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NERC NORTH SEA
COMMUNITY RESEARCH PROGRAMME
QUALITATIVE ASSESSMENT OF NUTRIENT MEASUREMENTS
SEPTEMBER 1988 TO AUGUST 1989

Preliminary report to the
Department of the Environment

BY
D.J. HYDES AND H. EDMUNDS

REPORT NO. 269
1989

Natural
Environment
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OCEANOGRAPHIC SCIENCES
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Natural Environment Research Council

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ABSTRACT

This report provides an initial qualitative review of results obtained for the plant nutrient elements N, P and Si between September 1988 and August 1989. The NERC North Sea Community Research Programme (NSCP) is being undertaken to improve our understanding of the North Sea ecosystem. Nutrient measurements are being made within a co-ordinated programme of chemical, biological and physical measurements. By this, we will achieve a better understanding of the possible stress to the ecosystem resulting from present levels of nutrient inputs. The overall aim of the programme is the development of a water quality model which can be used as a basis for future management decisions about the North Sea.

Surveys of the southern North Sea south of 56°N were conducted monthly. Contoured maps of the distributions of salinity, nitrate, phosphate, silicate, NO_3/PO_4 and NO_3/Si from each survey are presented here. The major processes controlling distributions are the biological growth and decay cycle, river inputs and the circulation pattern. Winter nitrate appears to be dominated by river inputs with two low areas where plankton growth was still occurring. Distributions of phosphate are more complex. Recycling of phosphate is significant. Nitrate/phosphate ratios are lower than in ocean waters most of the year and are the reverse of what is found in the rivers. This suggests significant depletion in nitrate inputs via estuarine processes. In late spring, phosphate may be the limiting nutrient in some areas. Water mass movements significantly effect nutrient distributions, and such variations should be taken into account in any attempt to monitor changes within the North Sea.

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1. PREVIOUS OBSERVATIONS

1.1 Introduction

Improvements in agricultural production, sewage disposal and detergent formulations have greatly increased the input of nutrients to the North Sea during this century (GERLACH, 1988; LIDGATE, 1988; DE JONG & DE OUDE, 1988). These excess nutrients have been blamed for many of the ills of the North Sea, such as the occurrence of toxic algal blooms and anoxic events. It is possible to hypothesise connections between excess nutrients and these events. However, no direct evidence exists to connect the two together because of the complexity of the eco-system. The interaction between the biota and nutrients is controlled by physical and sedimentological processes as well as biochemistry.

In this first part of the report we review previous work on North Sea nutrients to provide an insight into that complexity. The network of interactions needs to be understood before models can be developed which will allow us to understand the interactions between the different processes involved. This section owes much to a number of recent reviews, particularly those of Nelissen and Stefels (1988), Brockmann *et al.* (1988) and Gerlach (1988). We concentrate on the southern area of the North Sea south of about 56°N. This is the area in which man's activities have most impact. An important conclusion of previous work is that even this area cannot be treated as a single receiving area for discharges. It consists of a number of distinct areas in which the water is resident for different lengths of time with consequent variations in ability to absorb anthropogenic inputs. To determine properly whether or not increased inputs are having a deleterious effect on the North Sea environment, it is important to identify those areas which are most at risk rather than making estimates based on the entire sea.

1.2 Definitions

1.2.1 What is meant by "seawater nutrients" ?

The nutrients are those chemicals which are essential for the growth of photosynthetic plants - phytoplankton - in the sea. This covers a wide range of elements and compounds. Some of these are needed in greater amounts than others so there is a distinction between the macro-nutrients (e.g..the elements C, H, O, N, Si, P, Mg, K and Ca) and the micro-nutrients (e.g..Fe, Mn, Cu, Zn, B, Na, Mo). The second distinction is that some of these elements are known to be present in sea water in short supply relative to the quantities required for continuous growth. It is these elements which are sometimes referred to as the "limiting nutrients" and which are commonly thought of when the term "nutrient" is used. These elements are nitrogen - N, phosphorus - P and silicon - Si. Blooms of plankton in the sea decay when one of these elements becomes depleted in the water. In experimental systems, growth can be stimulated by addition of the depleted element. Concentrations of N and P have increased in the rivers flowing into the North Sea during the last fifty years due to increased fertilizer use (N and P), use in detergent formulations (P) and more systematic collection of sewage (N and P). The expected consequence would be that increases in limiting nutrient concentrations in sea water would produce an increase in phytoplankton production in the North Sea.

1.2.2 What is meant by "eutrophication" ?

It is unfortunate that the word "eutrophic", which has a simple meaning with a straightforward etymological definition, is used with an undue lack of regard for this meaning when the North Sea ecosystem is being discussed. Such lack of precision is dangerous because the semantic breakdown leads to a failure of communication. The etymologically correct meaning of a eutrophic environment is one with sufficient nutrients present to sustain growth (HOLMES, 1979). A second meaning appears to have developed in limnology, where a eutrophic lake is defined as one in which the hypolimnion suffers oxygen depletion during the summer (WALKER, 1988). From this has developed the use of "eutrophic" to imply an environment stressed by the presence of excess nutrients.

Much of the North Sea is a naturally eutrophic system in the strictest sense of the word. Therefore, in the interests of avoiding confusion, use of the the word "hypertrophic" (GERLACH, 1988) to describe environments where excess nutrients are stressing the ecosystem should be encouraged.

1.3 Importance of Nutrients

To quote Gerlach (1988):

> "Nutrients are called fertilizers by the farmer. They are not pollutants *per se* but biostimulants."

They are essential elements for the growth of life in the sea. Their presence or absence effects the development of plant life through Liebig's law of the minimum factor. The production of 3.3 kg of plant biomass requires 1 mole of phosphate, 16 moles of nitrate, 90 moles of water, 106 moles of carbon dioxide and 310 kJ of sunlight. A reduction in any one will reduce the amount produced, whereas all have to increase proportionally for a higher yield to be achieved.

Phytoplankton are the grass of the sea. It is the production of this plant material that is the base of the marine food chain and so supports the development of higher organisms. In a balanced system, phytoplankton production is matched by zooplankton grazing. A limited supply of phytoplankton will limit the development of zooplankton and consequently fish. Problems arise where there is an excess of phytoplankton production. The excess plankton rots removing oxygen from the water and the eco-system is damaged. The formulation given above is only an average. The actual nutrient ratios required by different organisms vary so that changes in the nutrient ratio in the water can favour the development of particular plankton species, the occurrence of which can be detrimental to the eco-system (NELISSEN & STEFELS, 1988; BROCKMAN *et al.*, 1988; OFFICER & RYTHER, 1980).

1.4 Determinants of nutrient distributions

The major factors determining the observed distribution of nutrients in the North Sea are:

1. The balance between biological removal and regeneration processes at a given time of year.
2. The quantity of nutrients in the river inputs.
3. The circulation pattern.

Superposed on these factors are the influences of:

1. The weather, which varies the circulation and river inputs.
2. Atmospheric and dumped inputs which add to the nutrient load.
3. Sediment movement and turbidity which influence biological production and regeneration processes.

1.4.1 Biological control

When the distribution of nutrients in the North Sea is viewed over a year the most obvious feature is the overall change in concentrations between winter and summer, resulting from the biological growth and decay cycle (Fig. 1).

Plant production will occur when there are sufficient nutrients and light. At the latitudes of the North Sea, the annual cycle in the amount of light energy reaching the sea surface is the major control of the initiation of production in spring and its curtailment in autumn. Nutrient concentrations in solution go through a cycle which is the reverse of the production cycle. Nutrient concentrations fall in the spring as they are taken up by the growing plankton and then rise again in autumn and winter as they are regenerated from the detritus of the preceding seasons' production.

The actual onset of production in spring is determined by the amount of light energy reaching plankton cells which depends on the weather (i.e. cloud cover), the turbidity of the water and the depth of mixing of the water. It is the balance of these which determines which regions of the North Sea experience earlier blooms than others (PINGREE *et al.*, 1977; CUSHING, 1973). For examples: the waters over the Dogger Bank are sufficiently shallow that plankton remain close enough to the surface for limited production to take place even in winter; in the Southern Bight, production tends to start off the Dutch coast as the water contains less suspended sediment than on the British side.

The type of plankton which grows best at a particular time of year can be determined by the amount of available nutrients. Spring conditions are suitable for the production of diatoms which require silicate for building their shells. Diatom production ceases when the silicate concentration is depleted to near zero in solution. Diatoms are then succeeded by non-siliceous phytoplankton species. Initially, nitrate and phosphate are still present in the water which favours the development of larger organisms. Subsequently, at low nutrients concentrations, smaller organisms dominate the biomass formed by primary production (OWENS *et al.*, 1989).

The progress of plankton production, after the initial depletion of nutrients following the spring bloom, depends on how efficiently an area is re-supplied with nutrients. The differing degrees of limitation that can occur in the North Sea are exemplified by comparison of the standing crop of plankton in different areas through the year (CUSHING, 1973). North of the summer Flamborough Front, spring and autumn peaks in production contrast with a period in the middle of the year when the supply of nutrients to euphotic surface waters is largely prevented by the presence of a thermocline. In the transition zone between the stratified waters North of the Flamborough Front and the well mixed waters of the Southern Bight, there is sustained production throughout the sunnier parts of the year. In the Southern Bight, there is a decrease in the standing stock from June onwards. These differences support the suggestion by Pingree *et al.* (1978) that the transition zones between stratified and well mixed waters are the most productive in the summer months. In the transition region, it is the summed effects of physical processes which make this effectively the most continuously-productive environment in the North Sea - rather than simply the supply of nutrients. The Southern Bight is richer in nutrients but less productive because the higher energy of the environment tends to disrupt plankton communities, and effective light levels are lower due to the turbidity of the water.

1.4.2 River Inputs

Human activities have increased inputs of soluble forms of nitrogen and phosphorus to the North Sea throughout the present century. To put anthropogenic inputs into their proper perspective they need to be compared to the natural fluxes of nutrients through the system. The estimates of Gerlach (1988) and Nelissen and Stefels (1988) are summarised here.

Gerlach (1988) suggested that for the area south of 56°N the contribution to the overall concentrations of nitrogen and phosphorus in the sea from rivers and dumping had increased from natural levels of 14 and 7 to levels of 34 and 36 percent respectively in 1980.

The effect appears more pronounced if individual areas are considered, as was done by Nelissen and Stefels (1988). A summary of their estimates is given in Table 1. Their outer and inner continental water masses correspond approximately to the 8 µM and 10 µM contours in Figure 2. The inner waters of the German Bight and Jutland Current are massively affected by anthropogenic sources of nitrogen and phosphorus, seventy percent of the nitrogen and eighty percent of the phosphorus being anthropogenic (Table 1).

1.4.3 Circulation

Nutrients entering the North Sea from rivers do not enter a simple well mixed system. In the whole North Sea, Laevastu (1963) recognized eight water masses with distinguishable discontinuous characteristics. These are shown in Figure 3. Lee (1980) considered that six primary water masses were distinguishable on the basis of their temperature, salinity and nutrient characteristics and that Laevastu's regions 1 and 8 were a mixture of these. These subdivisions are listed in Table 2. These divisions were broadly followed in the establishment of the ICES boxes for considering the North Sea (FTNS 1983) (Fig. 4).

Acting on these water masses, inducing mixing within and between them, is the current pattern. The residual currents at any one time have tidal, wind and density induced components. The day-to-day current patterns can vary widely as the climatic forcing varies; however, long term average flows in the North Sea are apparent and have been characterised for some time (CARRUTHERS, 1925).

The nutrient distribution patterns drawn by Johnston (1973) (Fig. 2) reflect the influence of the average flow pattern. The distribution of nutrients (Fig. 2) shows the influence of the residual anti-clockwise circulation coupled to the inflow of nutrient-rich ocean waters and the input of nutrients from rivers. The important features of the winter pattern are:

1. The way that the circulation concentrates the high river inputs from the major river systems in the German Bight and along the Danish coast within the Jutland Current. This is the area highlighted by Nelissen and Stefels (1988) to be most under threat from hypertrophication, and where periods of anoxia have been observed.

2. The relatively low concentrations seen in the central area. The concentration in this area is lower than would be expected if the only supply of nutrient to it were from river water. Possible explanations which may contribute to the maintenance of these low concentrations are:

    (a) this area is the distal end of inputs of nitrate rich ocean waters;
    (b) primary biological production is able to continue in the shallow water over the Dogger Bank during the winter;
    (c) the detritus of production is advected away from this area so that the amount of regeneration from the sediments in winter is low.

1.5 Cumulative Impact of Increased riverine Inputs

The above estimates (1.4.2) of the effect of increased discharges into coastal areas are based on a single year's inputs. The effect over a single year is immediate in the areas considered by Nelissen and Stefels. These are areas of relatively low salinity compared to the bulk of the North Sea. Circulation models estimate that residence times of waters in the North Sea are of the order of a year (PRANDLE, 1984). This would suggest that if the nutrients simply remained in solution then river inputs would be flushed out each year and there would be no build up of nutrient concentrations at higher salinities in the bulk of the North Sea. The recent data analysis by Dickson *et al.* (1988) is consistent with this. Dickson *et al.* (1988) have analysed historical data for sea areas off the British coast between 1960 and 1987 on a year-by-year basis. Their analysis, which only covers the western side of the North Sea, detects an apparent cyclic variation in nutrient concentrations which is consistent between the different areas selected rather than any consistent upward trend with time. This result suggests that the North Sea is flushed to the Atlantic Ocean sufficiently rapidly that the excess anthropogenic nutrients do not accumulate.

Dissolved nutrients are transferred to bio-mass which may not be as mobile as nutrients in solution. Some of this bio-mass will swim away, be fished out, be buried in sediments but some will be regenerated into solution adding to the next year's total concentrations. If this is a significant process then the effective overall concentration of nutrients in the North Sea will have increased during the twentieth century. That is, the amount of nutrient available to support primary production will have increased; this may or may not be the same as an increase in the winter concentration of nutrients, depending on the rate at which the nutrient is regenerated and how it is dispersed. How much solid phase storage of nutrients occurs is an important question, with respect to how quickly reductions in nutrient concentrations in rivers might ameliorate the situation in saline waters.

The current and tidal patterns in the North Sea are such that little new sediment accumulation can occur in the central area and fine-grain material is swept into quieter, deeper water or estuaries. The bulk of regeneration from biomass will therefore take place in these areas. De Jong and Postma (1974) estimated that productivity in the western Wadden Sea increased from 80 $gC/m^2/y$ in 1950 to 240 $gC/m^2/y$ in 1970. Thus, the same areas which are being directly effected by increased riverine inputs are being further effected by the recycling of biological detritus.

1.6 Summary

Inputs of the nutrients nitrogen and phosphorus have increased through this century so that now, in the inner waters of the German Bight and Jutland current, about 70-80% of these elements in the water are of anthropogenic origin. However, away from coastal regions, concentration changes have not been detected due to the rapid flushing of the system and uptake into the biosphere. This does not mean that the ecosystem is unaltered by the increased inputs.

To understand properly the fate of nutrients in the North Sea, we require a model into which we can feed the following information:

1. River and dumping discharges.
2. Atmospheric inputs.
3. Ocean water nutrient concentrations.
4. The mixing and circulation pattern.

5. Biological productivity, including the influences of nutrient ratios.
6. Sedimentation and advection of organic detritus.
7. Regeneration fluxes from sediments and higher organisms.

Such models will be developed in the next few years.

2. PRELIMINARY CONSIDERATION OF NEW DATA FROM THE NERC NORTH SEA COMMUNITY PROGRAMME

2.1 The NERC North Sea Community Programme (NSCP)

The NSCP is comprised of a number of multi-disciplinary studies directed towards the formulation of a 3-D hydrodynamic model to improve our understanding of chemical, biological and sediment processes in the North Sea; and the development of that model into one which is capable of use in water quality management of the North Sea. It involves the combined efforts of UK oceanographers in university research groups and NERC's own laboratories. The programme, which is designed to run for five years, is managed from the Proudman Oceanographic Laboratory which is providing the core of modelling expertise.

The most significant first part of the programme is a fifteen-month period of continuous ship observations. This started in August 1988 and will end in October 1989. Each month, a twelve-day-long survey cruise is being conducted along the track shown in Figure 5. The nutrient data discussed here was collected on those cruises. In the second half of the month, the ship has been used to study particular processes occurring in the North Sea. In the three years following the field work, the data collected will be analysed and our understanding will be refined by fitting it to model calculations.

2.2 The Nutrient Diagrams

2.2.1 How they were drawn

This report includes a compendium of diagrams displaying the results of nutrient measurements made in the NSCP between September 1988 and August 1989. The data are presented in the form of two-dimensional contour diagrams for the surface concentrations of salinity, nitrate, phosphate and silicate, and for the ratios of nitrate to phosphate and nitrate to silicate.

Each element is plotted on a fixed scale which is used for all the diagrams. This enables the month-to-month changes to be appreciated. Six contour levels are used to aid the clarity of the diagrams. For salinity, an arbitrary scale is used to distinguish the characteristic water masses classified by Lee (1980) which have salinities between 34 and 35 psu. Variations in the large volumes of water with salinities below 34 psu are shown in less detail. Nitrate, phosphate and silica concentrations are shown using square progression scales to reflect the approximately two-dimensional dispersal of nutrients from river sources. The concentration ranges were chosen appropriate to January concentrations. The ratios N:P and N:Si were highest in May so the scales were set for that month. A square scale is used for the N:Si ratio, as this appeared to group the wide range of values better than a linear scale. A linear scale was used for the N:P ratio.

The diagrams were drawn using the default interpolation settings within the "UNIRAS-UNIMAP" (version 5.4) contouring computer software system as licensed to the NERC.

2.2.2 Cautionary Note

The data for nutrients used to draw the diagrams presented here is "raw" data - that is, data taken straight from the ship. For the final data set, checks of the data are required to test for any systematic errors in calibrations which may have arisen between cruises, and errors in determining zero values. Before the final data set is published, our results will be compared with determinations made by other groups working in the North Sea during the period of the project.

For example, the salinity measurements shown here were those taken from the shipboard CTD. Some of the calibrations carried out so far have shown that errors as large as 0.1 psu are present in some of the data. However, such corrections do not invalidate the patterns shown in the diagrams. Our priority at this stage of the project is to establish the scales of changes we will model in future and to assess which are the important interactions controlling the system.

As stated above, the diagrams were drawn using the default settings within "UNIRAS-UNIMAP". As yet, no testing has been carried out to check on the physical reality of features revealed in the contour plots.

2.3 Preliminary qualitative assessment of the results

The NSCP is proving to be successful in accumulating a much greater density of data covering the annual cycle in the North Sea than has ever been achieved before. This creates the problem of how to comprehend such a large data set. This can only be done by an iterative procedure looking at aspects of the data in greater detail with regard to an increasing number of the possible interactions through the North Sea eco-system.

At this stage in the programme, with one cruise left to complete, we are in the process of collating the data, looking for errors and, as exemplified in the paragraphs below, trying to establish what are the major features of the data set. Complete interpretation of the nutrient data will only be possible when the data from other parts of the programme become available to us.

Included in the set of diagrams are results for the salinity distribution. The first thing the salinity plots show is the rapidly changing environment of the North Sea. Particularly in the Southern Bight, the salinity pattern is determined by the changes in flow of high salinity water through the Dover Straights. With regard to nutrient distributions, it can easily be seen that the high levels of nutrients in the German Bight correspond to the lower salinity of these waters.

2.3.1 Nitrate

Over the twelve months of data shown here, nitrate levels were lowest in July 1989. Concentrations increased between September 1988 and February 1989 when the highest values were recorded. These distribution patterns (CR-37, 39, 41, 43) suggest that the main inputs are from the rivers. An early task of our modelling work will be to see if the apparent rate of advection of river water into the interior of the North Sea suggested by these diagrams is consistent with known estimates of advection.

