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The Distribution of Nutrients and Phytoplankton in the North-East Irish Sea

JR Allen, EG Jones, TM Shammon, KR Nicholas, SJ Hawkins
and RG Hartnoll.

Port Erin Marine Laboratory
University of Liverpool

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Report to the National Rivers Authority, North West Region.

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University of Liverpool

Port Erin Marine Laboratory
Port Erin
Isle of Man
IM9 6JA

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INTRODUCTION

This report is the product of a collaborative research project carried out between Port Erin Marine Laboratory (PEML) and National Rivers Authority (NRA) North West Region during 1995. The aim of this project was to examine spatial trends in nutrient concentrations and associated phytoplankton communities in the north-east Irish Sea.

Concentrations of nutrients and their possible effects on phytoplankton are of interest in the Irish Sea as a whole, and in the north-eastern area in particular, for several reasons. Firstly, long-term studies at PEML have shown that concentrations of dissolved inorganic forms of both nitrogen and phosphorus have increased considerably in the Irish Sea since the 1950's and 1960's (fig.1), (Slinn 1990, Shammon *et al* 1995). Secondly, parts of the English coastal region off the Wirral and West Cumbria are candidate High Natural Dispersion Areas (HNDA) under the EU Urban Waste Water Treatment Directive, raising the possibility that comprehensive treatment of sewage discharged in this area will be of low priority in the future. These HNDA areas receive land-based nutrient inputs from two major industrial discharges and several river catchments. Furthermore, the Irish Sea as a whole is semi-enclosed and there is concern about the ability of anthropogenic inputs to disperse: water residence times in some areas are high, estimated at between three and six months for the north-eastern sector by the MAFF model (Dickson & Boelens 1988).

The term 'eutrophication' has been defined in many ways, encompassing to various degrees, inputs of nutrients or organic matter and their effects on the environment. Throughout this report the term will be used in a restricted sense: to describe nutrient enrichment from anthropogenic sources, leading to increased production of phytoplankton. Such eutrophication has been linked to environmental problems in other European coastal areas (e.g. Smayda 1990, Hallegraeff 1993, Caddy 1993). Environmental problems include excessive growth of algae, often of nuisance or toxic species, sometimes leading to de-oxygenation of the water and mortality of benthic fauna during bloom die-off. Both increasing overall nutrient levels and a shift in the atomic ratios of the major nutrients have been identified as causative factors in the onset of nuisance phytoplankton growth (Ryther & Dunstan 1971, Smayda 1990).

The causal relationships of phytoplankton stocks and eutrophication are not clearly understood however, as natural variability is high and physical parameters possibly dominate. Predicting the effect of nutrient changes on phytoplankton assemblages is therefore difficult and a wide range of responses have been recorded. In the, brackish Baltic Sea blooms of blue-green algae are the major problem associated with eutrophication (Rosenberg *et al* 1990), while in the more saline Black Sea the dinoflagellate *Prorocentrum minimum*, (=*Exuviaella cordata*) abounds (Marasovic *et al* 1990, Smayda 1990). Coastal regions of the North Sea have experienced massive *Phaeocystis* blooms in recent years (Bätje & Michaelis 1986, Riegman *et al* 1992), and an increase in reports of nuisance blooms of flagellates (*Gyrodinium aureolum, Prorocentrum minimum* and *Chrysochromulina polylepis*) has occurred in the Kattegat/Skagerrak area (North Sea Task Force 1993). In the German Bight increased nutrient concentrations have been accompanied by increased phytoplankton biomass, mainly of nanoflagellates of uncertain trophic state (Hickel *et al* 1993). In the semi-enclosed Adriatic Sea, however, dense blooms of both diatoms and dinoflagellates have been connected to eutrophication from the Po Delta and associated problems have included deoxygenation and surface scums (Marchetti 1992). Evidence of eutrophication and associated effects on phytoplankton communities is strongest in seas which are enclosed or semi-enclosed. Although the nutrient status of water may play a major role influencing phytoplankton communities, other studies have indicated that the vertical stability of the water column is of greater importance (Pingree *et al* 1976, Holligan & Maddock 1980), while in the open North Sea long-term changes in phytoplankton largely reflect climatic changes (Owens *et al* 1989).

Description of the Study Area

The physical, chemical, biological and geological make-up of the Irish Sea has been described in some detail in various reviews (Dickson & Boelens 1988, Irish Sea Study Group 1990). The eastern Irish Sea is generally shallow (<50m) while a deeper trench lies to the west of the Isle of Man (>100m). Net water transport is northwards through the St George's and North channel, but this is dependant upon prevailing weather and net transport may be southerly for months at a time. Internal circulation is also variable and wind-dependant. In the eastern Irish Sea currents typically show a southwards drift off St Bees Head and a two layer circulation in Liverpool Bay. Differences between surface and bottom currents may also be seen to the north-east of the Isle of Man with surface water moving westward out of the Solway Firth and bottom currents travelling eastward.

The majority of the Irish Sea is shallow and well mixed. The main area of stratification lies to the south-west of the Isle of Man where deeper water and reduced currents allow summer thermal stratification. This area is thought to be responsible for a large proportion of the production of the Irish Sea. Thermal stratification may also occur in Liverpool Bay in summer. A stratified region also occurs off the Lancashire and Cumbrian coasts, but haline effects are thought to be more important here, with stratification most marked in winter and spring. Predictive modelling based on depth and tidal stream amplitude place most of the water between the Isle of Man and Cumbria in a 'transitional' category with weak fronts along the north and southern borders with mixed water masses (Pingree & Griffiths 1978). Such fronts are sometimes apparent on satellite images but there is a lack of published information from hydrographic studies in this north-eastern sector. Fronts may act as barriers restricting transfer and dispersal of material between adjacent water masses (Balls 1987).

In seas surrounded by land masses both atmospheric and land-based inputs of nutrients may be important (Paerl 1995). No information on atmospheric inputs for the area is available at present. Land-based inputs from major riverine, sewage and industrial sources are summarised in Table 1 (NRA data). The most important individual inputs of nitrogen in the north eastern sector are from the River Eden (36%) and BNFL Sellafield (17%). Individual sewage outfalls are of minor importance by comparison, with the total of all major outfalls in the area accounting for approximately 12% of all inputs. Previous studies (Foster 1984) have shown that the major pool of inorganic nitrogen in the northern Irish Sea lies in the Liverpool Bay area. Net water transport is from the Liverpool Bay area into the north eastern sector and it is likely that this transport is also a major source of nitrogen. The nitrogen input from Sellafield is set to increase as reprocessing of fuel at THORP comes on line (discharge consent is 4078 te/annum,

Table 1
Estimated nutrient loads from the English coast directly to coastal waters of the north-east Irish Sea (north of Blackpool and east of the Isle of Man). Estimated loads are in tonnes per annum. All figures are derived from NRA data. Industrial contributions are estimated from routine samples (figures to mid 1995), N as DIN, P as P_2O_5-P. Loads from major rivers are a catchment total for 1994, as DIN and ortho-P and include major tributary and sewage input. The rivers Ribble and Mersey are outside the immediate area of study and figures are included for comparison only. Sewage figures are based on flows and the composition of 'standard sewage' based on total nitrogen (as N) or phosphorus (as P) .

	N	P
Industrial		
Albright & Wilson	—	825
BNFL Sellafield	1500	—
Rivers		
Eden	3211	157
Derwent	838	11
Leven	403	9
Kent	601	6
Lune	983	10(?)
Wyre	337	23
Total north-east rivers	6373	216
(Ribble)	(7065)	(996)
(Mersey)	(11346)	(1838)
Sewage direct to coastal waters		
Workington/Whitehaven area	280	94
Millom	60	20
Barrow-in-Furness	165	55
Morecambe	116	39
Blackpool	471	157
Total coastal sewage	1092	365
Total of all major inputs to north-east Irish Sea	**8965**	**1406**

end 1995 estimate 1700 te/annum). Inputs of phosphorus in the north east Irish Sea aregreatly dominated by the industrial outfall at Albright and Wilson, Whitehaven, which currently accounts for 59% of all major inputs. The sum of all sewage outfalls is responsible for around 26% and all rivers (dominated by the Eden) for 15% of total inputs from land.

Studies on phytoplankton in the Irish and Celtic Seas have centred mainly around the frontal systems (Pingree *et al* 1976, Savidge 1976, Fogg *et al* 1985). Information on the phytoplankton of the north-east Irish Sea is particularly scarce. The effects of increasing nutrient concentrations in the Irish Sea are unclear. There have been no long-term studies on phytoplankton communities to complement nutrient data. Chlorophyll measurements have been made at the Cypris Station (for locatio see fig. 3c) since 1966 however, and these provide an index of phytoplankton standing crop. Both the maximum and mean figures for the main growth season show a great deal of inter-annual variation which has increased in recent years (fig. 2), with an apparent tendency towards occasional elevated mean and maximum figures. Massive blooms of *Phaeocystis* have been recorded relatively frequently in recent years in Liverpool Bay and the eastern Irish Sea but details of their duration, extent or historical occurrence are difficult to find. Blooms of the dinoflagellate *Gyrodinium aureolum* have resulted in mortality of benthic fauna in the north east Irish Sea, but this mortality was associated with reduced oxygen concentrations rather than toxic effects (Helm *et al* 1974). Red tides of the non-toxic dinoflagellate *Noctiluca scintillans* have been regularly reported from around the Isle of Man in recent years (Shammon *et al* 1995), but again no historical data are available.

SAMPLING PROTOCOL AND METHODOLGY

Dates of cruises and location of sampling sites

The initial aim was to take samples off the Cumbrian coast on four occasions throughout the seasonal production cycle. Sampling trips were planned for mid February (winter nutrient maxima), early April (start of phytoplankton growth), late May (phytoplankton peak) and mid July (post-peak summer sample). For all but the April samples, PEML sampled on an offshore grid and NRA on an inshore pattern (see map Fig. 3). It was planned that the two vessels the RV Roagan (PEML) and the Coastal Guardian (NRA) would carry out sampling concurrently on the separate grids. For April samples only, PEML carried out sampling on the inshore grid, and no sampling was done on the offshore grid (fig. 3). Due to problems of poor weather conditions sampling dates were delayed and concurrent sampling was not always possible. The Solway Protector, which has no on-board analysis facilities, had to be used for sampling by the NRA in May and July. Actual sampling dates were as follows.

Inshore Grid	Offshore Grid
20th March - NRA	2nd March - PEML
3rd April - PEML	—
31st May - NRA	23rd May - PEML
24th July - NRA	24th July - PEML

The cruise pattern for the offshore grid consisted of 17 legs in a zig-zag pattern to boundaries nominally defined by points 6 and 16 nautical miles from Maryport, St Bees Head and Hipsford Point, and the latitude boundaries 54°02.5'N and 54°42.5'N, with a 2.5' latitude spacing between the ends of the legs. The inshore grid ranged from the closest practicable point inshore to the 6 nautical mile line defined above, and within the same latitude boundaries as the offshore grid, giving 16 legs.

A total of 86 sampling sites were distributed over the legs of the offshore grid, in addition to 12 sites spaced along the transit path from and to the Isle of Man (fig. 2). Nominal positions and site identifiers are given in appendix table A. Surface phytoplankton, nutrient and salinity samples were collected and surface temperature and fluorescence were recorded from all 98 stations on each sampling date, except March where phytoplankton was taken from the ends and middle of the grid legs only. A CTD cast and bottom nutrient samples were taken at the ends and middle of each grid leg (a total of 35 sites). Surface water samples were taken for chlorophyll *a* analysis at transit sites and at the ends of legs (30 sites) with samples also taken at the middle of the legs in July.

On the inshore grid in March the NRA determined surface temperature, salinity, nutrients (Skalar autoanalyser) and fluorescence (Meerestechnik Electronik fluorometer) and collected phytoplankton samples. Sampling and analysis is automated on the Coastal Guardian and results were taken from a two minute sampling frequency. In May and July surface temperature, salinity, nutrients and phytoplankton samples were collected by the NRA, from a total of 58 sites distributed along the cruise path (fig. 3), nominal positions and site identifiers are given in appendix table A. On each NRA cruise, samples were also collected at the ends of the legs only (17 sites), for analysis at the Nottingham Laboratory for nutrients, chlorophyll *a* and suspended solids. On the PEML April cruise surface samples (temperature, salinity, nutrients, fluorescence and phytoplankton) were taken from 63 sites on the inshore grid plus 12 from the transit legs (fig. 3), and bottom samples (salinity and nutrients) at the ends of the legs. Surface water for chlorophyll *a* analysis was taken from the ends of the legs and transit sites. No CTD casts were made in April.

Inevitably some results were lost due to malfunction of equipment, human error etc. Major gaps in results include: No analysis of phytoplankton from inshore March samples as corresponding positions could not be provided for NRA collected samples; no salinity/temperature/fluorescence data for legs 8, 9, 15 or 16. of the same cruise due to computer malfunction; no fluorescence data for CTD casts in May due to CTD malfunction; no nutrient data legs 1 to 3 of inshore grid in May due to computer problems and rejection of some nutrient results from May offshore grid due to analytical problems (approx. 10% of results rejected).

Sampling and analytical methods

The following analytical methods are for PEML analysed samples only. NRA analysed samples were determined using methods normally used on coastal surveys. Methodolgy between the two institutions was broadly similar, and was standardised wherever possible.

'Surface water' supply on board the Roagan is supplied by a direct intake pipe approximately 2m below surface water level. Surface temperature was recorded in the flowing water supply by meteorological office mercury thermometer. Water samples for salinity were stored in stoppered glass bottles and analysed using a Plessey 9230N bench salinometer.

Water for nutrient determination was immediately filtered through GF/C filters and placed in the freezer. Two samples were taken at each site and only one set of samples thawed for analysis, leaving a back-up in case of analytical problems. Nutrient analysis was carried out using an Alpkem RF/A2 autoanalyser using standard colorimetric techniques as advised by the manufacturer. Artificial seawater (Grasshoff 1976) was used for blanks and background wash to overcome salinity effects. Deionised (UHQ) water was used in artificial seawater for ammonia determination.

Surface fluorescence was determined using a Turner fluorometer with continuous water supply, calibrated using results from simultaneously collected chlorophyll *a* samples. Chlorophyll *a* was determined using slow acetone extraction using the formulae given by HMSO (1980), 3L of water were filtered for each sample.

Bottom water samples for nutrients and salinity were collected using an IOS type sampling bottle deployed in conjunction with the CTD. Profiles for salinity, temperature, density and fluorescence were obtained using a Seacat SBE 19 (Seabird Electronics Ltd) conductivity, temperature, depth profiler. 'Seasoft' software was used to align data and to produce results averaged over 1m depth intervals. Standing stocks for the water column (mg Chl *a* m^{-2}) were calculated by summing each 1 metre depth value for the whole cast. Simpson's (*et al* 1978) stratification parameter was calculated from CTD data as an indication of the degree of mixing in the water column. A SuperCalc® template written by P.

Edwards (PEML) was used for this purpose. A value of zero indicates mixed water, negative numbers indicate stratified water. A value of -8 was chosen to indicate fully stratified conditions in these shallow depths (Fernandes 1993).

