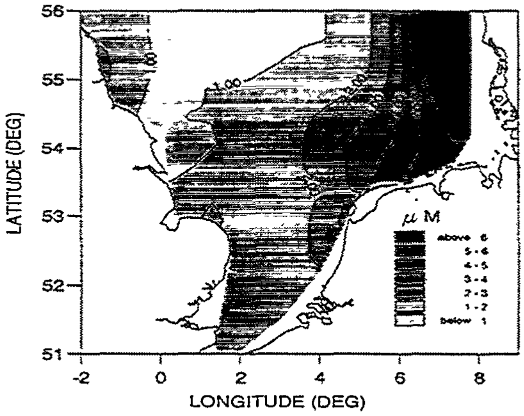
AUGUST 1989 (CH57)
OBSERVED AMMONIUM DISTRIBUTION



NOVEMBER DAY 8
MODELLED AMMONIUM DISTRIBUTION

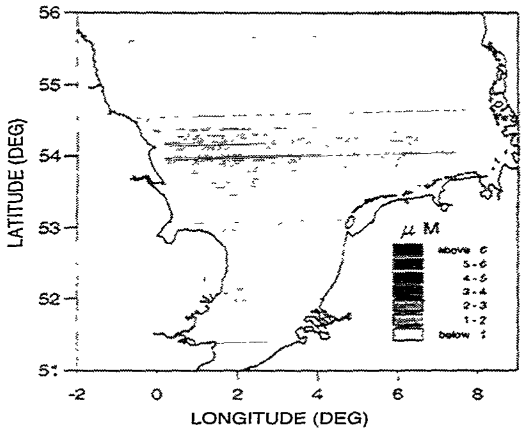


NOVEMBER 1988 (CH39)
OBSERVED AMMONIUM DISTRIBUTION

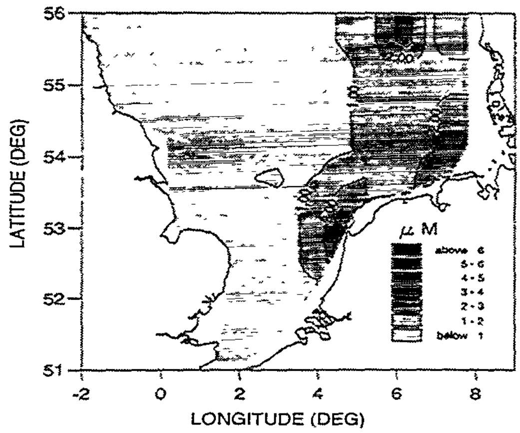


The model uses observed river water concentrations. For the elevated ammonia to cover such a wide area river inputs would have needed to be high for a longer period than is possible given the frequency of sampling. One possibility is input of ammonia from sediments continuing into the autumn for longer than primary production. Plankton growth in the summer and autumn quickly remove ammonia from solution. Estimates of ammonia fluxes in the model are based on NSP observations and so probably underestimate the flux from coastal sediments.

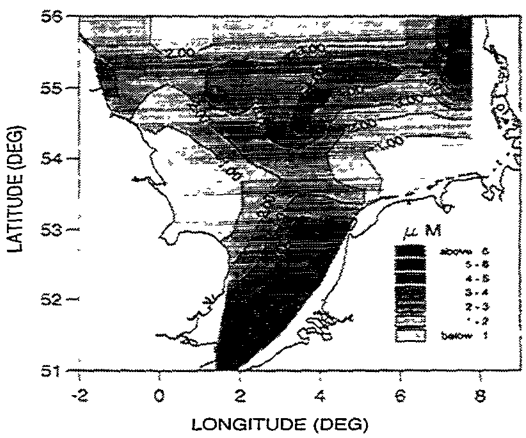
FEBRUARY DAY 4
MODELLED CHLOROPHYLL DISTRIBUTION



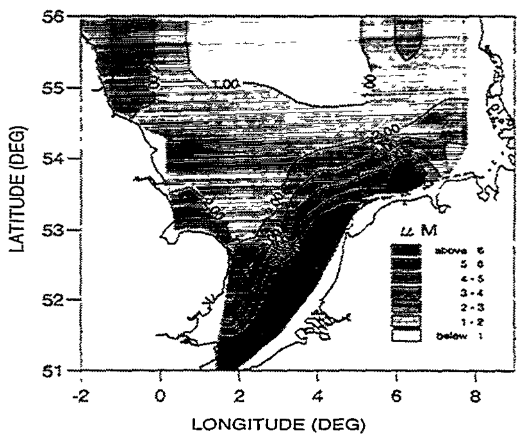
FEBRUARY 1989 (CH45)
OBSERVED CHLOROPHYLL DISTRIBUTION



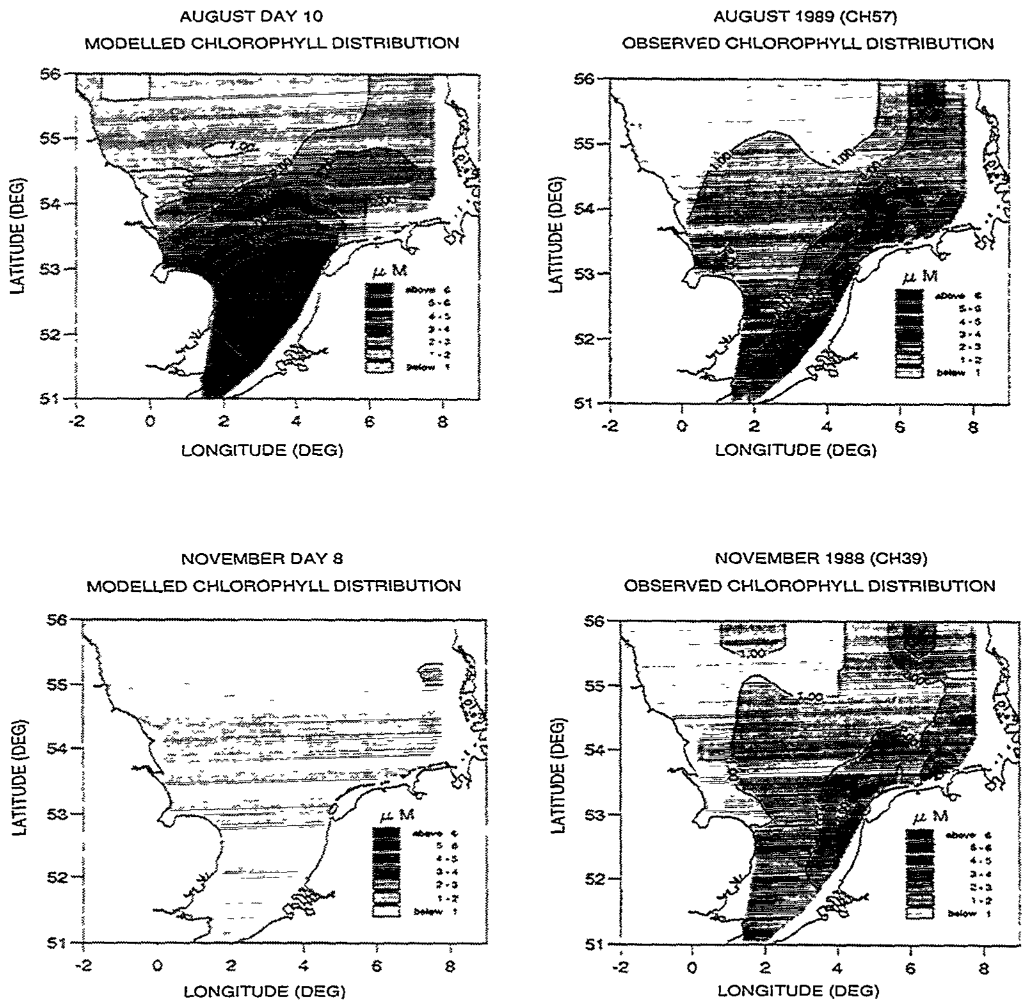
MAY DAY 4
MODELLED CHLOROPHYLL DISTRIBUTION



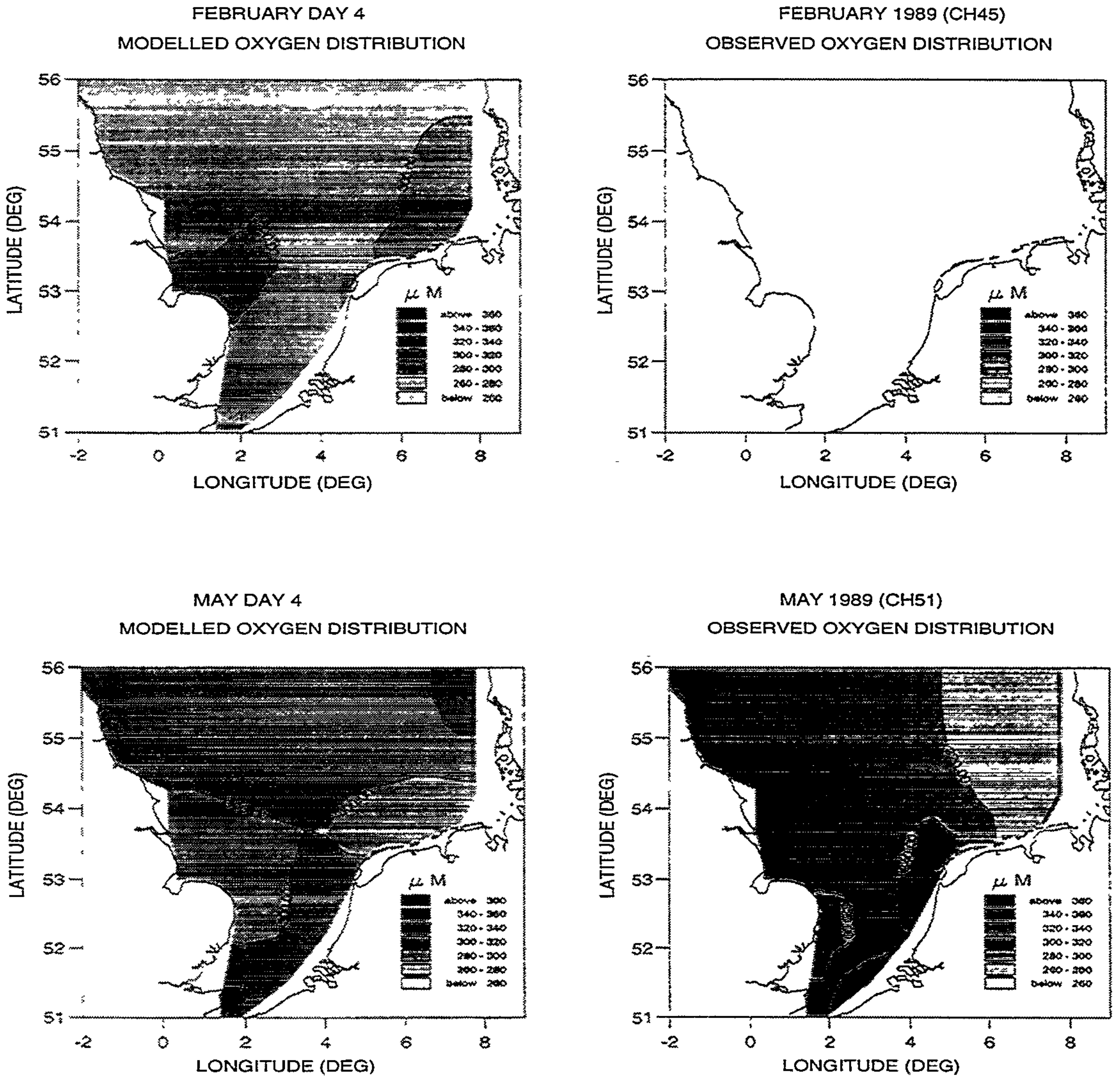
MAY 1989 (CH51)
OBSERVED CHLOROPHYLL DISTRIBUTION



Observed levels of chlorophyll suggest that a low level of production does continue through the winter in shallow areas of the North Sea such as over the Dogger Bank and off the Danish Coast. This production is limited to specific species and is not reproduced well by the model which considers the plankton as an mixed population.

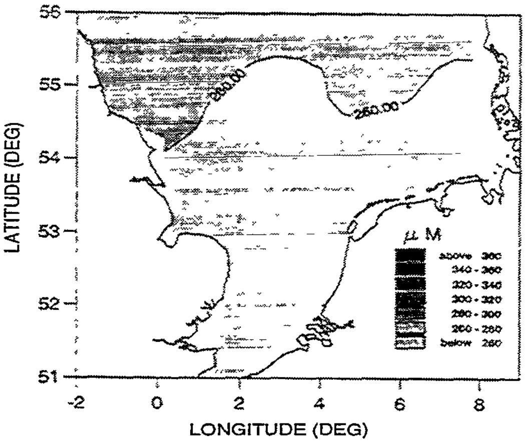


The model reproduces well the relative amounts of production in different areas of the North Sea. In particular the more limited production off the UK coast. In the analysis of model sensitivity this limitation of production is related to the higher suspended sediment concentration off the UK coast. This limits the amount of photosynthetically available radiation penetrating the water column.

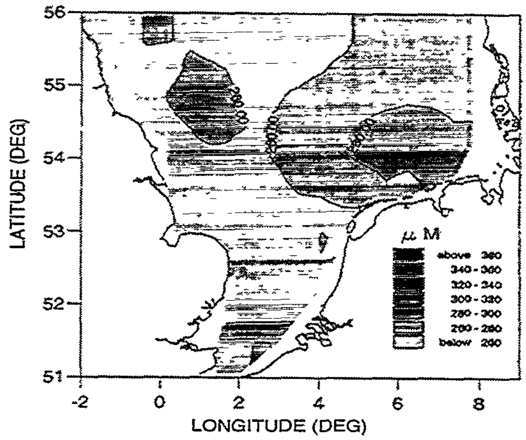


Concentrations of dissolved oxygen depend on a number of factors. These include as well as gains from photosynthesis and losses due to respiration, physico-chemical exchange of oxygen with the atmosphere which is dependent on physical conditions and the temperature and salinity of the water. The relative increases in concentration in May correspond to the less advanced state of the bloom at that point in the model compared to the May observations.

AUGUST DAY 10
MODELLED OXYGEN DISTRIBUTION



AUGUST 1989 (CH57)
OBSERVED OXYGEN DISTRIBUTION



NOVEMBER DAY 8
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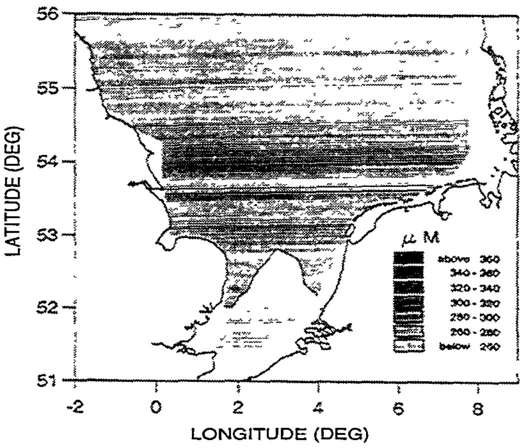

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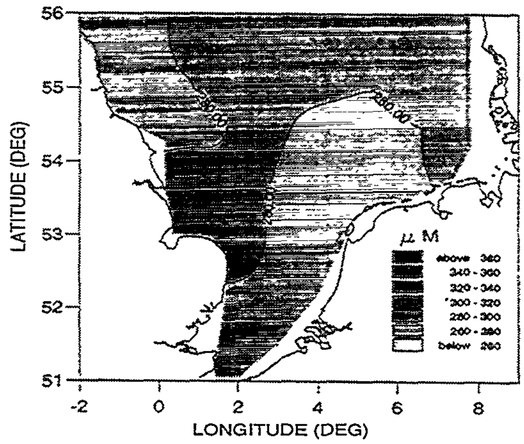


The lower oxygen concentrations in November relative to February are in part due both to the higher temperatures in November and to he removal of oxygen by the mineralisation of organic detritus.

FOREWORD

It has been suggested that increased inputs of the dissolved plant nutrient elements, nitrogen and phosphorus, cause environmental problems such as anoxic events and blooms of nuisance algae in marine waters. Excess nutrients may contribute to the occurrence of nuisance plankton blooms (e.g. *Gyrodinium aureolum*, TANGEN, 1977), and the recent extensive bloom of *Chrysocromulina polylepis* (DUNDAS *et al.*, 1989, MAESTRINI & GRANELI, 1991). The concentration of the effect in limited areas may lead to occurrences such as the oxygen depletion events observed in the German Bight in 1981-83 (RACHOR & ALBRECHT, 1983). Rivers flowing through populated areas contain about four times the "natural" nitrogen load and seven times the "natural" phosphorous load. One million tonnes of nitrogen enter the North Sea each year (VAN PAGEE & POSTMA, 1987). This equals the estimated total load of nitrate-nitrogen present in the southern North Sea (south of 56°N) in winter. These inputs extend along much of the coastal area of the North Sea (BROCKMAN *et al.*, 1990). The effect may be intensified by the circulation pattern of the sea which tends to localise the impact to a narrow coastal region (NELISSEN & STEFELS, 1988). To better understand the causes and effects of these so called eutrophication problems, we need to synthesise our available knowledge. The most appropriate way to do this is by using the available information and understanding to construct mathematical models of the processes involved. This allows the testing of the comparability of different measurements and ideas. Potentially such work can lead to a prognostic capability so that likely effects of changes can be forecast. For efficient management of the North Sea, it is essential to quantify the impact on the ecosystem of anthropogenic inputs relative to those of natural fluxes. In a wider context we need to understand how terrestrial inputs are sequestered in or exported from shelf seas. For example, it is not known whether the North Sea is a net importer or exporter of nutrients to or from the Atlantic Ocean.

The Natural Environment Research Council North Sea Community Research Programme (NSP) conducted a major fieldwork campaign investigating the physics, biology, chemistry and sedimentology of the southern North Sea in 1988 and 1989. This work is described in detail in the papers contained in CHARNOCK *et al* (eds 1994). A unifying aim of the programme was the idea of developing a prognostic water quality model from that data base (HUTHNANCE *et al.*, 1993). The NSP provided the first sufficiently coherent data set for the North Sea against which water quality models, which aim to predict changes involving the annual cycle of primary biological variables, can be tested and calibrated. Most ecological models of the North Sea (e.g. BARETTA *et al.*, 1993, FRANSZ *et al.*, 1991, LANCELOT *et al.*,1987) have not had the advantage of such a data set while others that have (e.g. TETT and WALNE, 1995) have concentrated on the one-dimensional (vertical) variations. More recent models are beginning to make use the larger data sets now available (HYDES *et al* 1996, MOLL 1997)

The principal purpose of the DoE contract "North Sea Nutrient Model" (PECD 7/8/179) was the development of a model structure and writing of the required computer coding for the model to be run. In addition, the NSP data base provided a much improved resource for obtaining direct information on the functioning of the system which had not been possible before. Therefore this report is comprised of three main areas. Firstly Part 1, details some of the new understanding we have been able to gain of the North Sea system from quantitative analysis of the NSP data set. Then secondly in Part 2, we describe in detail the structure of the actual model that we developed, and provide information on all the components of the model. Thirdly in Parts 3, 4 & 5 we discuss:- the sensitivity of the model output to the main driving forces that are included in the model (Part 3); the flow of nutrients across the boundaries of the model (Part 4); and the limitations of the present model (Part 5).

PART 1

QUANITATIVE ANALYSIS OF THE NEW DATA AVAILABLE FROM THE NERC NORTH SEA PROGRAMME

1.1 Introduction

Although increased inputs of nutrients (N and P) from rivers and atmosphere to the North Sea are well documented (BROCKMAN *et al* 1988), until recently little data had been collected in shelf sea environments in a systematic manner. The NERC North Sea Programme provided a data set that could be analysed both statistically and quantitatively. The processes involved could then be described for the first time in terms of the actual quantities of nutrients involved, and the special and temporal relationships could be described mathematically. PRANDLE *et al* (*In Press*) carried out a numerical analysis of the results from the NSP surveys. This produced an informative and concise summary of the cycles that were observed, We present in Section 1.2 of this Part of this report a short version of that paper. In section 1.3 we present a quantitative analysis of the observed NSP data. This shows the value of this data set, as we can extract from it information both about the relative magnitude of the sources of nutrients in the North Sea, and also the relationship between the supply of nutrients and the amount of production that actually occurs.

1.2 An analysis of the seasonal cycles of temperature, salinity, nutrients and suspended sediment in the North Sea, south of 56°N, in 1988 and 1989, based on PRANDLE *et al (In Press)*

1.2.1 Précis

A simple mathematical and statistical approach has been taken to summarise the large data base of information available from the 15 consecutive monthly surveys of the UK North Sea Project (NSP). The seasonal cycles of temperature, salinity, phosphate, nitrate, nitrite, silicate, ammonium and suspended particulate matter (SPM) are determined by analyses of observed data. Changes through the seasonal cycle are approximated to a cosine wave. The mean concentrations and standard deviations over the whole area through time were salinity 34.26(±.74), ammonia 1.3(±1.0)µM, nitrate 4.9(±6.0)µM, nitrite 0.4(±0.5)µM, phosphate 0.5(±0.3)µM, silicate 2.5(±2.5)µM and suspended sediment 2.6(±3.5)mg/l. A seasonal cycle accounts for most of the variance in temperature and nutrients. Salinity shows little seasonality. The spatially-averaged seasonal amplitudes for both nitrate and silicate are approximately equal to their mean values - this is consistent with these being limiting nutrients. Correlations between the determinands are calculated. These calculations confirm the similarity in the spatial distributions for the nutrients, especially between nitrate, phosphate and silicate. Maximum concentrations are confined to the coastal regions except for ammonium and nitrite for which they occur offshore. Spatial distributions of the anomalous (non-seasonal) components can be interpreted to indicate the effect of specific riverine and oceanic exchanges. Correlations between nitrate, nitrite and ammonium correspond to the inter conversion of these compounds.