The January distribution is re-drawn in Figure 6. When the two diagrams are compared they appear quite similar, considering that the Johnston diagram is a composite of several years' data whereas Figure 6 shows the results of a single survey.

A striking feature of both diagrams is the low concentration area over the south western end of the Dogger Bank. This is due to continuing phytoplankton production in this region during winter (CUSHING, 1973). Production occurs throughout the year over the Dogger Bank because the water is sufficiently clear and shallow that year round the critical depth is greater than the water depth (PARSONS *et al.*, 1984). A second low area is present at 55°30'N west of 6°E. This may also be an area of continuous production. Data from other work in the NSCP may confirm this. It is from this area that production-associated decreases in nitrate appear to spread out in March and April.

Composite diagrams of nutrients in the North Sea all tend to be drawn showing a continuous flow of nutrients from the Rhine-Scheldt round into the German Bight (GERLACH, 1988; POSTMA, 1978). This does not appear to be true for the periods of the January and February cruises (43-45). In both cases, the contour diagrams suggest a substantial flow of nutrients from the Rhine-Scheldt to the south-west, with a relatively low concentration area immediately off the Rhine. At certain times during the NSCP cruises, the POL climate circulation model indicates that the flow off the Rhine was to the south-west (R.Proctor, pers. comm.). The corresponding salinity diagrams (43, 45) show higher salinities off the Rhine. Further north and round into the German Bight, the higher nitrate concentration contours show a wave-like structure (37, 39, 43, 45, 47, 49). Again, a corresponding structure is present in the salinity distributions. If this apparent pulsed flow from the Rhine is real, it needs to be taken into account in any future monitoring plans. Our modelling work will, at an early stage, assess the reality of this structure and the time and space scales over which it might be formed. Our data needs to be compared with more detailed Dutch surveys to see what they say about transport north from the Rhine in the strong density driven flows which might not have been sampled in the NSCP surveys. Two more intensive surveys to look in greater detail at near-shore flows off the Rhine are planned by POL for 1990.

The accepted view is that, in the Southern Bight, primary production starts in the spring in the shallow, relatively clear waters off the Dutch coast and then progresses west towards the more turbid waters off East Anglia (BROCKMANN *et al.*, 1988). A first glance at the nitrate distribution in March would suggest that the low values off the Dutch coast were due to depletion by production. The salinity pattern suggests, however, that it may be a circulation effect. In April, nitrate concentrations are again high along the Dutch coast. If this replacement of low-nitrate, high-salinity water was simply an advective phenomenon, then a back-of-the-envelope calculation suggests that current speeds as high as 15 cm/s would be required to bring the change about.

By the time of the May cruise, the fall in concentrations was unambiguously due to biological production. The inhibition of production in the turbid waters off East Anglia results in the plume of higher nitrate waters stretching out north-east from the East Anglian coast. The shape of this plume corresponds closely to the sediment plume described by McCave (1973) and visible in satellite images (T.Moffat, pers. comm.).

In June there was a maximum in nitrate concentrations off the Elbe. The concentration in this area was still relatively high compared to winter and summer values. The high N:P ratio suggests that production in this area might have been limited by lack of available phosphate, relative to nitrate. The decrease in nitrate concentrations and the N:P ratio between June and July may result from either summer estuarine denitrification cutting off the supply of nitrate to the area, or anoxic conditions releasing sufficient phosphate to allow primary production to remove the nitrate from the water. The possible limitation of the growth of *Phaeocystis pouchetii* by lack of phosphate in the water has previously been discussed by van Bennekom *et al.* (1975) and Veldhuis *et al.* (1987).

2.3.2 Phosphate

The rapid regeneration of phosphate relative to nitrate and silica is evident in the September 1988 results; substantial (relative to winter and summer values) concentrations of phosphate being detected in the more coastal regions. The September 1988 distribution appears to be a logical development of the distribution found in August 1989. This is a satisfying result in that it suggests that we have observed a reproducible annual cycle.

Much of the input of phosphate in late summer may be provided by inputs from sediments. Anoxic conditions within sediments release phosphate, which is bound to iron oxide phases on surfaces of sediment particles, when iron goes into solution. Postma (1978) suggested that the annual maximum in dissolved phosphate observed in Wadden Sea waters was due to this process. Our data suggests that this effect can be seen off the Wadden Sea in August. A similar process may explain the highs in concentration seen off the Rhine and Humber estuaries. The Humber high also corresponds to a sag in the dissolved oxygen concentration (D. Purdy, pers. comm.). The lack of corresponding maxima in the nitrate and silicate concentrations suggest that these maxima do not have a fresh water source.

In winter, the minimum in phosphate concentration noted by Postma (1978) as occurring off the Dutch coast is discernible in the NSCP results. Postma suggested that this minimum was the product of a water mass that was distal to all inputs of phosphate and possible continuing winter production. The salinity is relatively high in this area, agreeing with the first part of the suggested mechanism; we have no data as yet for production. In contrast, a low concentration area equivalent to that seen in the nitrate results does not show up over the Dogger Bank in the contoured results. This may have several explanations: it may simply be that the contour intervals are not set correctly to show it; the effective nitrate-to-phosphate ratio in the plankton growing on or over the Dogger Bank may be high; input of phosphate may continue from the sediments during winter.

2.3.3 Silicate

In contrast to the phosphate, the silica diagrams show lows corresponding to the winter areas of continuing production suggested by the nitrate results. This is consistent with diatom production which in turn would be expected at the relatively high levels of nutrients present in winter. In the succession of diagrams, 43-45-47, spring diatom production appears to spread out from the winter production area centred on 55°30'N, 5°E. The March distribution also shows clearly the patchiness of the production process.

2.3.4 Nitrate-phosphate ratio

Harvey (1926) first noted that nitrate and phosphate tend to be removed from seawater in near constant proportions. This is reflected in the ratio found in sea water (REDFIELD, 1934) which in many water masses is between 15 and 16 (N:P) (COOPER, 1937, 1938; TAKAHASHI *et al.*, 1985). An unresolved chicken-and-egg question (or, more fashionably, one about the workings of Gaia) is whether the plankton determine the ratio in sea water or their utilisation of nitrate and phosphate is determined by the ratio in the water. This ratio (16:1) is a characteristic of ocean waters. A much wider range of values has been reported from coastal waters ranging between zero and 25 (SPENCER, 1973).

The N:P ratio in the North Sea will be determined by a number of factors. Ocean water will enter the area with a ratio close to 16. Values estimated for riverine inputs vary between 11 for the Forth to 687 for the Thames (based on van Pagee and Postma, 1987), while the most significant input from the Rhine has a ratio of 19. On a year-by-year basis, the ratio in the total inputs from British east coast rivers varied between 21 and 37, with a mean of 26, over the years 1976 to 1987. Similar variations are likely to have occurred in continental inputs. Coastal waters would be expected to exhibit ratios higher than 16 in most areas. Where no nutrient limitation is effecting plankton growth, because N and P are taken up during primary production in a fixed ratio of 16, the initial effect of primary production will be to increase the ratio in the water, where the ratio is above 16, and to decrease it where the ratio is below 16. Subsequently, the ratio in the water will be lowered by zooplankton which have a higher N:P ratio than phytoplankton. Their soluble excretion products, therefore, have a relatively low N:P ratio. Similarly, P is released more rapidly from plankton detritus than N. This will also lower the ratio in the water. On this basis, we would expect to observe high N:P ratios tending to greater than 16 in North Sea waters in winter and low values in the summer.

The standard maps of Johnston (1973) suggest a uniform ratio close to 16 over most of the North Sea in winter. The limited data of Brockmann and Kattner (1985) for February 1984 show the expected ocean N:P ratio in northern areas but values below 10 between 54° and 56°N. In summer, their data shows values below 3 in areas most isolated from fresh water and ocean inputs. Our more complete data set shows a similar cycle to that of Brockmann and Kattner (1985) with low summer and higher winter values of the N:P ratio. The highest values of the ratio are observed between April and June. The question which comes to mind is: did Johnston assume that the N:P ratio was 16 when drawing up his distribution patterns or has the ratio changed?

Looking at our results in more detail: At the start of our observations in September 1988 values were uniformly low, less than 5 in most areas. In October, a region had developed between the Humber and Thames where the values were between 5 and 10. By November, values had increased outwards from the coast. The patterns are similar for nitrate, phosphate and the N:P ratio, with low values in the band of high salinity water down the middle of the data field. That all three patterns are similar suggests that the N and P have a common source at this time of year in river waters with similar N:P ratios of at least 15-20, as suggested by the higher values off the Humber and Elbe. In December, values had increased to above 10 in the southern region below a line between the Humber and the western end of the Wadden Sea. By January, values in the German Bight had increased to above 20. An interesting feature, for which we have no explanation at present, is the band of relatively low nitrate water which stretches NNE from the Wash in January. This is also apparent in the N:Si ratio but not in the nitrate distribution. Little change is apparent between January and February except that the low nitrate region is no longer apparent.

With the start of increased primary productivity in March, the ratio falls below 5 over the Dogger Bank. This is consistent with the effect of removal in the ratio 16:1 into phytoplankton from waters containing nitrate and phosphate in a ratio less than 16. The ratio also decreases relative to February values off the western Dutch coast. If the Redfield ratio applied to phytoplankton growing in this area, the ratio would have been expected to rise. Similarly, in April, off the Belgian coast south of the Rhine, the decrease in nitrate concentrations is consistent with production in this area but the ratio fell from above 20 to below 5. North of the Rhine, the increase in N:P ratio probably resulted from the increase in fresh water in this area. Comparison of the salinities south of the Rhine also suggests some of the change in ratio in this area may have been due to changes in salinity as well as productivity.

Between April, May and June ,the N:P ratio reached its maximum levels in the relatively low salinity waters of the Rhine out-flow, German Bight and Jutland Current. This suggests that in this stage of the productive period the supply of phosphate to plankton is more limited than that of nitrate.

Between June and July, the N:P ratio began to fall back to the low levels seen at the start of the survey period. This was presumably due to the increasing importance of zooplankton and sediment regeneration in determining the N:P ratio.

Further interpretation of the N:P ratio requires a closer look at the changes in the water masses in particular areas month by month and information on the actual productivity in different areas. Consistency of changes in the N:P ratio with these estimates of these changes will be a useful check on their validity and improve our understanding of nutrient up-take ratios.

ACKNOWLEDGEMENTS

The measurements reported in this document would not have been possible without the assistance of the many people who have taken part in the NSCP. In particular, our fellow nutrient analysts, Brian Grantham (CR-41, 47, 55), Robin Howland (CR-33, 51) and Tony Bale (CR-61), and the atmospheric chemists who helped them and us out when we "had to crash".

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Table 1 - Composition of inputs of total N and P to different areas of the North Sea as percentages of total input (based on Nelissen & Stefels, 1988).

Source	A	B	C	D
NITROGEN				
N. Atlantic	75	27	)	-
Channel	8	25	) 43	9
Atmosphere	4	8	3	2
Rivers	12	36	52	86
Discharge and Dump	1	4	2	3
PHOSPHORUS				
N. Atlantic	81	34	)	-
Channel	6	25	) 47	9
Atmosphere	2	3	1	1
Rivers	8	29	47	83
Discharge and Dump	3	9	5	7
ANTHROPOGENIC PERCENTAGES				
N	11	34	45	69
P	10	36	49	78

AREAS:

A - Whole North Sea
B - South of 56°N
C - Outer continental water
D - Inner continental water

TABLE 2 - Characteristics of the water masses in the North Sea (Lee, 1980)

Water mass	Temperature (°C)		Salinity psu	Winter maximum: inorganic nutrients (µM)			Summer minimum: inorganic nutrients (µM)		
	Winter	Summer		phosphate	nitrate	silicate	phosphate	nitrate	silicate
North Atlantic	6-8	12-14	35	0.6-0.8	10	4-6	0.1-0.4	1-4	2
Channel	5-7	16-17	34.75	0.3-0.5	7	6	0.1	1	1
Skagerrak	2-5	14-17	34	0.4	7	4	0.1-0.1	-	-
Scottish Coastal	4-6	12-14	34-35	0.6	-	-	0.2	0.5-1	2
English Coastal	4-6	14-18	34-34.5	0.7-1.2	35	14	0.1-0.4	1-4	1
Continental Coastal	2-4	17-19	34	2.0-3.0	45	20-30	0.1-0.4	10-20	1-2

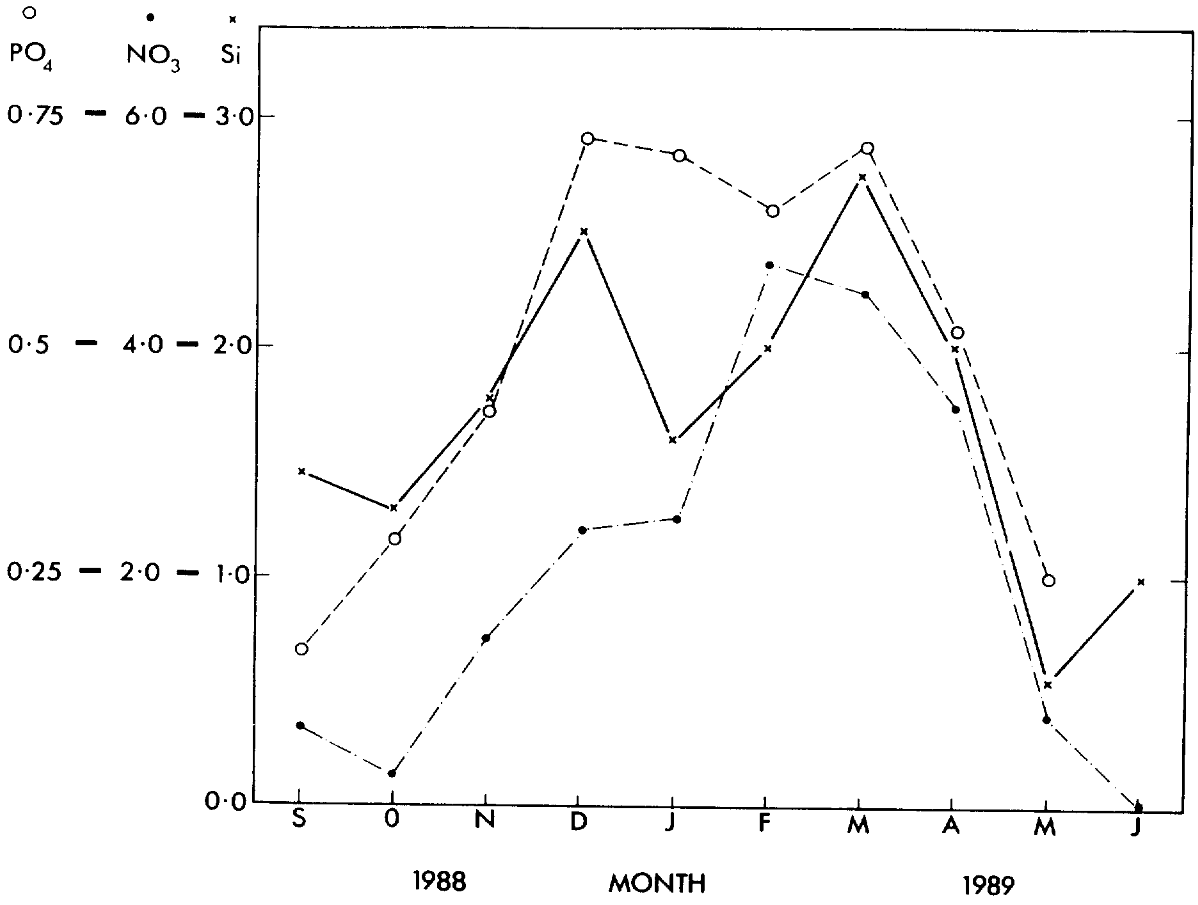


Figure 1 Cruise-by-cruise variation in the concentrations of Nitrate: ●, Phosphate: O, and Silicate, X. Summarised as the concentration at a salinity of 35 psu estimated by a least squares fit to the full data set for each month.

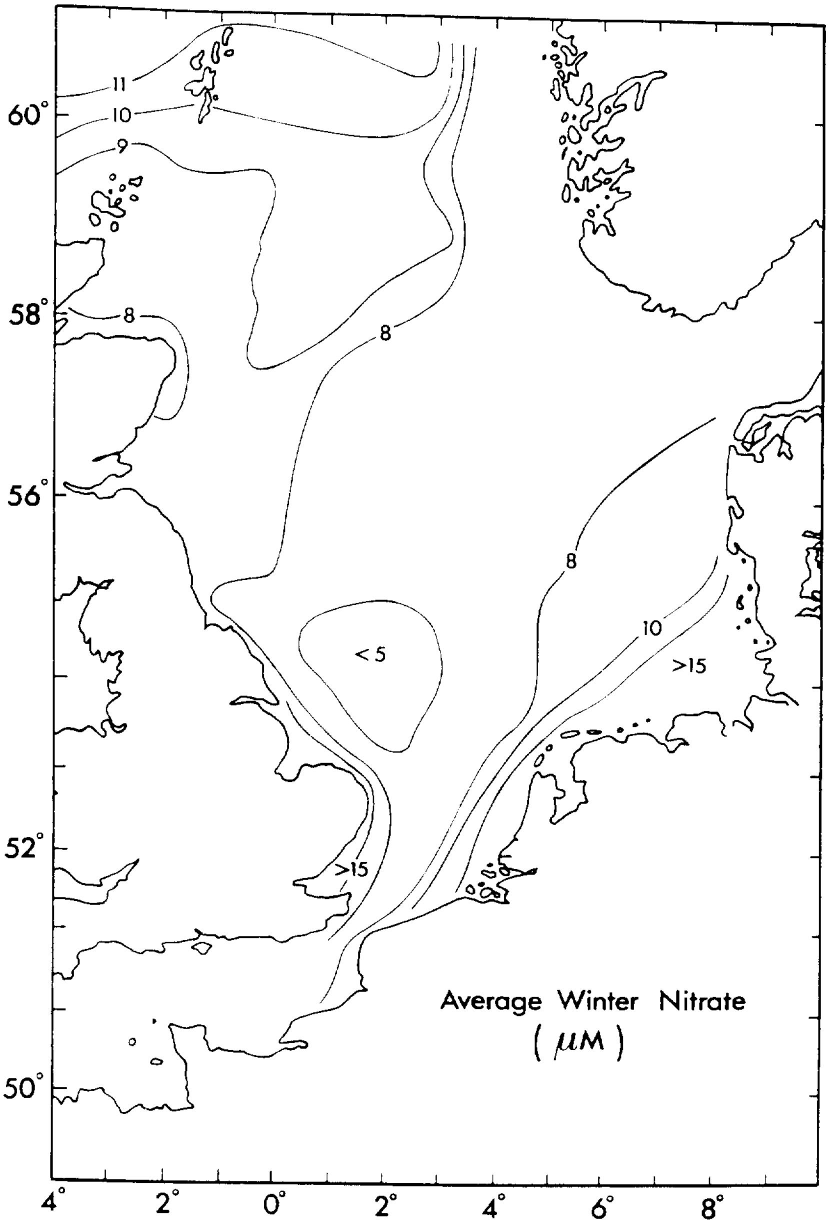
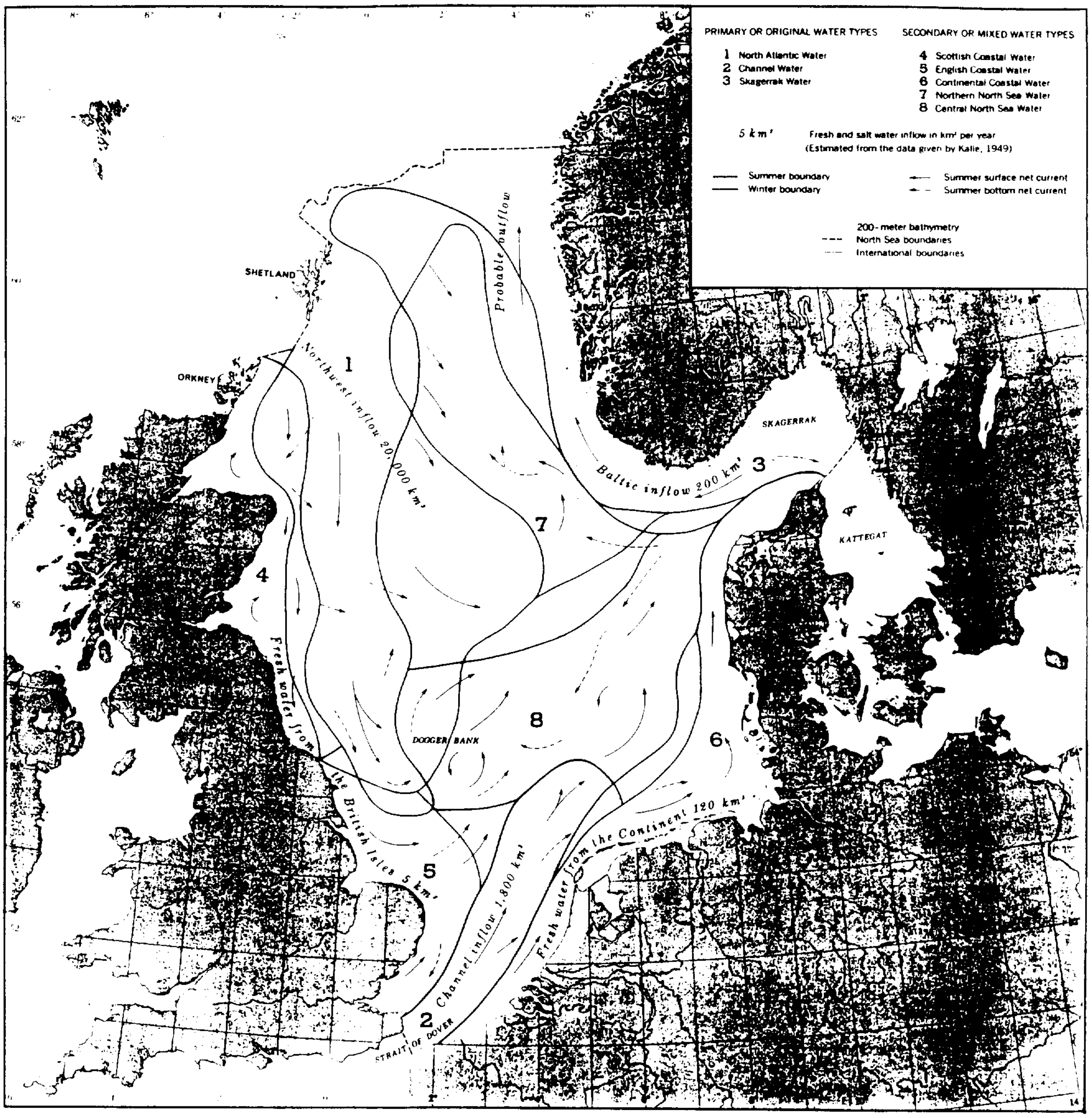