Phytoplankton samples (150ml) were preserved immediately using acidified Lugols iodine. All samples were analysed by PEML. Subsamples (25ml for winter, 5ml in spring/summer) were settled in Utermöhl type counting chambers and the whole sample counted at x200 magnification. Phytoplankton was identified according to the 26 categories outlined in appendix table B. The use of this limited number of categories based on taxonomic and morphological groupings allowed rapid enumeration of samples and avoided some of the problems of difficulty of identification of preserved samples to species level. Such low level identification is normally sufficient to identify trends in community composition using multivariate statistical ordination methods. Images of the most abundant species were captured for future reference using an image analyser.

Quality control and intercomparison exercises.

The accurate measurement of low level dissolved nutrients in seawater is notoriously difficult and good quality control procedures are essential for reliable results. A detailed protocol for sample treatment and analysis is followed at PEML which essentially complies with the recommendations given in Gillooly *et al* (1992). This procedure includes the use of a laboratory reference standard. In addition PEML subscribes to the 'Aquacheck' service provided by the Water Research Centre, which gives regular independent assessment of nutrient analysis. A summary of results is given in appendix table C. Problems with the underestimation of ammonia at low levels is apparent in these results, but determination of all other nutrients is within acceptable limits of accuracy. Accurate seawater determinations of ammonia is a recognised ongoing problem for all analysts of marine waters (Kirkwood & Aiminot 1995). Samples provided by WRc are also preserved and analysed alongside routine samples as a further check on reliability of results.

In order to check the comparability of results between NRA onboard, NRA Nottingham and PEML samples an intercomparison exercise was organised by Peter Jones of NRA North West in January 1995, which involved a total of six laboratories. While somewhat large differences were apparent for some determinands, an Aquacheck exercise carried out shortly afterwards indicated that only ammonia was outside acceptable accuracy limits for PEML analysed samples.

In addition duplicate samples were collected for nutrient and chlorophyll from the offshore and inshore grids from the eastern or western ends of the legs respectively. These were transported to the collaborating partner and analysed for intercomparison. It was originally hoped that sampling trips would be conducted concurrently and that samples could be exchanged immediately to allow comparisons at the time of analysis of true samples. Any errors in analysis may not be constant for any one laboratory over even short time scales, so that to facilitate corrections to standardise results, analysis of true samples and intercomparison samples must be carried out at the same time. Due to differences in sampling dates and delays in exchange of material this was not possible for any of the cruises. Furthermore, the actual number of compared samples was often too low and differences erratic over the range of concentrations. Therefore, while differences in determined results sometimes occurred, it was not deemed appropriate to make any correction to figures before combining results onto contour diagrams. It is for this reason that NRA and PEML results are contoured separately on maps in the following section.

Some generalisation in differences between analyses can be made from all intercomparison exercises carried out. Firstly there is an obvious problem with under-estimation of ammonia at PEML. It is possible that this is due to air-borne contamination of blank water and considerable effort continues to be directed to solve this problem. Secondly silicate estimation tends to be lower at PEML than by NRA onboard analysis, and more particularly than Notts estimation. The reasons for this are unclear as quality control checks have indicated good performance for silicate at PEML throughout 1995. Finally chlorophyll *a* estimation by both UNESCO and HMSO methods at PEML were often substantially lower than Notts estimation. Notts analysed values sometimes seemed unusually high, especially for winter samples (values up to 10 μg-l^{-1} in March). Due to low chlorophyll values in the open sea PEML filters 3l of water for analysis, while the NRA filters only one. It is possible that this difference in analysis methods generates differences in accuracy between laboratories.

While there is no doubt that differences in determinations for individual samples do occur between laboratories, these are often small compared to the spatial variation between samples over the area of study, so that spatial descriptions from combined datasets will still give a valid representation of trends.

Presentation of results

All contour diagrams are produced using Surfer® for Windows v5.03 (Golden Software). Position of contours is determined using the kriging method and grids are blanked using a detailed land boundary. This process extrapolates data for areas in which no samples have been taken, so close attention to the location of sampling sites (figs 3) should be made when making detailed study of the trends. In particular there were no samples taken from the north-west of the mapped area, due north of the Isle of Man. Separate diagrams are drawn for PEML and NRA results and then overlaid to form a composite picture. It should be noted that such maps are not corrected for earth curvature and there is some distortion from north to south when compared to admiralty charts. An average scaling factor for the area of 1 deg. long. to 1.7153 deg. lat. was used in the plotting of these maps.

CTD plots were produced using Seasoft v4.211 from aligned data.

Multivariate statistical analysis and associated plots was carried out using PRIMER v4.0 (Plymouth Marine Lab.). Details of statistical treatment are the subject of a separate section of this report.

RESULTS

Physical patterns

Surface temperatures generally showed inshore (English coast) to offshore trends on all sampling dates. In March coldest temperatures were found inshore with warmer water generally towards the south-west of the sector, off the south-east coast of the Isle of Man. Temperatures over most of the area were between five and seven degrees Celsius. In April inshore-offshore variation was reduced, but warmer temperatures were again found towards the south-west of the sector. By May the shallow coastal water was warmer than offshore areas, surface temperatures ranging from 10 °C to 13.5 °C. In July the inshore-offshore differences were most marked, ranging from 14.4 °C to 18.4 °C. Water temperatures were generally coldest towards the south-west of the sector and warmest off the Duddon Mouth and Walney Island.

Surface salinity generally showed an increasing trend from the north-east to the south-west of the study area (figs 4 to 7). Lowest salinities (<32.5‰) were usually found towards the Solway Firth, extending along the Cumbrian coast and highest salinities (>34‰ off the south-east coast of the Isle of Man. Surprisingly, an area of high salinity was present in May, in the inshore area just south of the Solway Firth (fig. 6). The apparent penetration of low salinity water as delineated by the 33‰ contour was greatest in March and April and much reduced by July.

The amount of mixing between surface and bottom waters is restricted when the density of surface water is reduced by solar heating or freshwater run-off to produce thermal or haline stratification of the water column. CTD casts taken on offshore grids demonstrated that such density stratification was present in some areas of the north-east Irish Sea. Both the distribution of stratification, as indicated by Simpson's stratification parameter values of less than -8, and the degree of stratification, were greatest in March (fig. 8). This winter/spring stratification was due to surface water of reduced salinity. An example of the structure of the water column, as shown by CTD cast, is illustrated in figure 9. two main areas of stratified water were apparent, one to the north and one to the south of a line west from St Bees Head (lat. 54° 30'). Stratification was much reduced in May (fig. 10), when freshwater influence was lower. By July however warming of surface waters had resulted in patches of stratified water (fig. 11). These were centered on the same positions as the winter stratified areas. The patch south of 54° 30' consisted of thermally stratified water (e.g. fig. 12), while the area north of this line was stratified due to both thermal and haline effects.

Patterns of nutrient distribution

In March, April and May the majority of dissolved inorganic nitrogen (DIN) was present as nitrate. In July nitrite levels represented a higher proportion of total oxidised nitrogen (TON) than in earlier months, but at this time all forms of nitrogen were present at very low concentrations. Nitrate was plotted for all months (figs 13 to 16) as other forms of inorganic nitrogen (ammonia and nitrite) were frequently below detection limits .

Despite a delay of 18 days between PEML and NRA sampling in March, chlorophyll *a* levels remained low (see later section) and good agreement in nitrogen levels was seen between the grids. Hence it is likely that both datasets represent samples taken before the onset of increased phytoplankton growth and are typical of winter samples. A decreasing trend was seen from north-east to south-west with highest concentrations (up to >370µgl^{-1} nitrate-N) towards the Solway firth, extending along the Cumbrian coast and lowest levels offshore to the south west of the study area (fig. 13). In early April nitrate levels inshore had decreased slightly, while offshore concentrations were broadly similar (fig. 14).

By late May nitrate levels had reduced across the area and were now lower close to the English coast than offshore (fig. 15). There was no data from sites close to the Solway Firth in May. A large area of higher nitrate levels was present offshore between the Isle of Man and the north Cumbrian coast, the western extent of which is unclear due to a lack of samples. Nitrate levels were also elevated inshore between St Bees head and Drigg point. In July nitrate distribution was now more depleted offshore and levels were very low (<5µgl^{-1}) throughout most offshore areas of the north east Irish sea (fig. 16). Concentrations were below the detection limit (<0.05µgl^{-1}) in some cases. Inshore nitrate was slightly higher along the Cumbrian coast with elevated patches towards the Solway Firth, South of St Bees and south of the Ravenglass estuary.

Nitrite concentrations were low in all samples, being generally<4µgl^{-1} in March April and July and <8µgl^{-1} in May. Ammonia results from offshore stations were probably unreliable. NRA inshore values in March showed highest levels towards the Solway Firth and around the mouth of the River Duddon (up to 54 µgl^{-1}). In May inshore ammonia were mostly in the range 70-100µgl^{-1} with higher values off Duddon mouth. July ammonia ranged from 12-63 µgl^{-1} inshore with highest values offshore from Duddon mouth.

Maximum concentrations of orthophosphate on all sampling dates were found around the Whitehaven/St Bees head area (figs 17 to 20), with levels here higher than towards the Solway Firth, in contrast to nitrate results. In March marked inshore English coast to offshore gradients are seen with higher levels inshore (fig 17). In early April inshore concentrations had reduced somewhat but this trend is still evident (fig. 18). In May and July phosphate levels were low offshore (generally in the range 3 to 13 µgl^{-1} in May), with highest concentrations clearly associated with the Whitehaven/St Bees Head area (figs 19 & 20). In May an area of slightly higher concentrations was present offshore between the north of the Isle of Man and the Solway Firth, although this is not as marked as in the case of nitrate.

In March highest concentrations of silicate were associated with the Solway Firth, declining offshore (fig. 21). Distribution of silicate closely followed that of lower salinity water. In April, levels were lower over the whole study area, but still highest along the Cumbrian coast (fig. 22). By May silicate levels were much depleted throughout the north east Irish Sea and were lower inshore than offshore, with riverine influence no longer obvious (fig. 23). Highest Silicate levels in May were present between the north of the Isle of Man and the Solway, although distribution did not closely match the similar patch of higher nitrate and phosphate concentrations. In July silicate remained low compared to winter values, but offshore concentrations were slightly higher than in May. The distribution of silicate in July was patchy, with no clear inshore/offshore trends (fig. 24).

Information on vertical distribution of nutrients is available from surface and bottom samples from the offshore grid only. In March similar vertical trends were seen for all nutrients with highest concentrations in surface water and most marked differences in areas of strong haline stratification (fig. 25, for positions of site codes see appendix table A). In May surface/bottom differences were more marked, but highest concentrations were now in bottom samples (fig. 26). Although stratification was reduced in May the most marked nutrient differences occurred where stratification was present. In July some differences in vertical distribution were seen between nutrients (fig. 27). Total oxidised nitrogen (TON) and silicate were generally at higher concentrations in surface samples. For silicate in particular marked vertical differences were clearly associated with thermal stratification. Levels of TON were now very low throughout the whole water column. Levels of orthophosphate were also higher in bottom samples in the main area of thermal stratification, but in samples to the north of the grid higher levels were present in surface water. While the most likely cause of elevated surface levels is freshwater run-off, there is no support for this from either salinity profiles or patterns of silicate distribution.

Phytoplankton communities and standing stocks.

Counts of phytoplankton cells did not always suggest the same trends in phytoplankton production as the distribution of chlorophyll. Pearson's product moment correlation tests were carried out on May and July offshore samples between concurrent or winter (March) nutrients and chlorophyll a and total phytoplankton counts. Significant ($P<0.01$) positive relationships were found betwen both winter TON and silicate (but not phosphate), and July chlorophyll, fluorescence and total phytoplankton densities. July phosphate and silicate (but not TON) also showed positive correlations with concurrent levels of these variables. No significant positive correlations were found between May phytoplankton or pigments and any nutrients, and concurrent relationships were in some cases strongly negative. Where a positive correlation was found between nutrients and indicators of phytoplankton biomass, this was normally stronger for chlorophyll than for counts.

The distribution of chlorophyll *a* in surface waters of the north east Irish sea was plotted from fluorometer readings, except in the case of the inshore area in May and July when it was necessary to use a limited number of acetone extraction-derived values. In March all readings were less than $1\mu gl^{-1}$ indicating very low phytoplankton biomass across the whole area (fig. 28). By early April chlorophyll was starting to increase along the Cumbrian coast, especially close to the mouths of the Solway Firth and Duddon river (fig. 29). At the end of May chlorophyll levels had increased offshore but higher concentrations were still found along the Cumbrian coast (fig. 30). Maximum chlorophyll levels of $> 6\mu gl^{-1}$ were concentrated in two areas: towards the Solway Firth and in an area centered around Seascale and extending offshore. By July chlorophyll had reduced at many offshore sites. Highest levels were again inshore, particularly along the Cumbrian coast from south of the Solway Firth to the Ravenglass estuary (fig. 31).

Standing stock figures give an indication of phytoplankton biomass summed over the whole water column. In sea areas which are shallower than the critical depth for photosynthesis the standing stock may be lower due to water depth rather than to factors limiting phytoplankton growth. Standing stock figures are only available for offshore areas in March and July. Values were surprisingly similar for both dates, being in the range 40 to 60 mg m^{-2} over much of the area (figs 32 & 33). In March lower levels were present in shallower water to the north east and south east (fig. 32). While in July higher levels were found in the area of thermohaline stratification north of 54^{o} 30' and in northern regions of the thermally stratified patch to the south of this line (fig. 33).

The concentrations of diatoms, dinoflagellates and total cells were mapped over the north east Irish Sea for May and July. In May highest cell numbers were found offshore between the Isle of Man and the English coast with generally lower levels to the south west and close to the English coast (fig. 34). An area of lower densities was seen offshore, between the north of the Isle of Man and the Solway Firth, which corresponded to the area where nitrate and orthophosphate remained at higher levels. Phytoplankton in May was dominated by diatoms, the distribution of which followed that of total counts. Dinoflagellates were present in lower numbers, with maximum densities found just offshore from Sellafield and Ravenglass (also an area of higher chlorophyll *a*), and to the south east of the sampling area. A varied dinoflagellate community was present, dominated by species of Peridiniales, Gymnodiniales and *Ceratium* (in order of importance). The inshore chlorophyll peak towards the Solway was not reflected in phytoplankton cell counts.

In July dinoflagellates and small flagellates and monads less than 15µm dominated the phytoplankton and are the main influence on the distribution of total counts. Highest concentrations of dinoflagellates were found in two offshore areas, one to the north and one to the south of the study area (fig. 35). Dinoflagellate communities were not strongly dominated by one group, consisting of species of Gymnodiniales, Peridiniales, *Ceratium*, Prorocentrales and Dinophysiales. Very high densities of cells <15µm were found in association with dinoflagellates, especially in the patch to the north. The dense dinoflagellate patch to the south was not well represented by chlorophyll *a* distribution. Diatom distribution was patchy in July with higher numbers found outside the main dinoflagellate concentrations. The most dense diatom communities were found to the south west of the study area, off the Manx coast.