1.2.2 Introduction

The UK North Sea Project (NSP) monitored the annual variability of a number of parameters to form the basis for developing water quality models. Observations were made at over 100 locations along a 3000km track surveyed on each of 15 consecutive months. The area covered ranges from the Dover Strait to an E-W section along 56°N. The general features of the annual cycle of nutrient and plankton levels in the North Sea have been established for sometime GERLACH (1988), BROCKMAN *et al*(1988), NELISSEN & STEFELS 1988, JOHNSTON (1973) CUSHING (1973). But what has been lacking are data sets of sufficient coherence and breadth of synoptic coverage of an appropriate range of determinands that they could be used as the basis for calibrating models linking physical and chemical processes to biological production (HUTHNANCE *et al* 1993, HYDES *et al* 1996, RADACH *et al* 1993). The UK North Sea Programme (NSP) was the first to provide sufficient information that changes in nutrient concentrations and plankton biomass can be investigated quantitatively (HOWARTH *et al* 1993).

A problem with such data sets can be their size. The aim of this work was to see how successfully the annual cycle of nutrients in the southern North Sea could be summarised, and if this procedure could lead to new insights into the relationships of changing water masses, nutrients and sediment loads.

1.2.3 Method

The data were interpolated to provide values on a 35km rectangular grid (30' longitude x 20' latitude). Gridded values were then analysed to determine (i) the annual means, (ii) the seasonal amplitudes and phases and (iii) the percentage of the observed variance accounted for by (i) and (ii). Finally, cross-correlations of all these values were calculated for the parameters: temperature, salinity, phosphate, nitrate, nitrite, silicate, ammonium, total suspended particulate matter and depth. These parameters were selected on the basis of there being, on average, at least 90 data locations per survey on at least 12 of the monthly surveys. The interpolation procedure used for gridding the original observations involved approximating a plane by least squares fitting. For each monthly survey of each parameter, a separate plane was fitted to all observed data for each grid point, only depth-averaged values were considered.

1.2.4 Results

The seasonal cycles

TABLE 1 lists the spatial mean values together with the spatial mean values of the phase ø. Simple descriptions of the cycles derived from the above are summarised below, where A_0 = Seasonal mean value, A_1= Seasonal amplitude, max = date corresponding to maximum amplitude, P = Percentage of total variance attributable to seasonal variance

TABLE 1

Spatial means and standard deviations of A_0 , A_1, percentage variance accounted for by the seasonal cycle, and month of maximum

	Temp	Sal	P04	N03	N02	Si	NH4	Sed
A^0	10.18	34.28	0.518	5.329	0.418	2.705	1.072	2.773
s A_0	1.269	0.630	0.127	3.316	0.177	1.196	0.421	2.726
A_1	4.221	0.155	0.375	5.471	0.408	2.284	0.448	1.612
sA_1	1.475	0.102	0.110	3.790	0.297	1.551	0.325	1.577
P%	89.2	37.3	95.2	91.5	78.7	92.7	84.6	77.3
Max	SEP	FEB	JAN	JAN	DEC	DEC	NOV	JAN

Temperature:

A_0 = 10.2 °, A_1 = 4.2°, C, max = September 3r, P = 89%

The seasonal cycle approximation accounts for 89% of the total variance, the mean (A_0) values ranges from 7°C at the NW limit to 12° - 13°C along the continental coast. The apparent lower temperature of northern waters is due to the depth averaging including the relatively large mass of water below the thermocline in the deeper areas. The seasonal amplitude varies in a similar fashion from 2°C in the NW to 6°C in the German Bight. The non-seasonal anomalies are greatest in the deeper waters along the northern boundary. This is likely to be due to advective changes in water masses not being masked by the dominant effect of solar heating in shallower southern waters.

Salinity:

A_0= 34.3, A_1 = 0.15 psu, max = February 5, P = 37%

The seasonal cycle for salinity accounts for only 37% of the variance. The mean values show freshest water of 32.4 psu in the German Bight with saltiest 34.8 psu at the N.W. limit. Salinities are generally lower along the coasts where river inflows and the depth integrated effects of any imbalance between precipitation and evaporation are enhanced. The seasonal amplitude is everywhere less than 0.5 psu with the maximum associated with Rhine outflow.

Phosphate:

A_0 = 0.52, A_1 = 0.37 μM, max = January 11, P = 95%

The seasonal cycle accounts for 95% of the phosphate variance. Mean values range from 0.3 to 0.75 μM with largest values occurring closest to the coast. The seasonal amplitude shows a similar distribution with values ranging from 0.2 to 0.6 μM.

Nitrate:

A_0 = 5.3, A_1 = 5.5 μM, max = January 29, P = 90%

The seasonal cycle accounts for 90% of the nitrate variance. Mean values range from 1 to 11 μM with largest values occurring along the coasts and smallest in the central parts of the northern boundary. The seasonal amplitudes correspond almost exactly with the mean values, indicating a seasonal cycle ranging everywhere from near zero in July to a maximum in January of up to 22 μM.

Nitrite:
A_0 = 0.42, A_1 = 0.41 μM, max = December 28, P = 79%

While, overall, the seasonal cycle accounts for 79% of the nitrite variance, significant anomalies occur both in the German Bight and in the central region close to the northern boundary. Mean values range from 0.2 to 0.8 μM with minimum values in the west and maximum offshore of the Danish coast. The seasonal amplitudes show a similar distribution with amplitudes ranging from 0.1 to 1.0 μM with the maximum occurring offshore in the eastern section.

Silicate:
A_0 = 2.71, A_1 = 1.55 μM, max = December 29, P = 93%

The seasonal cycle accounts for over 93% of the silicate variance. Mean values range from 1 to over 5 μM with largest values along the UK and Danish coasts. Seasonal amplitudes show a similar distribution with values ranging from 1 to 6 μM.

Ammonium:
A_0 = 1.07, A_1 = 0.45 μM, max = November 18, P = 85%

The seasonal cycle accounts for 85% of the ammonium variance with the largest anomaly found off the Danish coast. The mean values range from 0.6 to 1.4 μM with the largest values located along the continental coast, particularly in the German Bight. The seasonal amplitudes range from 0.2 to 1.2 μM with a similar distribution to the mean values.

Suspended Particulate Matter:
A_0= 2.77, A_1 = 1.61mg/l, max = January 13, P = 77%

The seasonal cycle accounts for approximately 77% of the SPM variance with the largest anomaly close to the NW limit. Mean values range from 0.5 to nearly 6 mg $^{-1}$ and seasonal amplitude from 0.5 to 5 mg $^{-1}$. Reduced SPM concentrations occur along the western section of the northern boundary and in the Rhine outflow region off the Dutch Coast.

Correlations

Gridded Observations (TABLE 2)

The highest correlations of approximately 0.8 are calculated between phosphate, nitrate and silicate. This indicates that not only are their geographical distributions similar but, also, that their rates of variation in concentration are reasonably constant throughout time and space. The next most correlated parameters, all approximately 0.5, are phosphate with both nitrite and SPM together with nitrate and temperature (negatively correlated). Parameters with correlations of less than approximately 0.1 are SPM with temperature, salinity and ammonium; temperature with ammonium and nitrite with salinity.

TABLE 2

Correlation of $f_{i,j,t}$ for each parameter for all i, j and t

(Approximately 2910 paired values for each coefficient)

	Temp	Sal	P04	N03	N02	Si	NH4
Sed	-0.11	-0.07	0.493	0.446	0.214	0.377	0.107
NH4	-0.01	-0.47	0334	0.304	0.379	0.458	
Si	-0.35	-0.40	0.794	0.703	0.470		
N02	-0.27	-0.10	0.521	0.392			
N03	-0.49	-0.37	0.799				
P04	-0.40	-0.23					
Sal	-0.23						

Seasonal Mean A_0 (TABLE 3)

Maximum correlations (all > 0.75) are again found between phosphate, silicate and nitrate. Salinity and ammonium show high (negative for salinity) correlations (> 0.6) with all parameters except temperature and SPM. Remaining correlations > 0.5 are between phosphate and SPM, 0.61, silicate and nitrite, 0.56; and temperature and nitrate, 0.60.

TABLE 3

Correlation of Means, A_0 for all i and j

(194 paired values for each coefficient)

	Temp	Sal	P04	N03	N02	Si	NH4
Sed	0.462	-0.12	0.611	0.468	-0.06	0.235	0.004
NH4	0.316	-0.90	0.592	0.767	0.667	0.853	
Si	0.238	-0.91	0.753	0.861	0.564		
N02	0.278	-0.59	0.239	0.413			
N03	0.596	-0.89	0.908				
P04	0.482	-0.69					
Sal	-0.39						

Seasonal Amplitude $A1_1$ (TABLE 4)

The nutrients phosphate, silicate and nitrate all show correlations in excess of 0.9 indicating that their seasonal cycles are closely related. Correlations in excess of 0.7 are calculated for ammonium and these three nutrients. Likewise correlations in excess of 0.7 are found for salinity and nitrate and temperature and phosphate.

TABLE 4

Correlation of seasonal amplitudes, $A^1{}_{i,j}$ for all i and j

(194 paired values for each coefficient)

	Temp	Sal	P04	N03	N02	Si	NH4
Sed	0.473	0.015	0.386	0.406	-0.02	0.228	0.106
NH4	0.582	0.610	0.748	0.810	0.468	0.773	
Si	0.610	0.395	0.907	0.929	0.391		
N02	0.517	0.705	0.496	0.393			
N03	0.077	0.464	0.937				
P04	0.782	0.489					
Sal	0.463						

Anomalies, Gridded Observations $Ei_{j,t}$ (TABLE 5)

Again, the maximum correlations (approximately 0.6 to 0.7) are found between nitrate, silicate and phosphate. In addition, there is a high negative correlation with salinity of phosphate, nitrate and silicate. This suggests that the non-seasonal processes which affect salinity concentration (variability in oceanic and river flow conditions) may also contribute to the non-seasonal phosphate, nitrate and silicate variation.

TABLE 5

Correlation of anomalies, $E_{i,j,t}$ for all i, j and t

(Approx. 2910 paired values for each coefficient)

	Temp	Sal	P04	N03	N02	Si	NH4
Sed	-0.24	-0.19	0.278	0.270	0.190	0.327	0.145
NH4	-0.32	-0.12	0.140	0.122	0.183	0.215	
Si	-0.06	-0.66	0.562	0.691	0.023		
N02	-0.21	-0.03	0.047	0.028			
N03	0.003	-0.61	0.681				
P03	0.072	-0.55					
Sal	0.019						

1.2.5 Discussion

Phosphate, nitrate, nitrite and silicate exhibit strong seasonal cycles with maximum values in December/January. Fitting of the seasonal cycle assumes that the removal and regeneration processes which give rise to the cycle are symmetrical. We cannot say from this analysis whether the earlier occurrence of the silicate maximum in December is due to more rapid regeneration than the other nutrients or due to its more complete and earlier removal by the diatoms which are the dominant plankton at the start of the spring bloom. Nitrate and silicate have seasonal amplitude values (A_1) approximately equal to the mean values (A_0) indicating near-zero values in June-July and thereby suggesting their limiting role in microbiological processes.

Maximum values are generally found along coasts and minima in the deeper northern waters. The sources influencing these distributions are: i) Boundary seas - the English Channel, Northern North Sea and Baltic; ii) Rivers - the Forth, Tyne, Tees, Humber, The Wash outflow, Thames, Rhine, Wadden Sea, Ems, Weser and the Elbe; iii) Resuspension and regeneration at the sea bed; iv) Atmospheric input; v) Internal recycling.

River and Boundary Inflows

Depth averaged temperature is not greatly affected by riverine inputs. Colder water is present on the northern boundary in deeper areas, whilst warmer water associated with the English Channel region extends up the continental coastline into the German Bight. Salinity is slightly lower in regions of major river outflow, particularly in the German Bight.

The highest mean silicate levels are associated with the German Bight region followed by the Wash. Most noticeable is the steady fall away from the coast and towards the Northern Boundary of mean silicate concentrations. The amplitudes have a similar distribution. The exceptions to this are regions in the German Bight, at the northern boundary and at the mouths of the Rhine and Humber.

Elevated phosphate levels occur at the mouths of the Thames, Wash and Humber, Rhine, Wadden Sea, Ems, Weser and Elbe. The non-seasonal effects in the region of the Humber may indicate that the discharge of phosphate loads from the Humber is more out of phase with the production regeneration cycle than for other rivers or simply that the tendency for this phase difference is most easily observed off the Humber. Concentrations of phosphate dissolved in river water tend to increase as river flow decreases. So concentrations will tend to be highest in summer when flows are lowest. Conversely concentrations of dissolved nitrate tend to increase with flow so that the seasonal variation in nitrate inputs is better matched to the seasonal cycle of concentrations in the North Sea than is the case for phosphate (BALLS, 1992, 1994). Nitrate concentrations are elevated at the mouths of the Wash, Humber, Thames, Rhine, Wadden Sea and in the German Bight from the mouth of the Elbe northwards. The region of the northern boundary has the lowest nitrate concentrations. The area with the least variance accounted for by the seasonal cycle is the mouth of the Ems.

The nitrite maximum in the main area of the North Sea occurs in December, but at the river mouths and the Northern Boundary, the peak occurs much earlier in August, September and October (data not shown). Mean nitrite levels are high at the mouth of the Weser and in the north eastern area of the grid. Concentrations in the north-west are low with some increase at the mouths of the Tyne and the Wash. The amplitude distribution for nitrite again is high near the Weser and in the north east but a patchy effect is more evident. This may be an indication of biological turnover of nitrite.

Ammonium has high seasonal mean values in the German Bight and at the Dover Strait. All the British river outflows appear to be sources of ammonium, particularly the Tyne. The patchiness observed with ammonium amplitudes (which differs from nitrite amplitude patches) may be due to biological activity. This patchiness observed with nitrite and ammonium data is not seen for the other parameters.

The sediment distribution has well-defined maximum values on the coast off south east England. The amplitudes also appear largest in this area, but with an arm extending north eastwards to an area north of the Wadden Sea. This area was associated with patchiness of amplitudes for both nitrite and ammonium.

Nitrogen balance

Nitrogen is present in seawater in a number of different forms (WARD 1992). The three principal inorganic forms - ammonia, nitrate and nitrite were determined during the NSP surveys. The distributions of the three compounds are determined both by their source terms and their involvement in microbiological processes, which depending on the particular environment, can either reduce nitrate to ammonia or oxidise ammonia to nitrate. In either case nitrite is produced as an intermediate compound. In certain conditions nitrite is reduced (denitrified) to di-nitrogen which is lost from solution as nitrogen gas. The relative importance of denitrification in the North Sea is not yet well constrained by direct measurements (LAW & OWENS 1990), but comparison of the ratio of nitrogen to phosphorus in the different inputs to that observed in the North Sea suggests it must be significant. This analysis gives an N:P ratio of 10, (based on the mean values of A_0 in Table 1) which is lower than the value in ocean waters coming into the North Sea which is close to the Redfield Ratio of 16 (REDFIELD, 1934; SPENCER 1975) and substantially lower than in river inputs (HUPKES 1990,1991; BROCKMAN *et al* 1988).

The inter-relationship between the different nitrogen containing compounds is partly demonstrated by the degree of statistical correlation between them. Correlations between nitrate and nitrite; nitrate and ammonium; and nitrite and ammonium are all higher through space alone than through both time and space (0.413; 0.767; and 0.667 versus 0.392; 0.304; and 0.379 respectively). Correlations through time alone for nitrate with ammonium and nitrite with ammonium show little positive correlation. In some areas there is negative correlation, which indicates that net reduction of one parameter is accompanied by net production of another. As the nitrogen containing compounds show fairly high correlation through space, this net reduction/production through time is unlikely to be merely due to advection. The reduction of nitrate under anoxic conditions may explain the negative correlation (-0.308) of nitrite with dissolved oxygen (using original, un-interpolated, paired data) which occurs during summer months, whilst the correlation value over the full fifteen month period is positive, 0.228.

1.3 A quantitative assessment of the sources of nitrogen supporting productivity in the North Sea, based on the new data available from the NERC-NSP

Drawing up a realistic budget is now possible using the accurate and comprehensive data set produced by the NERC North Sea Community Research Programme (NERC-NSP). During the NERC-NSP the different forms of nitrogen determined were:- particulate nitrogen in suspended and bottom sediment samples, and, dissolved inorganic nitrogen (DIN) as ammonia, nitrate and nitrite in water bottle samples.

Input budgets, can best be prepared for the autumn and winter periods when biological removal tends to a minimum. A direct comparison can be made between observed increases and estimates of inputs over the subsequent winter period. A budget was calculated for the period

November 1988 to January 1989. (These being the appropriate months with the most complete data sets). The observed change in the nutrient load between November and January was first calculated. To do this the concentration data was interpolated onto a 12x12 km grid. Then using a corresponding bathymetry the tonnage of nutrient present in each grid cell was calculated. The change in tonnage is then the difference between the sums for each month. This value can then be compared to estimates of the inputs taking into account imports and exports across the boundaries. Estimates of river inputs were based on average flow and concentration data for rivers entering the North Sea.

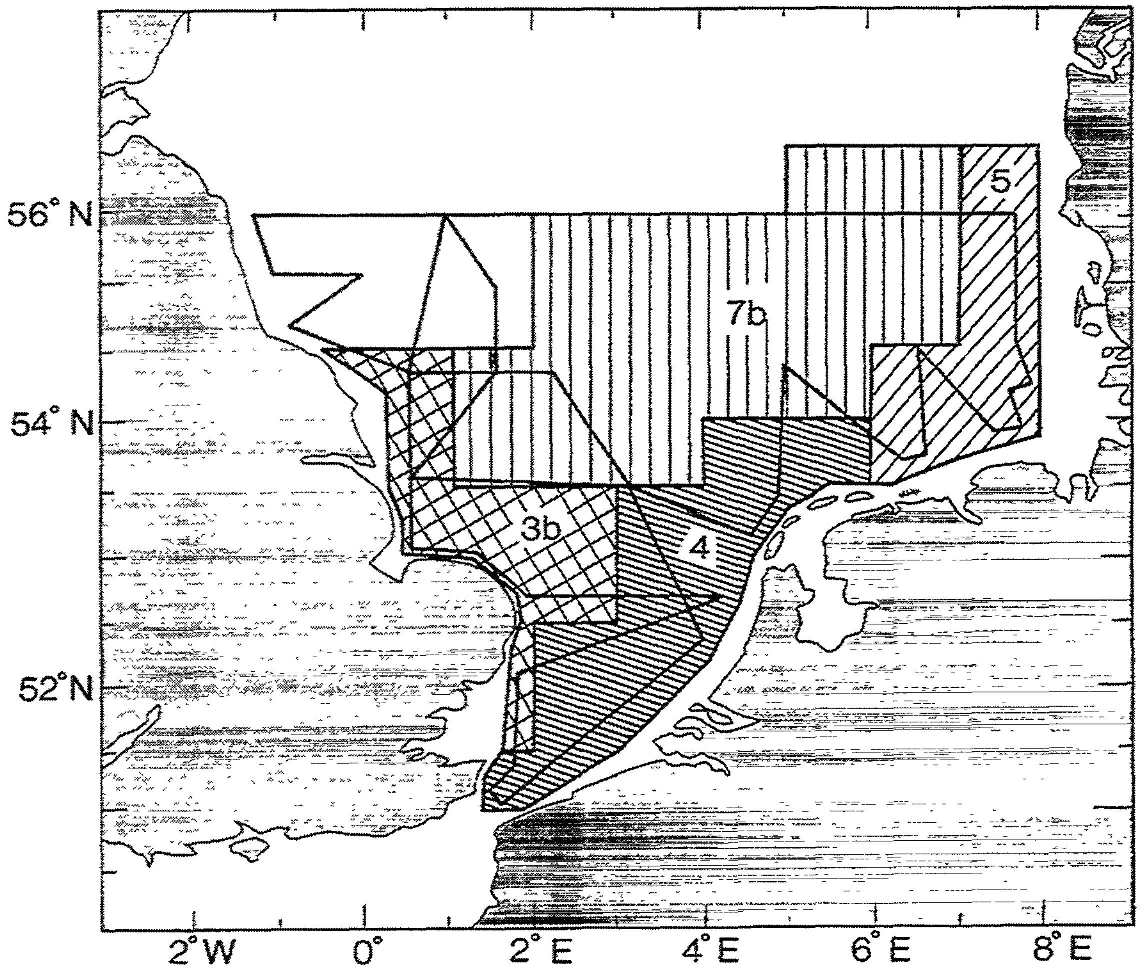


FIG. 1.3.1. Map showing NERC-NSP cruise track and subdivision into North Sea Task Force boxes. The boxes provide an approximate division of the North Sea into distinguishable water masses (ICES 1983). Between August 1988 and October 1989 waters were sampled at approximately 120 sites each month, on a grid designed to examine the important hydrographic features. Areas and volumes of the boxes are 3b, 910.7km^3, 32544km^2; 4, 1196.1km^3, 44208km^2; 5, 781.6km^3, 36576km^2; 7b, 3085.8km^3, 77616km^2

Exchanges through the Dover Straits and across the 56°N boundary, sediment exchanges of dissolved DIN (nitrate and ammonia) and silicon (NEDWELL *et al* 1993) and atmospheric inputs (RENDELL *et al* 1993) were calculated using NSP data. Dispersion of inputs was calculated by tracking notional particles (of water containing DIN from different sources) in current fields derived from a two dimensional meteorologically driven model (HAINBUCHER *et al* 1987, PROCTOR & SMITH 1992). Changes in the whole southern North Sea are compared in TABLE 1.3.1. Relative contributions to the DIN budget in different NSTF boxes (FIGURE 1.3.1)are compared in FIGURE 1.3.2.