Figure 2 Winter concentration of Nitrate in the North Sea based on the diagram drawn by Johnston (1973), showing the contours used by Gerlach (1988).



Oblique stereographic conformal projection for the North Atlantic, center 54° N 38° W

Figure 3 The water masses of the North Sea. The divisions made by Laevastu (1963).

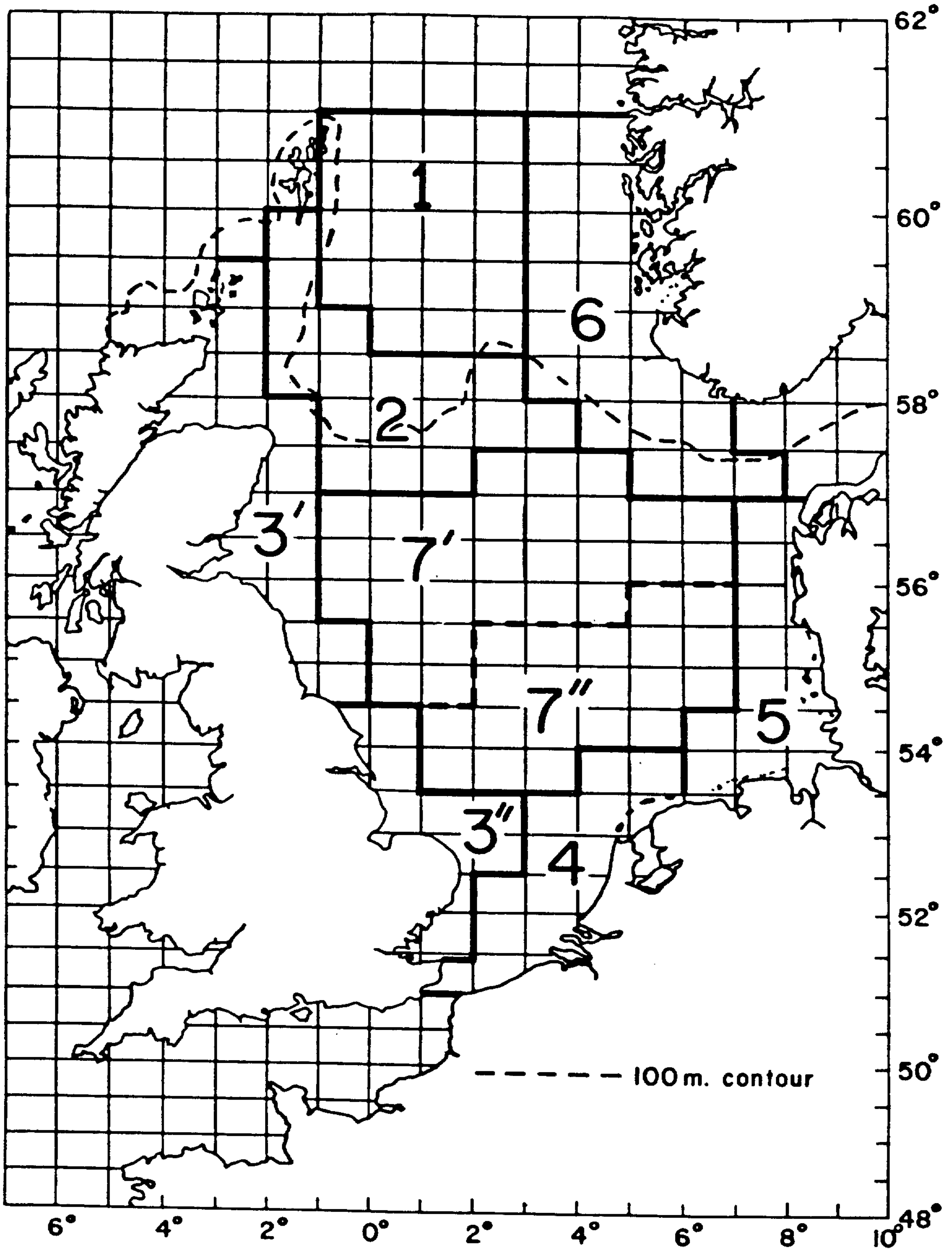


Figure 4 The divisions of the North Sea water masses into boxes considered to be appropriate for the modelling of North Sea processes by ICES (FNTS, 1983).

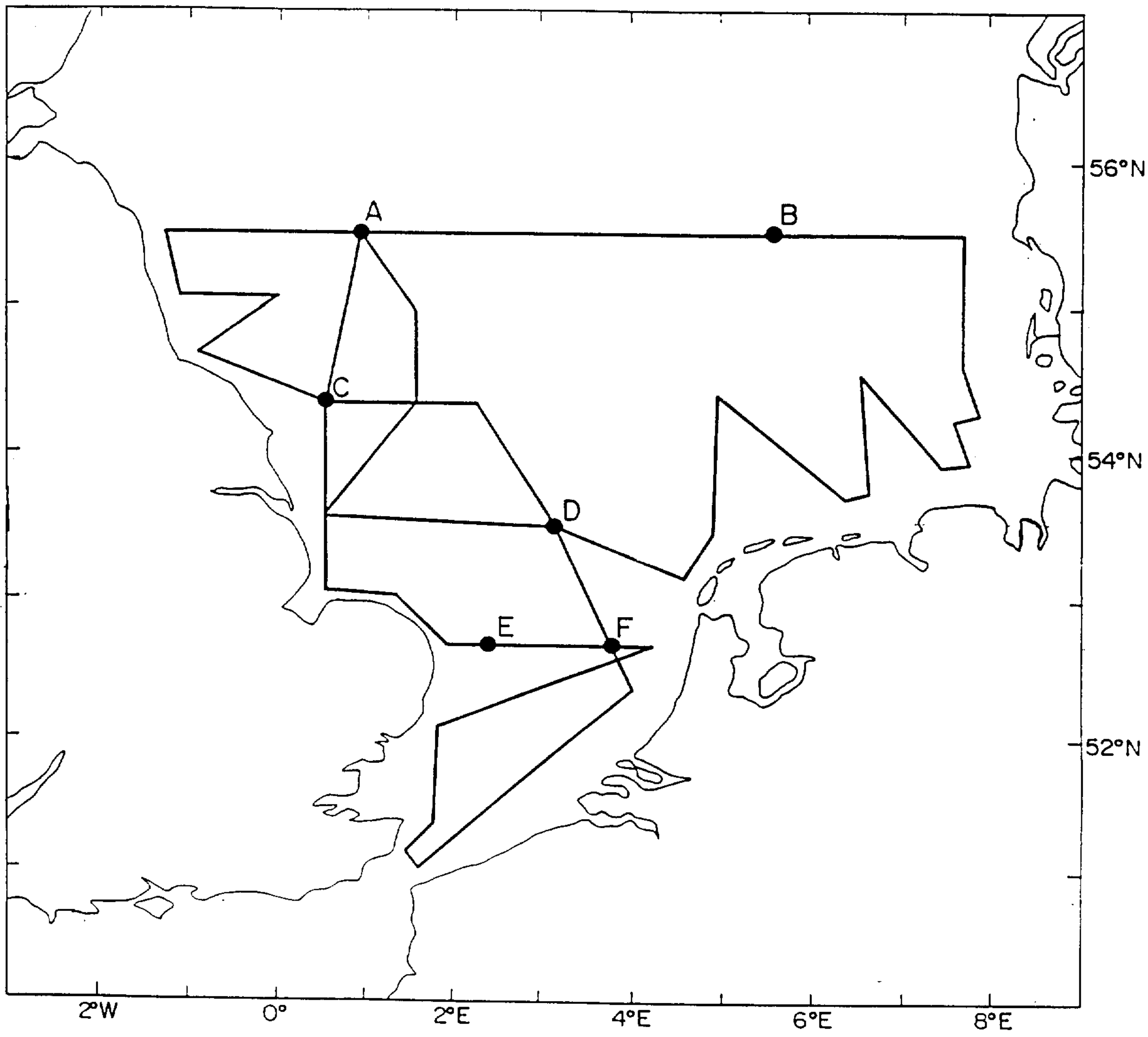


Figure 5 This diagram shows the approximate cruise track which each of the NSCP survey cruises aimed to follow, weather permitting.

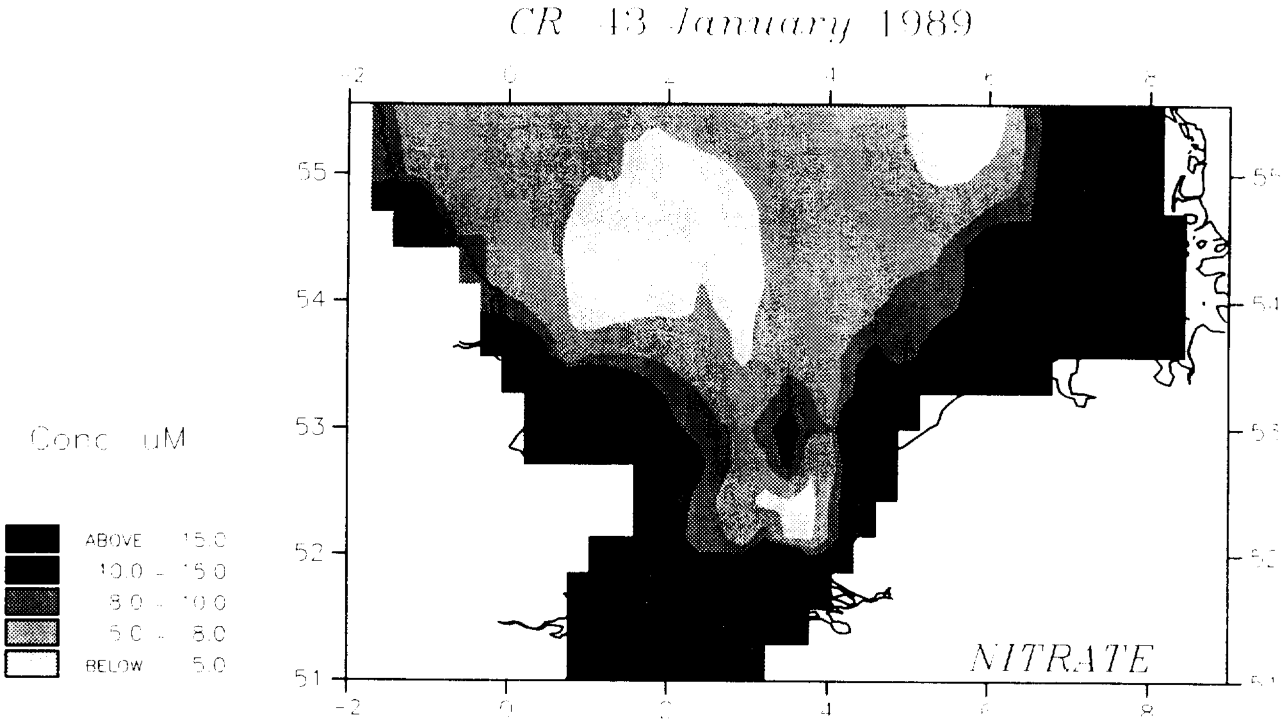
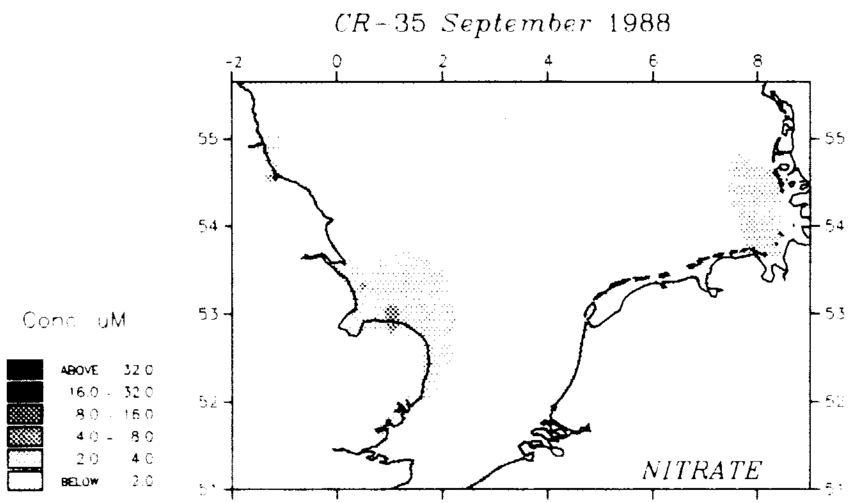
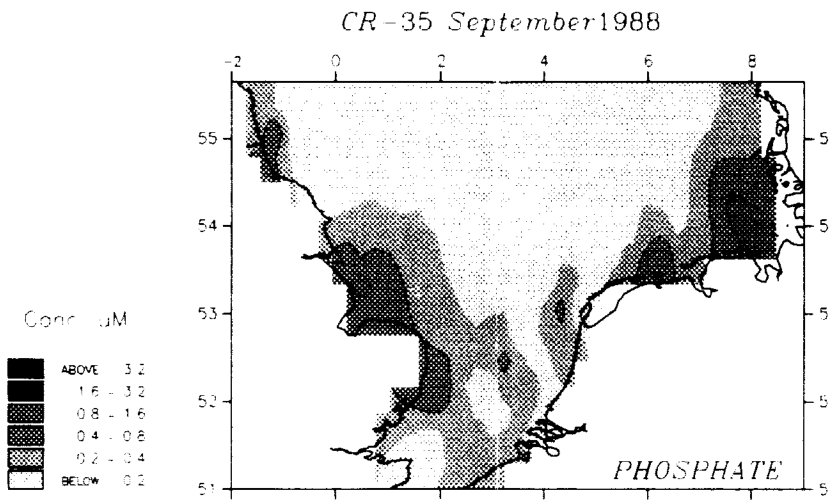


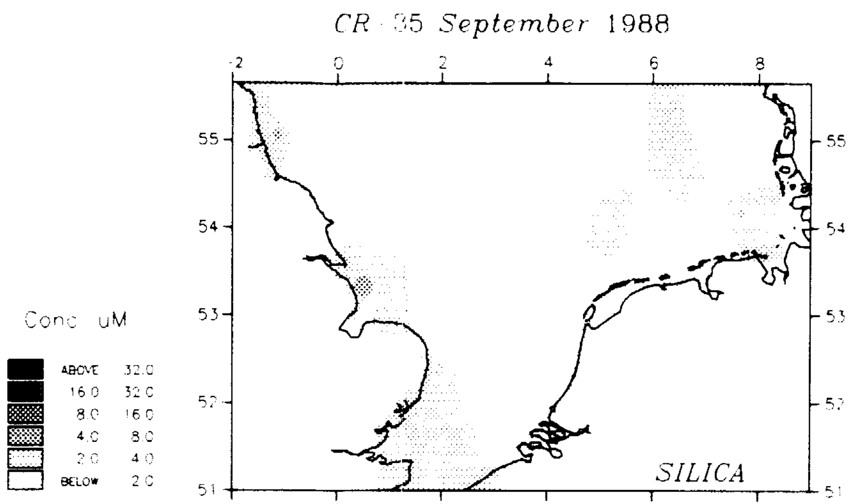
Figure 6 The Nitrate results for January 1989 (CR-43) are redrawn in this diagram, using the same contour intervals as the Johnston-Gerlach diagram, Figure 2.