Average species densities over all sites were calculated to demonstrate the main seasonal trends (fig. 36). This clearly shows the dominance of diatoms in May, with *Nitzchia*, *Asterionella* and *Chaetoceros* having the highest cell counts, with *Rhizosolenia*, *Leptocylindrus* and *Thalassionema* also important. In July small cells < 15µm were numerically dominant with microzooplankton an important component of the assemblage. While average densities of Gymnodiniales and Peridiniales were slightly lower in July than in May, densities of all other dinoflagellate groups had increased.

The meaningful assessment of phytoplankton standing crop has many problems. Chlorophyll *a* content varies with condition of the cells and from species to species. In particular chlorophyll *a* may be a poor indicator of biomass of dinoflagellates, many of which are heterotrophic, or contain other pigments. The most abundant species were often very small cells such as *Nitzchia* and microflagellates, so that cell counts might not always give a good representation of relative biomass. Estimation of biomass from cell volume is possible but very time consuming for diverse assemblages such as those seen. The accuracy of such estimates is also open to question. It was only possible to count phytoplankton greater than approximately 5μm length, hence very small species, which can account for a large proportion of the phytoplankton biomass, may have been missed.

ANALYSIS OF PHYTOPLANKTON COMMUNITY STRUCTURE AND ENVIRONMENTAL VARIABLES

Multivariate analysis techniques

The aim of statistical analysis was to further describe the complex phytoplankton community data and to identify any trends or discrete groups on each sampling date. In addition an attempt was made to relate these groupings to environmental variables. All statistical analyses were carried out using PRIMER.

Cluster analysis

Patterns of similarities in species composition between samples (sites) were observed using the CLUSTER procedure of PRIMER. Phytoplankton species data for each site were fourth root transformed to downweight the importance of very abundant species. Only those species having an abundance > 5% of the total in any one sample were retained. A similarity matrix was calculated from Bray-Curtis coefficients and hierarchical agglomorative clustering performed using the group average linking method to produce a dendrogram. Clustering is designed to delineate groups of sites with distinct community structures and can be misleading if there are gradations in species assemblages. Hence clustering was used in conjunction with ordination techniques (non-metric multi-dimensional scaling).

Non-metric multi-dimensional scaling (MDS)

The advantages of MDS over other ordination techniques are that because it is based on ranks it makes few model assumptions about the form of the data. Gradual changes over community or environmental gradients are also effectively displayed. MDS uses ranks of similarities to construct a two dimensional 'map' of the samples. Distances between the position of samples on the plot represent the relative similarity of the samples, so that similar samples will be placed close together. For most data sets there is some distortion or stress between the similarity ranking and the corresponding distance rankings on the plot. The stress level gives a measure of adequacy of the MDS representation. Stress levels less than 0.1 indicate good representation of the data, stresses over 0.3 indicate that the points are close to being arbitrarily placed. It was therefore decided that further consideration of patterns highlighted by MDS would only be carried out for plots with stresses of less than 0.15.

MDS was performed using PRIMER on species-sample data based on fourth root transformation and Bray-Curtis similarity coefficients. The maximum size of data matrices in this program is 125 rows x 125 columns. Reducing the phytoplankton data set to those sites where a complete set of surface water environmental parameters were successfully recorded normally brought data files within these limits.

Matching of phytoplankton community to environmental patterns

Patterns in phytoplankton community structure may be linked to environmental variables using the BIOENV procedure of PRIMER in which ranks of similarities are compared using a rank correlation coefficient (weighted Spearman coefficient). This procedure was only carried out for groups of samples with low stress values in species-sample MDS plots. Correlations were performed between species-sample similarity (from MDS) and environmental dis-similarity matrices (based on untransformed data and euclidean distance). A coefficient close to zero implies no match between patterns of species-samples and environmental variables while values close to -1 or 1 imply complete opposition or agreement in the two sets of ranks of similarities. No assessment of the significance of the match in pattern can be made since the ranks are based on a large number of strongly interdependent similarity comparisons. What the BIOENV procedure does do is identify which individual or combination of environmental variables best match the patterns in community structure. No conclusions about causality can be drawn from any relationships, however suggested relationships may be used to select variables for further study to investigate causality. Another problem is that of strongly related environmental variables (e.g. salinity and silicate) the effects of which can be impossible to separate.

BIOENV requires a full data set, so it was necessary to reduce species and environmental data to only those sites with no missing determinands.

Determining discriminating species

Where distinct communities or trends in phytoplankton assemblages were indicated by MDS it was necessary to identify the characteristic species categories. This was achieved by carrying out MDS on the species similarities to determine which species varied in association with each other. The species list (rows) was then ordered according to the position on this MDS plot and the sample sites (columns) ordered to match the position on the sample similarities MDS plots and cluster diagrams carried out previously. Phytoplankton abundances were then plotted with symbols sized on an arbitrary abundance scale (different for each species) to produce a shade diagram displaying trends in abundance across the species and samples groupings.

Discriminating species were also identified by dissimilarity breakdown using the SIMPER procedure.

Standard procedure

Phytoplankton species abundance and environmental data for each sample date was first converted to a standard format use in PRIMER. Information from inshore and offshore grids was analysed both separately and as joint files where applicable. Similarity matrices and cluster dendrograms were produced for phytoplankton abundances. MDS plots were constructed from ranked matrices and the stress value noted. For sample sets having an MDS stress of less than 0.15 (or close to this) some distinct patterns in phytoplankton communities were assumed and further analysis was carried out to determine discriminating species (SIMPER) and to link patterns to environmental data (BIOENV).

Results of statistical analysis

March

Phytoplankton data was only available from offshore sites in March. Both cluster and MDS analysis showed no clear grouping, all sites having a similar assemblage and abundance of species. Outliers on plots were site 16E, which had a low diversity and abundance of diatoms and site 71W which had a relatively high abundance of dinoflagellates and microzooplankton. MDS stress was 0.215, so no further analysis was carried out.

April

Phytoplankton samples were only taken from inshore and transit sites in April. No distinct groups were obvious from cluster or MDS analysis. Outliers on plots were site 54 and transit site B which had high and low proportions of dinoflagellates respectively. MDS stress was 0.216 so no further analysis was carried out.

May

Phytoplankton samples were taken from both inshore (31st May) and offshore (23rd May) grids. Phytoplankton communities in May showed the most notable trends of any sample date, as identified by MDS plot (fig. 37). An MDS stress of 0.117 applied to the plot of inshore and offshore samples used later in BIOENV (having a complete environmental data set). The shade diagram covering these sites showed a continuum of change from diatom dominated to dinoflagellate and small flagellate/monad dominated communities (fig. 38). Dissimilarity breakdown indicated that the diatoms *Nitzchia*, *Asterionella* and *Chaetoceros* (in order of importance) were most important in discriminating groups of samples from each end of the spectrum, accounting for a total of 42% of the dissimilarity. In the dinoflagellate dominated group of samples Ceratium, small flagellate/monads and Peridiniales were more abundant, these categories accounted for a total of 19% of the dissimilarity.

Patterns in phytoplankton communities in May were compared to concurrent temperature, salinity, nitrate, nitrite, ammonia, orthophosphate and silicate. Due to a lack of temperature data from many inshore sites it was necessary to do two analyses, one on all samples but omitting temperature from the analysis, and one on offshore stations only (phytoplankton MDS stress 0.186) including temperature. For combined inshore and offshore samples ammonia had the highest correlation of any single determinand ($r = 0.376$), followed by salinity, nitrite, nitrate then orthophosphate. Correlation coefficients for nutrients other than ammonia were very low ($r < 0.05$). The best match between environmental and phytoplankton patterns was achieved when salinity, nitrite and ammonia are considered together ($r=0.397$). For offshore stations only (now including temperature), salinity had the highest individual correlation ($r = 0.163$) and the best match is achieved by a combination of salinity, temperature and nitrate ($r = 0.183$). Unfortunately, much of the pattern in phytoplankton communities was lost when inshore stations were omitted.

Correlations were also made between the patterns of May phytoplankton and March nutrients (total oxidised nitrogen, orthophosphate and silicate) from sites with nominally the same position. It is likely that March nutrient concentrations will reflect levels initially available, before modification by phytoplankton. Patterns in phytoplankton showed little relationship to those in winter nutrients with all correlation coefficients being very low. The highest correlation was achieved with a combination of TON and silicate (r = 0.062). However the comparison of summer phytoplankton with winter nutrients at the same site is problematic due to the reduced penetration of nutrient rich river water in the summer. Simple links to salinity were not carried out as major industrial nutrient inputs have no associated salinity signal.

While correlations of similarity matrices did not identify any strong links with environmental variables, some generalisations about the types of sites at each end of the continuum can be made. Strongly dinoflagellate dominated samples were almost entirely from southern inshore sites, from Sellafield to the south of the grid. Strongly diatom dominated samples were more patchily distributed, but were all offshore sites. Two groups of diatom dominated sites were noted, one midway between the north of the Isle of Man and the Solway Firth, and one on the eastern side of the offshore grid opposite Selker point. In the latter area a sharp gradient occurred between dinoflagellate dominated sites inshore and diatom dominated offshore.

July

Phytoplankton samples were taken from both inshore and offshore grids on the same date (24th July). Cluster and MDS analysis of inshore only and all combined phytoplankton samples showed some weak grouping (MDS stress of 0.184 and 0.173 respectively). MDS analysis of offshore phytoplankton alone indicated stronger trends (stress 0.157). Patterns were less distinct than in May. A tendency towards two groups with some overlap was observed. In July only 6 species categories remained when those >5% in any sample were selected, compared to 17 remaining in analysis of May samples. Similarity and dissimilarity breakdown indicated that both groups were dominated by small flagellates/monads and microzooplankton but that abundances between the groups varied greatly. Variation in abundance of these two species categories accounted for a total of 48% of the dissimilarity. The group of samples having the highest abundance of small flagellates and microzooplankton also had higher abundances of dinoflagellates from the *Ceratium*, Peridiniales and Gymnodiniales groups, while the second sample group had higher numbers of the diatom *Rhizosolenia*.

Comparisons of offshore phytoplankton patterns with environmental variables gave maximum correlation with temperature alone (r = 0.325). All nutrients now showed small negative correlations, possibly due to uptake by phytoplankton cells. Samples from the low cell abundance / diatoms group tended to be from transit sites or sites to the west of the grid between north Isle of Man and St Bees Head. High cell abundance / dinoflagellate group sites were most typically found at the northern and southern extremities of the grid. These areas possibly reflected areas bordering stratified regions and nutrient influx, from the Solway Firth to the north and Liverpool Bay to the south.

SUMMARY

Major spatial and temporal trends

In winter and early spring environmental variables generally showed inshore (English coast) to offshore trends with lower salinity, lower temperature, higher nutrient water inshore. The influence of the freshwater discharge via the Solway Firth on nitrate, silicate and salinity distribution was particularly marked at this time. Phosphate concentrations were highest around Whitehaven and St Bees Head on all sampling dates. By May penetration of low salinity water was much reduced. In May nitrate and silicate concentrations were highest offshore but by July highest levels were once again inshore.

Levels of nitrate and silicate generally reflected a combination of coastal inputs and patterns of phytoplankton growth, being depleted inshore when chlorophyll *a* levels were at their highest in May. The spring increase in phytoplankton standing crop, as indicated by chlorophyll *a*, was seen first in inshore sites, especially associated with the major estuaries (April). Levels of all nutrients were reduced during May and July, but levels of inorganic nitrogen were particularly low in July in comparison to winter values.

Nutrient concentrations often showed considerable variation with depth. In particular, higher levels were associated with surface water in salinity stratified areas in March and lower concentrations associated with surface water when thermal stratification was established in July. Two main areas of stratification were present in both March and July, one to the north and one to the south of St Bees Head, lying more or less centrally between the Isle of Man and the English coast. In July in particular the southern area of stratified water ran parallel to the coast and coastal fronts may be present. Such fronts might affect the dispersion of coastal discharges.

Concentrations of nutrients at more southern sampling sites, and seasonal trends, generally showed good agreement with results from long term monitoring stations (Shammon *et al* 1995) situated along the 54°N parallel and 5km off the south east of the Isle of Man (the Bayrnagh Station). Nutrients at 54°N stations in January were slightly higher than those from southern sites at similar longitudes on the March Cumbrian coast cruise. In general, however, comparisons indicated that transit sites to the extreme south west of the sampling area were typical of surface samples in more open areas of the Irish Sea in winter and early spring. Seasonal variations in nutrients at the Bayrnagh Station in 1995 indicate that levels of orthophosphate and silicate may have been at winter maximum levels in March, but that the nitrate maximum may have occurred earlier in the year (January). Comparisons of data from 1995 with previous years suggests that the degree of thermal stratification encountered to the east of the Isle of Man in July may have been unusually strong. This is perhaps likely, due to the very warm summer of 1995.

Phytoplankton was generally dominated by diatoms from winter to late spring, while in July small flagellates/monads, microzooplankton and dinoflagellates were more important. In May a continuum of phytoplankton community types was seen from dinoflagellate dominated to diatom dominated sites. Dinoflagellate dominated sites were found mostly in southern inshore sites. In July, sites to the central northern and southern extremes of the study area had higher phytoplankton densities, dominated by small cells, microzooplankton and dinoflagellates while more offshore (south west) and well mixed (west from St Bees Head) sites had lower cell densities and higher proportions of diatoms.

Agreement between distribution of total phytoplankton cell counts and chlorophyll a concentration was sometimes poor. This is possibly due to the varying chlorophyll content with phytoplankton species or with cell condition or size. It is also possible that very small cells were present which were missed by counting, but retained by filtration of water for chlorophyll analysis. Where a positive correlation was found between nutrients and indicators of phytoplankton biomass, this was normally stronger for chlorophyll than for counts.

One particular restriction with the spatial distributions indicated by this work is that phytoplankton, chlorophyll and nutrient distributions are described mainly in terms of surface samples only. Variations in all these parameters will occur with depth due to both physical stratification of the water column and biological migration. Hence the results obtained will depend to some extent on sampling depth, time of sampling and degree of mixing of the water column.

Evidence of impact of nutrient inputs

Evidence of riverine inputs of nutrients, particularly nitrate and silicate, was most obvious in winter/early spring. The influx of nutrients with water movement from the south was not apparent in contour diagrams for any nutrient. The effect of the Albright and Wilson discharge was evident in the distribution of phosphate concentrations on all sampling dates. The influence of the BNFL Sellafield discharge on inorganic nitrogen was not clear, no local elevation being seen in March samples, but some evidence of this in late spring and summer. The exact interpretation of contour lines should be carried out with care however, as samples were not taken in close proximity to the discharge and small localised effects may therefore have been missed. The discharge regime may also influence results if the rate of discharge is variable.

No changes in community structure or density of phytoplankton cells occurred which could be clearly linked to nutrient inputs or other individual environmental variables. Relationships of phytoplankton with environmental variables are likely to be complex, interrelated and seasonally variable. Hence it is difficult to separate the effects of nutrient inputs, except under extreme circumstances. In this study examination of contour diagrams and statistical analysis indicate that phytoplankton communities may be more closely linked to physical properties, such as stratification and temperature, than to nutrient concentrations, although the associations in all cases are far from clear.