For the southern North Sea only 73% of the observed change in DIN load not be accounted for by the inputs we can quantify. FIGURE 1.3.2 shows that a higher proportions can be accounted for in NSTF boxes 4 and 5. These receive proportionally greater river inputs, but even in these areas, the quantifiable inputs do not account for the observed change in the DIN load. In contrast the silicon estimate is over budget. The relative size of the sediment inputs of DIN and silicon is consistent with observations of the greater build up of silicon in waters isolated below the thermocline in seasonally stratified areas of the North Sea (BROCKMAN *et al* 1988). The near balance of the silicon budget suggests that it is unlikely that we have greatly underestimated the river and oceanic input terms.

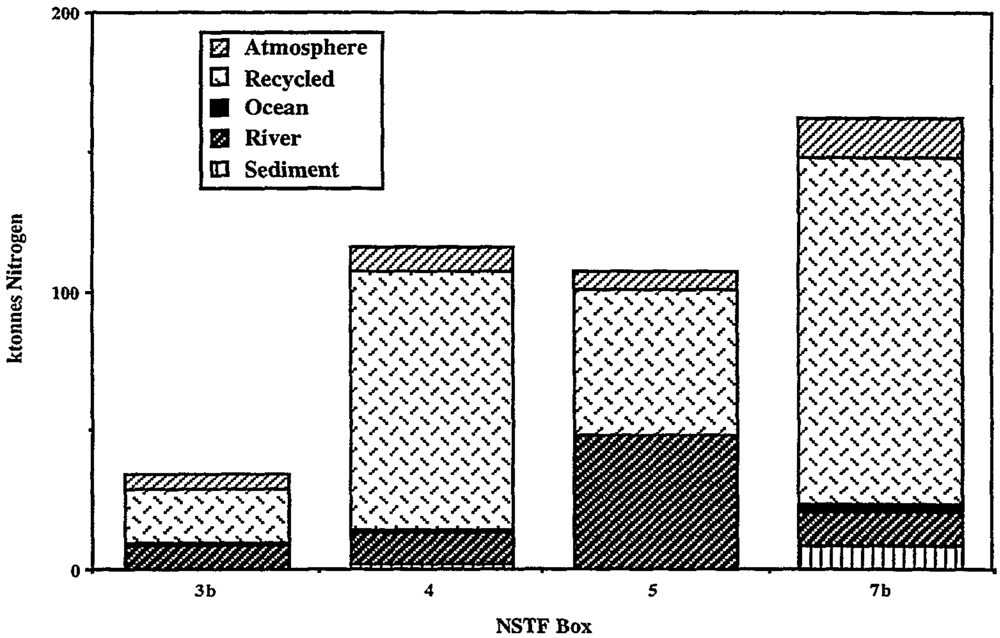
TABLE 1.3.1

Comparison of quantifiable nutrient input tonnages from different sources with measured change in southern North Sea between November and January

	DIN (ktonnes) N	% change N	Silicon (ktonnes)
Change Nov. to Jan.	526		242
River input	82	16	54
Atmospheric	38	7	0
Cross Boundary	12	2	4
Sediment Exchange	11	2	273
Recycled	383	73	

If the DIN is not from the sediment it must have an internal water column source, which probably has two components. BUTLER *et al* (1979) showed that through the year in the English Channel the sum of DIN and dissolved organic nitrogen (DON) compounds remains relatively constant, so that the winter increase is due to the post production oxidation of DON to DIN. Additionally a simple calculation suggests it may be supplied from organic detritus suspended in the water column. A change in DIN of 5x10^5 tonnes is about one sixth of the load of 2.9x10^6 tonnes of particulate nitrogen present in January. A decrease in the organic fraction of suspended sediment is observed over the winter period but we cannot quantify the likely release of DIN, because the actual quantity of nitrogen in suspended matter increases along with an increase in total suspended matter concentration due to increased stirring of bottom deposits.

FIG. 1.3.2. Stacked bar chart comparing contributions of different source terms to observed change in DIN load in different NSTF box areas of southern North Sea between November 1988 and January 1989.



The NSP data also enables assessment of the relationship between the DIN available to support primary production and the actual amount of production that occurs. It has been recognised for some time that plankton production can be supported by different sources of nitrogen (DUGDALE & GOERING 1967) which can be classified as "new" or "regenerated" production. Under open ocean conditions, "new" production is that supported by nitrate and "regenerated" production that supported by excretion of ammonia. In coastal seas the definition needs to be amended to allow for the possible advective input of ammonia, so that "new" production is that based on loadings and imports from rivers and adjacent water masses while "regenerated" production is that based on in-situ pelagic and benthic regeneration . To estimate the *f* ratio (new/total production) (WALSH 1991) for the North Sea we have taken "new" production to be that supported by the total DIN available before the spring bloom (the January load) plus the inputs of "new" nitrogen from rivers and atmosphere during eight productive months, the results are shown in TABLE 2. From this table it appears that recycling of DIN is the dominant source of nitrogen supporting production, implying that in the North Sea the high levels of primary production are maintained by efficient recycling rather than inputs of "new" nitrogen as has tended to be considered the case for shelf seas (WALSH 1991).

TABLE 1.3.2

Calculated annual production on basis of NSTF boxes converted to equivalent kilo-tonnes of nitrogen and compared with calculations of the available DIN at the end of winter and supplied from sources of "new" nitrogen over an 8 month productive period

NSTF box	3b	4	5	7b
Annual Production	338	1416	1478	1540
N Sources Winter Load	110	186	174	289
New N (river + Atmosphere ß)	58	79	152	109
Total Available N	168	265	326	398
Recycle factor (*f*)	0.5	0.19	0.22	0.26

(ß oceanic input is close to zero in productive period as concentrations are similar in and outside the survey area)

Both TABLE 1.3.2 and FIGURE 1.3.2 indicate significant differences in behaviour between the UK coastal box 3b and the Dutch/German coastal boxes 4 and 5. The lower recycling in box 3b corresponds to the lower productivity in this area (79gC/m2/year) compared to box 4 (181gC/m2/year). The lower production in box 3 is consistent with the suspended sediment loads in this area (HOWARTH *et al* 1993). Recent modelling work suggests that suspended sediment loads are a critical factor in controlling production in the North Sea through their influence on the amount of available light (TETT *et al* 1993) The minor contribution of river inputs (FIGURE 1.3.2) suggests the likely impact of the 50% reduction in inputs agreed by the states surrounding the North Sea will have a negligible impact on the North Sea as a whole. In the German Bight (box 5), where the supply of "new" riverine nitrogen does make a significant contribution to productivity (FIGURE 1.3.2, TABLE1.3.2), a 50% reduction in inputs would be expected to result in a significant decrease in production. The corollary of our finding that production is supported by nutrients retained within the system, is that it is the efficiency of the retention mechanism that will determine the time scale and magnitude of any decrease in productivity resulting from a decrease in inputs.

In conclusion the new data enables a budget to be drawn up for the southern North Sea of the sources of dissolved inorganic nitrogen (DIN) and silicon contributing to the winter maxima in concentrations of nutrients that support primary production in the following spring. In contrast to previous ideas about shelf seas the major supply is shown to be from recycling (from sediments for silicon and within the water column for DIN) rather than inputs of "new" nutrients from rivers and ocean waters. An estimate of the relationship between the quantity of available DIN and the observed production indicates that the high productivity of the North Sea is also maintained by extensive recycling during the production period The recycling factor *f* varies between 0.5 off the UK coast to 0.19 off the Dutch and German coasts.

PART 2

Details of Development Structure and Content of a 2-Dimensional Model of the Annual Cycle of Dissolved and Particulate Nitrogen Compounds in the Southern North Sea

2.1 Introduction

This report describes our work on the development of a depth-integrated two-dimensional time varying model of the physical dispersion and biological processing of nitrogen in the southern North Sea. This model is the first stage in the progress towards a prognostic water quality model for nutrients in the North Sea. The model is a fusion of the advection/dispersion general purpose 2-D model produced by P.O.L. (JONES, 1991) with the biological and necessary interfacing physical components of a 3 layer vertical processes model (TETT, 1990, TETT and WALNE, 1995). The biological processes model has state variables of nitrate and ammonium existing as dependent concentrations within its structure. This provides a framework for simulating the seasonal cycle in nutrient concentrations within the southern North Sea; the validity of these simulations is tested against NSP-Database nutrient data.

2.2 The Building Blocks

A brief description of each of the models amalgamated into the nutrient model is given below, followed by an explanation of how they were combined together.

P.O.L. 2-D General Purpose Model (JONES,1991)

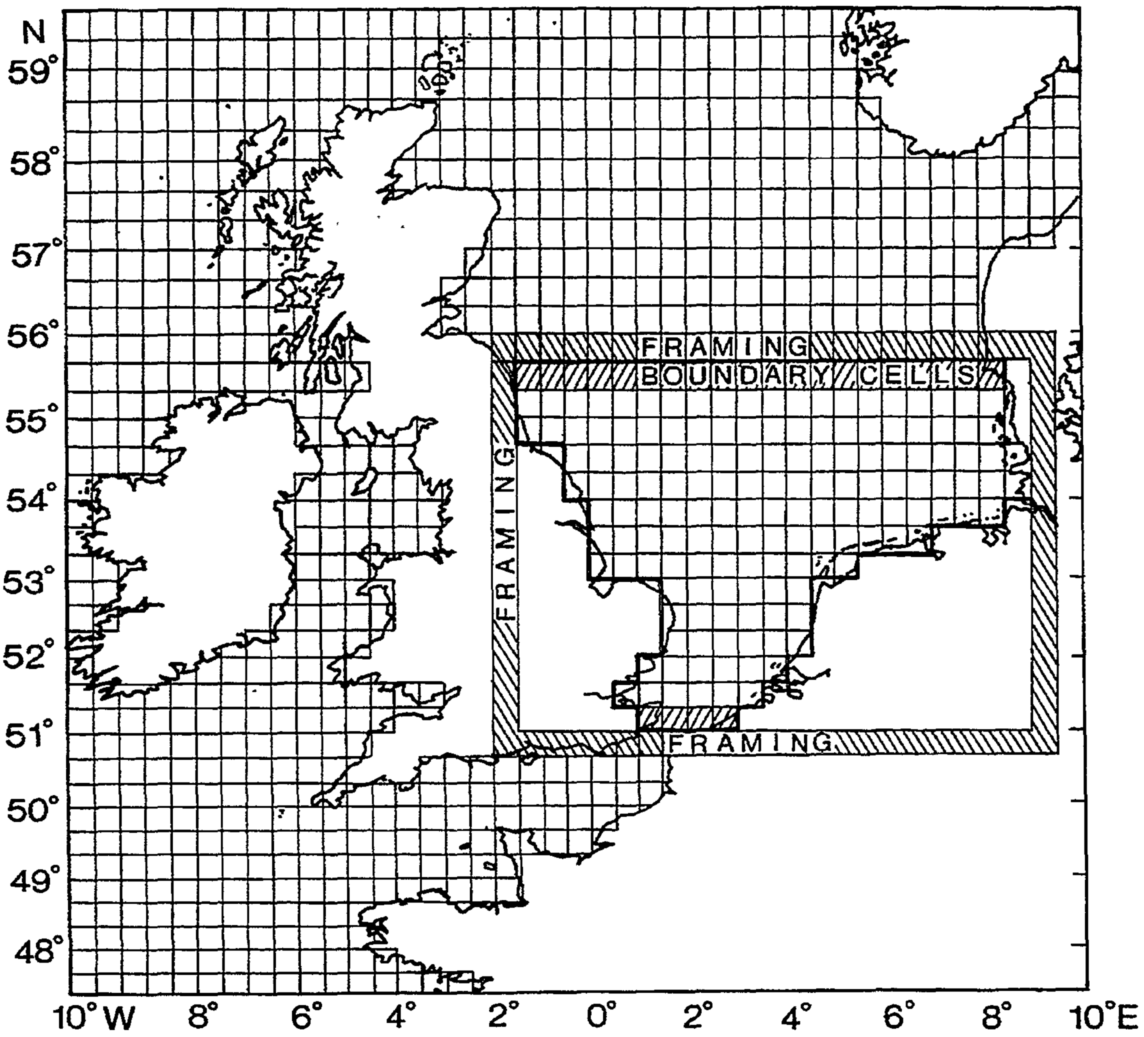
This is a transport and dispersion model designed for examining the long-term fate of conservative contaminants and is derived from a study of the dispersion of Cs^{137} (PRANDLE 1984). The model is comprised of grid cells 1/2° longitude by 1/3° latitude (approximately 35km square) covering the shelf seas around Britain and Ireland from 47°N-64°N and 14°W-13°E (FIGURE 2.1). The driving forces for advection are tidal and time-varying meteorological residuals; tidal amplitudes control dispersion. Each time step is of 6 hours with the net transport of water between adjacent cells and the associated concentrations calculated over this period. Around the grid is a framing area one cell wide included to avoid computational errors. The outermost non-land cells are considered boundary cells with attributed concentrations which input values to the model area. A subsection of the model can be used simply by specifying the required rows and columns (as in this case in FIGURE 2.1). The model code is modular which allows the insertion of specific processes without major changes to the original code.

1-Dimensional Biological Processes Model (TETT, 1990, TETT and WALNE, 1995)

This model is the integration of a physical and biological model to simulate productive and destructive microbiological processes in tidally stirred European shelf seas. In its original form it is a 5-layer, 1-D vertical model with no horizontal exchange. There is an oxygen air/sea gas exchange with the surface layer of water (layer 1). The water column is modelled by one or two well mixed layers (layers 1 and 3) with an intermediate layer (layer 2) representing the thermocline. If the water is not stratified, layer 1 extends to the base of the water column. Layer 5 is a sediment layer in which tidally driven resuspension and aerobic remineralisation occur and solute and particle exchanges are modelled across the sediment interface. A viscous layer (layer 4) overlying the sediment is included but not modelled. Rate-limiting physical fluxes take place only at the boundaries between layers. A set of differential equations exist for each layer describing the rate of change of the model's variables. The physical component predicts the inter-layer exchanges and the biological component predicts the state variable changes within the layer.

FIGURE 2.1

The model grid. 1/2° longitude by 1/3° latitude, covering the shelf seas around Britain and Ireland from 47-64°N and 14°W-13°E. The area used for the nutrient model is that enclosed by the framing boundary.



2.3 Combining the Models

As the hydrodynamic model is only 2-D, the water column had to be assumed to be well mixed. Although this is true for the whole year in the southern North Sea, coastal waters and Dogger Bank regions of the modelled area, it is far from correct in the seasonally stratified waters in the northern and central parts of the North Sea. The POL model is the host program with the inclusion of a biological module. The combined program is now run on the UNIX based Silicon Graphics Workstations at POL and SOC. The language of the host programme, is FORTRAN. The biological coding had to be converted from PASCAL to FORTRAN. To both reduce processing time and specifically apply the model to the NSP area, the model was limited to 1.5°W - 9.0°E and 51.0 - 55.6°N, 21x14 cells. In the hydrodynamics of the POL model, advection and dispersion over a time step move a volume of water from one grid cell to another together with a corresponding proportion of the grid cells concentration. This passive tracer concept was duplicated for the inter-cell transport of the seven biological state variables. Within each cell the biological processes were determined using the seven differential equations defined by TETT (1990). The state variable arrays have been declared three dimensional to accommodate the sediment layer concentration, where appropriate, and to allow for an expansion to a two layer water column model. At present only the top water layer is used, corresponding to a well mixed water column. As only part of the Tett model is incorporated in the combined model care had to taken to ensure that all the physical process information required by Tett's equations could be supplied from the POL model or that suitable simplifications of Tett's equations could be made. For example, the diffuse attenuation values required in determining the amount of photosynthetically available radiation were calculated using an observed regression on tidal stirring and water depth, both readily available in the POL model.

2.4 Description of Model Variables and Constants

2.4.1 State Variables and Equations

Seven state variables for the biological model have been chosen as the minimum number of biological and chemical compartments needed to adequately represent the microbiological processes that influence water quality in shelf seas (TETT, 1990). FIGURE 2.2 shows the interactions between these compartments. There is one equation for each state variable. They are slightly simplified from those used by Tett, because of the assumed homogeneous water column.

Microplankton Carbon Biomass XMICROCARB: mmoles C m^{-3}

change = [growth] - [grazing] - [sinking]

dMC/dt = [MEOO*MC] - [G*MC] - [(BW/DD)*MC]

Detrital Carbon Concentration XDETCARB: mmoles C m^{-3}

change = [messy eating and defecation] - [respiration] -[sinking] + [microplankton sinking and death] + [sediment exchange] dDC/dt = [(1 - GAMMA)*G*MC] - [CRVAL*DC] [(CW/DD)*DC] + [(BW/DD)*MC] + [(EXCSED] [CW*FD*DC)/DD]

Detrital Nitrogen Concentration XDETNIT: mmoles N m^{-3}

change = [messy eating and defecation] - [remineralisation] - [sinking] +[microplankton sinking and death] + [sediment exchange]

dDN/dt = [(1 - GAMMA)*G*MC] - [MRVAL*DC] - [(CW/DD)*DN] + [(BW/DD)*MN] + [(EXMSED * CW* FD* DN)/DD]

Microplankton Nitrogen Biomass XMICRONIT: mmoles N m^{-3}

change = [growth] - [grazing] - [sinking]

dMN/dt = [MEOO*MC] - [G*DN] - [(BW/DD)*DN]

Dissolved Oxygen Concentration XOXYGEN: mmoles O_2 m^{-3}

change = [microplankton growth] +[nitrate uptake] + [nitrification]- [detrital remineralisation] + [air-sea gas exchange] - [sediment uptake]

dO2/dt = [$^OQ^B$*MEOO*MC] + [$^OQ^N$*O2*NOU*MC] - [$^OQ^{NH}$*NHR*NH4] - [$^OQ^C$*CRVAL*DC] - [AIRO2FLUX]- [DFLO2]

Ammonium Concentration XAMMONIA: mmoles N m^{-3}

change = [uptake by microplankton] - [nitrification] + [zooplankton excretion] + [detrital remineralisation] - [sediment exchange]

dNH4/dt = -[NHU*MC] - [NHR*NH4] + [EXCR*GAMMA*G*DN] + [MRVAL*DC] - [DFLNH4]

Nitrate Concentration XNITRATE: mmoles N m^{-3}

change = [uptake by microplankton] + [nitrification] - [sediment exchange]

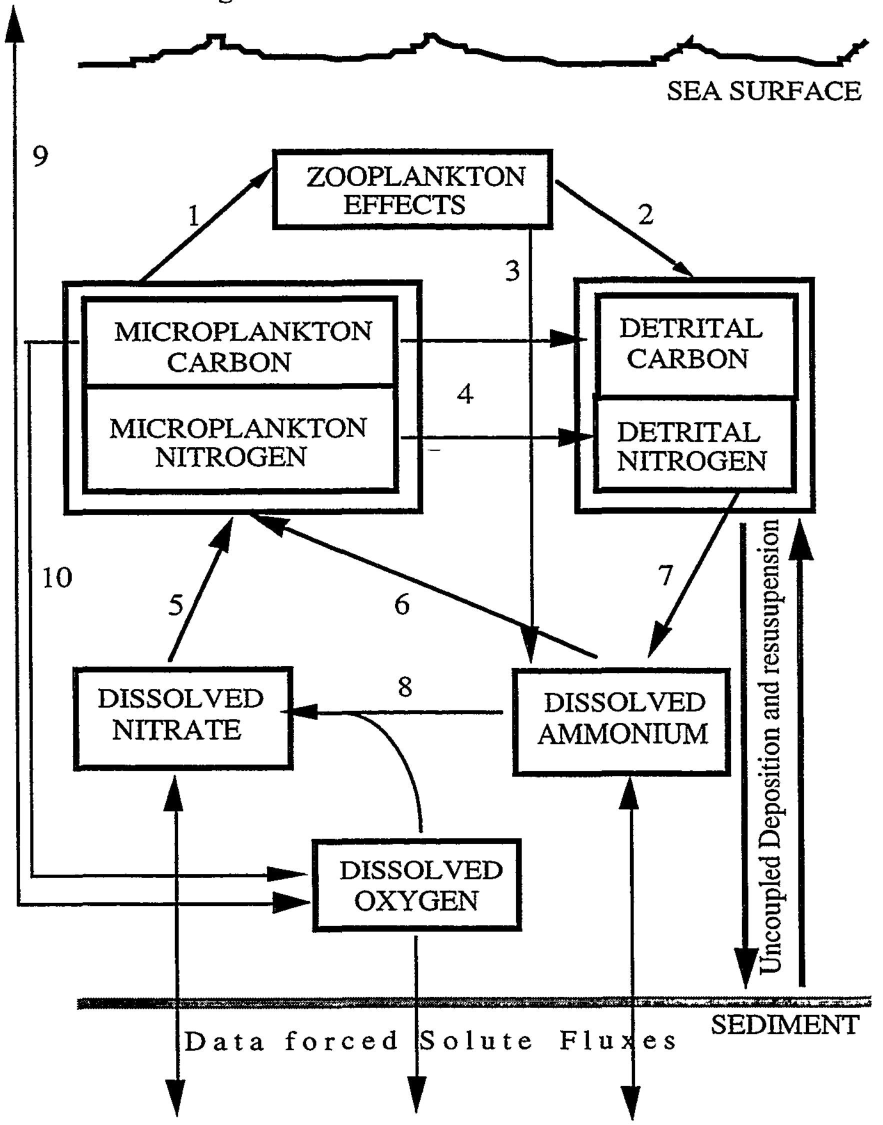
dNO3/dt = -[NOU*MC] + [NHR*NH4] - [DFLNO3]

2.4.2 Driving Variables

The hydrodynamic movement of water through advection and dispersion is driven by tidal and meteorological residuals. The tidal residuals were derived from the POL General Purpose Hydrodynamic Model by Eric Jones, considering the M2 tidal input (and with no wind component). The value of the current at each time step was summed and averaged over a tidal cycle. U and V components of the currents were extracted for each grid cell. These components differ from grid box to grid box but have no temporal variability. The meteorological residuals were derived using a uniform southward and eastward wind stress of 0.1 Newtons per metres squared in the POL model (Eric Jones). Unit wind stress components were extracted to give the U and V components. These have been multiplied by a factor of 10 to align them with a seasonality factor of the same magnitude. It is this seasonality factor that gives the wind residuals temporal (monthly) variability.