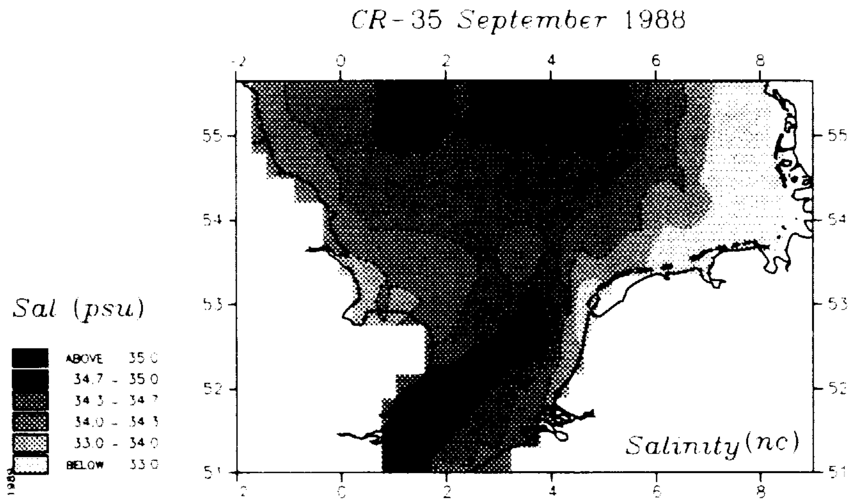
APPENDIX

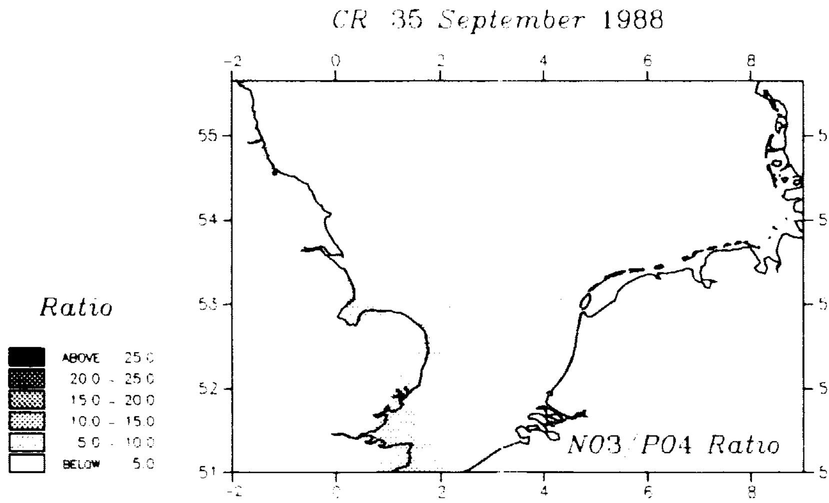
Monthly maps of nutrient distributions from RRS *Challenger* Cruises:
CR-37, CR-39, CR-41, CR-43, CR-45, CR-47, CR-49, CR-51, CR-53, CR-55, CR-57.

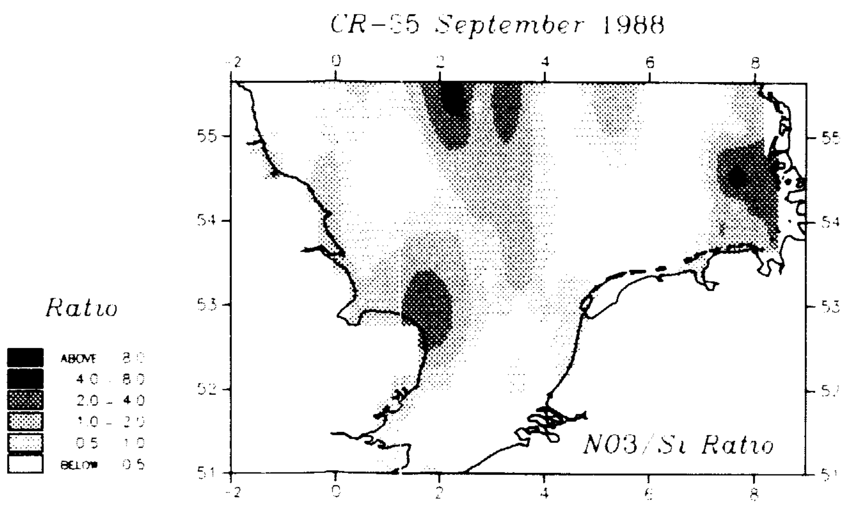




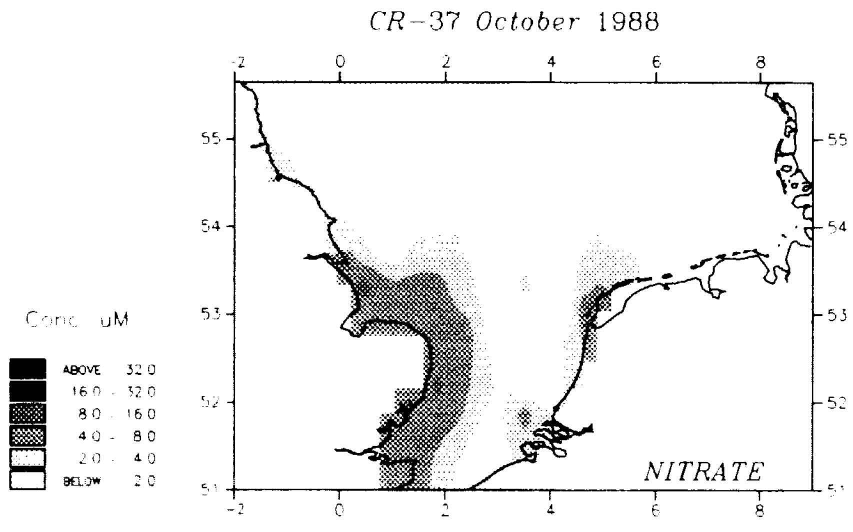


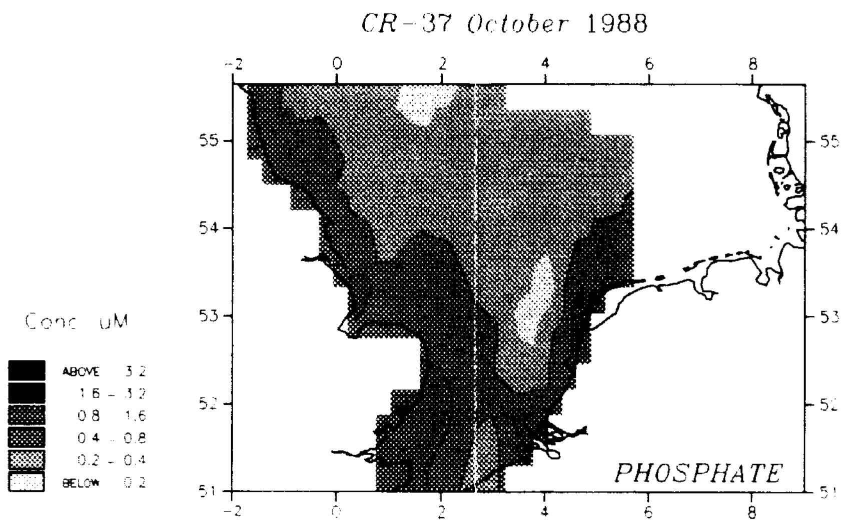






[illegible] 10 33am Friday 6th October 1989


CR-37 October 1988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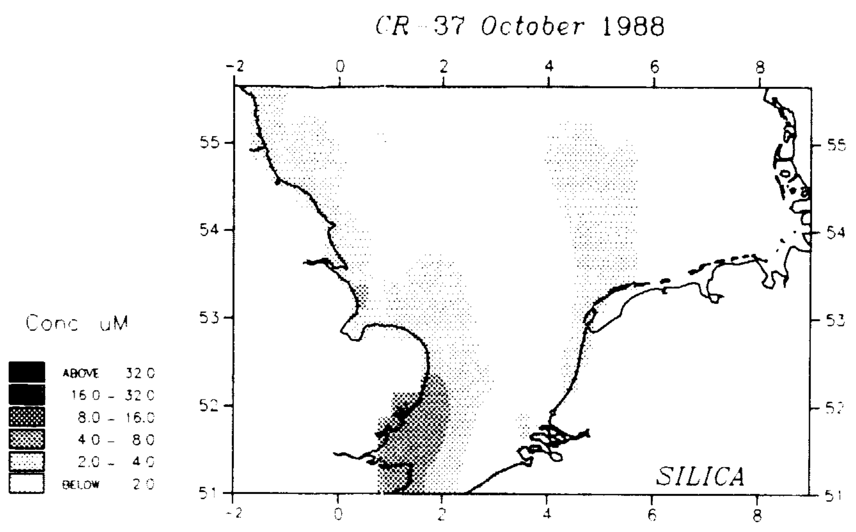
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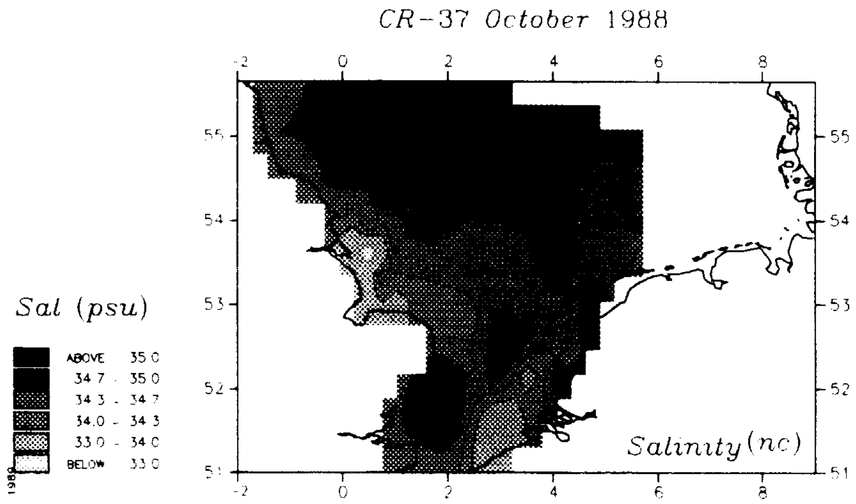
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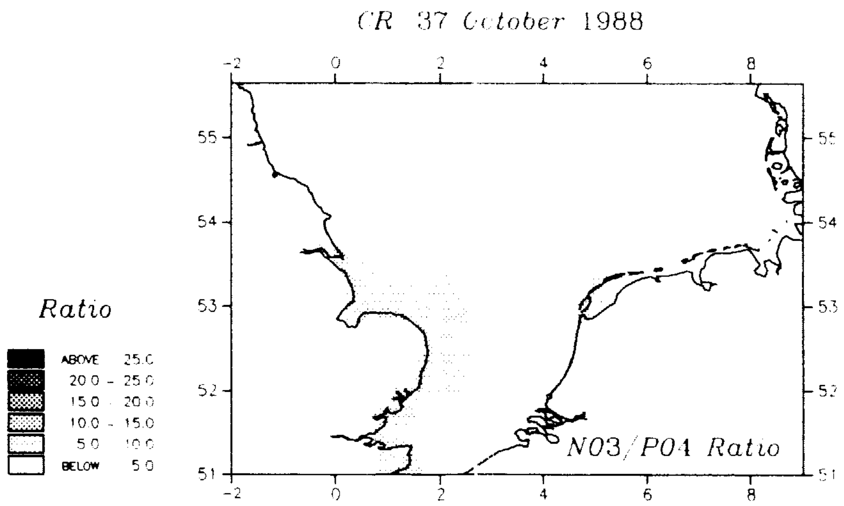
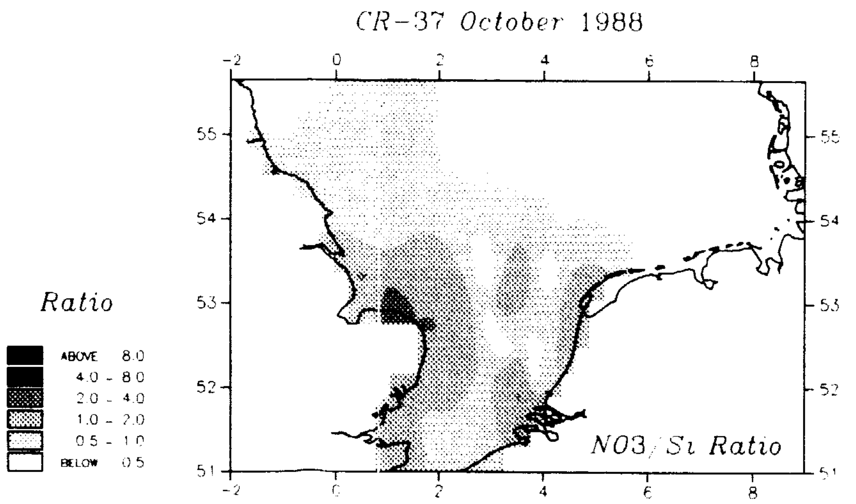
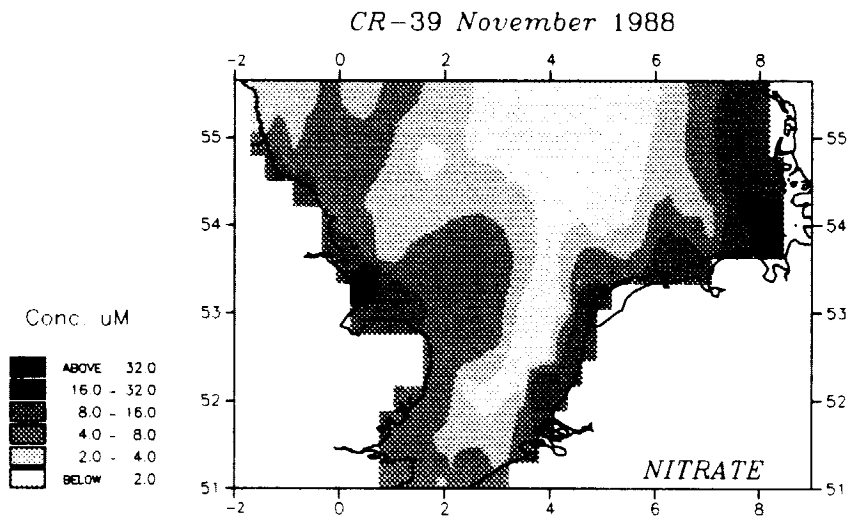
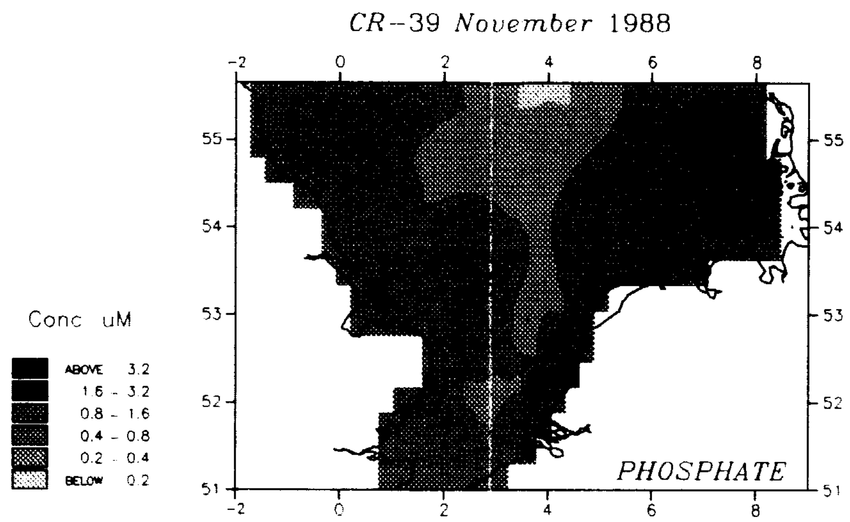
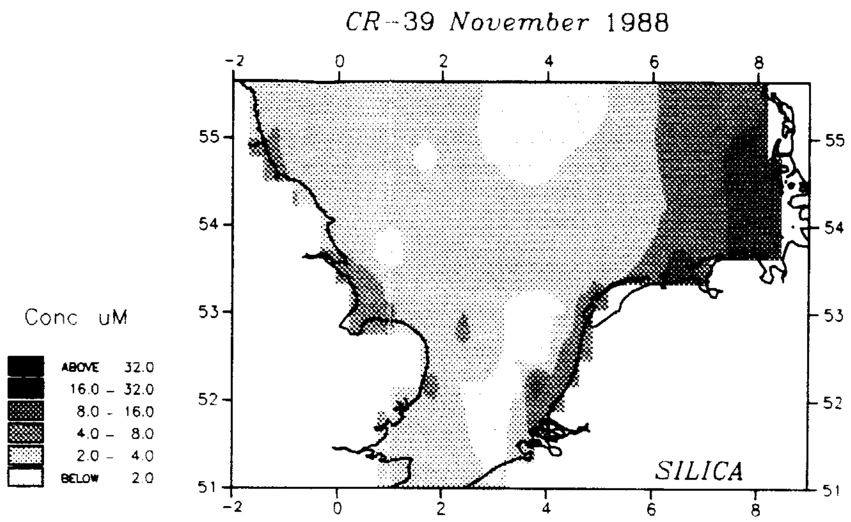

CR-37 October 1988

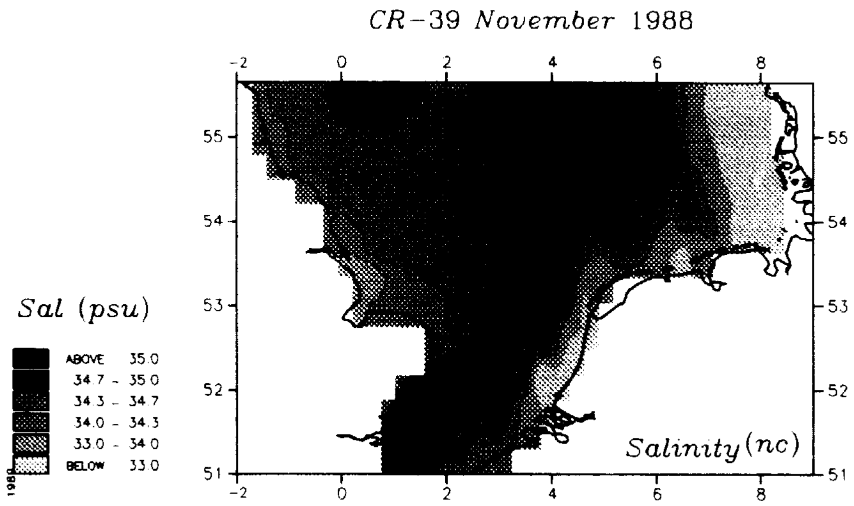

CR-37 October 1988

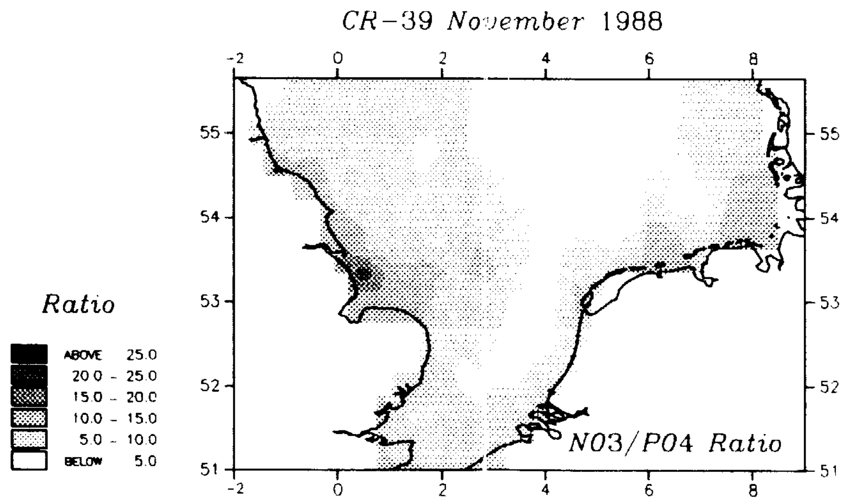
Plot at Wormley 10 43am Friday 6th October 1989