While no increases in phytoplankton cell counts were observed close to major nutrient discharges, increased chlorophyll *a* levels were seen around Sellafield in May, and less obviously, in July. While no changes in phytoplankton community structure were observed that could account for this anomaly, chlorophyll content is known to vary with the condition of cells so it is possible that chlorophyll content was affected by nutrient inputs. Also only cells greater than 5μm were counted, so that chlorophyll peaks could be due to high densities of cells smaller than this.

Under the guidelines of the Comprehensive Studies Task Team of the Marine Pollution Monitoring Management Group (1994) an area is deemed not to be adversely affected by nutrient inputs if, amongst other factors, there are no observations of summer dissolved available inorganic nitrogen (= nitrate+nitrite+ammonia) greater than 12 mmol m^{-3} (or approx 170 µg l^{-1}), in the presence of at least 0.2 mmol m^{-3} DAIP = orthophosphate; or there or no observations showing summer chlorophyll > 10 mg chl m^{-3} (i.e. >10µg l^{-1}). From only two summer sampling occasions (late May and July) in this study DAIN levels were below this critical value at all sites although one inshore site in May approached this level (156 µg l^{-1}). Chlorophyll concentrations exceeded 10 µg l^{-1} at one inshore site in May (10.9µg l^{-1}, between Sellafield and Ravenglass estuary) and chlorophyll > 6µg l^{-1} was present at some sites more than 6 nautical miles offshore. The highest inshore chlorophyll recorded in July was 7.9µg l^{-1}. As only two summer samples were taken it is possible that chlorophylls in excess of the 10 µg l^{-1} guideline were present on other occasions in the summer. Levels > 10 have been recorded by NRA coastal surveys in this area. A single chlorophyll value in excess of 10 µg l^{-1} does not necessarily indicate a eutrophic water body and such high values have been occasionally recorded at the Cypris Station, away from any immediate nutrient inputs.

Occurrence of nuisance phytoplankton species

No evidence of severe phytoplankton blooms or dominance of plankton by nuisance species was present in samples taken, or from observations made during the cruises. While samples were taken on only four cruises throughout the plankton growth season, blooms of phytoplankton were recorded from other areas of the Irish Sea around the time that cruises were taken. Most notably, dense *Phaeocystis* blooms were present in the Liverpool Bay area during May and localised 'red tides' of *Noctiluca scintillans* were recorded from both the north east and west coasts of the Isle of Man in late July. These species were present in low numbers in a limited number of samples only. The potentially toxic dinoflagellates *Dinophysis acuta* and *Dinophysis acuminata* were recorded in July from routine monitoring sites off the south west and south east coasts of the Isle of Man. In August at the Cypris station, to the south west of the island, densities of up to 4000 l^{-1} were present (Shammon *et al* 1995), levels which have occasionally resulted in diarrhetic shellfish poisoning at other European sites. These two species were present in low to moderate numbers at all offshore and most inshore sites in July. Maximum densities (up to 5600 l^{-1}) were present at sites 46E and 47 at the east of the offshore grid, offshore from Drigg point. While such moderate densities have caused problems in shallow waters, the greater water depth, often variable vertical distribution, absence of major bivalve fisheries and only occasional toxicity of the species did not give rise to serious concerns in this area.

Future considerations

The designation of a HNDA takes account of the current state of the local marine environment and its apparent response to sewage inputs. Industrial nutrient inputs and their likely future trends are not considered. The north east Irish Sea off the Cumbrian coast receives substantial inputs of both nitrogen and phosphorus from industrial sources. According to company information, the phosphorus input from Albright and Wilson, Cumbria will decrease (or has already decreased) substantially from pre-1992 levels. This discharge is currently responsible for approximately 59% of major phosphorus inputs (estimate from NRA 1995 figures). The BNFL Sellafield input of nitrate is, however, set to increase substantially in the near future, possibly to increase total nitrogen inputs from all sources by 29% if the consent limit is reached and all other inputs remain the same. Therefore it is possible that the ratios of major nutrients entering this area will change significantly over the next few years, with N:P, N:Si and Si:P ratios increasing. Such changes in nutrient ratios may have a considerable impact on phytoplankton communities (Justic *et al* 1995). While a higher Si:P ratio is thought to favour diatom over non-diatom (flagellate) dominated communities (references in Smayda 1990), increasing N:Si may have the opposite effect (Ryther & Officer 1981) and increasing N:P and N:Si possibly select for smaller algal species (Capriulo *et al* 1993). Altered nutrient ratios in coastal waters can therefore favour blooms of nuisance flagellate species and additionally may cause normally non-toxic species to become toxic (Hallegraeff 1993 and references therein). Nitrogen is generally considered to be the most limiting nutrient in the marine environment and increasing the amount of nitrogen entering coastal waters might possibly fuel eutrophication (Ryther & Dunstan 1971).

The aim of this study was to identify spatial trends in the nutrient and phytoplankton status of the north east Irish Sea off the Cumbrian coast. this work will be continued over the following year (1996). The aim of the next phase of the work will be more directed at identifying causal relationships between environmental parameters (including nutrients) and summer phytoplankton communities. A major problem here is the often confounding effects of environmental factors in inshore waters, where higher nutrients are frequently associated with lower salinities, higher temperatures and a shallower mixing zone.

While the study described in this report identified no strong links between phytoplankton communities and nutrient inputs, it is the result of a limited number of sampling occasions in a single (climatically unusual) year. Further work will give some indication of inter-annual variation and will increase the reliability of any conclusions drawn from this research.

CONCLUSIONS

- On all sampling occasions orthophosphate concentrations were highest around Whitehaven and St Bees Head.

- Winter nitrate was highest towards the Solway Firth and along the northern Cumbrian coast. In July highest levels (max. 67 $\mu g\ l^{-1}$) were recorded south of St Bees Head and off the Ravenglass estuary.

- Both winter (haline) and summer (thermal & haline) stratification was seen over large areas of the north east Irish Sea, with possible implications for local dispersion. Results from long term monitoring stations suggest that thermal stratification was unusually strong in summer 1995 compared to previous years.

- Marked vertical variations in nutrient concentrations were seen in summer stratified areas, with higher levels below the pycnocline.

- Strong positive correlations were seen between winter nutrients (TON and silicate) and both chlorophyll *a* and phytoplankton total cell counts in July, but no significant correlations were found between nutrients and any planktonic indices for May.

- The distribution of phytoplankton species assemblages did not show any clear relationship to patterns in nutrients or other environmental parameters.

- Summer chlorophyll concentrations were markedly higher along the Cumbrian coast than areas offshore. In May highest concentrations (max. 10.9 $\mu g\ l^{-1}$) were found towards the Solway Firth and around Sellafield. In July highest levels (max. 7.9 $\mu g\ l^{-1}$) were found along the coast between Maryport and just south of Sellafield.

- The plankton in March to May was dominated by diatoms of the *Nitzchia*, *Asterionella* and *Chaetoceros* groups. In July small cells < 15µm and microzooplankton were more important.

- No evidence of severe blooms of nuisance species were noted on the limited number of sampling occasions.

- A good representation of the spatial patterns in nutrients and phytoplankton assemblages was achieved during the course of this work. Continuing surveys will concentrate further on the relationships between these parameters.

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FIGURES

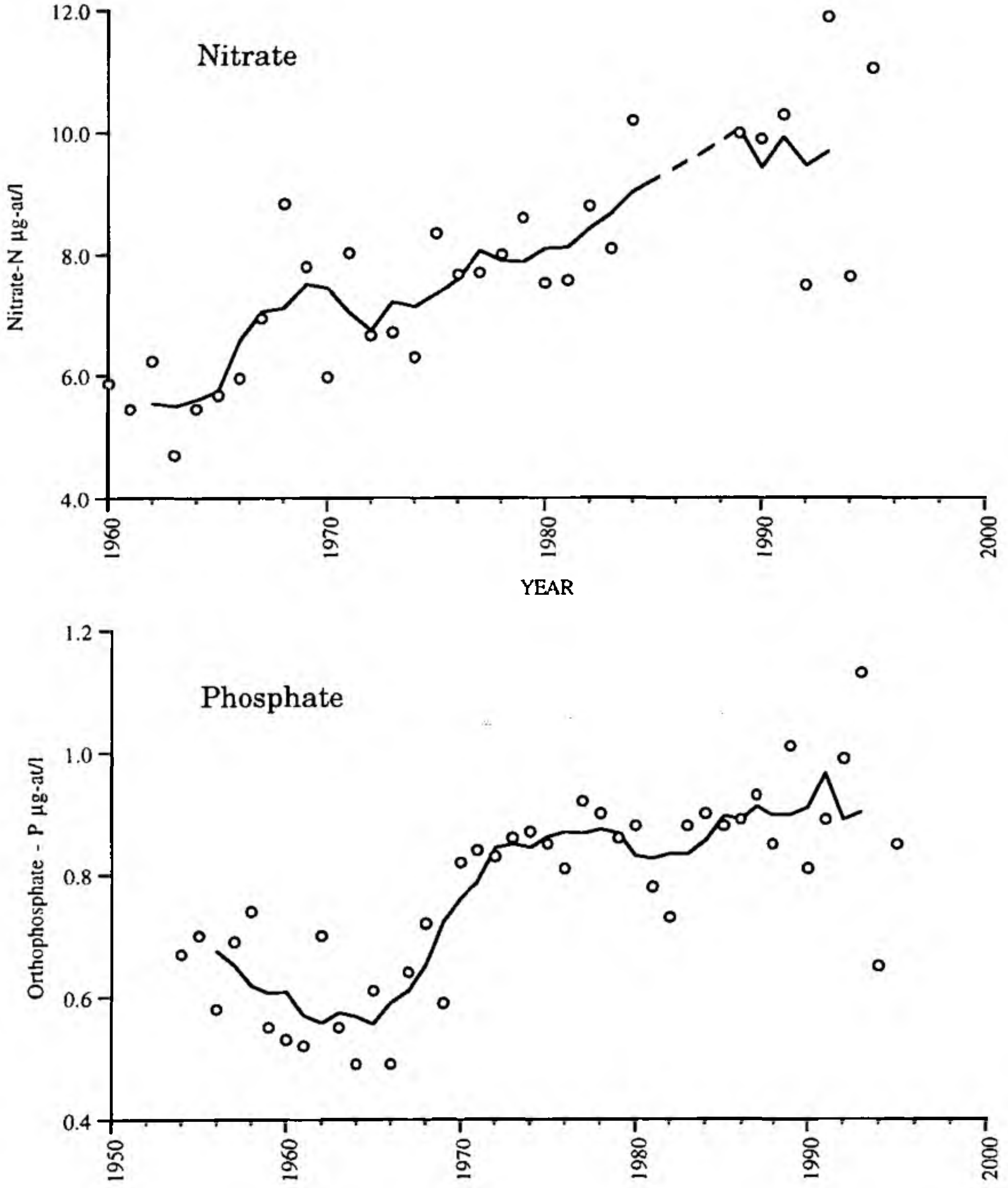


Fig. 1 Annual winter (Dec. to March incl.) maximum concentrations of nitrate (1960 to 1995) and phosphate (1954 to 1995), in surface water at the Cypris Station (open circles), with five year running means (line).

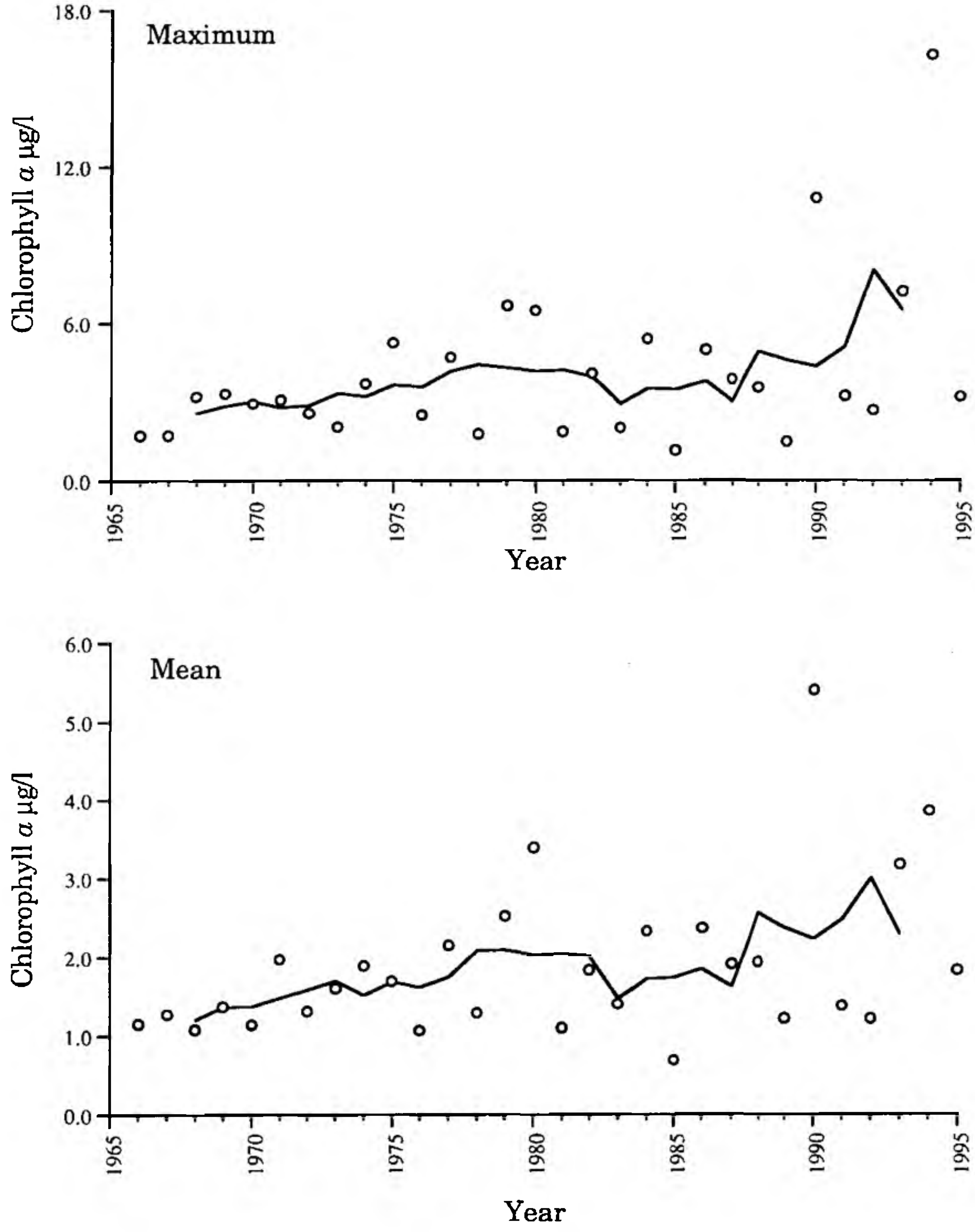


Fig. 2 Maximum and mean summer (April - August inclusive) chlorophyll *a* at the Cypris Station, surface water, 1966 to 1995. Individual yearly means (open circles) with five year running mean (line).