FIGURE 2.2

The biological and chemical structure of the North Sea Nutrient Model



1 Grazing
2 Messy feeding
3 Excretion
4 Sinking
5 Nitrate uptake
6 Ammonium uptake
7 Remineralisation
8 Nitrification
9 O_2 air-sea exchange
10 Photosynthesis

2.4.3 Constants

ALPHA	0.07	phytoplankton photosynthetic efficiency mmoles C (mg chl)$^{-1}$d^{-1} (Wm-2)$^{-1}$.
BPQ	1.0	photosynthetic quota for carbohydrate mmoles O_2/mmoles C.
BW	2.0	microplankton sinking rate, m/d.
CHLQMIN	1.0	minimum ratio, mg chl/mmoles N.
CHLQMAX	2.0	maximum ratio, mg chl/mmoles N.

CRMAX20	0.05	max. detrital C respiration at 20°C/d.
CRMIN20	0.0025	min. detrital C respiration at 20°C/d.
CRQ	1.0	mmoles O_2 consumed per mmolesC respired.
CW	5.0	detrital sinking rate, m/d.
DAYLEN	86400	number of seconds per day.
DEPOSITION	false	tidal event flag.
DETQMIN	0.06	minimum detrital mmoles N/mmoles C.
DT	0.25	time step, in days.
DXLONG	30.0	minutes of longitude per grid box.
DYLAT	20.0	minutes of latitude per grid box.
EROSION	true	tidal event flag.
EXCR	0.5	excreted fraction of nitrogen assimilated by zooplankton.
GAMMA	0.8	assimilated fraction of biomass eaten by zooplankton.
NTSTEP	120	number of time steps per month.
OHALFNIT	30.0	oxygen half-saturation for nitrification mmoles O_2 m^{-3}.
OMIN	0.1	minimum (micro)aerobic oxygen, mmoles O_2 m^{-3}.
QMAX	0.2	maximum cell nutrient, mmolesN/mmoles C.
QMIN	0.05	minimum cell nutrient, mmolesN/mmoles C.
R	0.6	proportion of phytoplankton. photosynthesis used in microplankton respiration.
RBO	0.04	basal microplankton respiration rate.
TIMESTEPFACT	1/120	unit converter to mmoles/m3/time step.
USTARD	0.01	critical depositional friction velocity, m/s.
USTARE	0.01	critical erosional friction velocity, m/s.
XEPSILON	0.02	optical absorption cross-section microplankton, m^2 mg chl^{-1}.
XK3SQRT	0.05	square root tidal drag coeff. of 0.0025.
XKE	10-6	erosion constant, m^{-1}s.
XMAXOHALFSAT	10.0	maximum detrital respiration half-saturation constant, mmoles O m^{-3}.
XMINOHALFSAT	1.0	minimum detrital respiration half-saturation constant, mmoles O m^{-3}.
XMO	1.95	PAR per Joule of total Irradience uE/Joule
XM1	0.95	optical coeff. allowing for surface reflection.
XM2	0.37	allows for near surface losses of polychromatic light.
XMRMAX20	0.085	max. detrital N respiration at 20°C /d.
XMUMAX20	2.0	maximum microplankton specific growth rate (/d) at 20°C.
XNHSHALF	0.24	half-saturation constant for ammonia uptake, mmoles N m^{-3}.
XNOSHALF	0.32	half-saturation constant for nitrate uptake, mmoles N m^{-3}.
XNHUMAX	1.0	max. uptake rate for ammonium, mmoles N/mmoles C /d.
XNOUMAX	0.4	max. uptake rate for nitrate, mmoles N/mmoles C /d.
XNITMAX20	1.0	maximum nitrification rate at 20°C, relative to ammonium /d.

XNOPQ	2.0	photosynthetic quota for nitrate uptake mmoles O/mmoles N.
XNORQ	2.0	mmoles oxygen consumed per mmoles ammonium.

2.5 Initialising the Model.

Before any modelling could begin the initial and subsequent boundary values of the state variables had to be decided on. As the POL model is set up to run from January to January and the condition of the biology during winter is fairly constant, January 1989 was taken as the starting time for the model run. Hence the initial values of the state variables for each cell were calculated from the survey cruise for that period, cruise 'CH43'. One of the prime objectives of the modelling investigation was the incorporation of data from the NSP wherever possible. For the initial fields of the state variables this meant accessing the NSP database at BODC, depth averaging the CTD values for the measured variables of ammonia, nitrate, dissolved O_2 and total organic seston and integrating these values across the model grid to get one value per grid cell. For the subsequent eleven months in the models year, values for each state variable were needed in each boundary cell (the northern transect along 55.5°N and the English Channel, 24 in all) to regulate the concentrations moving in and out of the model regime. The values were taken from the corresponding survey cruises, i.e. January to December aligned with cruises CH43 to CH61, CH39 and CH41. One value per cell per month was calculated by depth averaging the CTD values in the stations existing in the boundary cells. Interpolation provided the cell values where either no CTD station or no survey cruise reading existed. The values for microplankton carbon and nitrogen biomass, detrital carbon and nitrogen concentrations were calculated from the total organic seston concentration, the dry weight difference before and after incineration of total sediment. The carbon proportion of this was taken as 40% (P.Tett pers. comm.) which was subdivided into living and non-living components (microplankton and detritus respectively). The approximate relative proportions of these varied monthly through the year. The microplankton and detritus nitrogen values were calculated from their corresponding carbon values, the Redfield ratio of 6.5:1 (C:N) was used for microplankton and a 15:1 ratio for the detrital matter (TETT 1990).

Data were also required for the driving variables for the modelled processes. Water temperature data were acquired as for the state variables and a full grid of depth averaged values was interpolated for each month. Wind velocity was needed for the exchange of oxygen at the air sea interface. The wind values used in the POL model have a low temporal and spatial resolution and as the largest time scale for which an average wind speed is acceptable in the exchange process calculation is one day, (D. Wolfe pers. comm.), new data was required. The Meteorological Office model data for the North Sea is held at BODC on magnetic tape with a reading interval of 3 hours. As Zhihong Li at Bangor had written a program to extract the data onto a given grid-cell size for a given area and time, Peter Brocklehurst at BODC was able to extract and average the data into a daily wind speed value per grid cell data set, on our behalf.

Other necessary data were the phytoplankton grazing rate of each cell (the percentage of phytoplankton removed each day by zooplankton grazing) as a monthly changing variable. TETT (1990) calculated such values from zooplankton data from the Netherlands at 5 different sites in the North Sea. These sites had to be extended or 'regionalised' to cover all the model cells. In a similar fashion, the sediment flux data collected at the 6 core sites over the project period was expanded to cover the area. The flux values were obtained from the NSP-database. The sediment concentration of detrital C and N were calculated from the percentage of organic matter. The daily illuminance values were taken from the logged data while Challenger was at sea. Any missing or suspicious values were replaced by expected values. Each daily value was taken as being spatially constant.

2.6 Coding Implementation

The variations made to the state variable differential equations (excluding the inter-water layer exchanges in the simplification to one water layer) were in the air/sea exchange and the sediment exchange. The combined model does away with the unmodelled layers 2 and 4 of the Tett model. Hence the revised layering comprises one water layer (layer 1) and a sediment layer (layer 3). The introduction of a second water layer (not utilised due to the 2D limitation of the POL model) is conceived as a natural progression of the model, primarily with regard to a restricted depth of production and sub-thermocline oxygen depletion and nutrient build-up.

Air-Sea Oxygen Exchange

Empirically derived values for solubility, diffusivity and kinematic viscosity of oxygen in seawater were combined with water temperature and a three tiered wind velocity function to produce a piston exchange velocity.

Sediment Exchange

After consultation with Tett, it was decided to simplify the sediment exchange code, in particular, the dissolved constituent exchange. This was because the confidence in the sediment processes was less than that for those in the water column and because of the instability of these processes relative to the model's time step. As a result, the dissolved constituent fluxes are used from the NSP core data and regionalised over the area as previously described. The flux at any particular grid cell changes monthly. The particle resuspension process is unaltered from the Tett model, however, sediment concentrations of detrital C and N are yearly averages calculated from the NSP sediment core results for the percent organic content, and therefore are constant over the year.

2.7 Description of the Nutrient Model

The model coding has two major parts, firstly a reading in and initialisation section and secondly an iterative processing section based on time steps.

The model represents the area of the Southern North Sea by a grid system of I columns by J rows. Each grid box at present has a resolution of 1/3° latitude by a 1/2° longitude (approx. 35x35 km), with polar variation due to the convergence of the meridians. As a result of this IxJ grid box configuration, many of the arrays have two dimensions for easy correspondence to a spatial locality. Due to the intended expansion of the model to one which can have two water layers (1 and 2) separated by a seasonal thermocline, many arrays include a third - depth -dimension. A third layer representing the sediments (layer 3) is included in some arrays.

The arrays/variables fall into two categories, Driving and State variables. State variables are those calculated by the model and are updated on each time step. Driving variables are known for a given spatial and temporal location. Where there are seasonal variations in these, such as with temperature, the arrays holding the data need an extra dimension to allow the latitude, longitude and depth data to change temporally, usually on a monthly basis. Changes are governed by the instantaneous values of the state variables and those of the driving variables.

2.7.1 Data Input, Origins and Initialisation

All state and driving variable arrays are initialised to zero. State variable arrays (e.g. Microplankton Carbon Biomass - XMICROCARB) are 3-D, representing longitude, latitude and water column concentration. Driving Variables are represented in arrays which range from 1-D to 4-D depending on their spatial and temporal variability. The state variable arrays assume a well mixed water column modelled within layer 1. All the driving variable data and the initial state variable data are input. The data are read in from 14 different files, each named according to their contents. The units used for each of the state variables are in mmoles/m3 except where stated.

The filenames and the data stored in them are :-

AtmosInp.Dat: Contents : Wet and Dry Atmospheric Deposition input values for nitrate and ammonia. The aerosol values vary spatially while the wet flux values change both spatially and monthly for each grid box. The first values are aerosol fluxes (mmoles/m2/month) for nitrate and ammonia respectively followed by the wet deposition values (mmoles/m3). This data set was provided by Alan Tappin at Southampton University.

Sediment.Dat: Contents : Particulate and dissolved sediment values and regionalised sediment map for the NSP area. The particulate sediment values are read into array CMSED. These six values represent the percentage organic sediment core component for the six NSP core-sites averaged over all the cruises. The regionalised bottom sediment map (ISEDMAP) is then brought in to assign a sediment type, 1-6, to each grid cell, related to one of the six NSP core-sites. The correct particulate sediment value from CMSED is then inserted into layer 3 of the detrital state variable arrays ($XDETCARB_{(i,j,3)}$ & $XDETNIT_{(i,j,3)}$, carbon and nitrogen) according to $ISEDMAP_{(i,j)}$ representing the six NSP core sites over 12 months. The dissolved fluxes, to or from the sediment, are then input to their 6x12 arrays, $FLUXO_{(i,j,t)}$, $FLUXNO_{(i,j,t)}$ and $FLUXNH_{(i,j,t)}$. These hold twelve monthly values of the state variables XOXYGEN, XNITRATE and XAMMONIA for the benthic fluxes of oxygen, nitrate and ammonia, at the six NSP core sites. The units are flux per m2 per day. The value appropriate to a particular grid box is determined by the regionalised sediment map $ISEDMAP_{(i,j)}$,which allocates the values from the NSP core sites to the corresponding regions of different sediment types.

Biology.Dat: Contents : A regionalised grazing map $IGRAZMAP_{(i,j)}$, a grazing pressure $GRAZTYPE_{(t)}$, daily illuminance data $SURFILL_{(t)}$, total organic sediment field values $XDETCARB_{(i,j,1)}$ and initial ammonia and nitrate fields, $XAMMONIA_{(i,j,1)}$ and $XNITRATE_{(i,j,1)}$.

$IGRAZMAP_{(i,j)}$ assigns a zooplankton grazing type to each grid cell as with the sediment map. The five grazing types are then read in each having 12 monthly daily averaged values of grazing pressure ($GRAZTYPE_{(t)}$). These remove a percentage of the standing crop of microplankton biomass ($XMICROCARB_{(i,j)}$ and $XMICRONIT_{(i,j)}$) per day. The daily illuminance data ($SURFILL_{(t)}$) has one value per day covering the NSP area of total spectral irradiance averaged over 24 hours. This fits in with the biological part of the model which is set up to have a one-day time step, hence with no differentiation between night and day. The initial fields (all grid cell values at t=0) for the state variables XDETCARB, XMICROCARB, XDETNIT and XMICRONIT are derived from the input field of Total Organic (suspended) Sediment. This has a value per grid cell interpolated from depth averaged Challenger cruise CH43 CTD and bottle data. The units are in mmoles/m^3 and 40% is taken as being carbon (P.Tett). This is then arbitrarily split into detrital and microplankton carbon (95 and 5%) (D. Purdie and S. Thomson) and fixed nitrogen values are taken as ratios to these (15:1 and 6.5:1 respectively (P.Tett)). The initial ammonia and nitrate fields are input ($XAMMONIA_{(t=0)}$ and $XNITRATE_{(t=0)}$), interpolated from CH43 data..

AirSea.Dat: Contents : Air-sea exchange terms, $SEAAIR_{(t)}$, for cross-boundary oxygen flux. These are sea-water solubility, diffusivity and viscosity values through the water for a temperature range of 1-30° C.

River.Dat: Contents : Grid cell river inflow points for 11 rivers, river flows with monthly changing rates (m/s), and monthly varying associated river concentrations of detrital nitrogen and dissolved ammonia and nitrate. For UK rivers this data was assembled from data available from the DoE Harmonised Monitoring Scheme data archive that is held on the BODC North Sea database. Detailed data for the Rhine inputs was provided by Thea Smit from the Rijkswaterstaat database. Data for the Elbe was assembled from the reports of the Arbeitsgemeinschaft fur die Reinhaltung der Elbe (ARGE 1989, 1990a, and 1990b), data for the Weser and Ems came from the reports of the Niedersaechsisches Landesamt fuer Wasser und Abfall (1989, 1990). Understanding of the assessment of these inputs was helped by reference to BILLEN (1990) and HUPKES (1990).

Boundary.Dat: Contents : Boundary values were obtained from the appropriate data rows after interpolating depth-averaged cruise CTD and bottle data for the monthly survey cruises. These values were assign to the 15th day of each month. Values are assumed to vary linearly between the monthly observations. The monthly percentage splits for XDETCARB and XMICROCARB from the total organic suspended sediment are also input (see iii).

TempField.Dat: Contents : The temperature data is held in a 3-D array so as to have a value for each grid cell (the first two dimensions of array $TFIELD_{(i,j,t)}$) in the whole water column changing each month (the third dimension). This data was interpolated onto the grid area at BODC using the NSP data set

WindField.Dat: Contents : The wind field data is read into array $WFIELD_{(i,j,t)}$. A daily average magnitude of wind speed per grid cell was derived for the model year from 1989 Met. Office 3 hourly values. This data is used in the oxygen air-sea exchange calculations. A daily average wind speed was deemed the coarsest resolution acceptable before gusting effects nullify the validity of using a mean because it is necessary to keep the time increment significantly less than the response time of the system (WOLLAST, 1986). BODC interpolated this data set.

TideRes.Dat: Contents : Temporally independent tidally driven residual transportation values. Each grid cell has one U and one V component (QUTRES, QVTRES and a vertical component ZTRES) which is used by the advection terms (units are m^2/s).

WindRes.Dat: Contents : Temporally independent southerly, westerly and vertically wind driven residual transport values and a seasonality factor. As with the tidal residuals, each grid cell has one U and one V wind component (QUSRES,QVSRES QUWRES,QVWRES,ZSRES, ZWRES). Both the U and V components of the tidal and wind residuals are summed ($UTOT_{(i,j)}$, $VTOT_{(i,j)}$) and their value applicable on each time step throughout the year. The wind values are varied monthly by a scaling factor which is sinusoidal with a maximum in winter (January) and a minimum in summer (August).

TidalAmp.Dat Contents : Maximum tidal current amplitudes ($UAMP_{(i,j)}$ and $VAMP_{(i,j)}$), comprising the U and V components of the M2 tidal constituent. These are used to calculate the dispersion terms. They are spatially variable because tidal currents vary from place to place according to their proximity to amphidromic points. The maximum value is used to allow the model to be free from semi-diurnal and spring/neap cycles. Otherwise difficulties would arise with the initial temporal alignment of model data and the actual tidal state and with conflicts in the state variable calculations over the six hour physical model and 24 hour biological model time steps from the resulting current fluctuations. (The other tidal constituents (e.g. S2) could be included to vary this value and so simulate the spring/neap cycle, the frequency of which is significantly larger than the time step. S2 is about 45% of M2, these two being the main components.) These dispersion coefficients are also dependent upon the concentration gradient between adjacent grid cells and their relative depths. This introduces the vertical residual flows Z_RES which are read in with the other residuals. A grid cell tidal current magnitude ($UVMAX_{(i,j)}$) is required for attenuation calculations and is calculated from its UAMP and VAMP.

Bathymetry.Dat: Contents : The depth in metres for each grid cell. This has been derived by BODC. Once read in, a land mask is applied.

Evap.Dat: Contents : The averaged monthly evaporation interpolated over the NSP area to give each grid cell 12 monthly values in metres. There is no spatial variability. Received from Alan Tappin.

Rain.Dat: Contents : The averaged monthly precipitation interpolated over the NSP area to give each grid cell 12 monthly values in metres. There is no spatial variability. Received from Alan Tappin.

Chlorophyll and Oxygen Initialisation

The initial chlorophyll field ($CHL_{(t=0)}$), needed in the light attenuation calculation at the beginning of the time step, is determined from the microplankton $XMICRONIT_{(t=0)}$ and $XMICROCARB_{(t=0)}$ values. The initial oxygen field ($XOXYGEN_{(t=0)}$) is set at a value of 290 $mmoles/m^3$ for each grid cell.

2.7.2. Time Step Calculations

The model time step is six hours, with day of 4 time steps. 120 time steps to a month, and 12 months to a year. At each time step the boundary values are reset, the river and atmospheric inputs calculated, the total hydrodynamic residuals computed and the new state variable concentrations derived for each grid cell. In greater detail:-

The boundary values are read in, and assigned to the grid cells along the Channel (51° N) and northern boundaries (55.5°N). The grid cells in the non-modelled rows immediately below and above these rows are given the same value. A non zero value in these non-modelled boxes allows a calculation to be made of the advection and dispersion across all the boundaries of the boundary boxes.

For each of the river input grid cells, the new state variable concentrations are calculated from the relative volumes of the grid cell and its freshwater input and their relative concentrations. Hence the riverine water acts as a dilutent or strengthener depending on whether it has a lower or higher value than the grid cell.

The atmospheric inputs are divided by the grid cell volume and then added to the grid cell concentration for each grid cell.

The U and V components of the tidal, west and south wind residuals, (with multiplying factors) are summed.

The state variable calculations have two main divisions - the changes caused by water transport (physical part) and those resulting from internal water column processes (biological part).

2.7.2.1 The Physical Part

This section of code was originally from the POL General Purpose Model and deals with the advection and dispersion of water and associated state variable concentrations between grid cells around the model. The advection depends on the concentration in the specific grid cell, its neighbours' concentrations and the current going between them while the dispersion depends on the concentration gradient between adjacent grid cells, the dispersion coefficient and a constant (which is related to the time step and the length of the grid cell side). This has been duplicated in the nutrient model to determine the changes on seven rather than just one state variable concentration.

2.7.2.2 The Biological Part

The first section executes the air/sea exchange of oxygen (XO_{0-1}). A 'piston velocity' technique is used, primarily dependent on the wind velocity which is split into 3 tiers. An optics section follows which gives a water column average PAR (Photosynthetically Active Radiation) illumination value (XILL). This takes the surface incident irradiance ($SURFILL_t$) and calculates an effective biological parameter based on a number of different quantities, which are: reduction by surface reflectance (XM1), photosynthesis spectra (XM0), near surface losses (XM2), suspended sediment and seawater attenuation (SWLAMBDA) (empirically calculated from maximum tidal current amplitude and depth, $UVMAX_{(i,j,1)}$) and phytoplankton self-shading (XEPSILON). The illuminance for layer 1 at time t in a given grid cell is thus calculated by:

$$XILL = SURFILL_{(t)}*XM0*XM1*XM2*[(1-e^{-(SWLAMBDA + XEPSILON*CHL)* DD}) /(SWLAMBDA +XEPSILON*CHL)*DD)]$$

where

$$SWLAMBDA = .15 + 7.4*(UVMAX^3/DD)$$

It is assumed that the limitation on microplankton growth is either the lack of available light or the lack of available nutrients. Whichever of these two factors is the most restrictive, its value is used for the growth rate (MEOO). The photosynthesis value for MEOO (NETPHOT) is proportional to the 'optics' calculated water column illuminance (XILL) and the grid cells chlorophyll to carbon ratio (CHI).