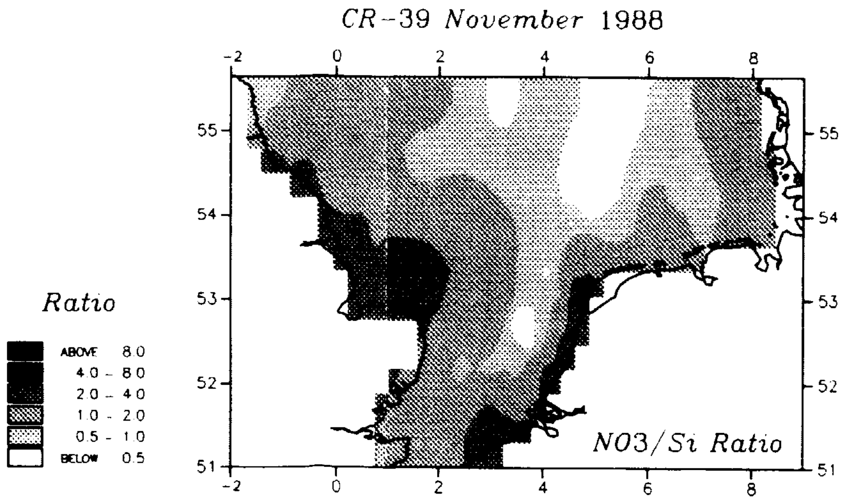




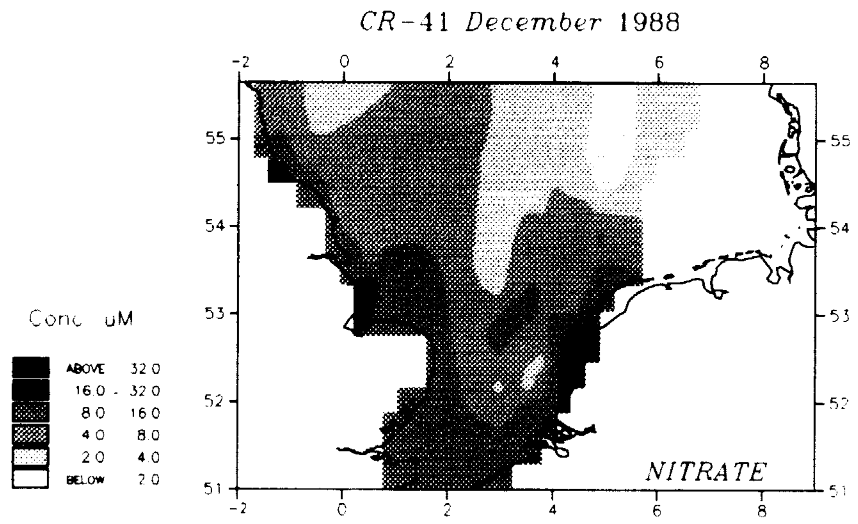


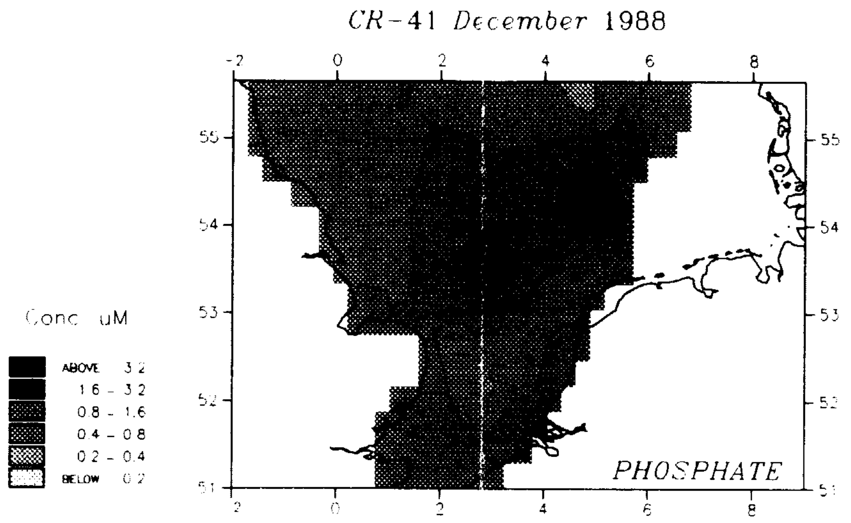


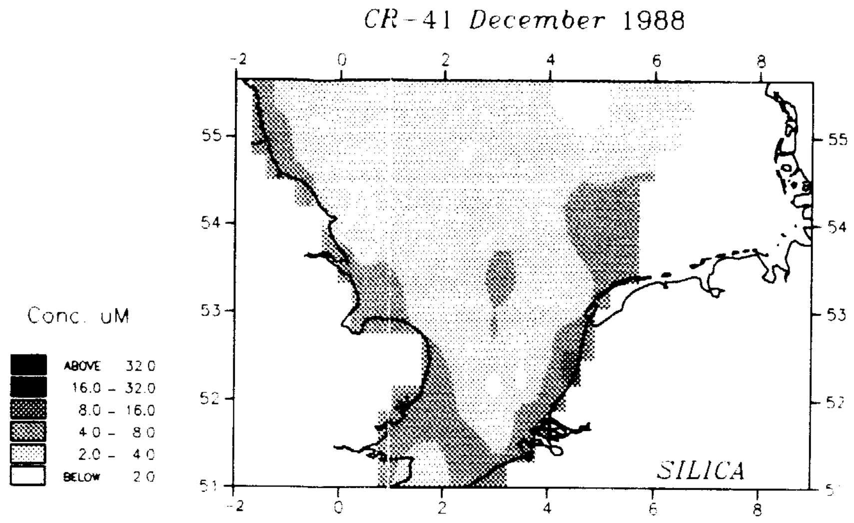


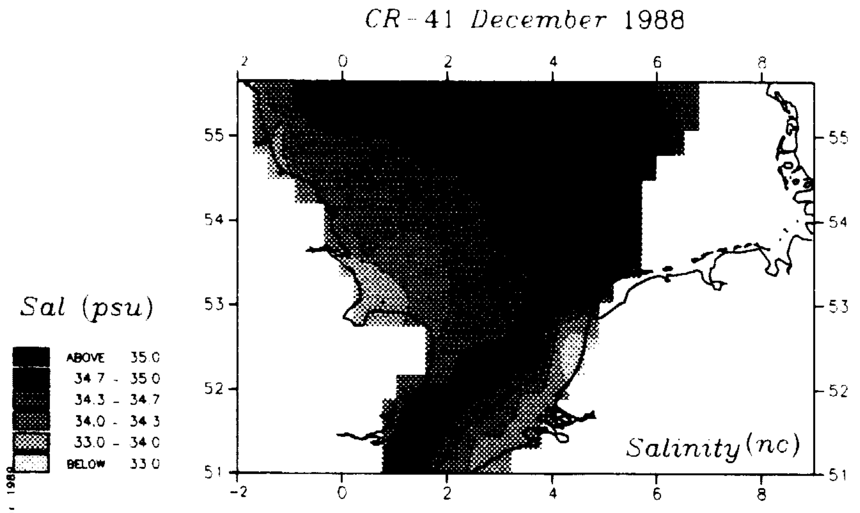


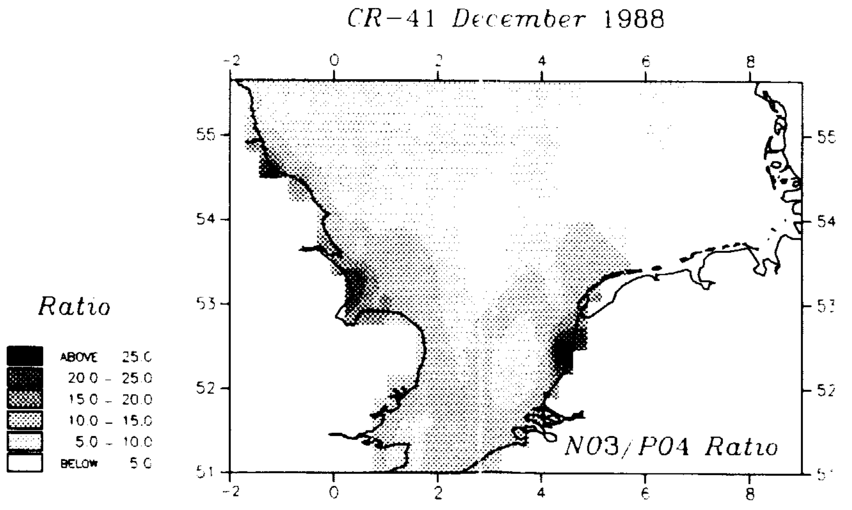
DJH at Wormley, 10:54am Friday 6th October 1989

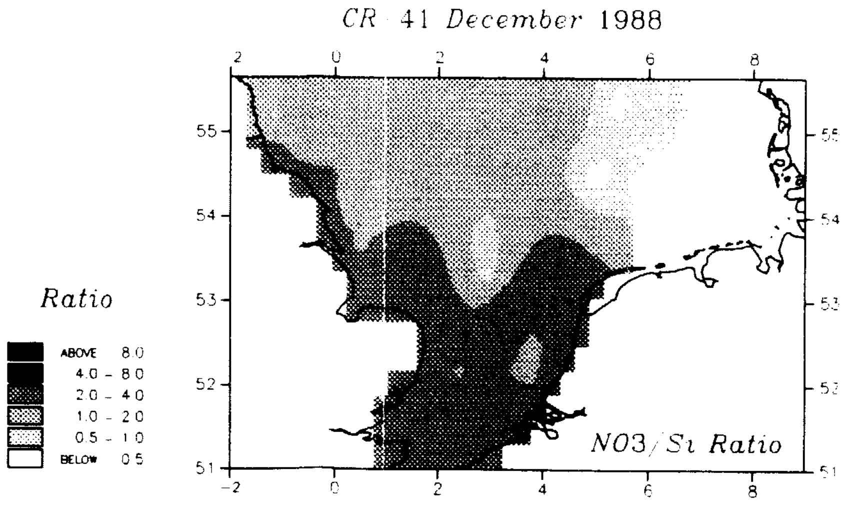




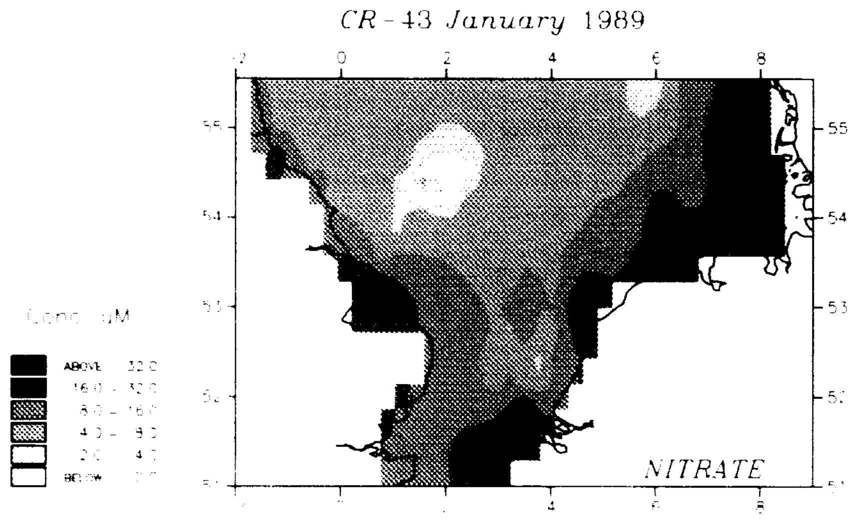


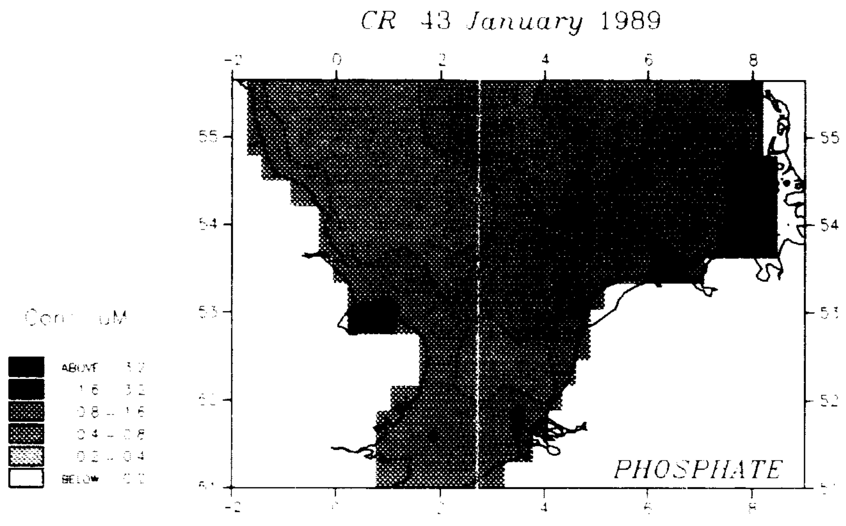


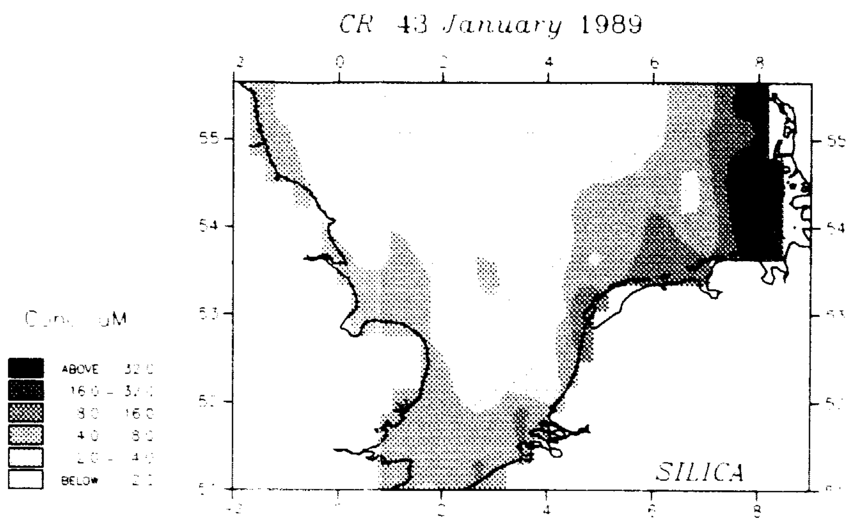


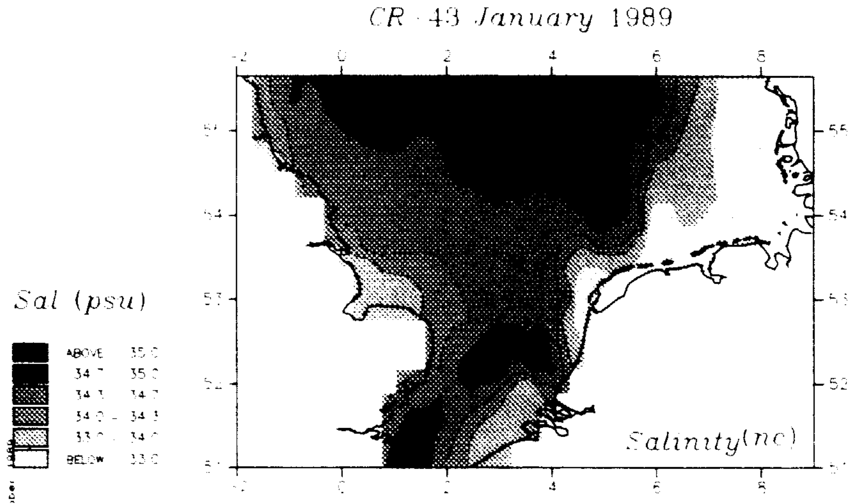


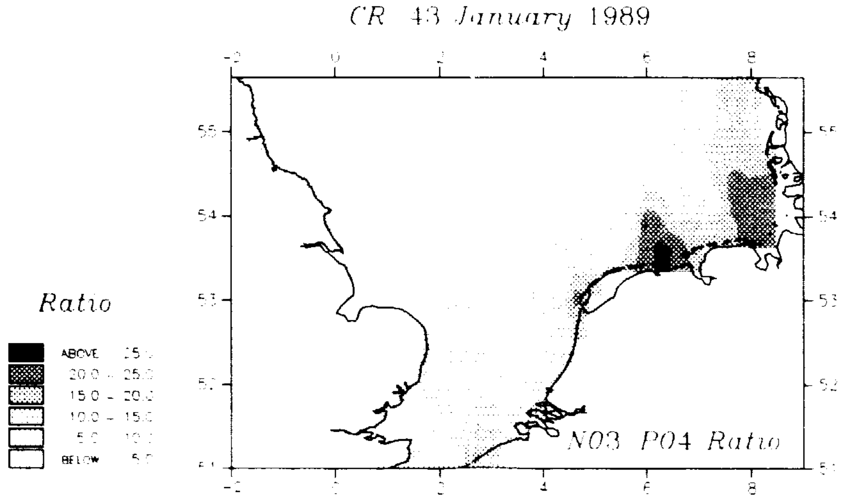
DJH at Wormley, 11:03am Friday 6th October 1989

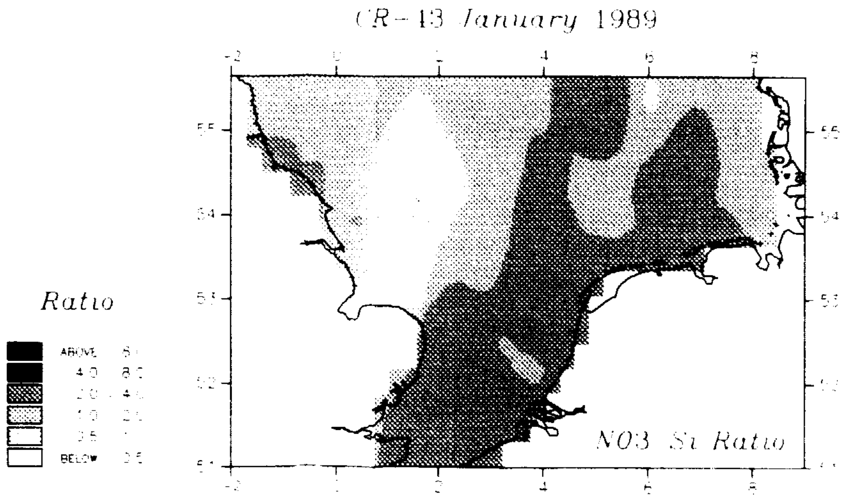

CR-43 January 1989
Conc uM
ABOVE 32.0
16.0 – 32.0
8.0 – 16.0
4.0 – 8.0
2.0 – 4.0
BELOW 2.0
-2
0
2
4
6
8
55
54
53
52
51
NITRATE

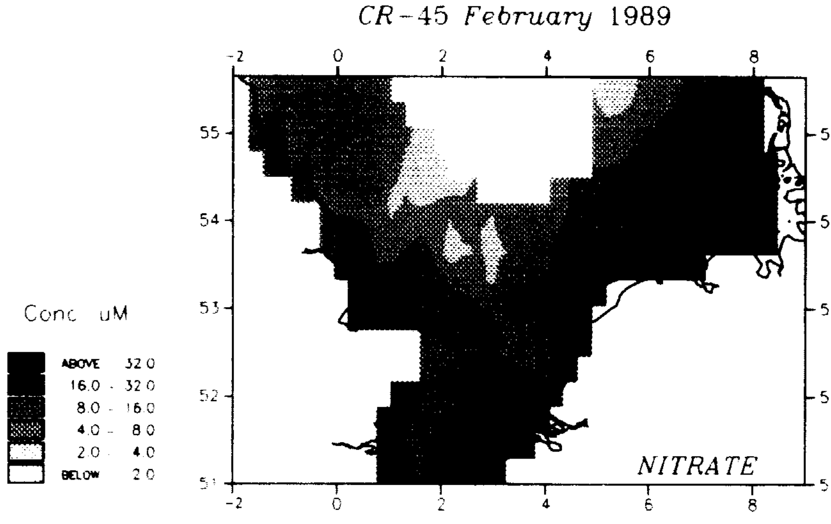

CR 43 January 1989
Conc uM
ABOVE 3.2
1.6 – 3.2
0.8 – 1.6
0.4 – 0.8
0.2 – 0.4
BELOW 0.2
-2
0
2
4
6
8
55
54
53
52
51
PHOSPHATE