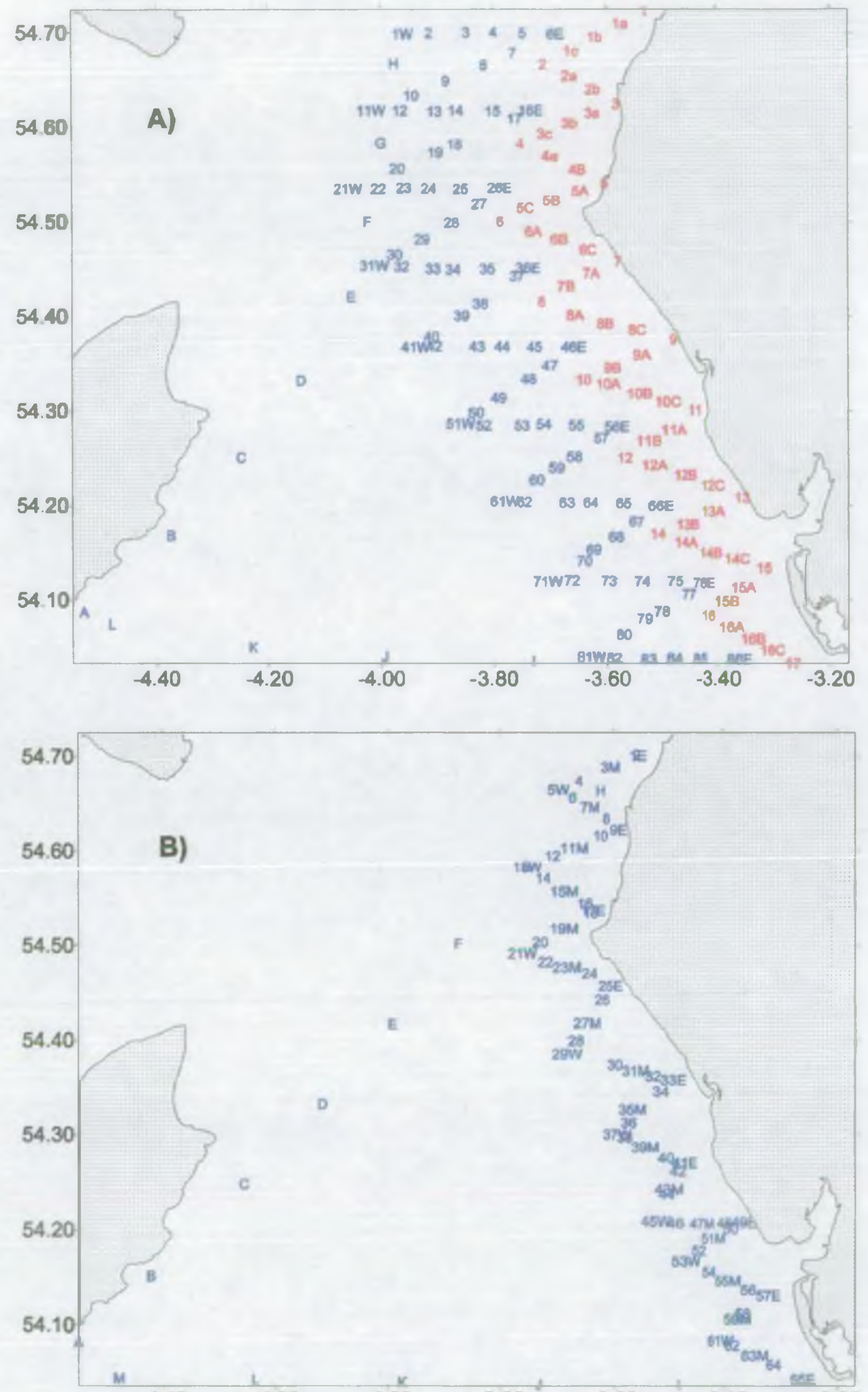
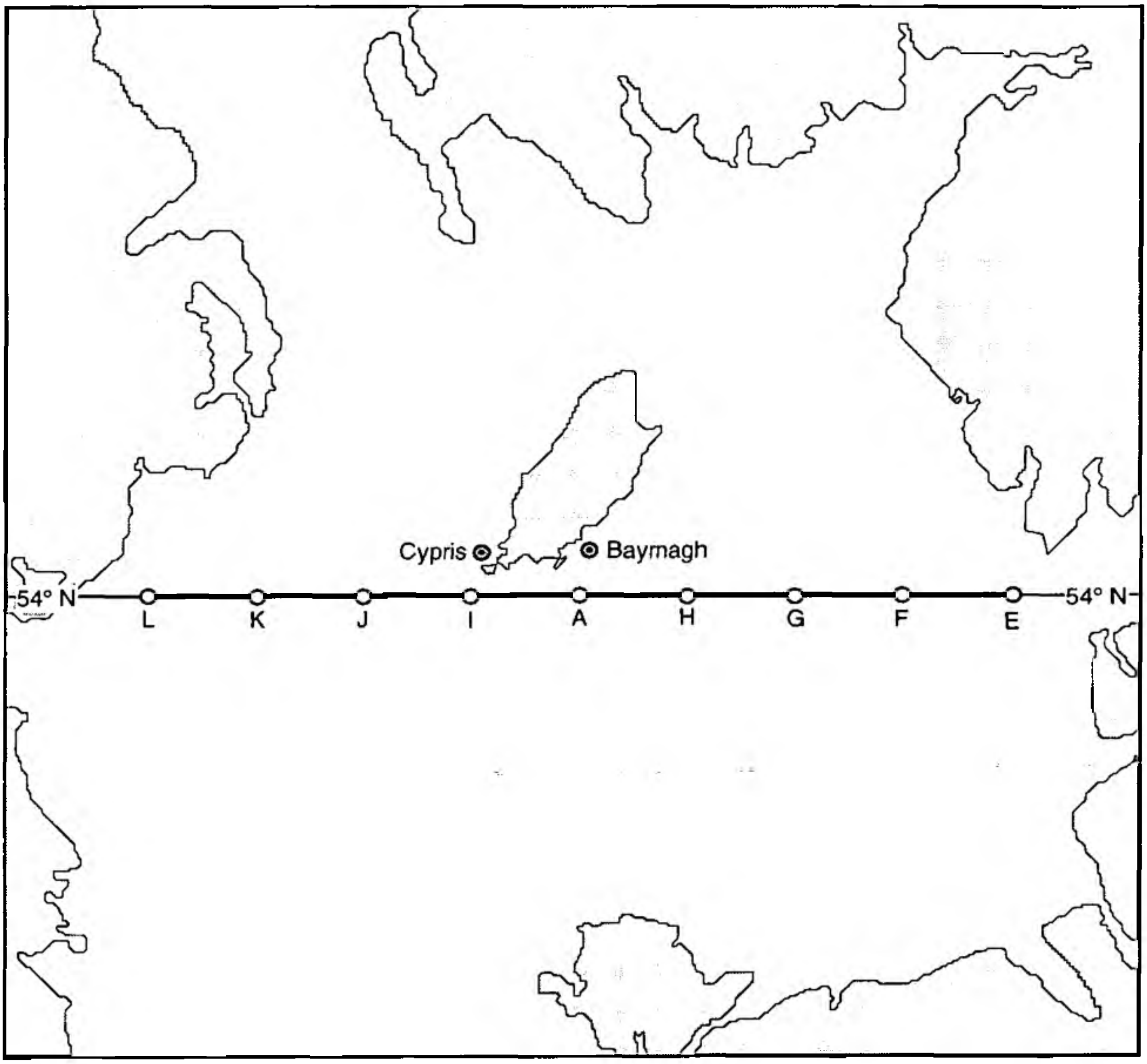


Fig. 3 A) Actual sampling sites and identifiers in May, nominal sites for March and July. Offshore grid (PEML) sites in blue. Inshore grid (NRA) sites in red. Samples on inshore grid in March followed the same cruise path but samples were taken every 2 minutes. For positions see appendix table A.
B) Positions of sample sites in April (PEML)



Site positions

Along 54 deg N parallel

	N	W
A	54 00	04 37
E	54 00	03 26
F	54 00	03 44
G	54 00	04 01
H	54 00	04 19
I	54 00	04 54
J	54 00	05 11
K	54 00	05 28
L	54 00	05 45

"Cypris Station"	54 05.5 N	04 50 W
"Bayrnagh Station"	54 05.0 N	04 30 W

Fig. 3 C)
Port Erin Marine Laboratory long term monitoring stations (nutrients).

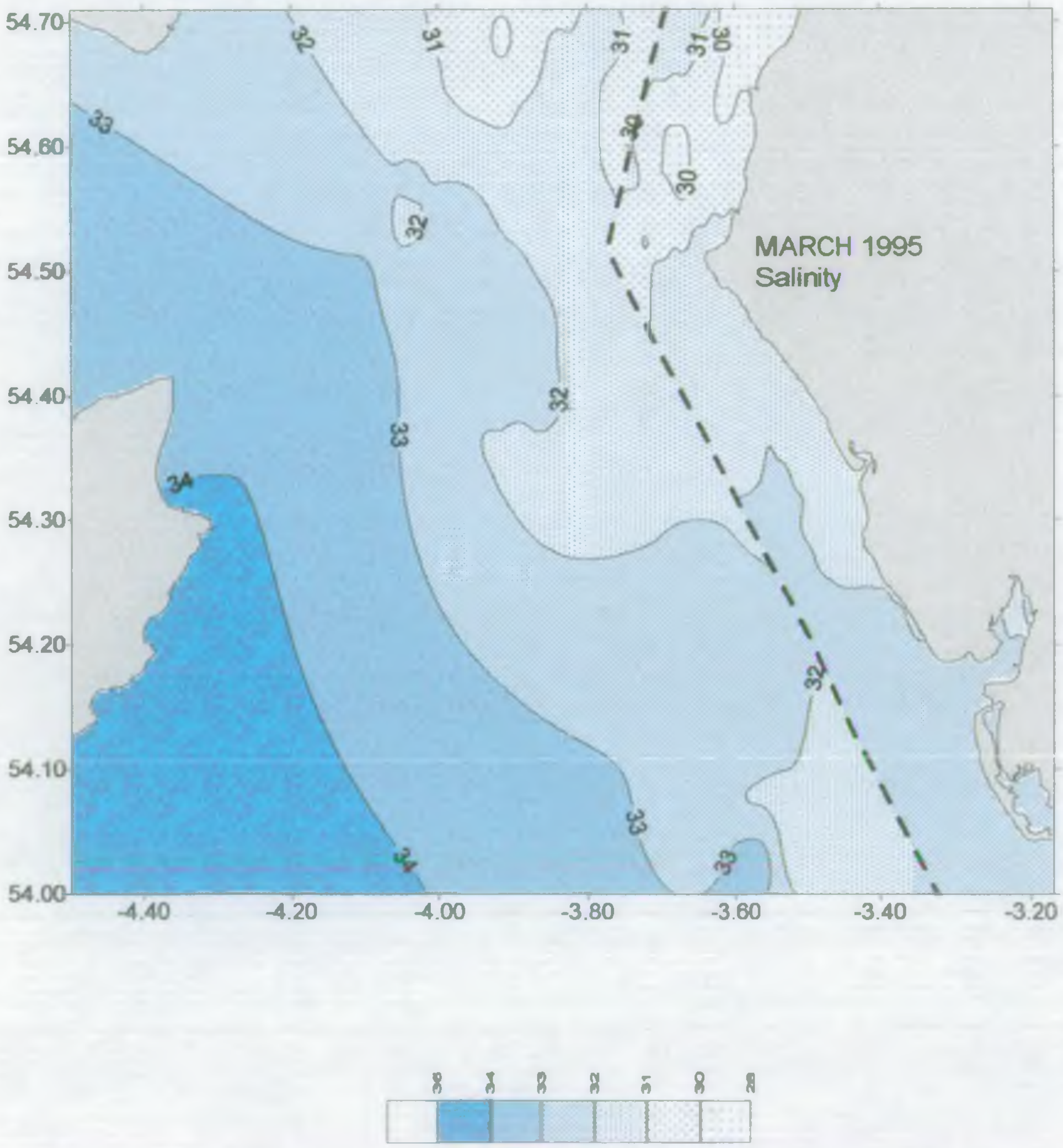


Fig. 4 Salinity (psu) in the eastern Irish Sea March 1995.
Contours west of the dashed line are derived from PEML samples (02/03/95).
Contours east of the dashed line are derived from NRA samles (20/03/95).

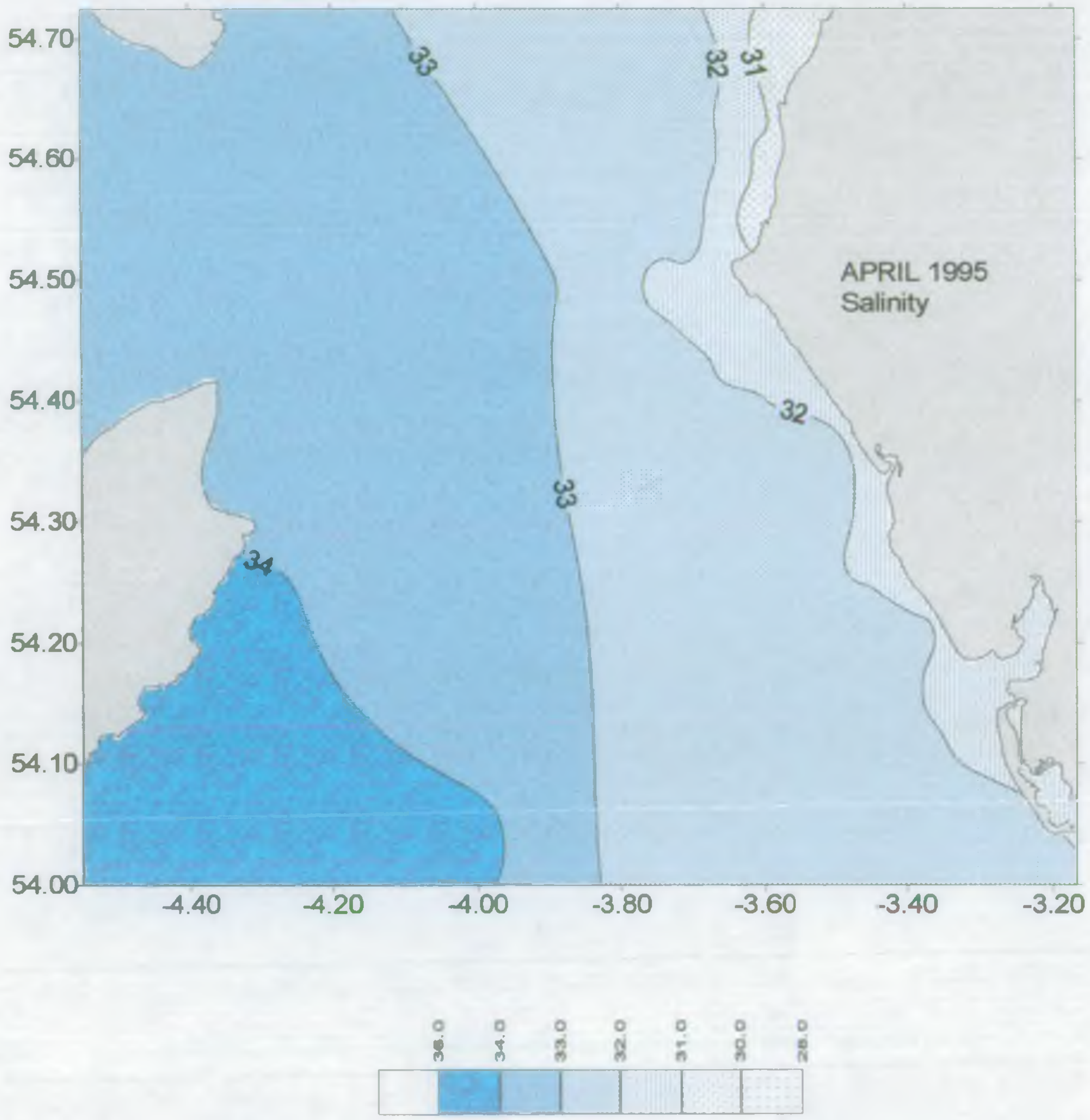


Fig. 5 Salinity (psu) in the north east Irish Sea 3rd April 1995 (PEML samples only)