NETPHOT = (ALPHA*XILL*CHI - RBO)/(1+R)

Photosynthesis is proportional to both light and chlorophyll concentration. Microplankton respiration is subtracted (RBO) and the inclusion of micro-heterotrophs reduces it by a respiration factor (R).

The nutrient limitation value for MEOO (NUTGROW) depends on the water temperature and the microplankton C/N ratio. Temperature encourages growth but an increase in the latter (brought about by a reduction in the microplankton uptake of NH4 and NO3 due to bloom depletion) reduces the growth factor.

NUTGROW = MUMAX20*T*(1-QMIN/Q)

where

$$T = e^{0.07*(WTEMP-20.0)}$$

The seven state variables are then taken in turn and the quantities which will change their concentration are calculated. All these biological state variable changes are calculated on a one day time step. Therefore the last action of the time step is to divide these changes by four to correspond to the physical 6 hour time step before adding them to the standing state variable concentration.

Microplankton Carbon Biomass XMICROCARB . The growth factor MEOO multiplied by the grid cells standing stock gives the productivity (PROD). A sinking rate (BW) removes a percentage of the standing stock (SINK) which is larger the shallower the water. The daily zooplankton grazing pressure, (G), also removes a percentage of the standing stock. A proportion of this (GAMMA) is assimilated by the zooplankton (ZOO) which is lost from the model as the zooplankton are not modelled. The remaining proportion (1-GAMMA) is considered a by-product of the zooplankton through faecal pellets and messy eating (FAEC).

Detrital Carbon Concentration XDETCARB . The grazed microplankton biomass (XMICROCARB) not assimilated by the zooplankton (FAEC) goes straight to detritus. The XMICROCARB lost through sinking becomes detritus. XDETCARB is lost through remineralisation (CRVAL, a function of oxygen, temperature and the XDETNIT to XDETCARB ratio). The detrital sinking rate (CW) is not applied to XDETCARB in a well mixed water layer (or layer 2 of the proposed 2.5D model), it occurs in the sediment exchange stage.

Microplankton Nitrogen XMICRONIT. Nitrogen is taken up from the nitrate and ammonia (preferentially) in the water column (XNHU and NOU) providing there is a sufficient amount to do so. An error is possible because the length of the time step (a day) could see demand exceed supply.

Routine SAFEUPTAKE deals with this. The amount (NUP) taken up is related to the amount of new XMICROCARB production, that is, more production strips more nutrient. Once nutrients become depleted uptake drops so the microplankton C:N (XMICROCARB:XMICRONIT) increases. As with carbon biomass losses occur due to sinking and grazing, but for nitrogen there is an extra term. A portion of the nitrogen that is grazed returns to solution via excretion (see 7) so only (1-EXCR)*GAMMA*G* XMICRONIT is lost from the system to the zooplankton. EXCR is presently a constant this is 40% of the grazed XMICRONIT and 80% of the grazed carbon. In recent runs of the model EXCR has been set to 100%, so that all the nitrogen taken up by zooplankton is returned to the system.

Detrital nitrogen XDETNIT. This value is determined from XMICRONIT in the same way XDETCARB was determined from XMICROCARB. Increases are from zooplankton grazing (FAEC) and microplankton sinking (SINK), losses are from remineralisation (MRVAL). As with XDETCARB, sinking losses are incorporated in the particulate sediment exchange because there is only one layer. The respiration losses differ from XDETCARB as different chemical processes are at work.

Ammonia XAMMONIA. A percentage of the XMICROCARB that was assimilated by the zooplankton is excreted as ammonia (EXCR*ZOO). The detrital nitrogen remineralisation (MRVAL) also increases the XAMMONIA concentration. Decreases are through microplankton uptake (XNHU) and conversion to XNITRATE .

Nitrate XNITRATE . Increases from XAMMONIA conversion and decreases from microplankton uptake (XNITRATE).

Oxygen XOXYGEN. Increases through a net production minus excretion photosynthesis quotient (BPQ) and nitrate uptake photosynthesis quotient (NOPQ). Decreases through XDETCARB detrital remineralisation/respiration quotient (CRQ) and XAMMONIA conversion to XNITRATE respiration quotient (NORQ). These quotients are to do with the release and uptake of oxygen as a result of the biochemical processes taking place.

2.7.2.3 Sediment Exchange

The final concentration change calculations concern the sediment interaction. These have two sections, particle (resuspension and deposition), and fluxes of dissolved nitrogen compounds and oxygen in or out of the sediment determined by respiration and remineralisation in the sediment.

XDETCARB and XDETNIT have a net increase or decrease in their water column concentrations depending on whether the erosion/resuspension of their layer 3 concentration is greater or less than the deposition from the overlying water. Erosion is dependent on maximum tidal current amplitude, ($UVMAX_{(i,j,1)}$), being above the specified friction velocity over a simulated tidal cycle. The greater the difference the greater the exchange variable ($EXCH_{(2,3)}$) which takes a small percentage of sediment from layer 3. This supply is invariant and therefore infinite. Deposition occurs when $UVMAX_{(i,j,1)}$ is less than the friction velocity over the 'tidal cycle'. The resultant percentage of the total possible deposition (FD) is applied to the detrital sinking rate (CW) and detrital concentrations (XDETCARB and XDETNIT) in the water column. The net increase or decrease is added through the water column by dividing by the depth ($DD_{(i,j)}$).

The grid cells sediment type (obtained from $ISEDMAP_{(i,j)}$) and the month of the year determine the dissolved constituent fluxes ($DFLNO3_{(t)}$, $DFLNH4_{(t)}$, $DFLO2_{(t)}$) for XNITRATE, XAMMONIA and XOXYGEN that are used. These are simply diluted through the water column concentration, again by dividing by the depth.

2.8 Subroutines, Functions and Glossary of Model Terms

2.8.1 Subroutines and Functions

The following is a breakdown of the model program in the form of a list that outlines the subroutines and functions. The subroutines are arranged alphabetically in the program. The first four procedures are called once only, while the remainder are used in each time step. The functions are all contained within the subroutine MIX.

2.8.1.1 Subroutines:

i. FILEOPEN This sets the standard i/o channels and opens the files required by the model program

ii. CONSTANTS This sets all the constants to their chosen values

iii. INITIALISE This procedure initialises all state and driving variables

iv. READDATA All the input data files are read in as described above

v. OPENBD Assigns the correct months value for each state variable into each boundary cell. The values are duplicated into the cells above the northern boundary and immediately below the Channel boundary to lessen error in the advection/dispersion code.

vi. RESID This calculates the total residual flow over the model area by summing the U and V components of the tidal residuals and the westerly and southerly wind residuals which have been scaled by a monthly factor (FCMETU, FCMETV).

vii. RIVIN This alters the concentration of the grid cells into which the rivers flow according to the flow rate and the concentration of the river in question. For each river the flows and the river concentrations of three state variables (XAMMONIA, XNITRATE, XDETNIT) vary month by month. The remaining state variables have constant concentrations (there is no microplankton carbon (XMICROCARB) or nitrogen (XMICRONIT) riverine input). The input is modelled by a mixing of the relative concentrations of the river and the grid box which is dependent on their relative volumes. The new grid box concentration is derived while the volume remains unaltered. If the river concentration equals the grid box concentration, then there will be no change despite a number of tonnes of water coming down the river. This will need modifying.

viii. EVAPORATION This subroutine simulates the removal of water from each grid cell to the atmosphere and calculates the effect on each of the seven state variables

ix. WETDEP This calculates the changes in concentration of all seven state variables due to the dilution effect of the rainfall

x. DRYDEP The contribution of dissolved inorganic nitrogen associated with aerosol to the concentrations of DIN in the water column is calculated.

xi. MIX This subroutine numerically solves all the equations in the model by using a forward finite difference approximation. Firstly it updates the grid cells' state variable concentrations by dealing with the advection and dispersion algorithms. This is done by a call to another subroutine ADVDIS (see below). Secondly, the grid cell concentrations are updated by the biological and chemical processes working internally within each grid cell, as defined by the governing equations. Mix also calculates the air-sea oxygen exchanges as well as returning a value for the water column average PAR illumination.

xii. ADVDIS This subroutine solves the hydrodynamic equations for each state variable using a forward finite approximation. The advection depends on the concentration in the specific grid cell, its neighbours' concentrations and the current going between them while the dispersion depends on the concentration gradient between adjacent grid cells, the dispersion coefficient and a constant (which is related to the time step and the length of the grid cell side). Once the equations are solved the cross-boundary inputs for each state variable are summed.

xiii. UNIOUT This routine gives the output of a chosen state variable concentration for the year, month and day in each grid cell location. The output format is UNIRAS compatible. That is, there are three columns of variables, X,Y and Z, where X is the latitude, Y is the longitude and Z is the modelled parameter. The starting latitude and longitude position is specific to the present model window output. This should be made more general, as should the degree step size if the model resolution is altered.

xiv. PRINT2 This is a remnant of the POL code. It gives the output normally sent to the end of the main program in the form of a field of numbers (126 characters wide) with a scaling factor if needed. The field of numbers outlines the geographical area of the southern North Sea

xv. DEPTHMASK Takes the supplied bathymetry and sets up the appropriate mask for the z points. This is done so as to exclude land points from any calculations.

2.8.1.2 Functions

i. CHLQB Returns the chlorophyll to microplankton ratio ensuring that the value is bound between upper and lower limits

ii. CR The relative respiration rate of detrital carbon is calculated which is dependent on oxygen concentration and a function of temperature.

iii. DAYMEAN This returns an average rate value for the time step as the initial conditions will change over that period. This is incorporated into BMEAN, the average concentration over the time step period.

iv. QF2 This ensures that the microplankton nitrogen to carbon ratio is limited between 0 and 1.

v. SAFEUPTAKE This function ensures against more nutrient being taken up than there actually exists. If demand exceeds the supply then the uptake rate is adjusted to use just what there is.

vi. SAFEQUOTA This keeps the XDETNIT : XDETCARB ratio within the maximum and minimum cell nutrient range (i.e. between QMAX and QMIN).

vii. TIDAL This vital function deals with the particulate sediment exchange code. A tidal cycle is simulated over the averaged time step by creating a sinusoidal curve whose amplitude is dependent upon the maximum tidal current (UVMAX). The fraction of the time step for which the 'tidal curve' is above a critical friction velocity (USTARE) determines the amount of erosion that occurs i.e.

IF UVMAX > USTARE THEN EROSION OCCURS

while the fraction of the time step over which deposition occurs is calculated by the relative time that the tidal curve is below the critical friction velocity (USTARD) i.e.

IF UVMAX < USTARD THEN DEPOSITION OCCURS

Hence a net particulate flux is calculated for detrital carbon and nitrogen by taking fractions of the total possible resuspension and deposition. For resuspension the calculations are dependent on tidal current magnitude (USTARM) and the sediment concentration. The latter is a constant infinite source (derived from NSP core data) which means that there is no depositional feedback. For deposition the calculations are dependent on the water column fallout (CW x XDETCARB (or XDETNIT)). That is, the deposition process is modelled. There are no modelled benthic processes for the dissolved concentrations. The fluxes are empirically derived from the NSP cruise data, which are divided by the grid depth and finally subtracted from the time step change state variables (DOX, DNOS and DNHS). This is done in the subroutine MIX.

viii XNOURATE This function ensures against rapid nitrate uptake which is caused by QMAX being overshot. Ammonia is treated as the preferred nitrogen nutrient.

2.8.2 Glossary of Model Terms

AERONO3	Aerosol flux of nitrate, mmoles/m2/month.
AERONH4	Aerosol flux of ammonia, mmoles/m2/month.
AIRO2FLUX	Air-sea gaseous oxygen flux, mmoles O m^{-2} time $step^{-1}$.
ALAT	Latitude in radians.
AREAGB	Area of grid box.
ASTEP	Value used for determining the output day.
DENOM	Denominator used in WETDEP to dilute state variable concentrations. Also used in EVAPORATION to concentrate state variable concentrations.
DRYNOINP	NO3 summing array for aerosol input to each grid box.
DRYNHINP	NH4 summing array for aerosol input to each grid box.
BBD	Microplankton carbon biomass boundary cell concentration, mmoles m^{-3}.

BINP	Boundary inputs assigned to this array.
BL	Dummy argument for XMICROCARB (in real function XNOURATE).
BRATE	Net microplankton carbon production rate, mmol C(mmol C)$^{-1}$ d^{-1}.
BMEAN	Water layer time step average microplankton carbon concentration, mmoles C m^{-3}.
XDETCARB	Detrital particle organic Carbon, mmoles C m^{-3}.
XDETCARB3	Constant concentration of detrital carbon in layer 3, mmoles C m^{-3}.
CBD	Detrital carbon boundary cell concentration, mmoles m^{-3}.
CHI	Nutrient replete value mg chl (mmoles C)$^{-1}$.
CHL	Phytoplankton biomass as Chlorophyll, mg m^{-3}.
CMSED	Six core sites yearly average C sediment content, mmoles C m^{-3}.
CONCDIFF	Concentration difference of oxygen between actual layer 1 value and expected value, mmoles O_2 m^{-3}.
CRVAL	Relative remineralisation/respiration rate of detrital carbon d^{-1}.
DATUM	Used in transferring current data from TARRAY.
DAYMEAN	Real function used to calculate BMEAN.
DX	Change in state variable concentration over a time step, mmoles m^{-3} ; superscript X equals MC (XMICROCARB) , DC (XDETCARB), DN (XDETNIT), MN (XMICRONIT), NO3 (XNITRATE), NH4 (XAMMONIA), O2 (XOXYGEN).
DD	Water column depth, m.
DEP	Depth array.
DEPMIN	Minimum depth.
DEPOSITION	False tidal event flag.
DFLNO3	Water column nitrate concentration change due to benthic nitrate flux, mmoles m^{-3}.
DFLNH4	Water column ammonia concentration change due to benthic ammonia flux, mmoles m^{-3}.
DIP	Dispersion in the negative U-direction.
DIM	Dispersion in the positive U-direction.
DJP	Dispersion in the negative V-direction.
DJM	Dispersion in the positive V-direction.
DSXP	State variable concentration between adjacent grid cells (U direction).
DSXM	State variable concentration between adjacent grid cells (U direction).
DSYP	State variable concentration between adjacent grid cells (V-direction).
DSYM	State variable concentration between adjacent grid cells (V-direction).
$DX_{(i)}$	Local grid box side length in metres (latitude dependent).
DXI	Constant needed for dispersion calculation in U-direction.

DY	Local grid box side length in metres (constant).
DYI	Constant needed for dispersion calculation in V-direction.
D2SX	Net U-direction concentration change due to dispersion.
D2SY	Net V-direction concentration change due to dispersion.
EROSION	True tidal event flag.
$EX_{(i,j)}$	Dispersion coefficient (E component).
EXCFLUX	Detrital C net benthic exchange, mmoles C m^{-3}.
$EXCH_{(La,Lb)}$	Interlayer exchange rate from layer La to Lb.
EXMFLUX	Detrital nitrogen net benthic exchange, mmoles N m^{-3}.
$EY_{(i,j)}$	Dispersion coefficient (N component).
FAEC	Proportion of microplankton carbon biomass gained as detritus through zooplankton faecal pellets and messy eating, mmoles C m^{-3}.
FCMETU	Annual sinusoidal variation factor applied to westerly wind residuals for monthly variability.
FCMETV	Annual sinusoidal variation factor applied to southerly wind residuals for monthly variability.
FD	Proportion of deposition allowed, given tidal regime.
FDIN	Total nitrogen uptake rate in XNOURATE.
$FLNO3_{(t)}$	(Monthly mean) dissolved state variable XNITRATE benthic flux mmoles/m2/d.
FLUXNO	Holds the benthic dissolved nitrate fluxes for the six NSP core sites, 12 monthly constant values for each, mmoles/m2/d.
FLUXNH	Holds the benthic dissolved ammonia fluxes for the six NSP core sites, 12 monthly constant values for each, mmoles/m2/d.
FLUXO	Holds the benthic dissolved O2 fluxes for the six NSP core sites, 12 monthly values for each site mmoles/m2/d.
FNH4	Uptake rate for XAMMONIA in XNOURATE.
FNO3	Uptake rate for XNITRATE in XNOURATE.
G	Proportional loss rate of phytoplankton by grazing, d^{-1}.
GRAZTYPE	Takes a gridcell's grazing pressure type from IGRAZMAP.
IGRAZMAP	Regionalised grazing pressure map allocating each gridcell a daily grazing pressure type.
IA	Number of points in full matrix (294).
IB	=IL + JL, i.e. no. of rows + no. of cols. required for printout.
IL	Number of columns in matrix of model (24).
IMON	Month counter.
IND	Parameter used in printout.
IND1	Parameter used in printout.
IROE	Row end used in printout.

IROS	Row start used in printout.
IS	Parameter used in printout (paired with ISTOP).
ISCAL	Exponent produced by scaling in PRINT2.
ISEDMAP	Regionalised sediment map allocating each gridcell a sediment type, 1-6, relating to NSP core sites.
ISEDTYPE	Takes a gridcell's sediment type from ISEDMAP.
ISPLIT	Splitting of matrix for printout.
ISTOP	Parameter used in printout - paired with IS (in PRINT2).
ITIME	The day.
IYR	Year counter.
IZB	Array holding i- positions of boundary elements.
I1	Western column limit of modelled area.
I2	Eastern column limit of modelled area.
JL	No. of rows in matrix of model.
J1	Top row limit of modelled area.
J2	Bottom row limit of modelled area.
KW	Gradient of AIRO2FLUX which is a linear function of wind speed, cm/hour.
LAMBDA	Diffuse PAR attenuation coefficient.
MEOO	Microplankton specific growth rate d^{-1}.
MO	Photosynthesis spectra.
MQC	= MQC = XDETNIT : XDETCARB ratio.
MRVAL	Relative remineralisation rate of detrital nitrogen d^{-1}.
MUL	MEEO in XNOURATE.
NAU	Determines if TA is required to give change in conc.. in box.
NAIR	AirSea.Dat file unit name.
NATMO	AtmosInp.dat file unit name.
NBIO	Biology.Dat file unit name.
NBND	Boundary.Dat file unit name.
NBOX	Number of non-land grid cells in model (174).
NBU	Determines if TB is required to give change in conc. in box.
NCMX	Values determining whether or not dispersion occurs in the U-direction.
NCPX	Values determining whether or not dispersion occurs in the U-direction.
NCMY	Values determining whether or not dispersion occurs in the V-direction.
NCPY	Values determining whether or not dispersion occurs in the V-direction.
NCU	Determines if TC is required to give change in conc. in box.
NDEP	Depth.Dat file unit name.
NDU	Determines if TD is required to give change in conc. in box.
NEVAP	Evaporation.Dat file unit name.
NETPHOT	Growth rate limited by photosynthesis net of respiratory losses d^{-1}.
NHR	Ammonia nitrification rate d^{-1}.

NL	Dummy argument for XMICRONIT (in XNOURATE).
NMEAN	Water layer time step average microplankton nitrogen.
NOU	Microplankton nitrate uptake rate mmoles N (mmoles C)$^{-1}$ d^{-1}.
NRAIN	Rain.Dat file unit name.
NRATE	Net microplankton nitrogen uptake rate, mmoles N (mmoles C)$^{-1}$ d^{-1}.
NREAD	Input logical unit no. (=5).
NRIV	Number of river inputs (11).
NSED	Sediment.Dat file unit name.
NSTART	Start of section of row in printout.
NSTEP	Step counter.
NSTOP	End of section of row for printout.
NTEM	TempField.Dat file unit name.
NTIDA	TidalAmp.Dat file unit name.
NTIDR	TidRes.Dat file unit name.
NU	Microplankton nitrogen (combined nitrate and ammonia) uptake rate mmoles N (mmoles C)$^{-1}$ d^{-1}.
NUP	Microplankton nitrogen uptake mmoles N d^{-1}.
NUTGROW	Growth rate limited by nutrient supply d^{-1}.
NWIN	WindField.Dat file unit name.
NWINR	WindRes.Dat file unit name.
NWRITE	Output logical unit number.
NZB	No. of elements on boundary.
PROD	Primary production mmoles C m^{-3}.
QL	XMICRONIT : XMICROCARB ratio in XNOURATE.
QN	Ratios in particles. $^{N}Q^{B}$ is phytoplankton nitrogen Quota, = XMICRONIT : XMICROCARB ratio, mmoles N(mmoles C)$^{-1}$.
$Q^{UX}RES$	Residual current. First superscript denotes direction (U,V,Z), the second denotes residual type, tidal or wind (T,S,W (southerly or westerly)), m/s.
RATE	BRATE in DAYMEAN.
RINP	Sums state variable river inputs.
RIVFLO	River flow m/s.
RIVVOL	River water volume m^{3}.
SEAAIR(t)	Diffusivity, viscosity and solubility of O2 in seawater over the temperature range 0 to 30 °C.
SEDNLOSS	Nitrogen loss to the sediment.
SEDNO3FLUX	Transfer array used for NO_3 flux from sediment.
SEDNH4FLUX	Transfer array used for NH_4 flux from sediment.
SINK	Proportion of XMICROCARB lost to detritus from the water layer through sinking, mmoles C m^{-3}.