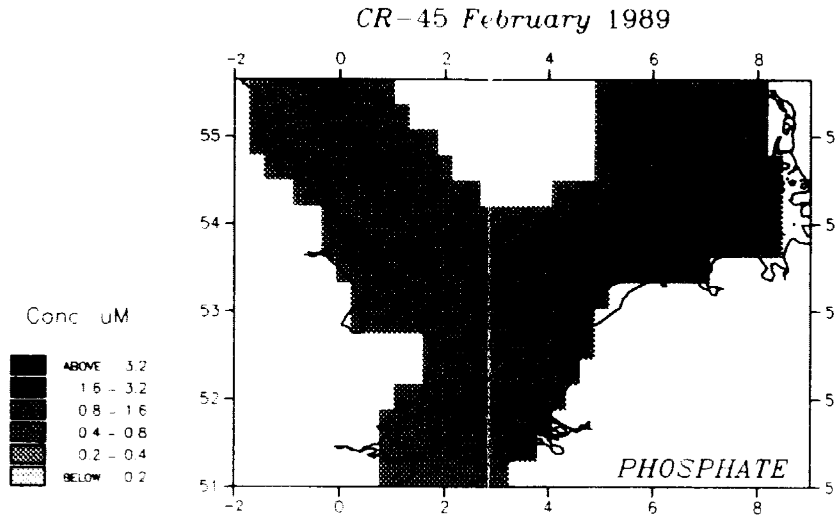

CR 43 January 1989
Conc uM
ABOVE 32.0
16.0 – 32.0
8.0 – 16.0
4.0 – 8.0
2.0 – 4.0
BELOW 2.0
-2
0
2
4
6
8
55
54
53
52
51
SILICA

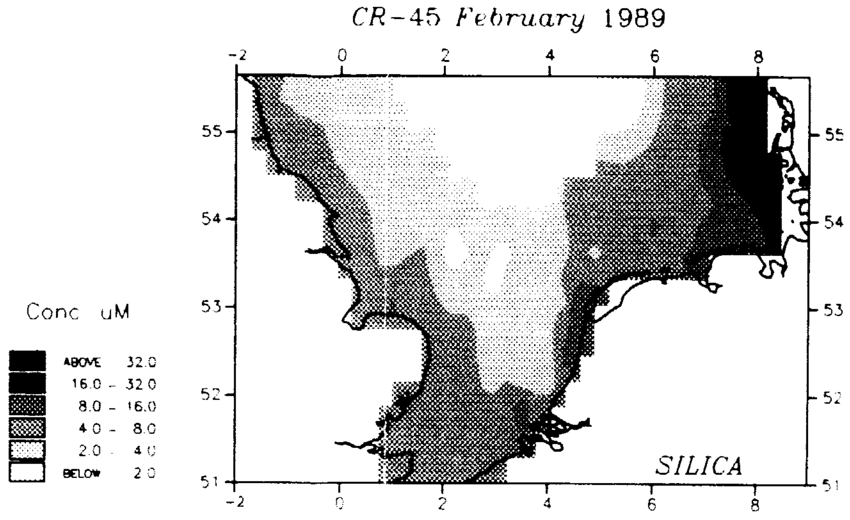

CR-43 January 1989
Sal (psu)
ABOVE 35.0
34.7 – 35.0
34.3 – 34.7
34.0 – 34.3
33.0 – 34.0
BELOW 33.0
-2
0
2
4
6
8
55
54
53
52
51
Salinity(nc)

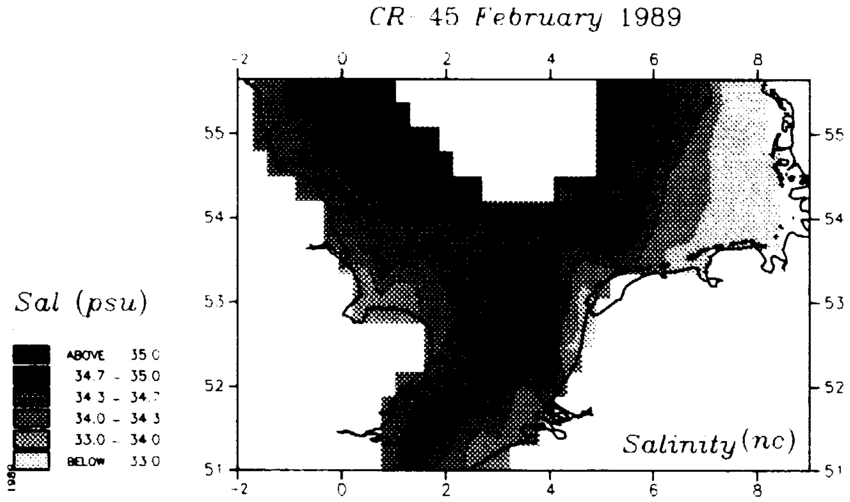

CR 43 January 1989
Ratio
ABOVE 25.0
20.0 – 25.0
15.0 – 20.0
10.0 – 15.0
5.0 – 10.0
BELOW 5.0
-2
0
2
4
6
8
55
54
53
52
51
NO3 PO4 Ratio

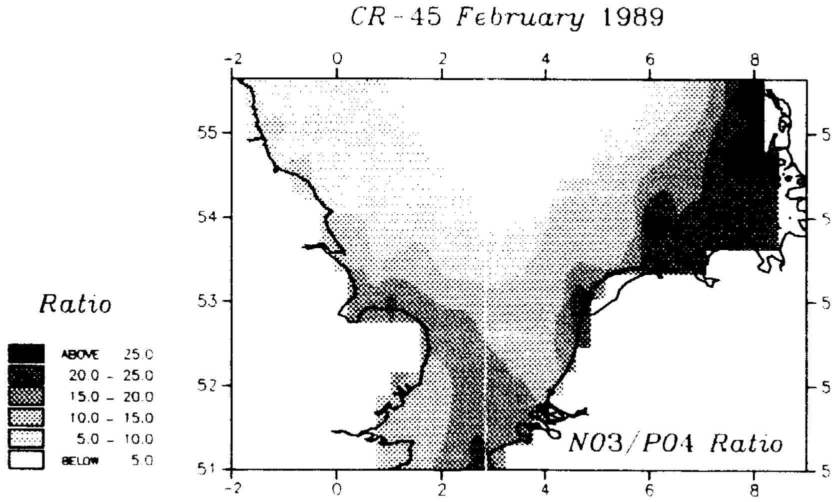

CR-43 January 1989
Ratio
ABOVE 8.0
4.0 – 8.0
2.0 – 4.0
1.0 – 2.0
0.5 – 1.0
BELOW 0.5
-2
0
2
4
6
8
55
54
53
52
51
NO3 Si Ratio

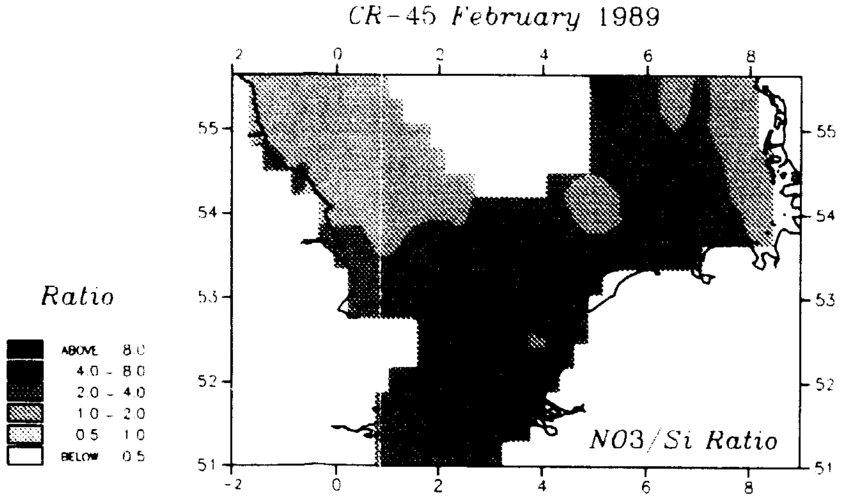




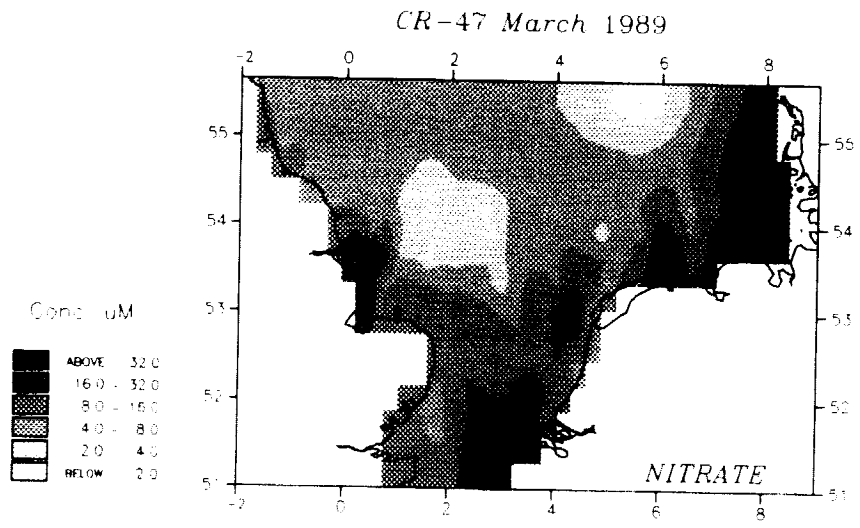


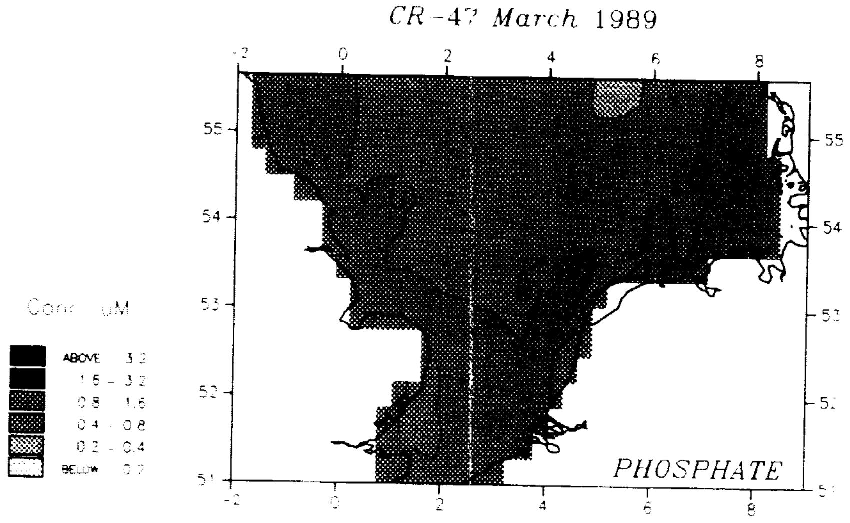


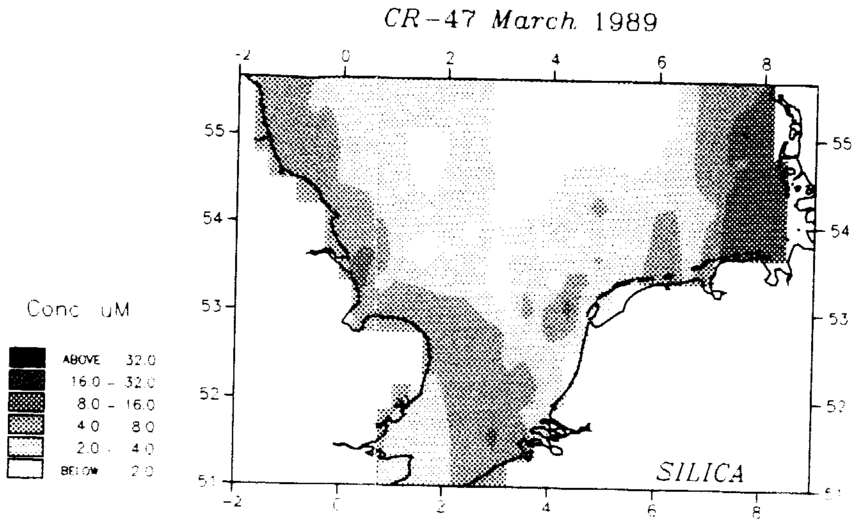


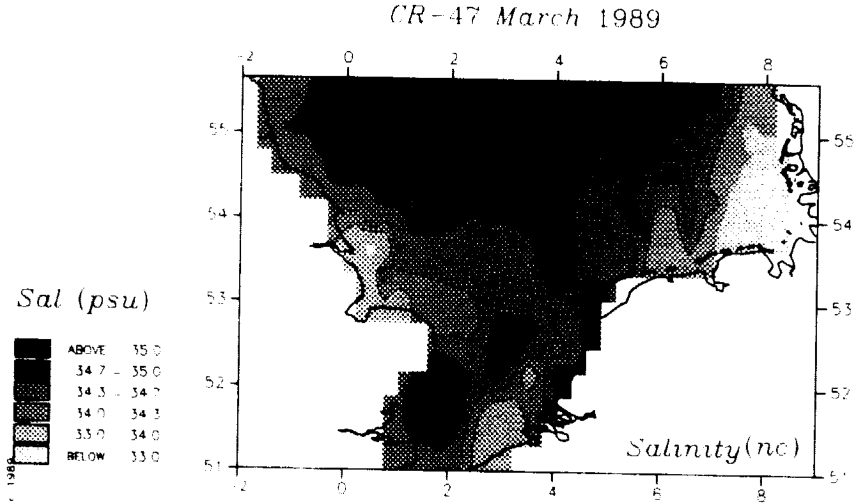


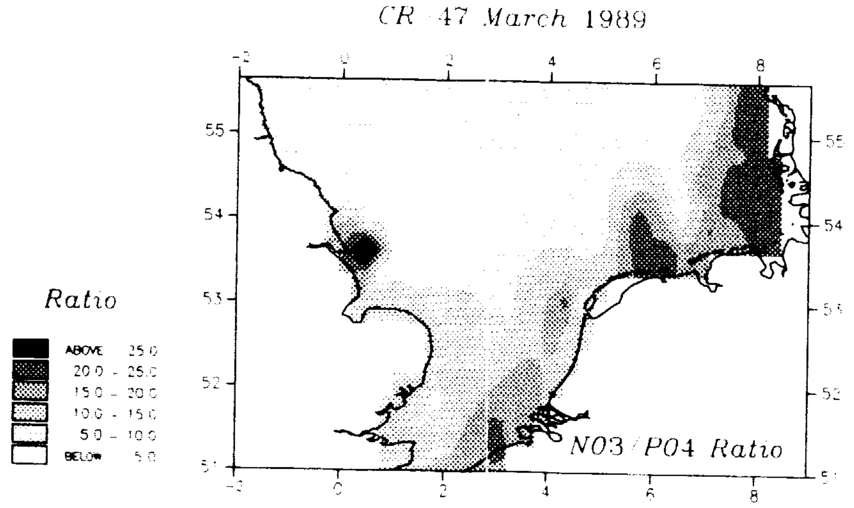
DJH at Wormley, 11 37am Friday 6th October 1989