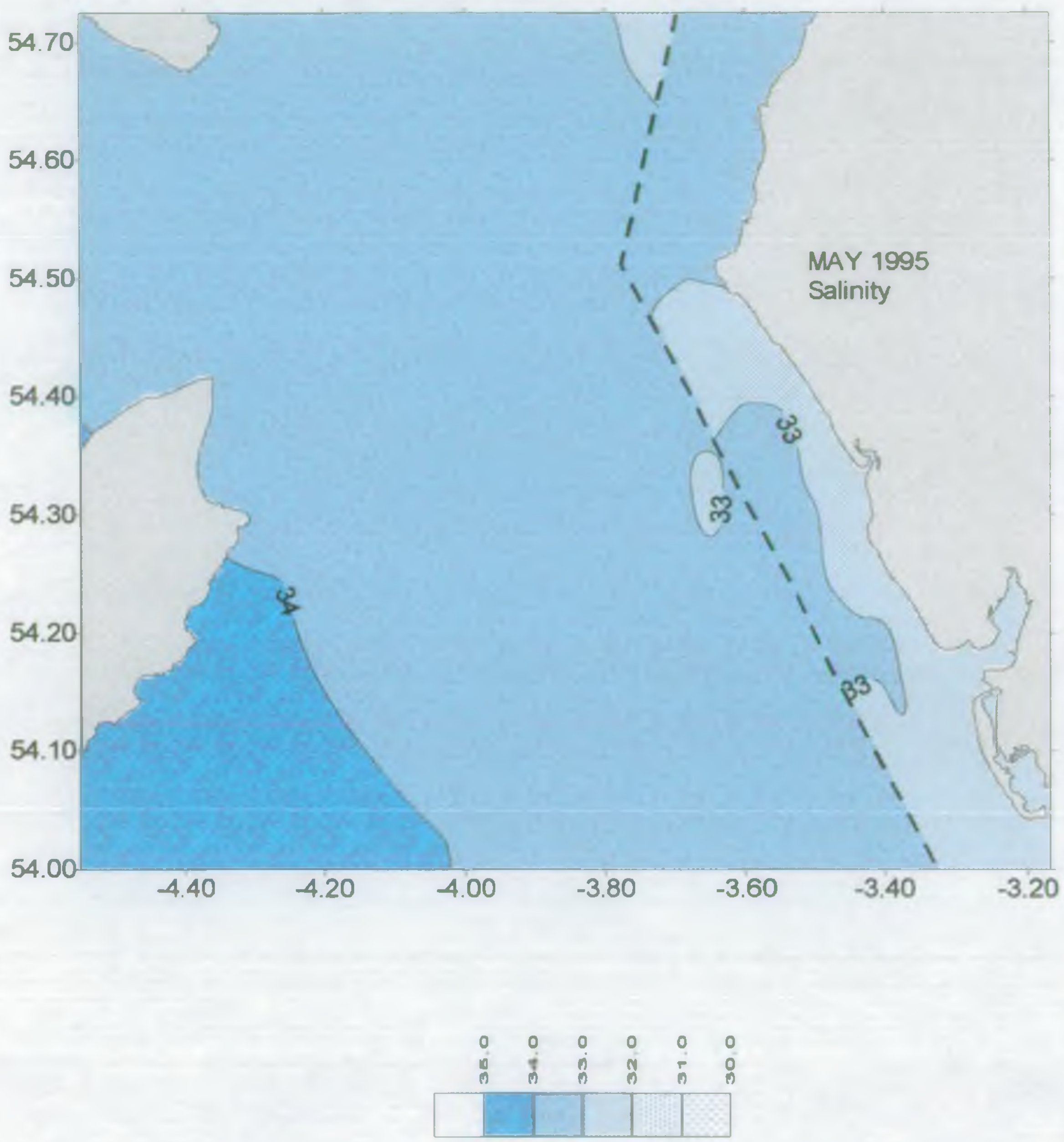


Fig. 6 Salinity (psu) in the north east Irish Sea May 1995
Contours west of the dashed line are derived from PEML samples (23/05/95).
Contours east of the dashed line are derived from NRA samples (31/05/95).

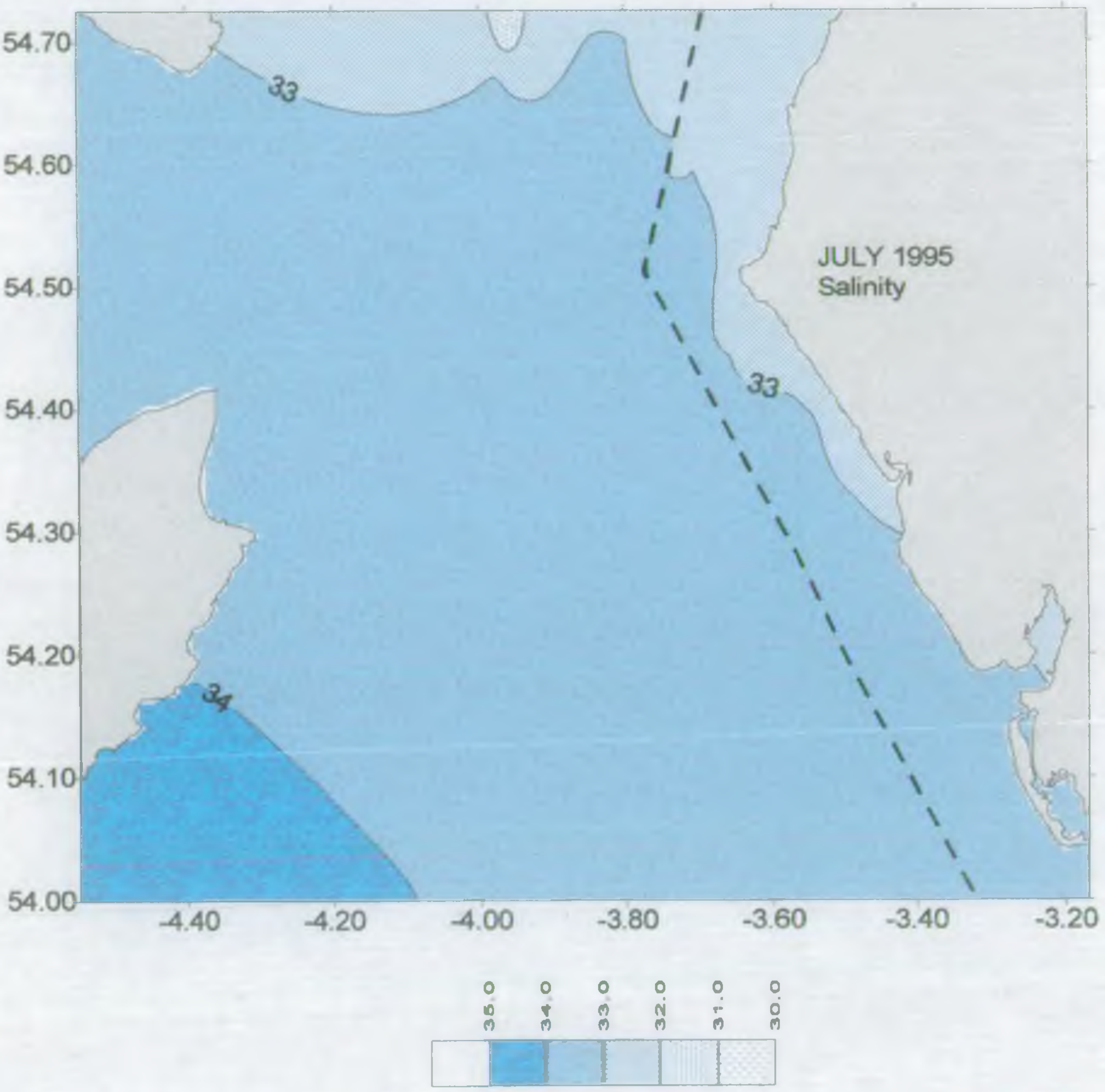


Fig. 7 Salinity (psu) in the north east Irish Sea July 1995.
Contours east of the dashed line are derived from PEML samples (24/07/95).
Contours west of the dashed line are derived from NRA samples (24/07/95).

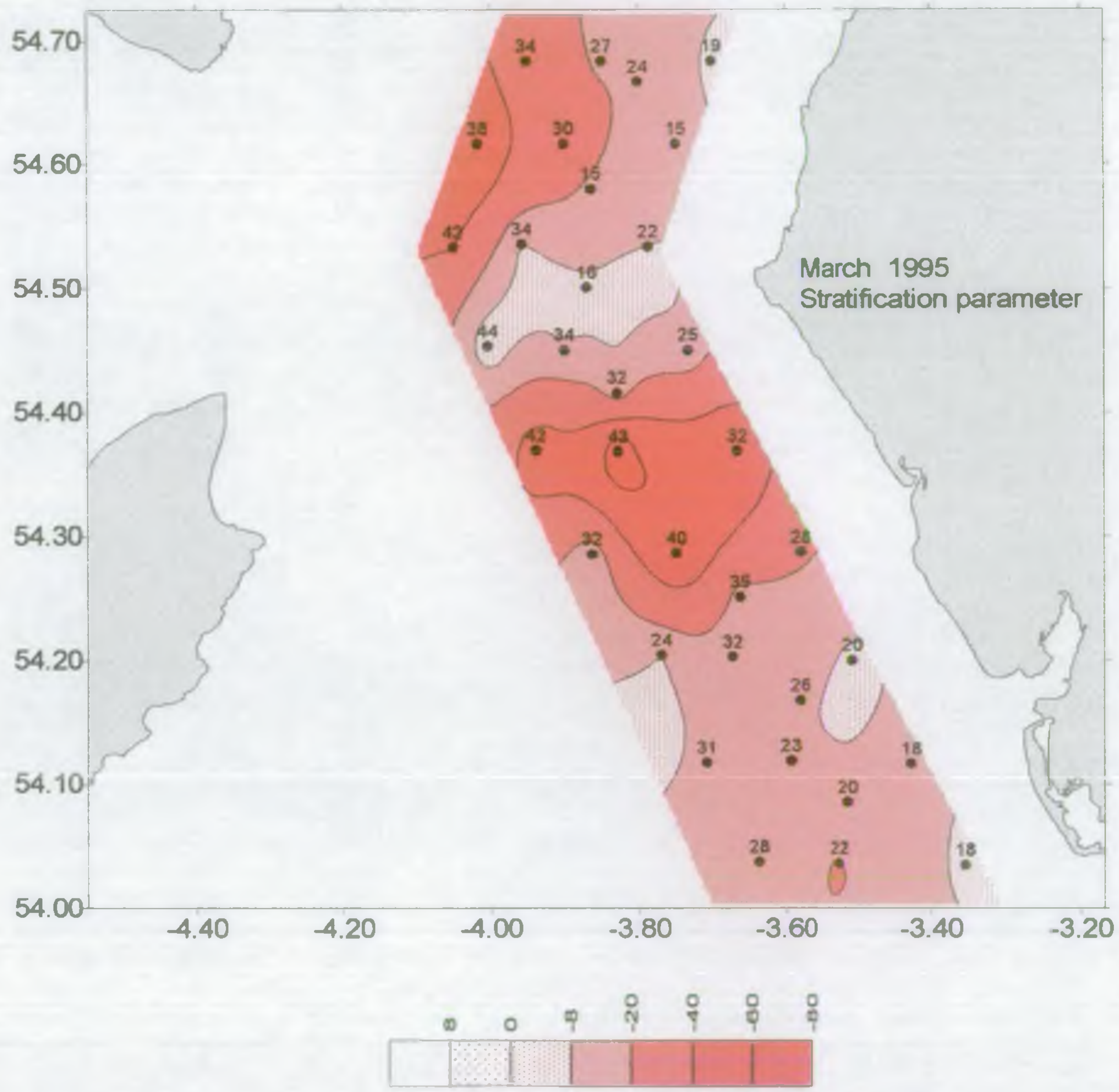


Fig. 8 Simpson's stratification parameter calculated from CTD data, 2nd March 1995. Position and depth (m) of casts are indicated.