SLAT	Latitude in degrees.
SNLAT	Starting latitude at top of matrix.
STAR	A large number to force asterisks in printout.
STARTLAT	Latitude for output to an umpdata file.
STARTLON	Longitude for output to an umpdata file.
STEPLAT	Step change in latitude for an umpdata file.
STEPLON	Step change in longitude for an umpdata file.
SURFILL(t)	Daily average surface incident illuminance W/m2/d.
SWLAMBDA	Attenuation due to seawater/suspended sediment.
TA	U1 flux in eastward direction (+ve).
TARRAY	Dummy argument for TEMPARRAY.
TB	U2 flux in eastward direction (+ve).
TC	U1 flux in westward direction (-ve).
TD	U2 flux in westward direction (-ve).
TEMPARRAY	Array for transferring the state variable calculations to the main program from which the output is written.
TFIELD	Data array holding water temperatures.
TIME	Time from start of run in seconds.
$UAMP_{(i,j)}$	Tidal current amplitude (E component) m/s.
UCURRENT	= UAMP.
UDSX	Total change in concentration in box in U-direction.
UDSY	Total change in concentration in box in V-direction.
UFACT	FCMETU in RESID subroutine.
UL	Used to calculate tidal current magnitude (UAMP2).
UPTAKENO3	Microplankton nitrate uptake rate, mmoles N (mmoles C)$^{-1}$ d^{-1}.
UPTAKENH4	Microplankton ammonia uptake rate, mmoles N (mmoles C)$^{-1}$ d^{-1}.
USTARM	Tidal current magnitude.
UVMAX(i,j)	Tidal current amplitude (magnitude) m/s.
UTOT(i,j)	Total residual flow (E component) m/s.
U1	U at western side of grid box.
U2	U at eastern side of grid box.
$VAMP_{(i,j)}$	Tidal current amplitude (N component) m/s.
VCURRENT	= VAMP.
VDSY	Total change in concentration in box in v-direction.
VFACT	FCMETV in RESID subroutine.
VL	Used to calculate tidal current magnitude (VAMP2).
VOLGB	Volume of grid box.
$VTOT_{(i,j)}$	Total residual flow (N component), m/s.
V1	V at southern side of grid box.
V2	V at northern side of grid box.

WETNOINP	NO3 summing array for wet input to each grid box.
WETNHINP	NH4 summing array for wet input to each grid box.
WFIELD	(Daily mean) wind speed 10m above sea surface, m/s.
WTEMP	Water Temperature, °C.
XAMMONIA	Dissolved ammonia, mmoles N m^3.
XDETCARB	Detrital particle organic carbon, mmoles C m^3.
XDETNIT	Detritial particle organic nitrogen, mmoles N m^{-3}.
XLAT	Current latitude while umpdata file is being written.
XLON	Current longitude while umpdata file is being written.
XILL	Downwards diffuse PAR Irradiance, µE/m2/s. (PAR -Photosynthetically Available Radiation 400-700 nm).
XMICROCARB	Microplankton organic carbon biomass, mmolesC m^{-3}.
XMICRONIT	Microplankton organic Nitrogen, mmoles m^{-3}.
XNBD	Microplankton nitrogen biomass boundary cell concentration, mmoles m^{-3}.
XNH4BD	Ammonia boundary cell concentration, mmoles m^{-3}.
XNITRATE	Dissolved nitrate, mmoles N m^{-3}.
XMBD	Detrital nitrogen boundary cell concentration, mmoles N m^{-3}.
XNO3BD	Nitrate boundary cell concentration, mmoles m^{-3}.
XNBD	Microplankton nitrogen boundary cell concentration, mmoles N m^{-3}.
XNH4BD	Ammonia boundary cell concentration, mmoles N m^{-3}.
XNO3BD	Nitrate boundary cell concentration, mmoles N m^{-3}.
XOXYGEN	Dissolved Oxygen mmoles m^{-3}.
XO2BD	Oxygen boundary cell concentration, mmoles m^{-3}.
ZOO	Proportion of microplankton carbon biomass lost to zooplankton through grazing, mmoles C m^{-3}.
ZOONLOSS	Transfer array used for N loss due to zooplankton.
ZSRES	Vertical southerly wind residuals.
ZWRES	Vertical westerly wind residuals.
ZTOT	Elevation above mean sea level.

PART 3

SENSITIVITY OF THE MODEL TO THE MAIN DRIVING FORCES

3.1 Method

We begin our discussion on the functioning of the model by looking at a series of tests on the sensitivity of the model to the main driving forces - biological processes, exchange with the Atlantic ocean, riverine and atmospheric inputs. All of these are acted on by the effects of wind driven and tidal circulation. The individual cases considered are listed in TABLE 3.1, and the resulting model output in terms of the total nitrogen in the water column is shown, for a 6 year period in FIGURE 3.1. In the cases considered processes are included one by one: in Case 1 only the wind (and tidal) residual flow is included, all other processes and inputs are switched off (zero open boundary input implies an ocean of zero concentration); in Case 2 the atmospheric input is added; Case 3 includes the open boundary flux; Case 4 includes the river inputs; Case 5 is Case 3 with biological processes; Case 6 includes all processes.

TABLE 3.1

Processes in Cases 1 - 6.

Case	Wind Effect	Biological Input	Boundary Input	River Input	Atmospheric Input
1	yes	no	no	no	no
2	yes	no	no	no	yes
3	yes	no	yes	no	yes
4	yes	no	yes	yes	yes
5	yes	yes	yes	no	yes
6	yes	yes	yes	yes	yes

TABLE 3.2

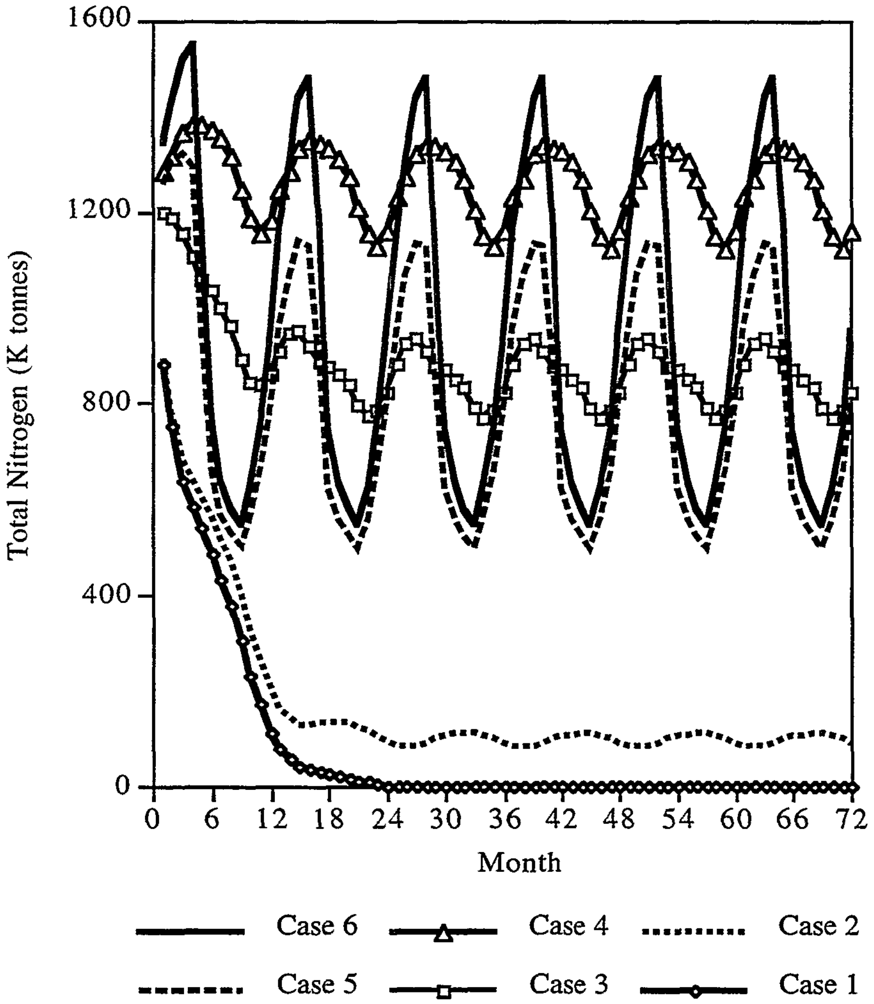
Maximum and minimum total N (k tonnes), Cases 1 - 6

Case	Maximum	Month of max	Minimum	Month of min	
1	80	1	5	4	
2	120	8	90	1	
3	950	3	770	10	
4	1300	4	1100	11	
5	1100	3	500	9	
6	1500	4	550	9	

The model run starts in all cases with the concentration field set at values corresponding to the observed January conditions.

FIGURE 3.1

Graphical display of the model output for the total nitrogen content of the water column for the six different cases listed in TABLE 3.1



3.2 Cases:-

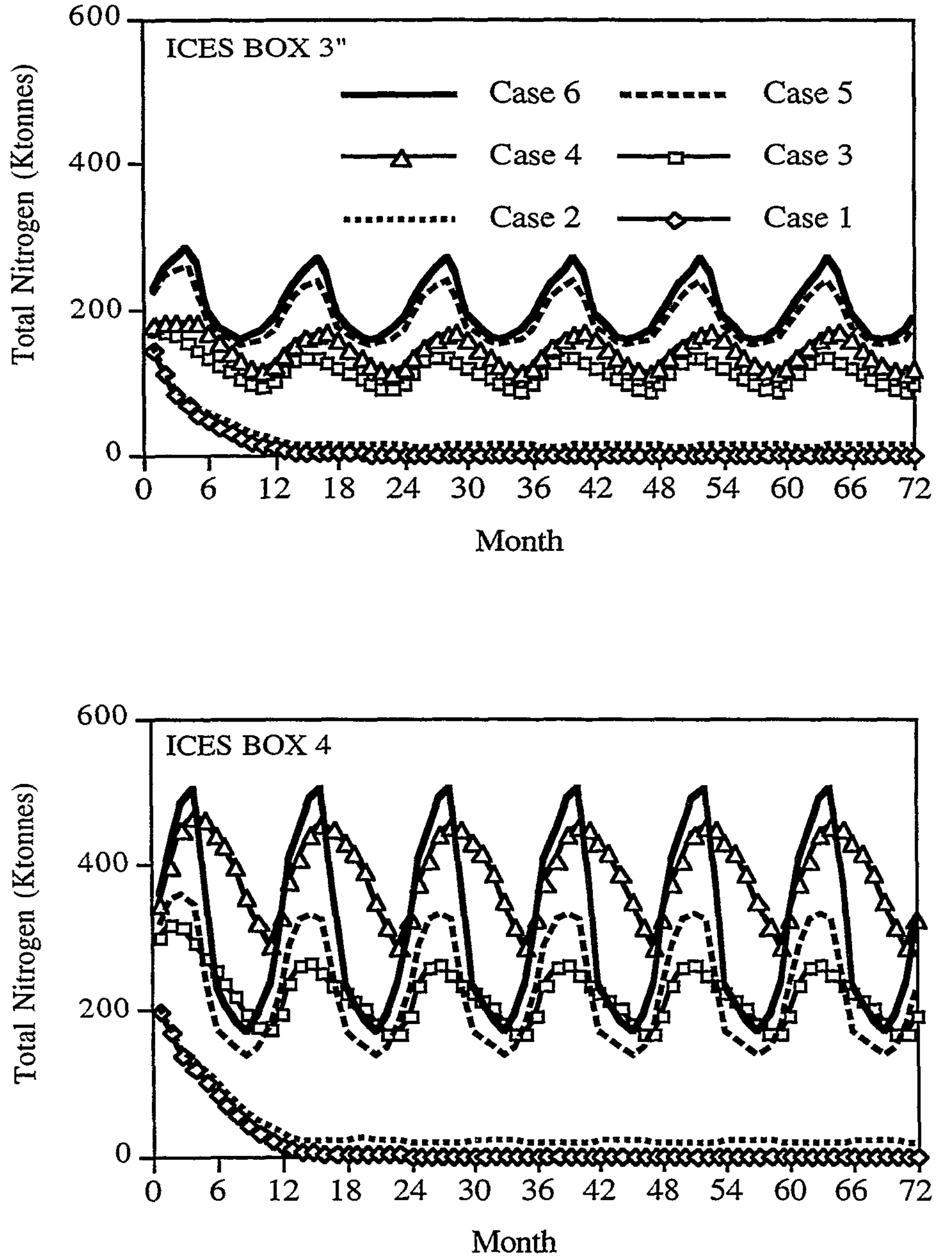
In Case-1 an artificial environment is created in the model by setting the concentrations in the boundary boxes and river and atmospheric inputs to zero. This destabilises the model and nitrogen concentrations run down at a rate determined by the advection and dispersion of nitrogen across the boundaries. From the FIGURE 3.1 and TABLE 3.2 it can be seen that the residence time for the area is about 12 months, in broad agreement with PRANDLE *et al.* (1993).

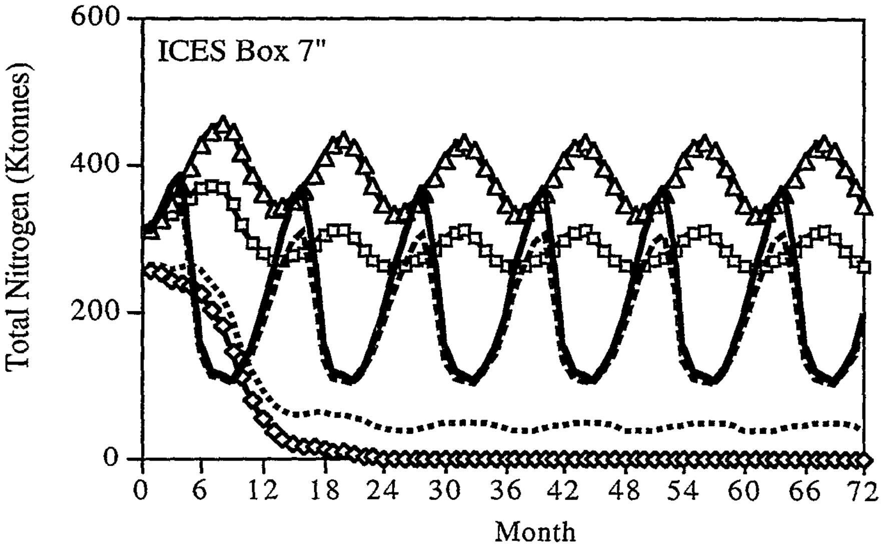
In Case-2 when the atmospheric input is included the modelled concentrations fall rapidly in year one (as in Case-1) but then a steady cycle of varying low nitrogen loads develops. The calculated concentrations are determined by a balance between a constant input from the atmosphere and loss of material across the boundaries. This loss terms varies as the strength of the wind field varies. Changes in the wind field change the amount of transport across the boundaries.

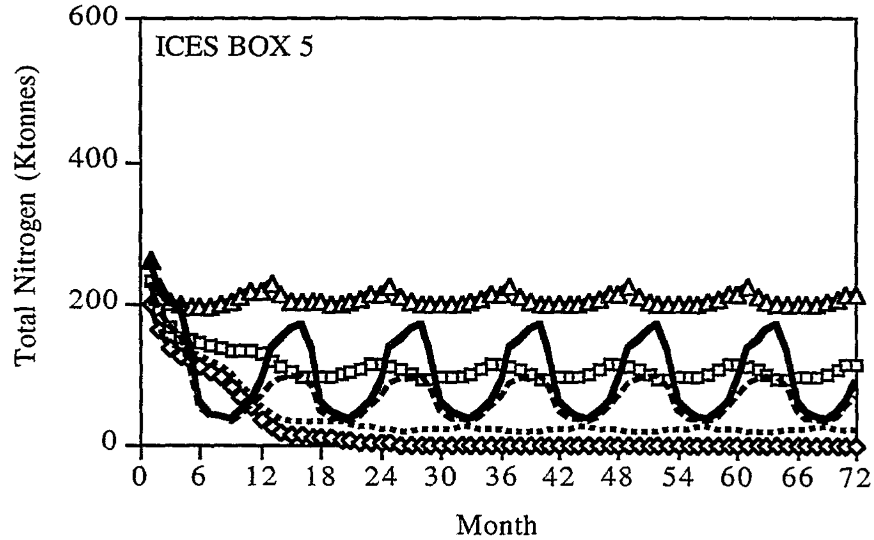
In Case-3 when the boundary values are reset to the observed concentrations the total nitrogen content stabilises at a higher concentration (maximum value 950 ktonnes, table 3.2) as now material is able to flow in and out of the model area across the boundaries. The cycle is controlled by the boundary flux which shows a maximum in March, declining thereafter due to advection. The shoulder on the downward slope reflects the atmospheric component seen in Case-2. The boundary inflow contains a biological component in that microplankton-N is one of the cross boundary components.

FIGURE 3.2

Total N from cases 1-6 in the ICES boxes for a six year simulation. Annual cycle of total dissolved inorganic nitrogen. Monthly tonnages for both modelled and observed data.





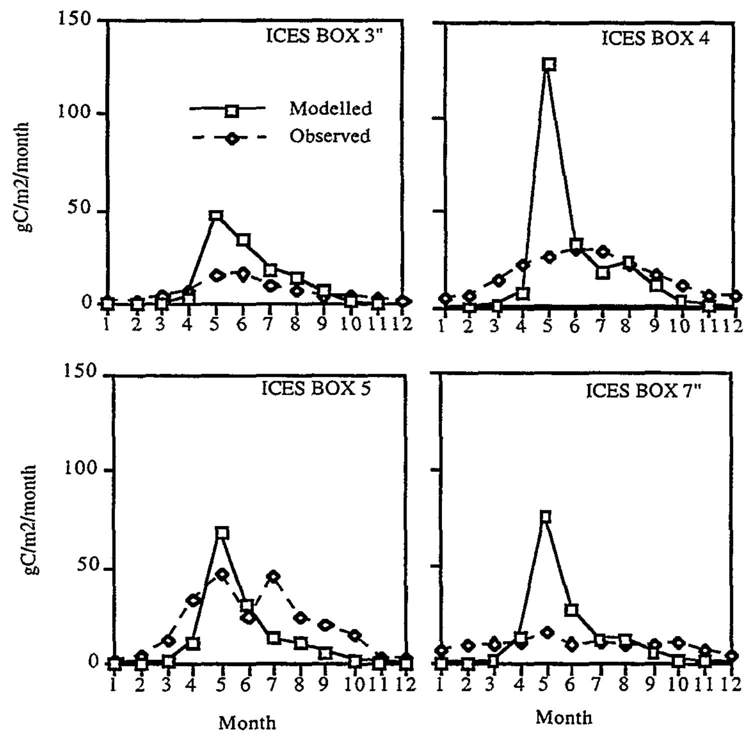


In Case-4 when the river input data is introduced into the model the winter maximum in total nitrogen increases to 1,300 k tonnes (TABLE 3.2). The appearance of the maximum is now determined by the balance between the effect of the wind and the seasonal variation in the riverine load. In Case-5 without river flow but with water column biological processes, the balance becomes one of cross boundary inputs balanced against productivity removal. Maximum load occurs at the end of the winter prior to the spring bloom. Total nitrogen levels in the water column are at minimum over spring and summer because losses of nitrogen to sediment and to zooplankton are greater than the inputs of nitrogen during this period.

The final case Case-6, represents a run of the complete model with all the quantifiable inputs and plankton growth, consumption and decay occurring as described above. The total nitrogen concentration undergoes a much greater change through the year than in Case-5 reflecting the riverine input.

FIGURE 3.3

Comparison of observed and modelled (year 2) primary production in each ICES box



Whilst the total N in the modelled region is a useful quantity more insight into the spatial variability can be obtained by examining the same responses (Cases 1 to 6) in NSTF-ICES boxes (ICES, 1983). These are shown in FIGURE 3.2 and calculations are performed for boxes 3",4,5 and 7". Significant differences between boxes can be seen, with biological processes having greatest impact in boxes 4 and 7". For the whole of the modelled area a comparison of the total dissolved inorganic N (DIN) (from Case 6) with those observed totals is given in FIGURE 3.4. Correlation between the calculated and observed monthly values explains 88% of the variance (i.e. r2=0.88).

Models like this one become informative when they can be used to determine the relative significance of the supply and sink terms to the area being studied. In this model proscribed inputs of nitrogen come from : - the rivers in the form of dissolved nitrate and ammonia and detrital particulate nitrogen - the atmosphere as nitrate and ammonia (OTTLEY & HARRISON, 1992) - the dissolved sediment flux-as nitrate and ammonia (NEDWELL *et al.*, 1993). These proscribed inputs can be compared to the modelled fluxes, which are :-(i) the flux across the northern and southern boundaries, varying in response to the concentration field in the modelled area; (ii) the removal of nitrogen into trophic levels higher than phytoplankton represented in the model by zooplankton grazing (TETT, 1990); (iii) exchange of detrital nitrogen to and from bottom sediments. In the present model this is only partly modelled, in that the flux to the sediment is determined by the concentration of detrital nitrogen calculated to be in the water column while the flux off the bottom is calculated from observed NSP data and the modelled degree of resuspension.

FIGURE 3.4

The comparison of the observed cycle and the modelled cycled. Total Nitrogen summed each month over the full area of the model.