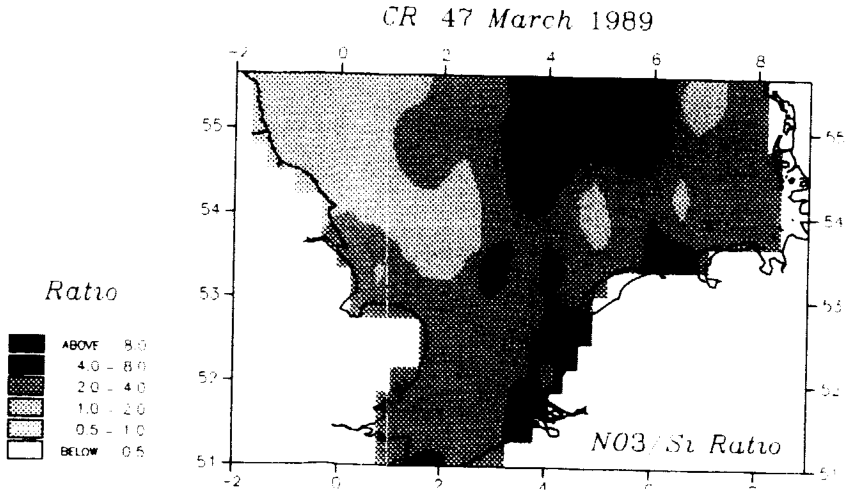




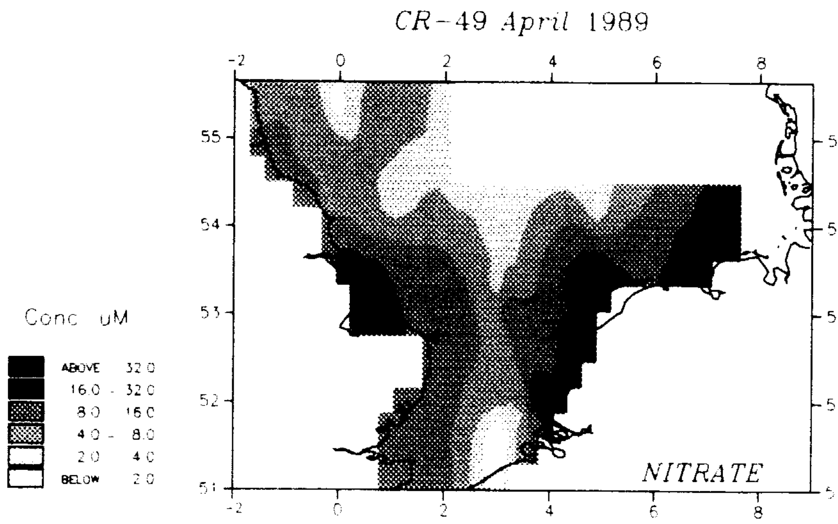


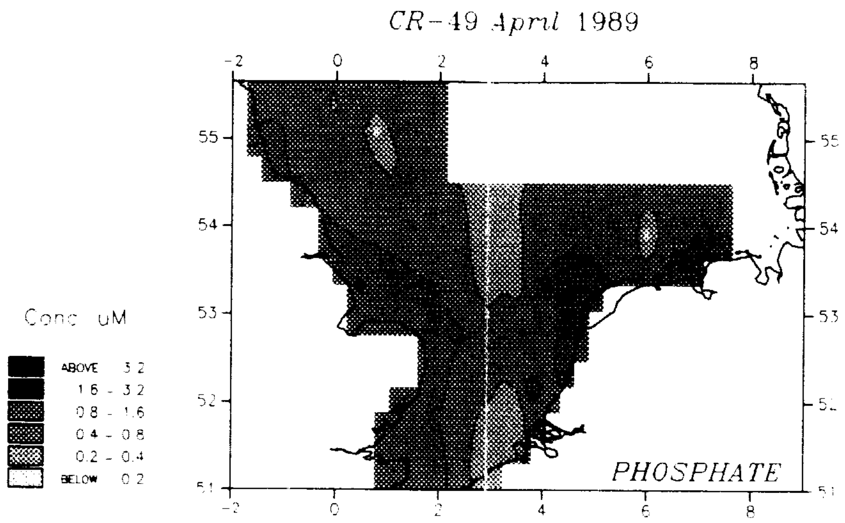


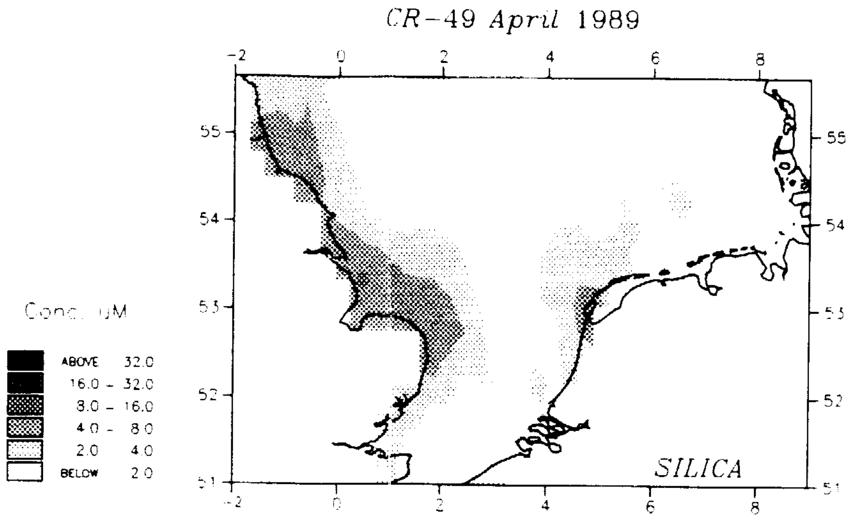


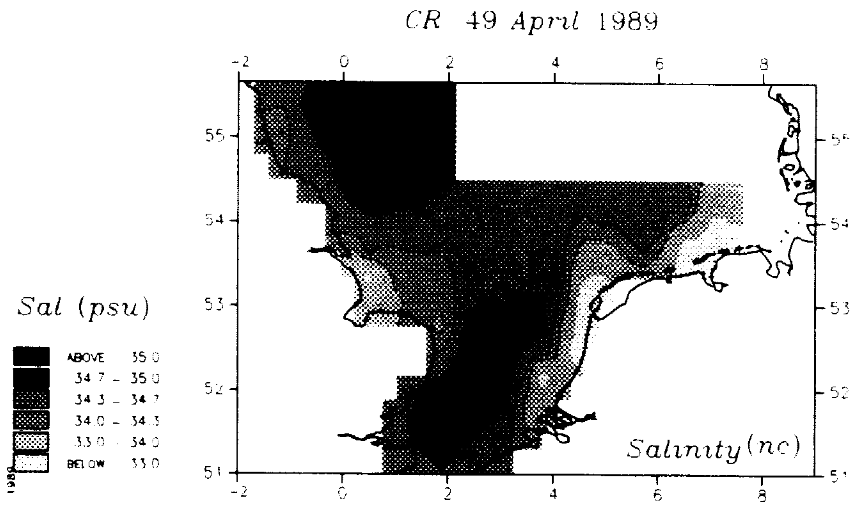


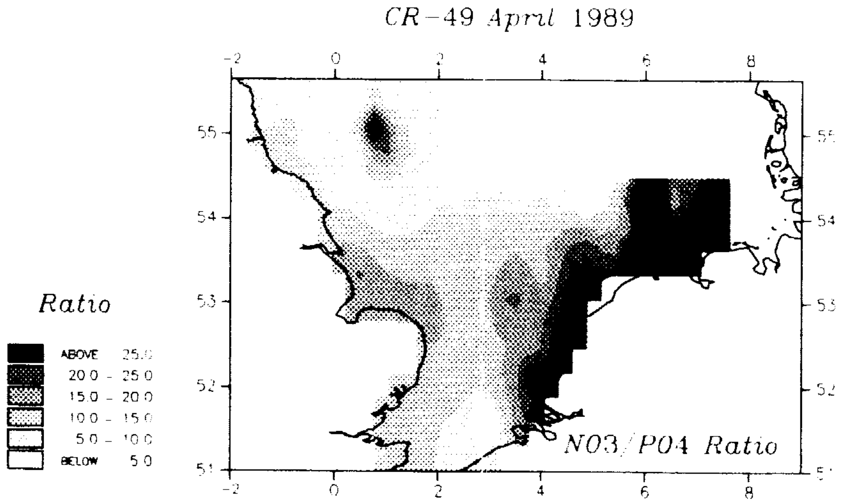
47am Friday 6th October 1989

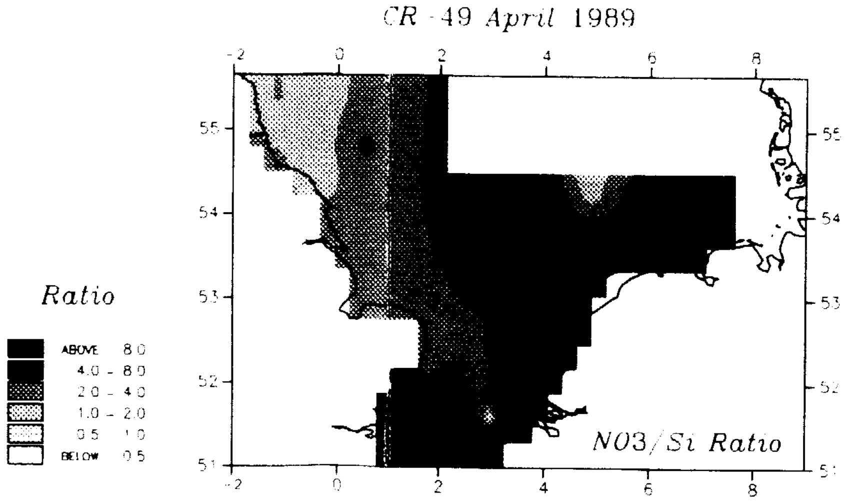






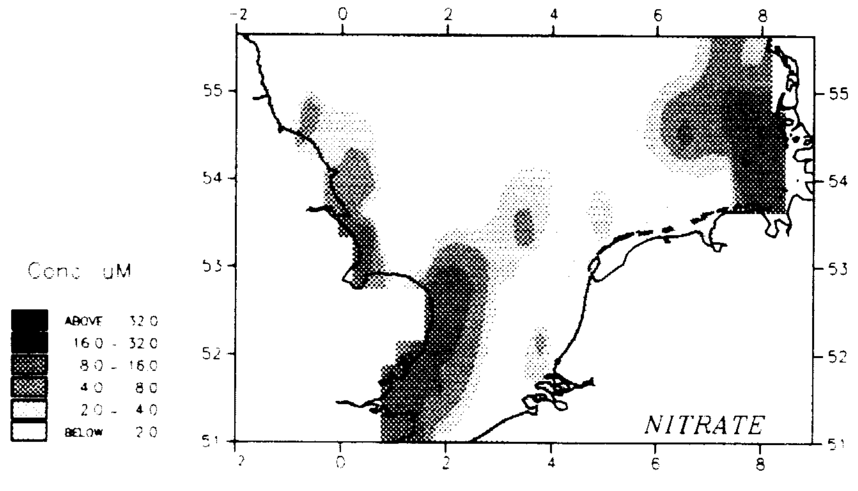




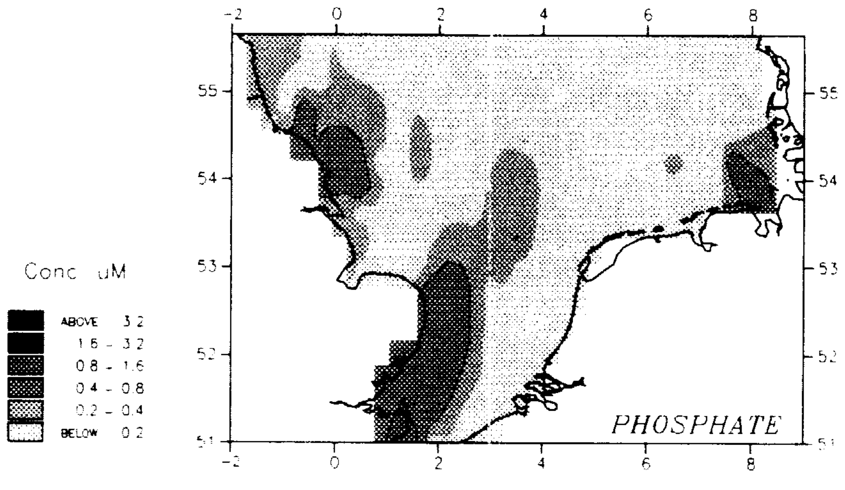


DJH at Wormley 12 04pm Friday 6th October 1989

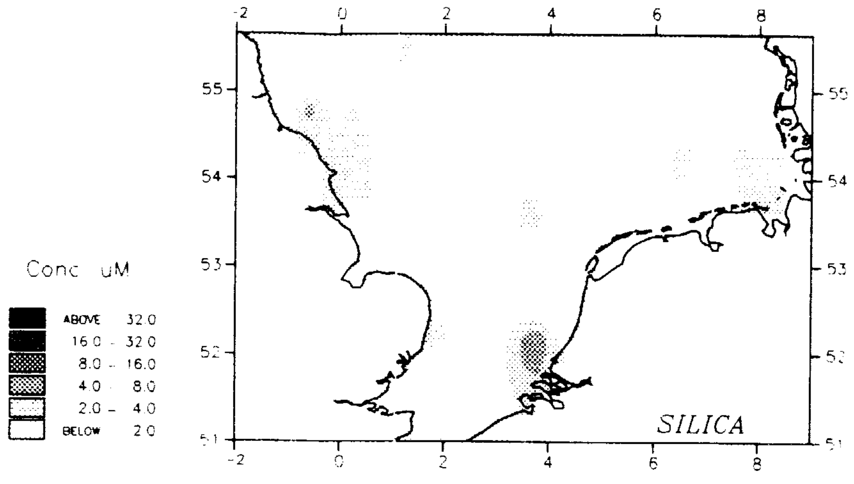
CR-51 May 1989



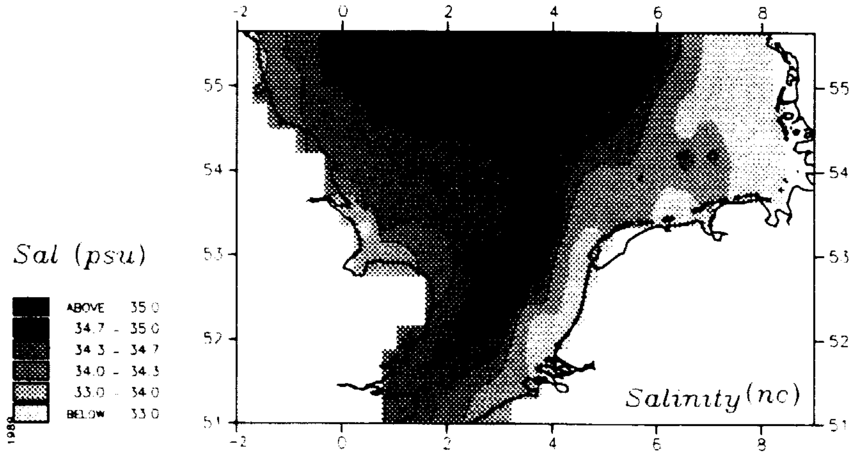
CR-51 May 1989



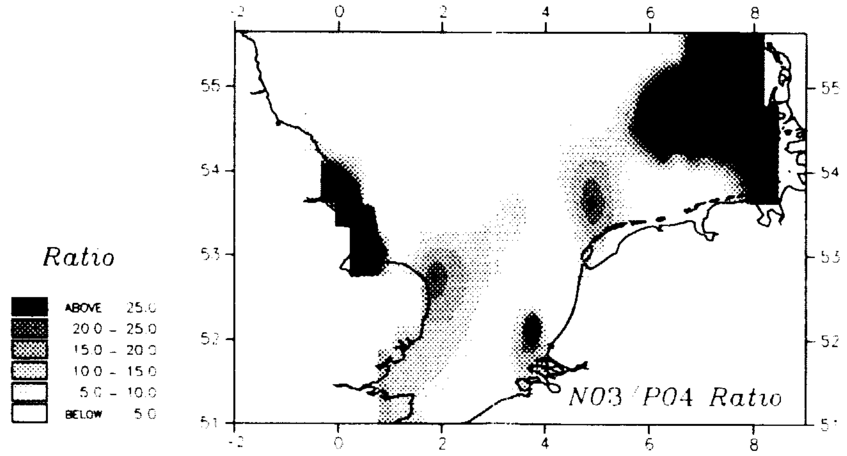
CR 51 May 1989



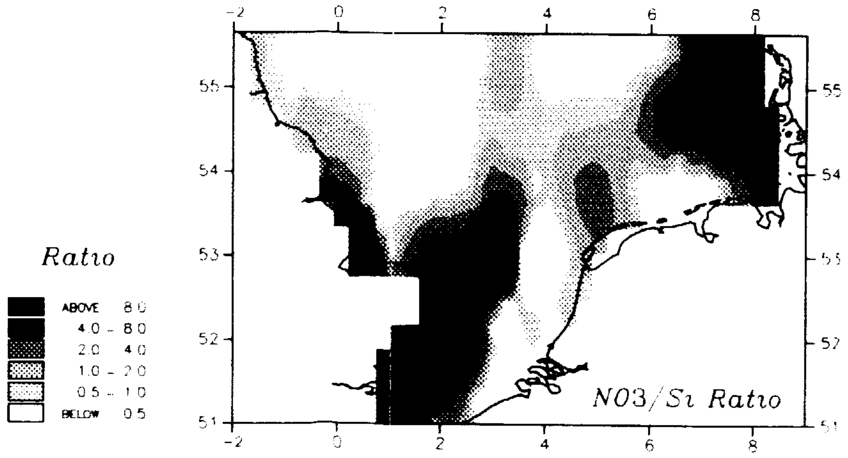
CR 51 May 1989



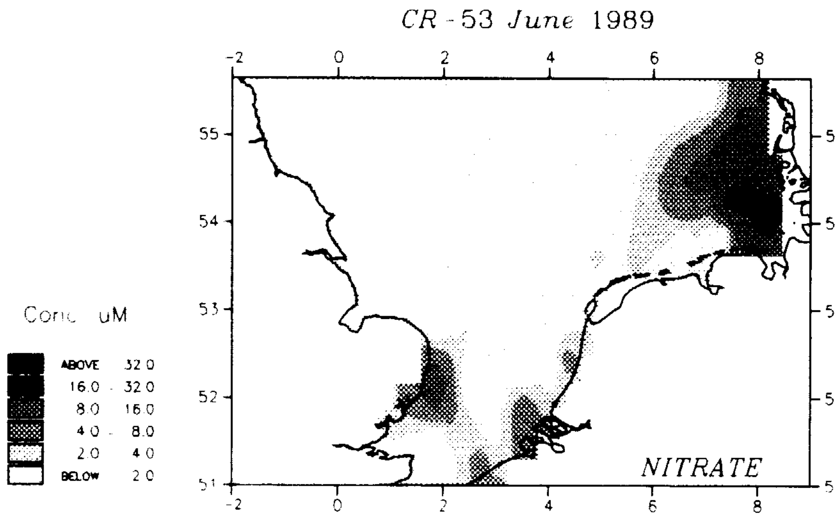
CR-51 May 1989

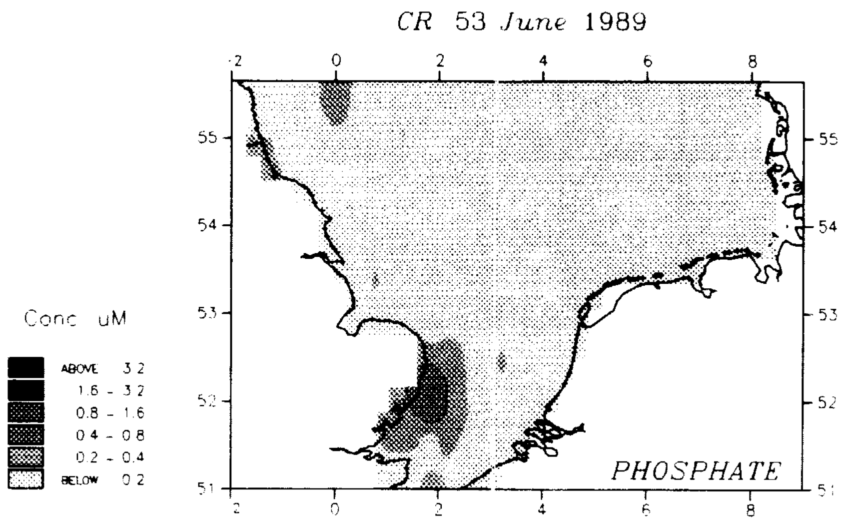


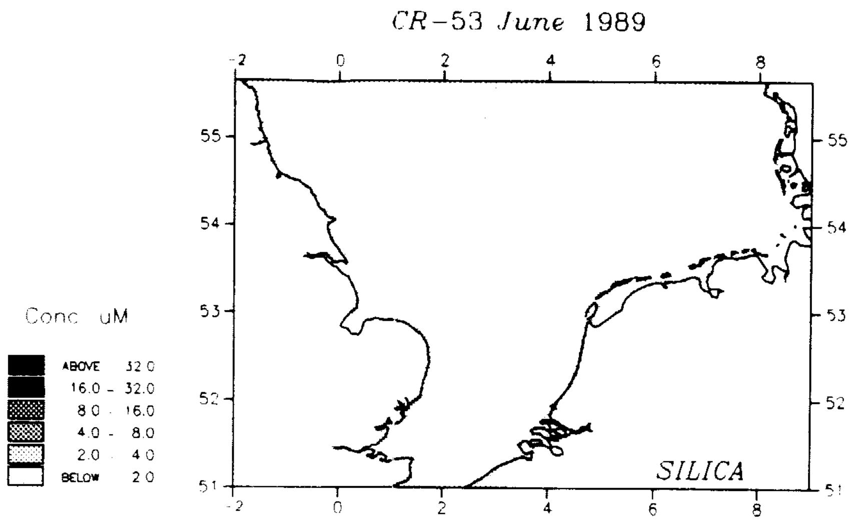
CR 51 May 1989

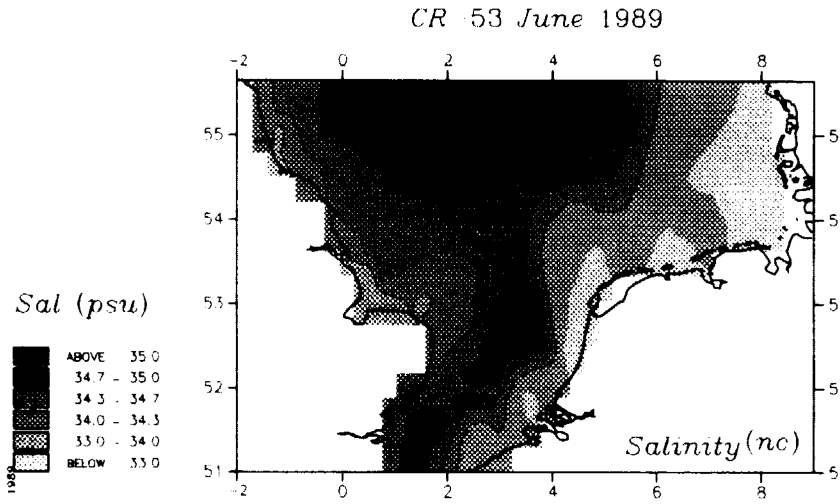


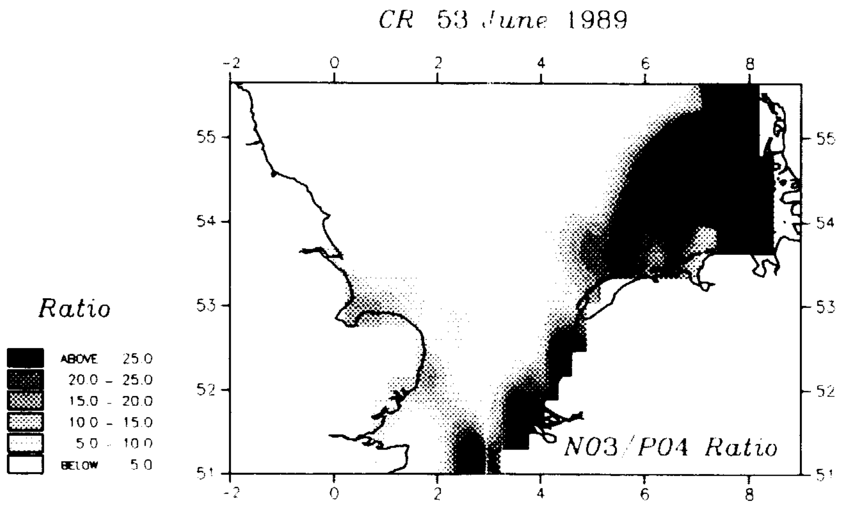
CJM at Wormley, 12:43pm Friday 6th October 1989