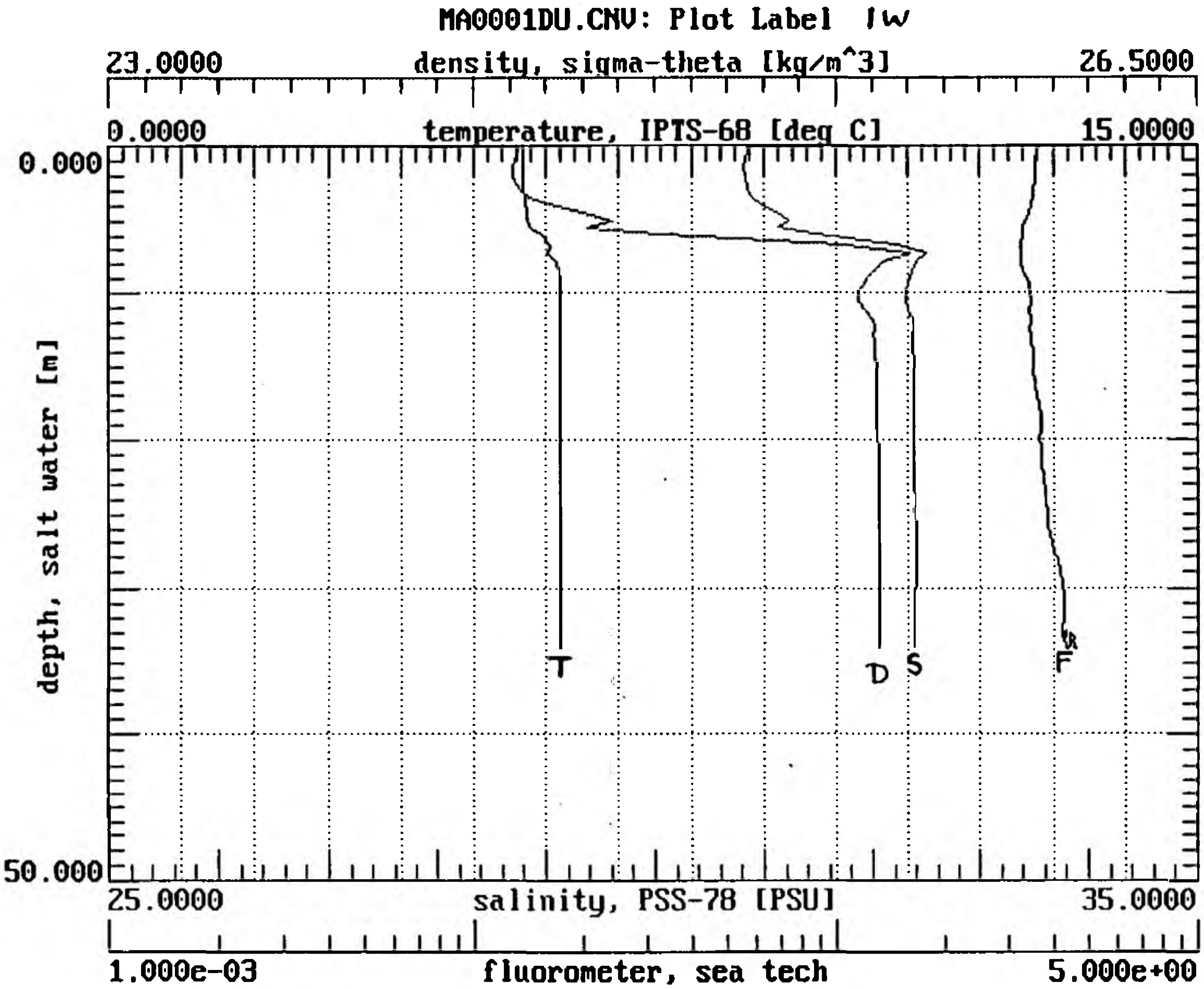


Fig. 9
Vertical structure of the water column in northern stratified region, March 1995, showing salinity stratification. Temperature, salinity, density and fluorescence from ctd cast (site 1W).

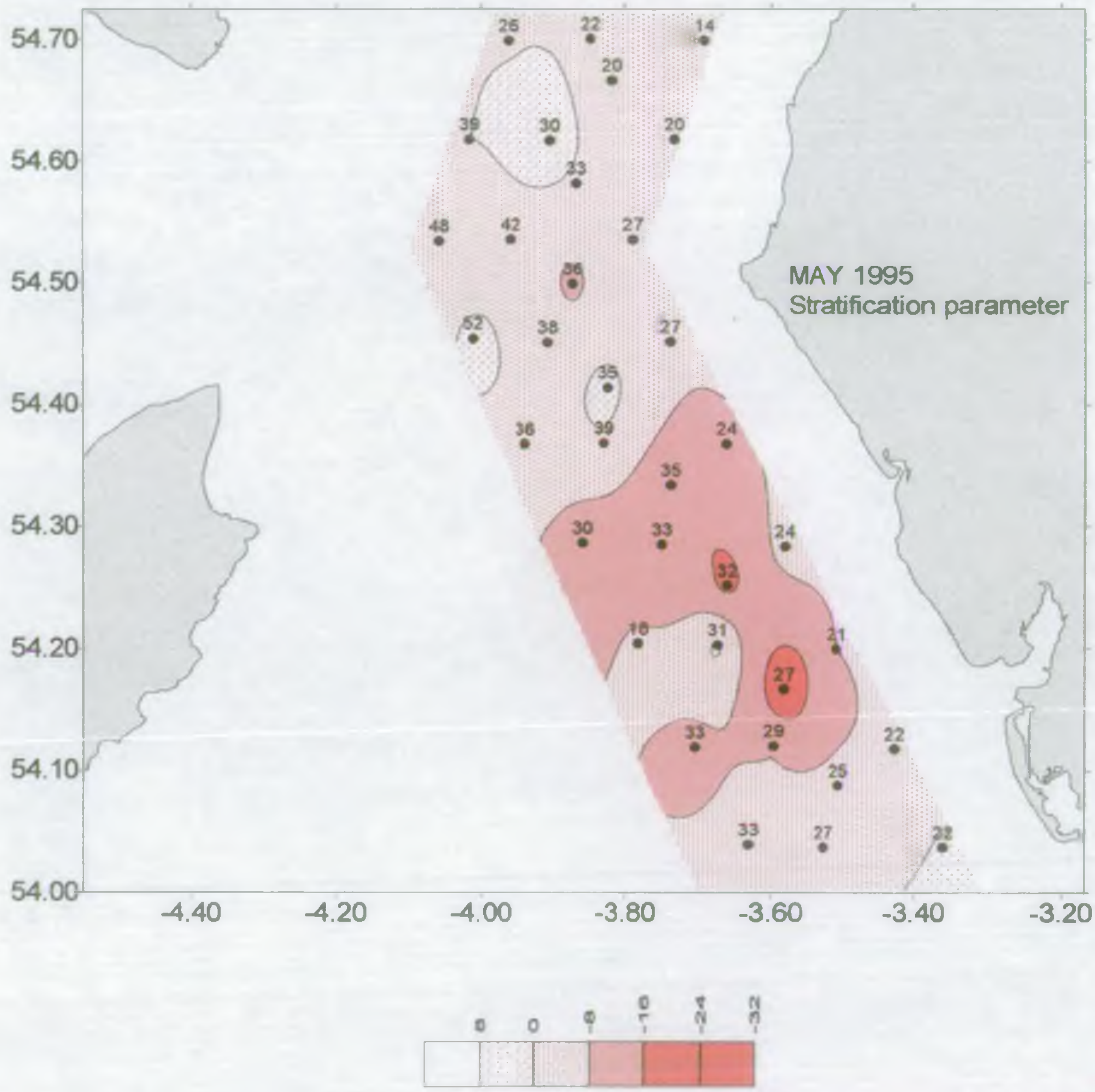


Fig. 10 Simpson's stratification parameter calculated from CTD data, 23rd May 1995. Position and depth of casts (m) are indicated.

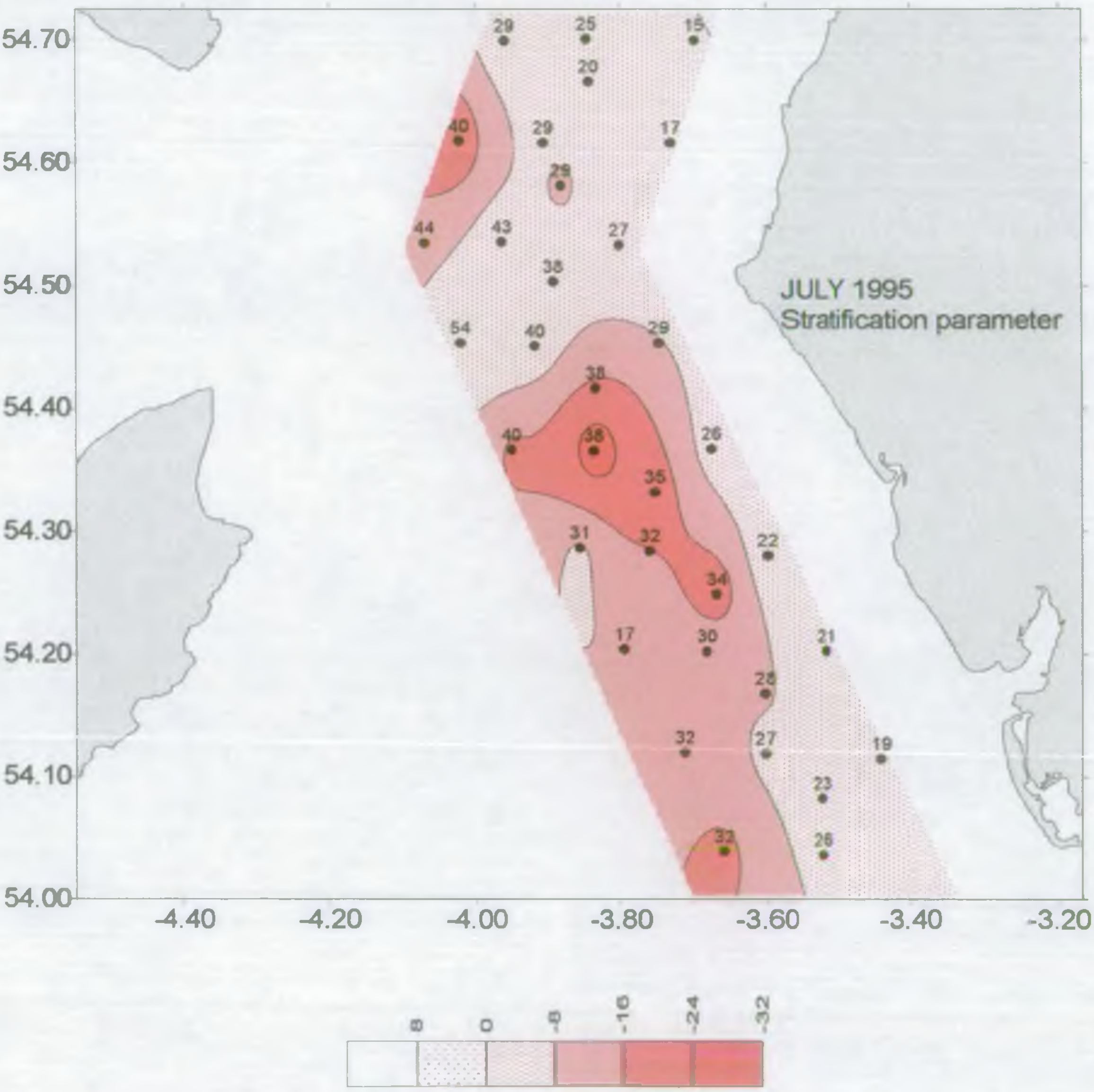


Fig. 11 Simpson's stratification parameter calculated from CTD data, 24th July 1995. Position and depth (m) of casts are indicated.

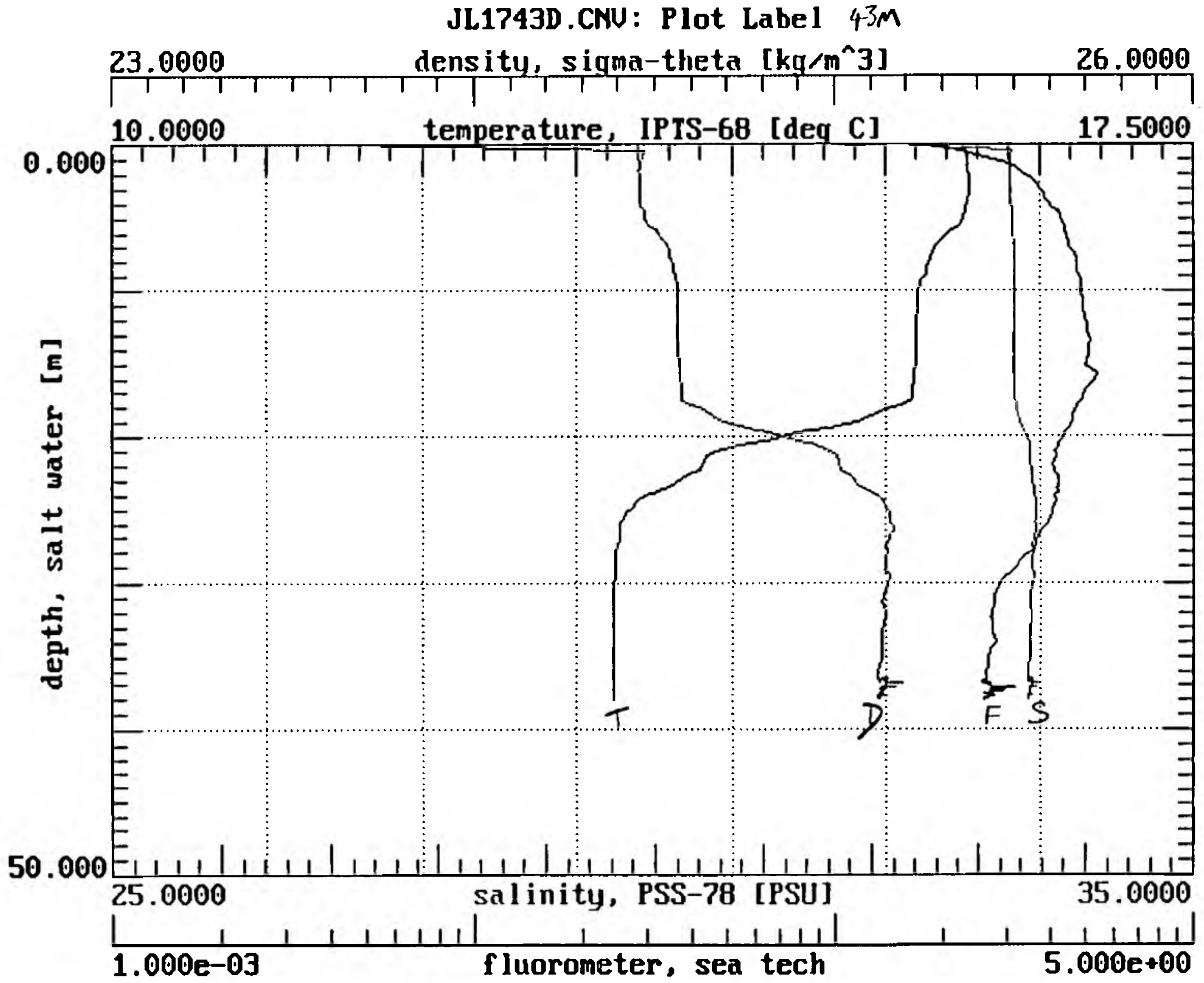


Fig. 12
Vertical structure of the water column in southern stratified region, July 1995, showing thermal stratification. Temperature, salinity, density and fluorescence from ctd cast (site 43M).