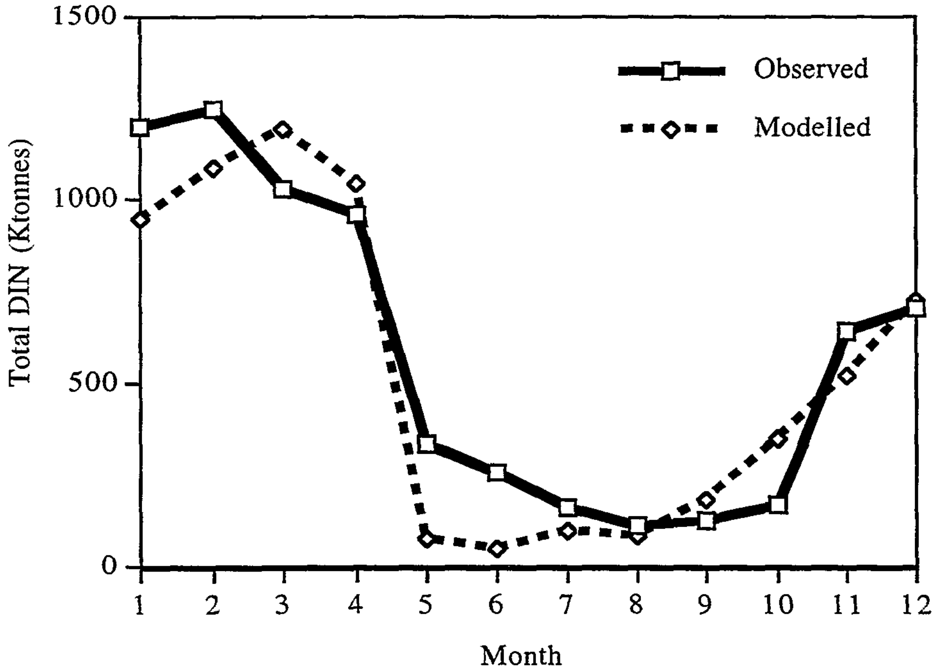


TABLE 3.3

Effect on sources and sinks of varying river nitrogen inputs
(negative indicates a sink of total N, units k tonnes)

Source/Sink	No Reduction	50% Reduction	100% Reduction
Sedimentation	-990	-800	-600
Zooplankton	-600	-540	-480
Sediment Flux	550	550	550
Atmos. Flux	200	200	200
Boundaries	260	310	360
Rivers	590	290	0

In TABLE 3.3 we show a break down of the total fluxes (sources and sinks) of nitrogen through the modelled area of the North Sea for three cases, in which all the model processes are active, but with the river inputs of (1) 100% of the nitrogen input during the survey period, (2) 50% of the input and (3) 0%. Reducing the river inputs of N increases the cross boundary contribution because the concentration gradient increases with decreasing river load. Sediment deposition is reduced more than zooplankton grazing.

An important aim in the development of models such as this is to be able to relate changes in nutrient inputs to the consequent changes in plankton production. In FIGURE 3.4 we compare the estimates of primary production during the NSP surveys made by JOINT and POMROY (1992) and HOWARTH *et al.* (1993) (which are based on C14 incubations and chlorophyll measurements) with the estimate of carbon production calculated by the model (Case 6). The annual primary production in the ICES boxes is given in TABLE 3.4. The interesting differences between peak production in the model in May (in all boxes) and in the observations may, in part, be the result of the different procedures for obtaining the production estimates for model and observation. For the model the cumulative monthly production is quoted. The production value from the NSP data is derived from observations in each ICES box (which were usually made in about 2 days on each cruise) so that often a single observation is being extrapolated to give the monthly value. Given the relatively short duration of the most intense period of the bloom it is not therefore surprising that it was not captured by the observations. Other observational techniques such as moored sensor arrays are needed to record features as rapid as the peak of the plankton boom in-situ c.f. TETT and WALNE (1995). The large model value in May in box 7", we suspect, reflects the limitations of the depth-integrated assumption because this area stratifies in the summer months beginning in May.

Presented in TABLE 3.4 are production estimates for the NSTF-ICES boxes with the river concentrations reduced by 50%. The differences in annual production in each of these box areas is summarised in TABLE 3.4 and shows that a 50% reduction in river concentrations gives a reduction in primary production of up to 18%.

TABLE 3.4

Annual production (gCm-2) in each the NSTF-ICES box areas

NSTF-ICES box	3"	4	5	7"
Observed	79	199	261	119
Model 100% rivers	120	220	140	150
% difference	52	11	-54	7
Model 50% rivers	110	180	120	140
% reduction	8	18	14	7

The model tonnage of nitrogen-biomass produced in each area is compared to the tonnage of dissolved inorganic nitrogen available to support production at the start of each month. This gives a measure of the amount of recycling of nitrogen that is required to support the observed production. This in turn can be compared to the amount of recycling that is estimated from the observed data (HOWARTH *et al.*, 1993). For the southern North Sea as a whole, from HOWARTH *et al.* (1993), a recycling factor of 0.2 can be deduced. This is in reasonable agreement with the modelled values given in TABLE 3.5. Significantly less recycling occurs close to the English coast (box 3") than elsewhere.

TABLE 3.5

Calculated annual production on the basis of NSTF boxes converted to equivalent kilo-tonnes of nitrogen and compared with calculations of the available DIN at the end of winter and supplied from sources of "new" nitrogen over an 8 month productive period. (N.B. Oceanic input is close to zero in productive period as concentrations are similar in and outside the survey area.)

NSTF-ICES box	3"	4	5	7"
Annual production	340	1420	1480	1540
N sources				
Winter load	110	190	170	290
New N (river + atmos)	60	80	150	110
Total available N	170	270	320	400
Recycle factor (f)	0.5	0.19	0.22	0.26

PART 4

ESTIMATION OF FLUXES OF NUTRIENTS ACROSS MODEL BOUNDARIES

4.1 Introduction

This section reviews how the model attempts to reproduce the major processes controlling fluxes of nutrients in and out of the North Sea system. In the Appendix specific detail is given of how these processes are included in the model. The relative magnitude of these processes is tabulated. One of the major sources of nutrients to the North Sea is material introduced in flow through the Dover Strait. This input is considered in comparison to other earlier estimates.

4.2 Model Processes

The major processes by which nutrients enter and leave the model domain, are hydrodynamic transport of water containing nutrients across the boundaries of the modelled area, input in river water, deposition from the atmosphere and exchange of both dissolved and particulate material with bottom sediments.

4.2.1 The Hydrodynamics

The hydrodynamics of the nutrient model are governed by advection and dispersion as used in the POL General Purpose Hydrodynamic Model (JONES, 1991; FLATHER, 1976; PRANDLE, 1984; PRANDLE *et al*, 1993, JONES & HOWARTH, 1995). In the model advection depends on the concentration of a nutrient in a specific grid cell, its neighbours' nutrient concentration and the current going between them. Currents in the model are based on calculated tidal and meteorological residual current fields. Dispersion is calculated from the concentration gradient between adjacent grid cells, the dispersion coefficient and a constant (which is related to the time step and the length of the grid cell side). For a mathematical description of the advection-dispersion formulations used in the model see Appendix A.

4.2.2 Cross Boundary Flow

Cross boundary exchange is the sum of the advective and dispersive movement of nitrogen containing materials between the relevant boundary grid boxes. The boundary exchange involves all seven state variables. Boundary values are derived from the NSP Cruise data by linearly interpolating depth averaged CTD and bottle data from stations along 55.5°N and in the Dover Strait. The northern boundary inputs are calculated on the boundary grid cells and for the southern boundary along the row of grid cells above the boundary cells.

4.2.3. River Inputs

Eleven rivers flow into the modelled area, these are the Tyne, Tees, Humber, Wash, Thames (English), Elbe, Weser (German), Ems, Ijslmeer, Rhine (Netherlands) and the Scheldt (Belgian). Each river provides monthly varying flows and concentrations of ammonia, nitrate and detrital nitrogen. Microplankton components have no riverine source in the model. The river inputs are modelled by adding the nutrient concentration of the rivers to the grid box nutrient concentration. These concentrations depend on the volumes of the river flow and the grid boxes concerned (i.e. the grid box concentration is multiplied by the grid box volume (VOLGB), and the river concentration is multiplied by the river volume (RIVVOL)). The nutrient concentration of the grid box is then reduced by a factor 1/(VOLGB+RIVVOL).

4.2.4 Atmospheric inputs

The atmospheric contribution is divided into wet and dry (aerosol) depositions of nitrate and ammonia. Wet deposition varies monthly and from grid box to grid box while dry deposition only varies spatially.

4.2.5 Sediment related fluxes

Particulate sediment exchange is controlled by two separate processes - deposition and resuspension. Deposition is modelled so that loss from the water column is determined by model calculations of the composition of material in suspension in the water column. Resuspension is determined on the basis of the NSP sediment composition data and modelled using the tidal amplitude to determine whether erosion or deposition is occurring. Dissolved nutrient exchange is calculated from the fluxes determined at the 6 NSP sediment sampling sites, extrapolated to the modelled area on the basis of bottom sediment type.

4.2.5. Internal Processes

The internal processes that affect the nitrogen in the model are: (i) zooplankton messy eating, (ii) zooplankton grazing, (iii) zooplankton excretion, (iv) zooplankton defecation, (v) remineralisation, (vi) nitrification, (vii) sinking, (viii) deposition, (ix) resuspension, (x) within sediment remineralisation. The sink of nitrogen within the model is that fraction of nitrogen which is taken up into zooplankton biomass and not returned to the system by zooplankton excretion or defecation.

4.3 Model Output

4.3.1 Model Calculations of Sources of Nitrogen to the Southern North Sea

TABLE 4.1 shows a break down of the different fluxes of nitrogen through the modelled area of the southern North Sea between 55.5°N and the Dover Strait for a standard run of the 2D nutrient model as detailed in Part 1 of this report. As described above certain fluxes are effectively independent of the models calculation of transport and biological processes, and the model simply sums inputs based on the NSP observation and other data sets. Inputs from rivers, sediments and atmosphere data are unaffected by the model formulation while cross boundary exchange depends entirely on the model. TABLE 4.1 suggests that rivers are the major source of new nitrogen to the North Sea, with input through the Straits of Dover as the second most significant source.

TABLE 4.1

Model Results for Annual Nitrogen Inputs (Ktonnes)to the North Sea.

Input	Nitrate-N	Ammonia-N	Detrital-N	Plankton-N	Total-N
Atmosphere	96	42	0	0	138
S Boundary	286	67	16	30	399
N Boundary	-55	56	-52	-17	-68
Rivers	407	51	135	0	593
Total	734	216	99	13	1062

Sinks	Total-N
Sediment	510
Zooplankton	540
Total	1050

In the present formulation of the model deposition of nitrogen detritus to sediments is the major loss of nitrogen from the system, rather than export to the Atlantic Ocean or loss to biological trophic levels higher than plankton.

4.3.2 Nutrient input through the Dover Straits

The amount of input estimated through the Dover Strait depends strongly on the estimate of water flow through the Strait used in the calculation. The model presently simulates a mean flow of 76 * 10^3m3/s. This compares to the latest estimate of the mean residual Channel flow of 110 * 10^3 m3/s. PRANDLE (pers. comm.). This is, in turn lower than the estimate of 155*10^3 (LAANE *et al.* 1990) and 168*10^3 (BROCKMANN *et al.* 1990) used in other recent estimates of nutrient flow through the Dover Straits, which were based on PRANDLE (1984), but higher than the estimate of 63*10^3 m3/s used by POSTMA (1973). PRANDLE's estimates of the flow have tended to fall over the last 20 years, from 240*10^3 m3/s to the most recent estimate of 110*10^3 m3/s. While his estimates have tended to larger than those of Pingree (PINGREE & MADDOCK 1977 and PINGREE & GRIFFITHS 1980). There are problems with the measurements of the Dover Strait water flow and the uncertainty with the data is due to the limitations of the presently available observations. Recent estimates have used HF Radar measurements to improve on earlier estimates which where based on a range of different techniques including current meter measurements and interpretation of the rate of dispersion of radio nuclide discharges from the Cap La Hague and Windscale reprocessing plants. Estimates of the Channel flow still remain uncertain as the HF Radar measures only the surface currents. It is hoped that the range of observations being made during the EC-FLUXMANCHE programme will lead to a further refinement of our ability to estimate flows through the Dover Straits through calibration of models with more extensive field data than has been possible before.

Estimates of fluxes from the English Channel to North Sea have been made by POSTMA 1973, BROCKMANN *et al.*(1988) and LAANE *et al.*(1991) The first two are simple estimates which assume that the winter concentration of dissolved nitrate-nitrogen can be taken to describe the amount of biologically active nitrogen present in the water column year round although its chemical form will change (c.f. BUTLER *et al.* 1979). Their estimates are 250 ktonnes and 705 ktonnes respectively the higher flux estimate of BROCKMANN *et al.* (1988) is due to the use of a higher flow rate. The fluxes were calculated simply assuming - Flux = Concentration x Residual water flow. More recently LAANE *et al.* (1991)have presented more detailed calculations of the likely flux. They calculated the total flux of the 3 (N, P, and Si) nutrients into the North Sea by combining distribution measurements (1986-1988) of the concentration of different nutrients (nitrogen, phosphorous and silicate) in the North Sea and PRANDLE (1984) water flow estimates. Averaged interpolated concentrations are then multiplied by the residual water flow for that month. This estimate is higher than previous ones because the particulate nitrogen flux is included in the total of 1411 ktonnes/yr. The inclusion of particulate nitrogen raises the estimated flux from 546 ktonnes/yr., a nearly three fold increase. LAANE *et al.* (1991) do not provide any of the original concentration data in their report. When we include particulate nitrogen (using data from the NERC-NSP) in our Model calculations this only raises the total nitrogen flux by 10% (TABLE 4.1). This disparity needs to be investigated..

4.3.3 Inputs to the English Channel relative to input through the Dover Straits

In TABLE 4. 2 the data on nitrogen inputs presented in the 1993 QSR for the English Channel are summarised. The total land derived discharge to the English Channel is 142 ktonnes/yr.

TABLE 4. 2 Channel Quality Status Report on Nitrogen Inputs to the English Channel

	RIVERS (Kilotonnes)		DIRECT DISCHARGES (Kilotonnes)	
	TOTAL UK Channel coast	FRENCH Total (Seine)	INDUSTRIAL (UK only)	SEWAGE (UK only)
RIVERFLOW (m3/s)	118	NI(432)	Not Applicable	Not Applicable
NITRATES				
Upper range	9.6	NI	0.06	0.99
Lower range	9.6	NI	0.06	0.94
TOTAL NITROGEN				
Upper range	11.9	142(100)	0.3	10.2
Lower range	11.9	142(100)	0.3	10.1

NI = No Information

This represents about one third of the model estimate of the nitrogen flux through the Dover Straits, and about 10% of the LAANE *et al* (1991) estimate of the flux. Inputs of nutrients to the English Channel are dominated by the River Seine, which provides 70% of the input.

PART 5

DISCUSSION OF MODEL LIMITATIONS

5.1 Introduction

Limitations of the model stem from two sources. One is the need to describe the system with a minimum set of equations that give a description of the processes known to be significant to the system, while maintaining the lucidity of the code to other potential users, and, keeping the computing power required to run the model at anyone time within the limits of available machines. The other is the limitation imposed by the detail available in the data sets required to drive the model. These data sets may either be observed data as for example in the case of riverine inputs, or, data sets derived from runs of other models as is the case with the residual flow data.

5.1.1 Stratification

A simplification used in the present model is that the equations are vertically integrated which makes the assumption that the waters of the southern North Sea are well mixed. This is true for the whole year in the southern bight of the North Sea, coastal waters and Dogger Bank regions of the modelled area. However, it is not so in the waters in the northern and central parts of the North Sea where summer stratification occurs. Expansion of the model needs to include stratification to take account of the restricted depth of production, sub-thermocline oxygen depletion and nutrient build-up.

5.1.2 Resuspension and deposition

Because of the relatively short residence time of water in the North Sea, the only place that the memory of what happened in one year can be passed to the next is when the decomposition of organic detritus in the sediment is sufficiently slow for material entering the sediment in a year to return to the water column in the next and subsequent years. Increased inputs over a number of years would create a reservoir of material in the sediment. Supply from this reservoir would reduce the likely immediate impact of a reduction in other inputs. In the present formulation of the model, organic detritus which the model calculates to reach the sea bed ceases to be considered by the model. The return of components of that organic matter to the water column in the dissolved flux is calculated only on the basis of the observed data. Similarly the composition organic detritus that is resuspended from the sea bed is based on integrated NSP core data. The amount of detritus that is resuspended by erosion is modelled using the tidal amplitude. Given the potential significance of the sediment "memory effect" to model predictions, it is a serious draw back of the model that sediment processes are not fully modelled.

5.1.3 Grid size

Unlike the sediment exchange processes, cross boundary exchange is fully determined by calculations included in the model. However as discussed in Part 4 of this report, there is considerable variation in the magnitude of estimates. This variation is in part due to how the hydrodynamic flow is calculated. Improving the calculation of the hydrodynamic flow of water and associated matter can be achieved by using a finer resolution. In particular the changes in current velocity with respect to location (e.g. $\partial u/\partial y$, $\partial u/\partial x$)becomes more significant the closer the coastline. The coastline morphology significantly alters the direction of the current. The land-water boundary on a coarse grid model has a greater effect on advection over a wider area than a finer grid model. In the present model the southern boundary is defined by 4 grid boxes. It is therefore not surprising that the model cannot reproduce the small scale processes which produce a number of different flow environments in the Dover Strait. A next step in model development would be to increase the resolution of the model from a 35km to 8km. At this resolution 11 grid cells would define the Dover Strait. JONES & HOWARTH (1995), have already shown using the higher resolution grid gives a distinct improvement in modelling the salinity distribution.

5.1.4 Residual Flows

Another aspect which degrades our ability to accurately model flow through the Dover Strait is the basis on which residual water flows are calculated. We know from the NSP Cruise data that at certain times the normal pattern of water flow is reversed and water flows out of the North Sea and into the English Channel. The present formulation of the model does not take account off these short time scale changes in flow. It is forced by climate rather than real weather conditions. The physical forcing of advection in the model is the result of "Tidal" and "Meteorological" residual motion. Tidal residuals are significant in shallow coastal waters such as the North Sea where bottom topography and land water boundaries accentuate the non-linearities in the system. They are the result of non-linear interactions between different tidal harmonics. Meteorological residuals are the result of wind imposed effects and are defined as 'the non-tidal component which remains after analysis has removed the regular tides', (PUGH, 1987). When the tidal component is removed from estimates of the overall water movement by subtracting the elliptical tidal motion using Fourier analysis (see Appendix C, C.2) PRANDLE (1984) has shown that, on average, wind forcing accounts for about 50% of the residual circulation. Presently, temporally independent unit wind stresses are used (see Appendix C). Smoothed monthly averaged factors are applied to these residuals to give them a seasonality. However, the wind data used to calculate these monthly factors shows that on daily time scales significant peaks in wind speed in the opposite direction to the monthly averages occur. Thus, a closer look at the meteorological residuals (i.e. the wind driven component of the advective transport), may prove to be significant if the model is to successfully simulate the flow of water through the Dover Straits. Real wind stress values that have been measured 10 metres above sea level at 3 hourly intervals are available from the Met. Office. This data has wind stresses acting in both directions along the Dover Straits. Such wind data for the period of the NSP cruise is already in use as WFIELD in the air-sea oxygen exchange part of the model.

5.1.5 River Inputs

When the total tonnage of nitrogen entering the North Sea calculated using the model is compared to the simple budget derived from fresh water flows and concentrations the model budget is lower. The discrepancy arises because the model calculates the input on the basis of the difference in concentration between the river water flowing into the grid cells into which the river debouches and the concentration already present in the box. Future work will aim to improve the modelling of riverine inputs.

There is some concern that significant processes may be occurring in the estuarine zone. This problem is one which is being addressed by the MAFF and DoE Joint Nutrient Study (JONUS). Results from JONUS suggests that significant removal and addition processes can take place. There are also more general problems with the estimation of river input in addition to ones pertaining to specific biogeochemical processes. One is the large temporal variability in the measurements of nutrient loads. In 1981 the Elbe river carried 273,000t of total nitrogen while in 1984 the figure was 142,000t (GERLACH, 1988). The other concern is with the position of the measurement. For example, the River Elbe is sampled at its tidal limit which is in fact 150km from the open sea.

5.1.6 Combined effects

The present model can investigate changes in river input loads (see Part 4 of this report). But as noted above it only runs at the moment with a fixed residual flow pattern. The volume of water entering in rivers is only a few percent of the volumes of water being exchanged across the boundaries of the North Sea. The degree to which river discharges are retained in the North Sea for any period of time depends on the flow pattern. It is therefore possible that changes in weather patterns from year to year and hence the associated change in residual flows may have at least as great an impact on likely production levels as variations in river loads. This requires investigation in future development of the model.

5.2 Discussion of model output in terms of its ability to reproduce processes and seasonal cycles

This first attempt at matching observed seasonal cycles with a simulation from a simple model has produced some encouraging results. The agreement between observed and modelled total dissolved inorganic nitrogen (FIGURE 3.3). By running the model with and without different inputs and processes (FIGURE 3.1) we can start to appreciate the role of each component in the seasonal cycle.

The calculation of annual primary production in ICES boxes (TABLE 3.4) shows that the model tends to overestimate production in all boxes except box 5 which shows a significant underestimate. Examination of the seasonal variation (FIGURE 3.4) shows the model has a large peak in each box in May apparently not supported by observations (HOWARTH *et al.* 1993), and that at other times of year the model tends to underestimate production when compared to the observed values. So that it is only on average that the model over estimates production relative to observation. It can be argued (TETT *et al* 1993) on the basis of detailed observations of bloom events using moored fluorimeters that the model actually better represents the shape of the production curve in spring than does the observed (NSP) data. However in the rest of the year the model tends to underestimate production. The reason for this needs to be investigated.