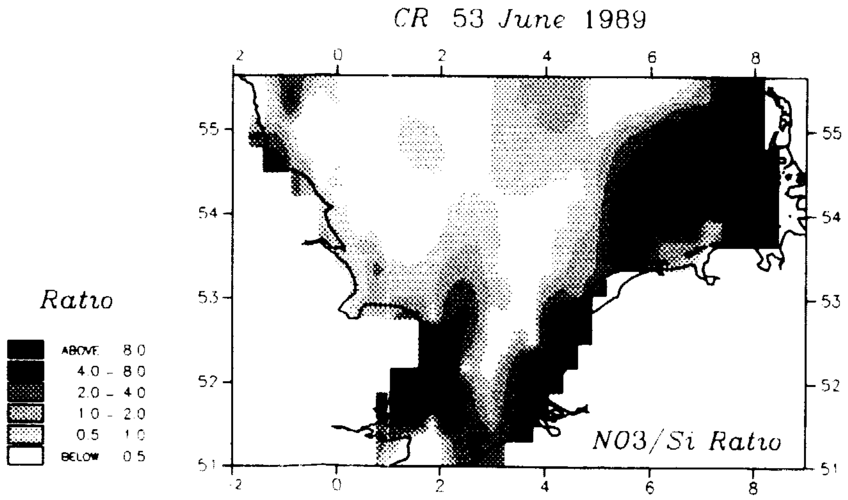




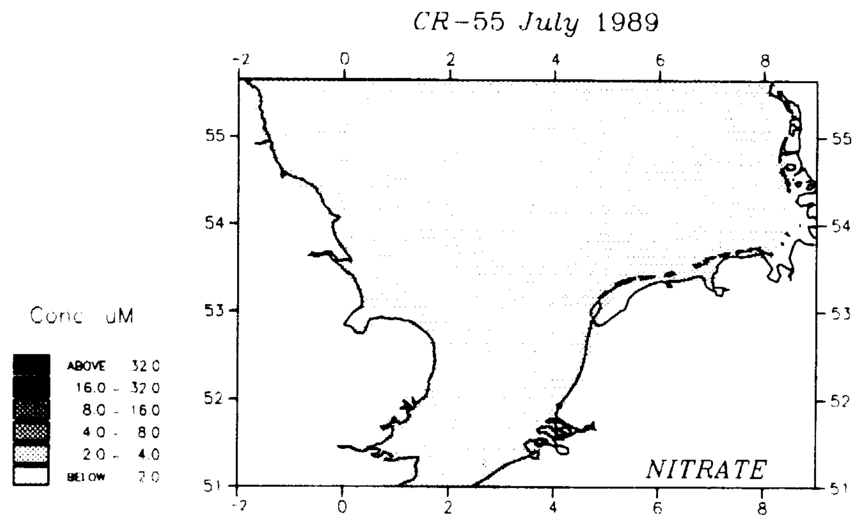


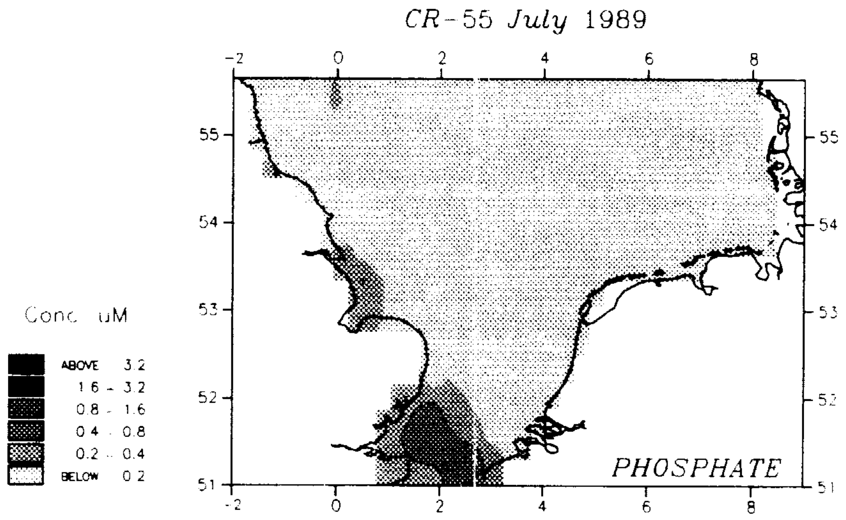


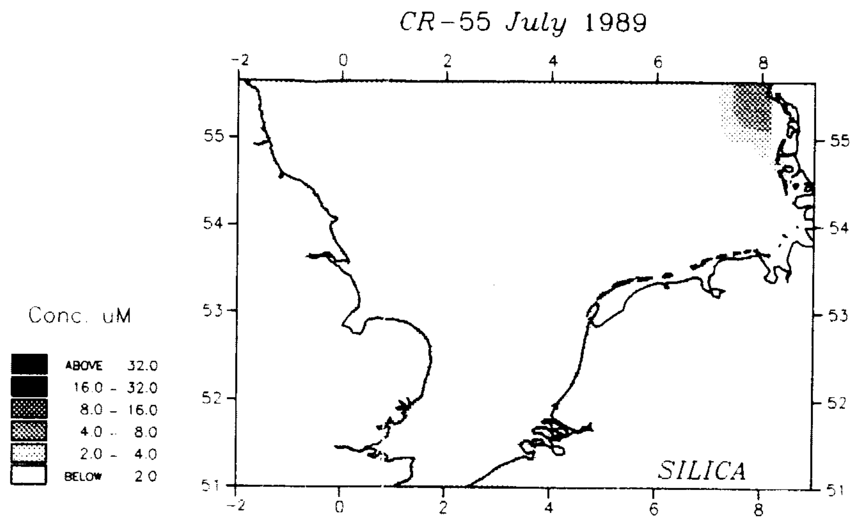


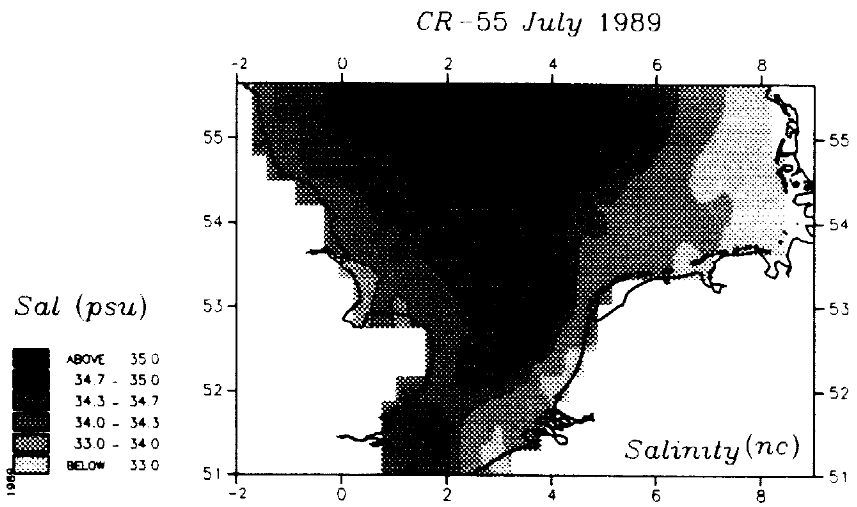


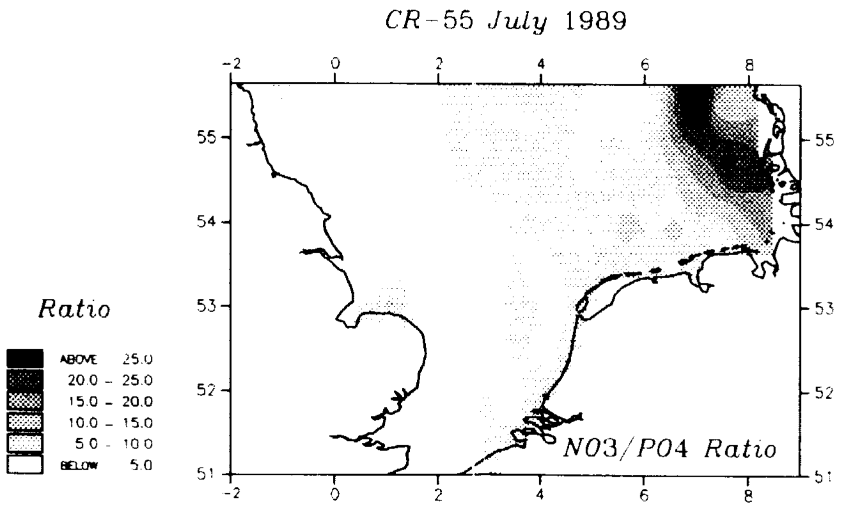
DJH at Wormley, 12 53pm Friday 6th October 1989

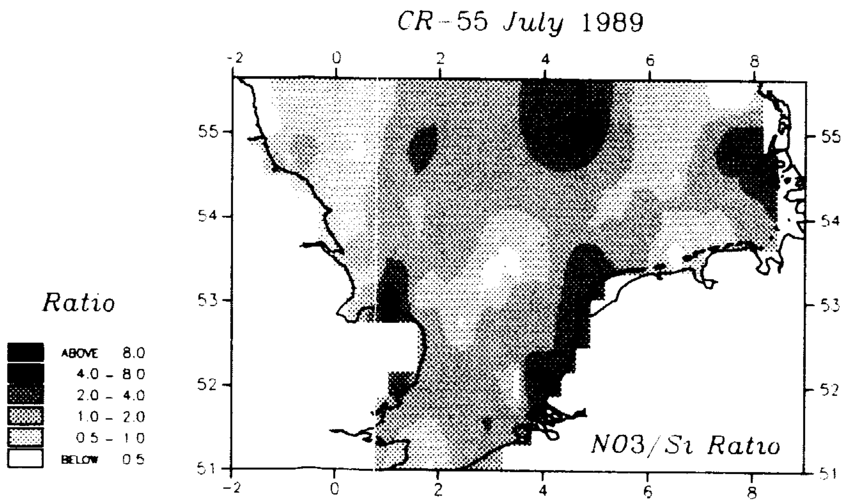




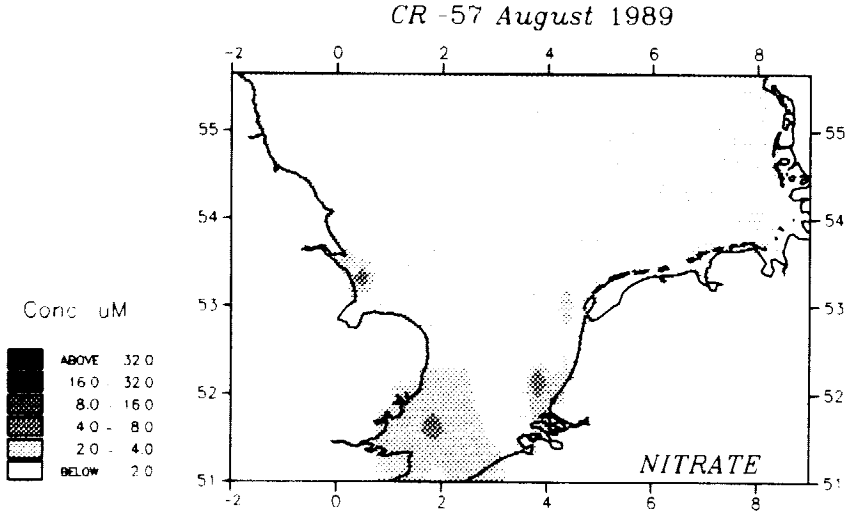


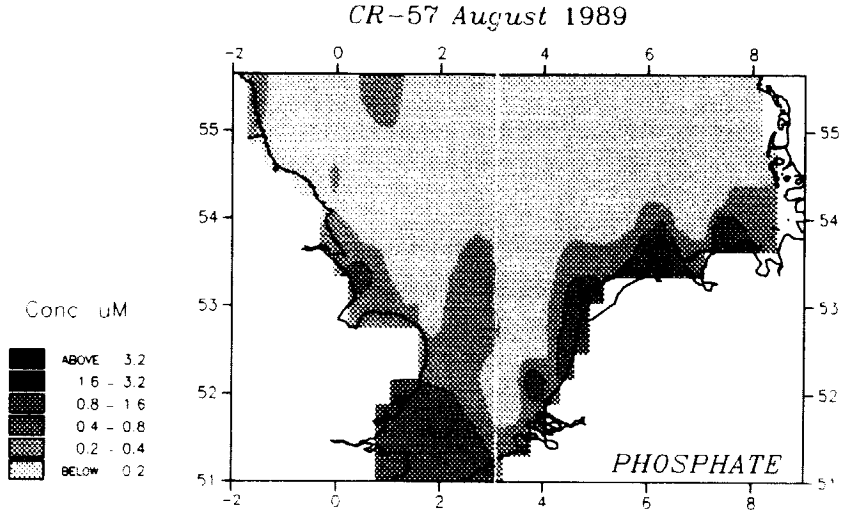


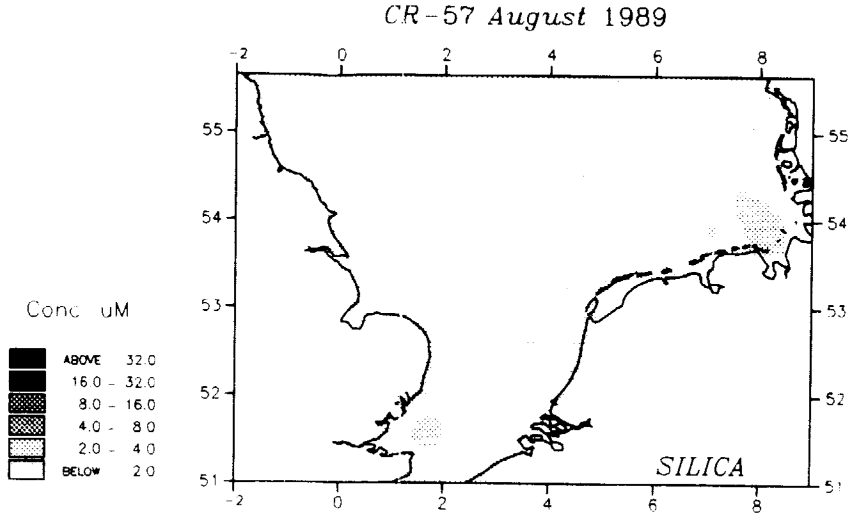


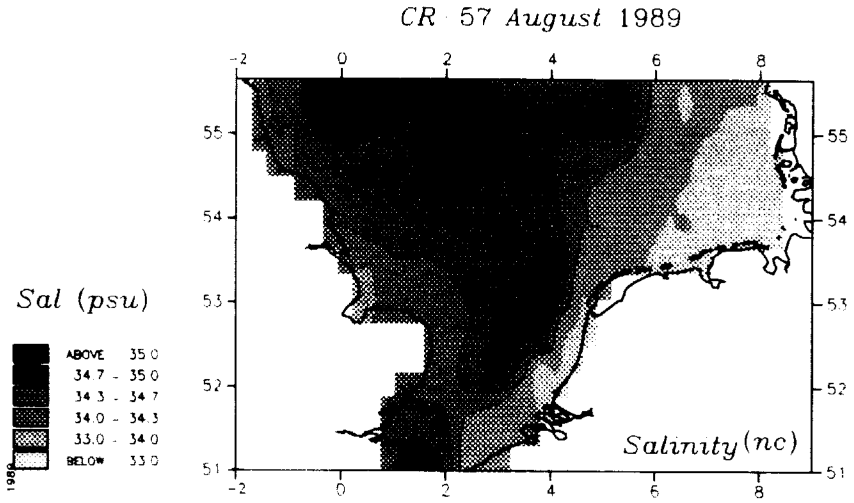


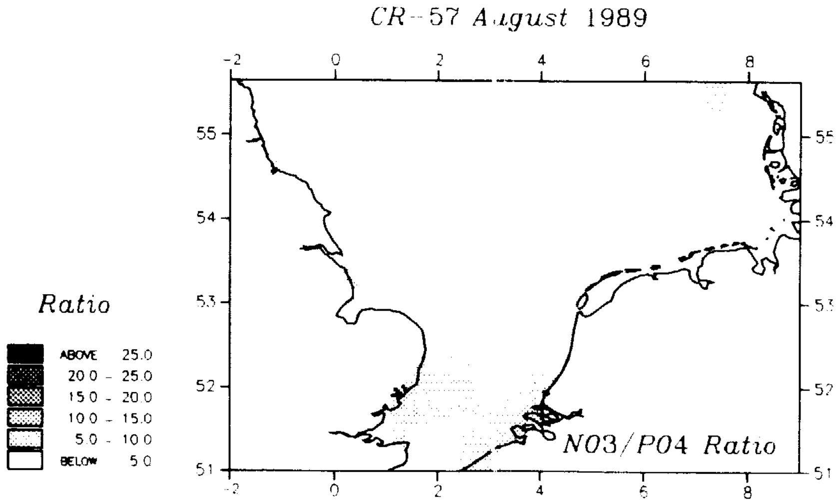
DJH at Wormley. 1.01pm Friday 6th October 1989

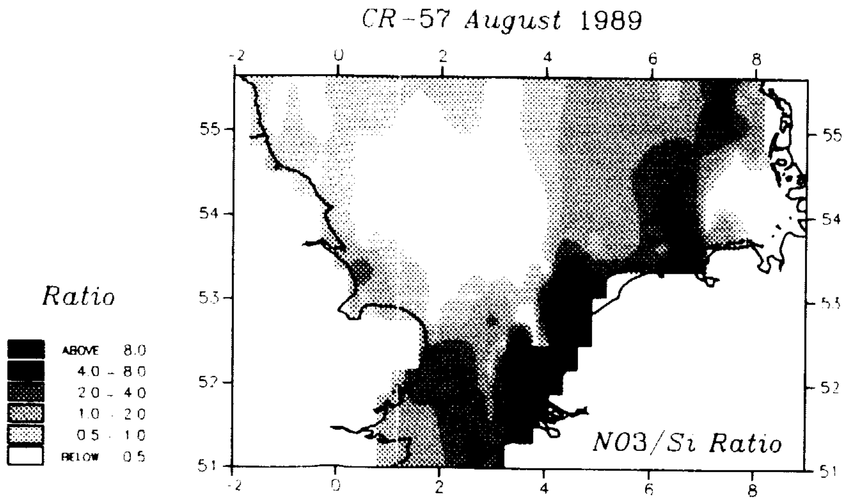

CR-57 August 1989


CR-57 August 1989


CR-57 August 1989


CR 57 August 1989


CR-57 August 1989


CR-57 August 1989

DJH at Wormley 1:12pm Friday 6th October 1989