The impact on the system of reducing the supply of nitrogen from rivers by 50% is considered (in the first year) to result in a reduction of annual primary production of up to 18%. The model is able to discriminate between different regions. ICES boxes 4 and 5 show the greatest impact (TABLE

3.4). This is to be expected as these regions are significantly influenced by the coastally-constrained river plumes (NELISSEN & STEFFELS 1988). The smaller influence of a river input on primary production in ICES box 3" is consistent with the model reflecting the effect of turbidity on photosynthesis caused by coastal erosion off the English coast, i.e. light is more important in limiting production in this area than the availability of nitrogen. That the percentage reduction in primary production predicted for ICES box 7", is as high as 7% may reflect a dispersion rate of nitrogen into the central area of the North Sea that is higher than actually occurs. This a numerical problem resulting from the relatively coarse grid on which the model is based. Dispersion of nutrients in the model is greater than it is in reality. It is also our intention to refine the grid size to (at most) 8km. Recent modelling of the North Sea salinity (JONES and HOWARTH, 1995 has demonstrated the need for high resolution in coastal regions to accurately simulate the near shore salinity gradients effectively. This is equally true for the nutrient distributions and increased resolution should significantly improve the calculations. The constraint of forcing the model to have a repeating seasonal cycle does not permit any predictions of long term reductions.

The model suggests that the southern North Sea is a sink for nitrogen, this is in accord with what would be suggested by the observed variation in the ratio of dissolved nitrogen to phosphorus compounds. All source waters to the North Sea contain N&P at a ratio close to or above the Redfield ratio (16), while central North Sea waters have winter values below 10. The likely main cause of the North Sea acting as a sink for nitrogen is loss of nitrogen as nitrogen gas from the system due to denitrification. The present implementation of the model does not include denitrification. The loss of nitrogen to the sediment that occurs in the model is due to the imbalance between the supply of material to the sediment which is modelled and the returned input from the sediment which is based on observed data. This difference implies a loss of nitrogen which may be due to denitrification. We are currently working on a version of the model which couples benthic and pelagic processes and takes account of denitrification (SOETAERT, 1996). A related problem was disclosed by examination of the production of ammonia in the system, this revealed a short coming with the nitrification rate constant transferred from the TETT (1990) model. Experiments showed that to get a reasonable approximation to the seasonal variation, published nitrification rates have to be decreased by two orders of magnitude (to give a time scale of 100 days) and we feel this component of the model needs further investigation.

The other significant sink implied by the model is that nitrogen is retained in higher trophic levels than phytoplankton. This an aspect of the model that requires further investigation. "Closure" of biological models a particular trophic level is an inherent problem. The question always arises how far do you extend the model through different trophic levels without loosing the balance between complexity and the ability to calibrate the model with available data. In future it may be better to constrain this loss term to a fixed quantity. This could be done on the basis of fish catches and observed migrations of zooplankton. Two current EU-MAST programmes may provide better information than was available during the NSP to enable us to do this in future. Given the lack of suitable calibration information this seems a more reasonable option than extending the modelled domain to areas remote from the central interest of the model.

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APPENDIX

APPENDIX A1 : Derivation of the advection-dispersion equation (using Cartesian co-ordinates)

The basic advection/dispersion equation used in this model is of the general type which gives the change of the concentration of a (living or non-living) substance (called the state variable) in time as

(A.1.1) $$\frac{dC}{dt} = \text{turbulent dispersion terms} + \text{action / reaction terms}$$

The term on the left hand side of (A.1.1) is called the total derivative of the state variable C and consists of the local change and the changes due to the motions of the water that pass a certain concentration of C by a point of observation i.e.

(A.1.2) $$\frac{dC}{dt} = \frac{\partial C}{\partial t} + u.\frac{\partial C}{\partial x} + v.\frac{\partial C}{\partial y} + w.\frac{\partial C}{\partial z}$$

The local change, $\partial C/\partial t$, is known as the local derivative of C, while the contribution of advection to C is given by the following three terms on the right hand side of (A.1.2). The u, v and w components denote the velocity of the water in x-(eastward), y-(northward) and z-(upward) directions respectively. Since the model is two dimensional in the horizontal plane, the vertical gradients are assumed to be negligible i.e.

(A.1.3) $$\frac{\partial C}{\partial z} = 0$$

The turbulent diffusion terms on the right hand side of equation (A.1.1) are parameterised by

(A.1.4)

$$\frac{\partial}{\partial x}\left(A_h.\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_h.\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_v\frac{\partial C}{\partial z}\right)$$

A_h = horizontal dispersion coefficient

A_v = vertical dispersion coefficient

From (A.1.3), equation (A.1.4) is reduced leaving just the first two terms.

Finally the chemical and biological processes in the model are contained in the action/reaction terms of (A.1.1). This leaves the full advection/dispersion equation as

(A.1.5) $$\frac{\partial C}{\partial t} + u.\frac{\partial C}{\partial x} + v.\frac{\partial C}{\partial y} = A_h.\frac{\partial^2 C}{\partial x^2} + A_h.\frac{\partial^2 C}{\partial y^2} + \text{action / reaction terms}$$

APPENDIX A2 : The Advection-Dispersion Formulation of the model

The mathematical formulation of the model is that used by PRANDLE(1984a) which is incorporated into the POL General Purpose Hydrodynamic Model as developed by Eric Jones (unpublished). The basic advection-dispersion equation used is that for turbulent incompressible flow of a conservative substance in two dimensions, i.e.

(A.2.1)

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}+V\frac{\partial C}{\partial y}=\frac{1}{D}\left\{\frac{\partial}{\partial x}\left(DE^{x}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(DE^{y}\frac{\partial C}{\partial y}\right)\right\}$$

$D =$ Gridcell water column depth

$C =$ Gridcell depth - averaged concentration

$E^{x}, E^{y} =$ Dispersion coefficients in the x-, y - directions

Although water is not incompressible, this assumption is a good approximation because the volume changes associated with the sea are small. Equation (A.2.1) indicates that the dispersion is depth averaged.

In order for the model program to solve (A.2.1) (a partial differential equation) Eric Jones' implementation of the upwind finite difference method is used. That is, (A.2.1) is converted to the finite difference form as follows:

(A.2.2)

$$\begin{aligned}\frac{C_{i,j}^{t+\delta t}-C_{i,j}^{t}}{\Delta t}=\frac{1}{D_{i,j}^{t}}\Big[\Big\{\Big[&T_{i-1,j}^{U,t}C_{i-1,j}^{t}n_1-T_{i,j}^{U,t}C_{i,j}^{t}(1-n_2)+T_{i-1,j}^{U,t}C_{i,j}^{t}(1-n_1)-T_{i,j}^{U,t}C_{i+1,j}^{t}n_2\Big]\Delta y\\&+T_{i,j}^{V,t}C_{i,j+1}^{t}n_3\Delta x_j-T_{i,j-1}^{V,t}C_{i,j}^{t}(1-n_4)\Delta x_{j-1}+T_{i,j}^{V,t}C_{i,j}^{t}(1-n_3)\Delta x_j-T_{i,j-1}^{V,t}C_{i,j-1}^{t}n_4\Delta x_{j-1}\\&-C_{i,j}^{t}\Big[T_{i-1,j}^{U,t}\Delta y-T_{i,j}^{U,t}\Delta y+T_{i,j}^{V,t}\Delta x_j-T_{i,j+1}^{V,t}\Delta x_{j-1}\Big]\Big\}\Big/0.5\Delta y(\Delta x_{j-1}+\Delta x_j)\\&+\Big\{(C_{i+1,j}^{t}-C_{i,j}^{t})n_5D_{i,j}^{U,t}E_{i,j}^{x}-(C_{i+1,j}^{t}-C_{i,j}^{t})n_6D_{i,j-1}^{U,t}E_{i-1,j}^{x}\Big\}\\&+\Big\{(C_{i,j-1}^{t}-C_{i,j}^{t})n_7D_{i,j-1}^{V,t}E_{i,j-1}^{y}-(C_{i,j}^{t}-C_{i,j+1}^{t})n_8D_{i,j}^{V,t}E_{i,j}^{y}\Big\}\Big]\end{aligned}$$

In this case transports are used and not depth-averaged currents i.e. $T^{U} = U(h+\zeta)$ and $T^{V} = V(h+\zeta)$ where ζ is the sea level elevation and h is the water column depth. U and V are calculated from the tidal and meteorological residuals (see Appendix D). An upwind difference scheme for the advective terms means that the following are defined as :

$$n_1 = 1 \text{ if } T_{i-1,j}^{U} \geq 0\ ;\ = 0 \text{ if } T_{i-1,j}^{U} < 0\ :\ n_2 = 1 \text{ if } T_{i,j}^{U} < 0\ ;\ = 0 \text{ if } T_{i,j}^{U} \geq 0$$

$$n_3 = 1 \text{ if } T_{i,j}^{V} \geq 0\ ;\ = 0 \text{ if } T_{i,j}^{V} < 0\ :\ n_4 = 1 \text{ if } T_{i,j-1}^{V} < 0\ ;\ = 0 \text{ if } T_{i,j-1}^{V} \geq 0$$

Equation (A.2.2) also eliminates those grid points which lie on land boundary points for the dispersion terms, such that

$n_5 = 0$ if $T^{U}_{i,j}$ invalid : $n_6 = 0$ if $T^{U}_{i-1,j}$ invalid

$n_7 = 0$ if $T^{V}_{i,j-1}$ invalid : $n_8 = 0$ if $T^{V}_{i,j}$ invalid

This formulation (A.2.1) can break down if stagnation points occur in the hydrodynamic flow fields supplied. That is, if a grid cell experiences either inflow or outflow only, there will be a monotonic increase or decrease in that grid cell. However, analysis of the model runs has shown that this does not occur. The dispersion in the model is related to tidal action only (as with PRANDLE, 1984a). Thus, the dispersion coefficients are related to M_2 tidal current amplitudes (UAMP, VAMP) by PRANDLE's (1984a) formulation :

(A.2.3)

$$E^x = \alpha.UAMP.R_x \quad ; \quad E^y = \alpha.VAMP.R_y$$

$UAMP =$ the M_2 tidal current amplitude in the x - direction

$VAMP =$ the M_2 tidal current amplitude in the y - direction

$$R_x = (UAMP^2 + \overline{VAMP}^2)^{1/2}$$

$$R_y = (\overline{UAMP}^2 + VAMP^2)^{1/2}$$

$\overline{VAMP}^2$ = average $VAMP^2$ of the squared current amplitudes in gridboxes (i, j), (i, j - 1), (i + 1, j - 1), (i + 1, j). See Appendix E

$\overline{UAMP}^2$ = average $UAMP^2$ of the squared current amplitudes in gridboxes (i, j), (i, j + 1), (i - 1, j + 1), (i - 1, j). See Appendix E

α = 500s (this differs from Prandle(1984) which was set at 1000s)

The model dispersion coefficients are limited between 50 m^2/s and 50,000,000 m^2/s. PRANDLE (1984a) found that values of E^x and E^y of between 100m^2/s and 1000m^2/s gave reasonable values of dispersion on the UK. Shelf.

$n_5 = 0$ if $T^{U}_{i,j}$ invalid : $n_6 = 0$ if $T^{U}_{i-1,j}$ invalid

$n_7 = 0$ if $T^{V}_{i,j-1}$ invalid : $n_8 = 0$ if $T^{V}_{i,j}$ invalid

This formulation (A.2.1) can break down if stagnation points occur in the hydrodynamic flow fields supplied. That is, if a grid cell experiences either inflow or outflow only, there will be a monotonic increase or decrease in that grid cell. However, analysis of the model runs has shown that this does not occur. The dispersion in the model is related to tidal action only (as with PRANDLE, 1984a). Thus, the dispersion coefficients are related to M_2 tidal current amplitudes (UAMP, VAMP) by PRANDLE's (1984a) formulation :

(A.2.3)

$$E^x = \alpha.UAMP.R_x \quad ; \quad E^y = \alpha.VAMP.R_y$$

$UAMP =$ the M_2 tidal current amplitude in the x - direction

$VAMP =$ ... tion

$R_x =$ (

$R_y =$ (

$\overline{VAMP}^2 =$ ... udes

... ee Appendix E

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Correction to:

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p. 82 - for Appendix D read Appendices A5 and A6

p. 83 - for Appendix E read Appendix A7

APPENDIX A3: Modelling the Boundary Inputs

The cross boundary inputs of the northern (56°N) and southern (51°N) boundaries are determined in the subroutine MIX. The northern boundary inputs are executed on the row of grid cells along the boundary grid cells (i.e. on row 3 in the coding). For the southern boundary, the algorithms for dispersion and advection are applied to the grid cells just above the boundary ones themselves (i.e. row 15).

The equation for the cross-boundary inputs is of these two forms:

BINP = BINP - ADVEC + DISP (1)

and

BINP = BINP + ADVEC - DISP (2)

The Northern Boundary:

The general movement of water across the northern boundary is both inwards and outwards (i.e. to the west the flow of water is into the model, to the east the flow is out of the model). This behaviour is catered for in the coding of the cross-boundary inputs by using equation **(1)**. That is, if the advection in the V direction is southwards (i.e. negative), then equation **(1)** for cross-boundary inputs becomes

BINP = BINP + ADVEC + DISP (3)

and so water and the state variables concerned enter into the modelled region.
If the advection in the V direction is northwards (i.e. positive) then **(1)** remains as

BINP = BINP - ADVEC + DISP

and water and the associated state variable concentrations leave the modelled area.

The Southern Boundary

The general movement of water through the southern boundary is northwards, in that water moves into the modelled area. Here, equation **(2)** is utilised. As V is northerly (i.e. positive), the flow is into the modelled zone. This accounts for the minus sign in front of the advection component which is in line with equation **(1)** for the northern boundary. Similarly, the minus sign preceding the dispersion component in **(2)** is placed there to concur with the dispersion component used in the northern cross-boundary equations (**(1)** and **(3)**).

APPENDIX A4 : Sediment Exchanges derived from the NSP Data

Real sediment exchanges (i.e. those that cross the sea-sediment boundary) come from the fluxes involving the dissolved constituents (**XO,XNOS,XHNS**). These are derived from the NSP core site data. Each grid cell ((**i,j**)) is assigned a sediment type (of which there are 6, with each one having 12 monthly values) via the sediment map, **ISEDMAP(i,j)** (see Example C1). The latter determines a grid cell's benthic input per timestep. Sediment types 1 to 6 represent NSP core sites 1 to 6 respectively. The direction of the flux is dealt with in the arrays read in at the start of the program (**FLUXO, FLUXNO, FLUXNH**).

The particulate exchange is controlled by two separate processes:

(1) the deposition, which is modelled so that the organic constituents involved (**B,C,XN,XM**) do not interact with the model once they hit the sediment, and

(2) the resuspension which is not modelled and instead relies on the NSP core data and the sediment map (**ISEDMAP(i,j)**).

<u>Example A4.1; Example of how benthic nitrate flux is inputted</u>

FOR **J** (i.e. sediment type) = 1 TO 6 AND FOR **I** (month) = 1 TO 12
READ IN **FLUXNO(I,J)** (units : mass per unit area per unit time)

FOR **J** (rows) = 1 TO 14 AND FOR **I** (columns) = 1 TO 21
i.e. for all 294 grid cells
READ IN **ISEDMAP(I,J)** (holds values 0 to 6, where 0 = land)

THE BENTHIC INPUT=**FLUXNO(ISEDMAP(I,J),month)/DD**

where **DD** is the depth of the grid cell water column, thus yielding units in mass per unit volume per unit time. The benthic input is then subtracted (the sign of the flux is accounted for in the data file) from the timestep change dissolved nitrate state variable.

There are six particulate organic carbon values which are read into array **CMSED(I)**. Each value represents the percentage of the six NSP core sediments that is organic carbon (averaged over all the cruises). The correct organic carbon sediment value from **CMSED(I)** is then inserted into the sediment layer (3) of the detrital state variables, **C(i,j,3)** and **XM(i,j,3)**, according to **ISEDMAP(i,j)** (see Example A4.2)

Example A4.2; How the correct C sediment value is inputted

FOR I (sediment type) = 1 TO 6
READ IN **CMSED(I)** (i.e. **CMSED(1)** = value1
CMSED(2) = value2, etc.)

ISEDMAP(I,J) holds values 0 to 6 for all 294 grid cells

IF **ISEDMAP(I,J)** .NE. 0 THEN for all 294 grid cells **(i,j)**

C(i,j,3) = CMSED(ISEDMAP(I,J))
XM(i,j,3)=CMSED(ISEDMAP(I,J))

APPENDIX A5 : Mathematical and Model Derivation of Tidal Residuals

Mathematically, tidal residuals occur when the sea level elevation, ζ (a cosine function which is significant in shallow waters), interacts with (i.e. is multiplied by) the velocity of the water, u or v (also cosine functions, see Example A5.1).

Example A5.1; Tidal Residual Derivation from The Continuity Equation[1]

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}(h+\zeta)u+\frac{\partial}{\partial y}(h+\zeta)v=0$$

h = water column depth, a constant
ζ = sea level elevation, a cosine wave
u, v = water velocity components in x-, y - direction, cosine waves
Since ζ is significant in shallow waters the continuity equation has the terms $hu+\zeta u$ and $hv+\zeta v$. These additions create tidal cycles which when integrated over the tidal period produce non - zero terms i.e. the tidal residuals.
In this model there is no vertical component to the water velocity. Only horizontal dynamics are treated here which assumes no vertical gradient and a well mixed water column.

This interaction is then added to a cosine function that is a product of the water column depth, h (a constant), and the velocity of the water. All of these cosine functions describe the tidal cycle for each component. The addition of cosine waves of different periods and amplitudes results in a combined tidal cycle. When such a tidal cycle is integrated over the resultant tidal period, non-zero terms are derived. It is these terms that are the tidal residuals. The tidal residuals used in the model were derived from an M2 tidally driven version of the POL General Purpose Hydrodynamic Model (i.e. with no wind component, Eric Jones, pers. comm.). The value of the currents at each time step over a tidal cycle were summed and an average current obtained per tidal cycle. These non-zero terms result from non-linear interactions and it is these that are defined as the tidal residuals.

[1] The law of conservation of mass is used in oceanography in the form of an equation of continuity of volume (or of density).

APPENDIX A6 : Derivation of the Meteorological Residuals

The meteorological residuals in the nutrient model were derived by adding wind components to the aforementioned POL hydrodynamic model. A uniform southward and eastward wind stress was applied to the POL model area. The sense of the wind stresses were chosen to agree with the fact that over the UK. continental shelf area the wind direction is generally northerly and westerly. After running the model, Fourier analysis removed the tidal effect which allowed westerly (positive in the x-direction) and northerly (negative in the y-direction) unit wind stresses to be extracted. The northerly components were multiplied by a factor of -1 to give them a southerly direction. Greater reflection contamination from the northern boundary, relative to the southern boundary, to the model area meant that a northerly wind stress, as oppose to a southerly one, was applied. The assumption is that the resultant wind residuals derived from both a northerly and southerly wind stress are the same in magnitude but of opposite sign. A monthly varying (averaged sinusoidal) factor (maximum in January, minimum in August) is applied to the wind residuals to give them seasonality. This factor originates from one of two sources (with both sources in units of Newtons per metres squared and in the first order of magnitude) :

(a) Norwegian estimates in which average monthly wind stresses are calculated from a mean annual wind stress taken over 33 years (1955-1988) and

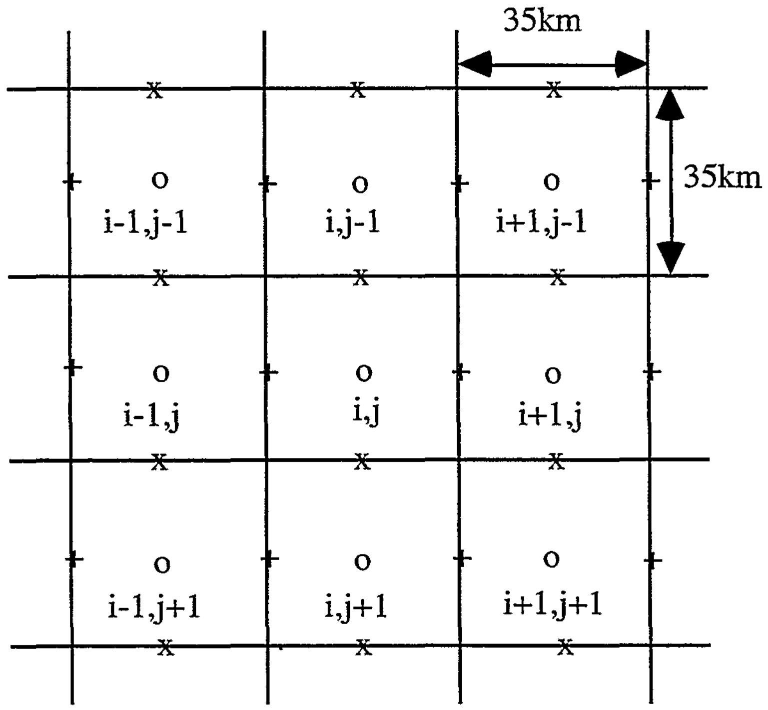
(b) Met. Office modelled values (spatially averaged) for the Challenger Cruise period (1988-1989).

The wind residuals derived for the model were an order of magnitude less (units 0.1 N/m^{2}) than the seasonality wind factor and so they have been multiplied by a factor of 10. The non-linearity of the model set-up means that using wind stresses of a higher order would produce unrealistic meteorological residuals.

APPENDIX A7 : The Numerical Grid Scheme of The model

To avoid confusion throughout this report the model grid scheme is set up as in Figure 1. The model grid boxes are indexed with i increasing from left to right but j increasing downwards.. The grid cell area is approximately 35km x 35km.

Figure 1 : The Numerical model grid scheme



o = elevation (z point)
\+ = East-directed current (u point)
x = North-directed current (v point)

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