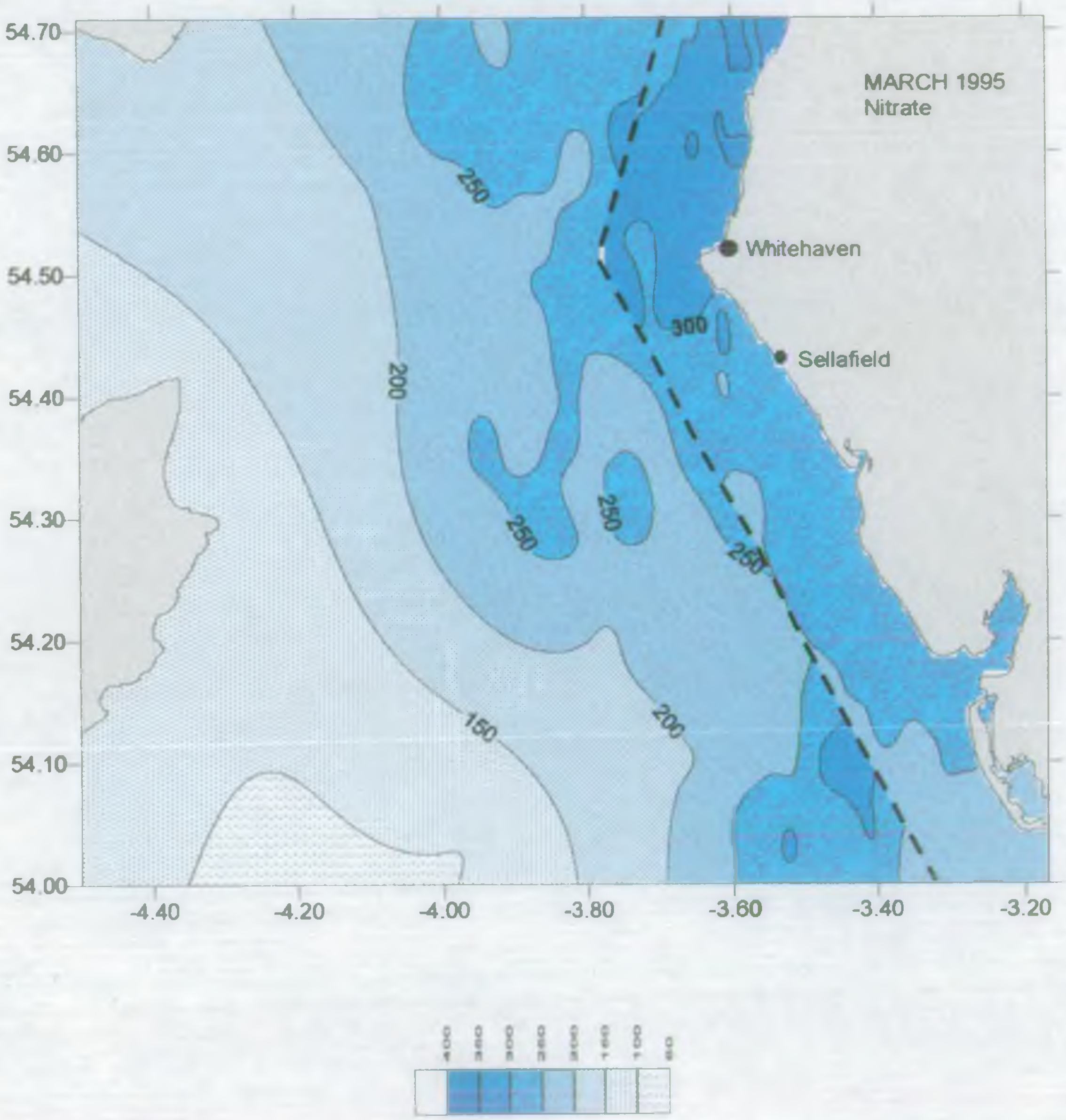


Fig. 13

Nitrate-N µg/l in the eastern Irish Sea March 1995.
Contours west of the dashed line are derived from PEML samples (02/03/95).
Contours east of the dashed line are derived from NRA samples (20/03/95).

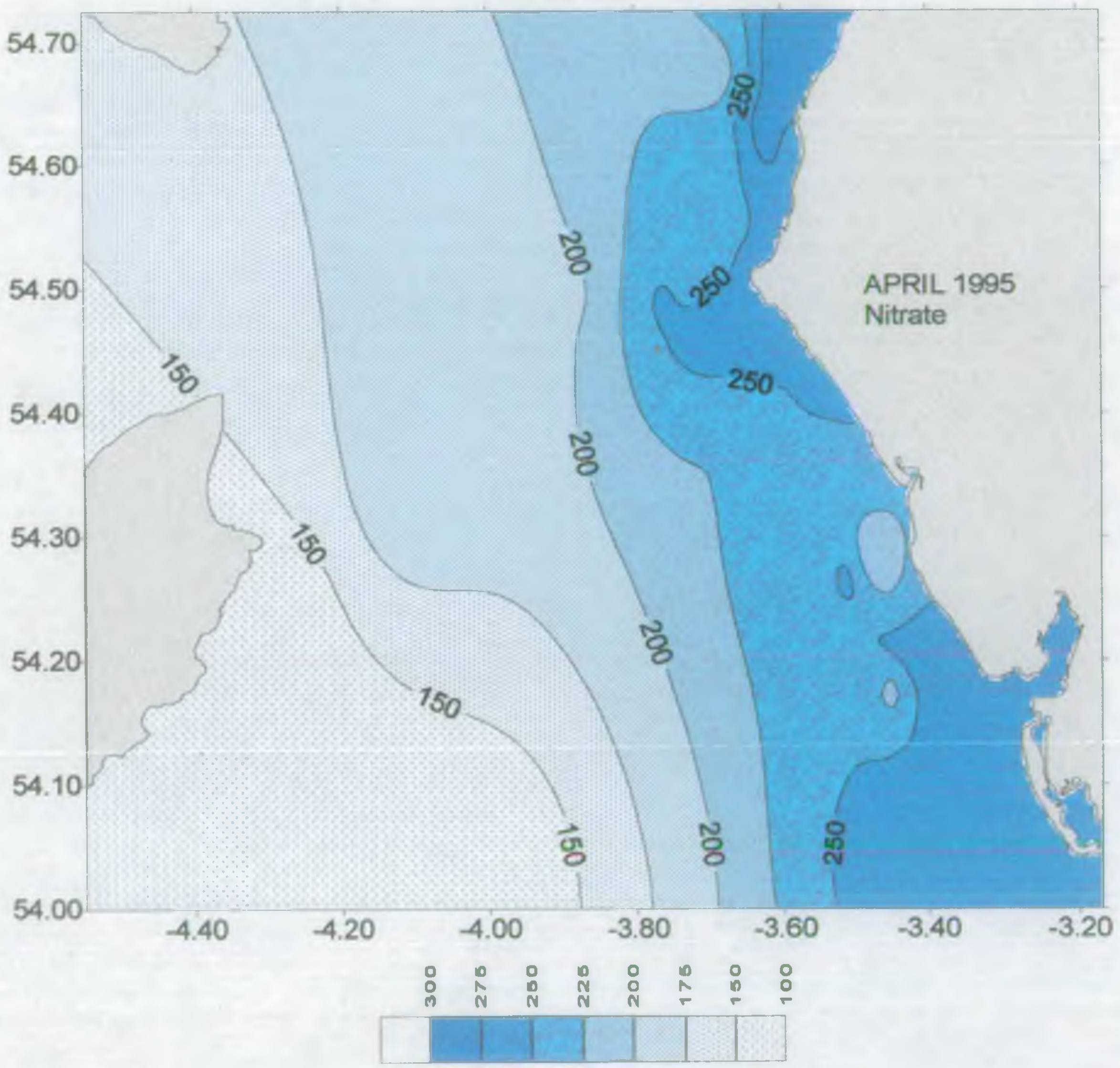


Fig. 14
Nitrate-N µg/l in the north east Irish Sea 3rd April 1995 (from PEML samples).

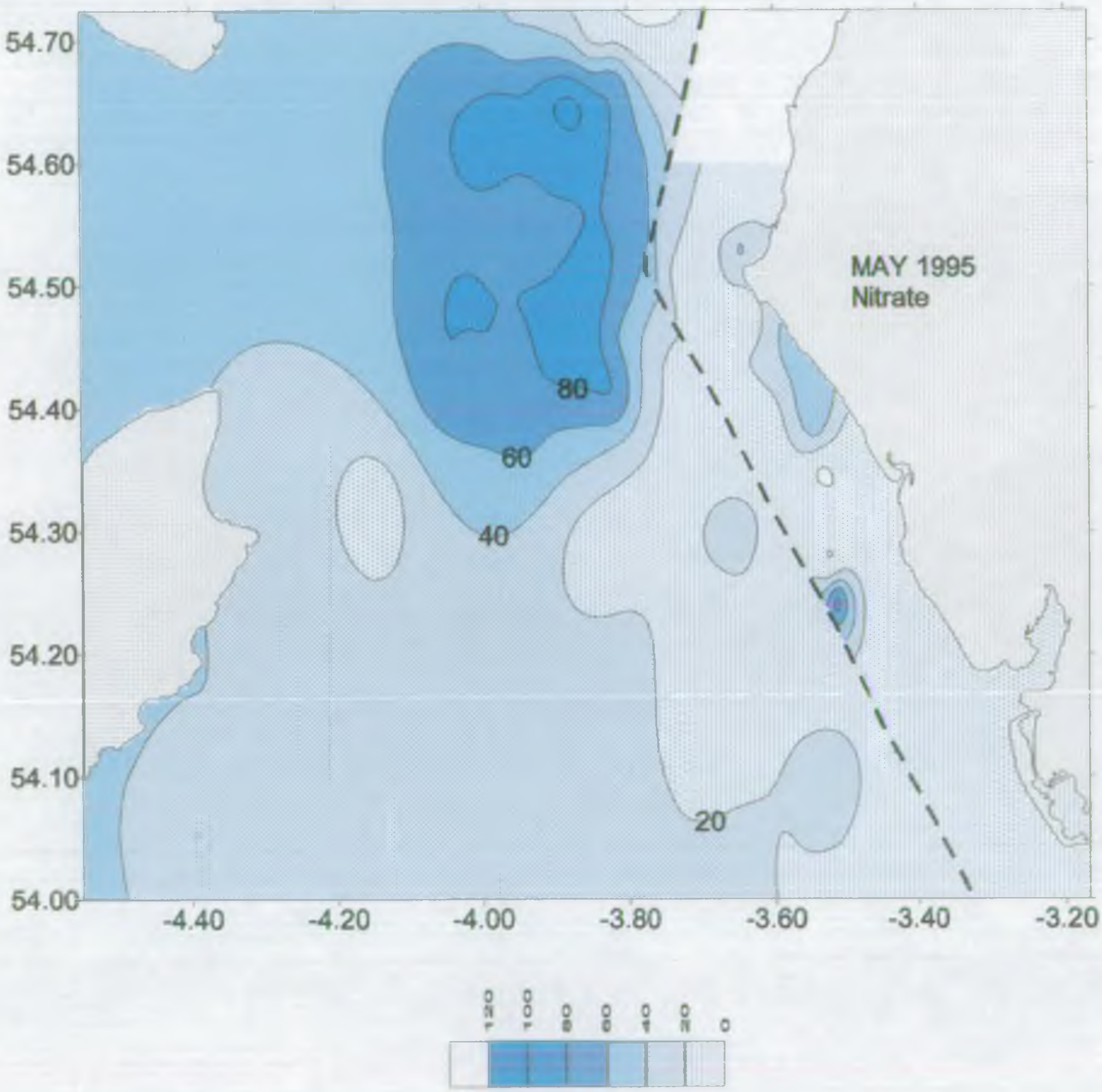


Fig. 15
Nitrate-N µg/l in the north east Irish Sea May 1995.
Contours west of the dashed line are derived from PEML samples (23/05/95).
Contours east of the dashed line are derived from NRA samples (31/05/95).

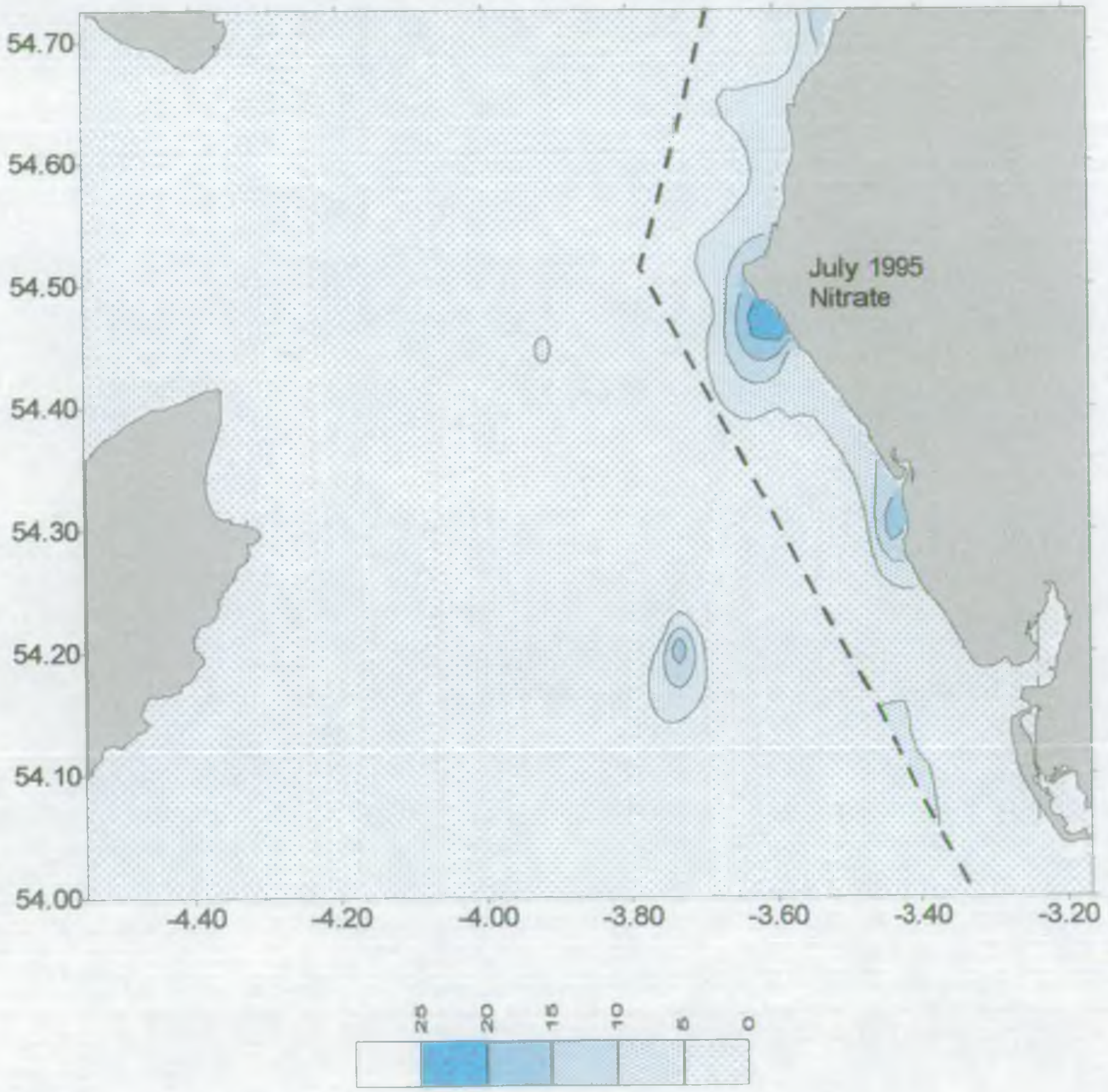


Fig. 16
Nitrate-N (µg/l) in the north east Irish Sea July 1995.
Contours west of the dashed line are derived from PEML samples (24/07/95).
Contours east of the dashed line are derived from NRA samples (24/07/95).

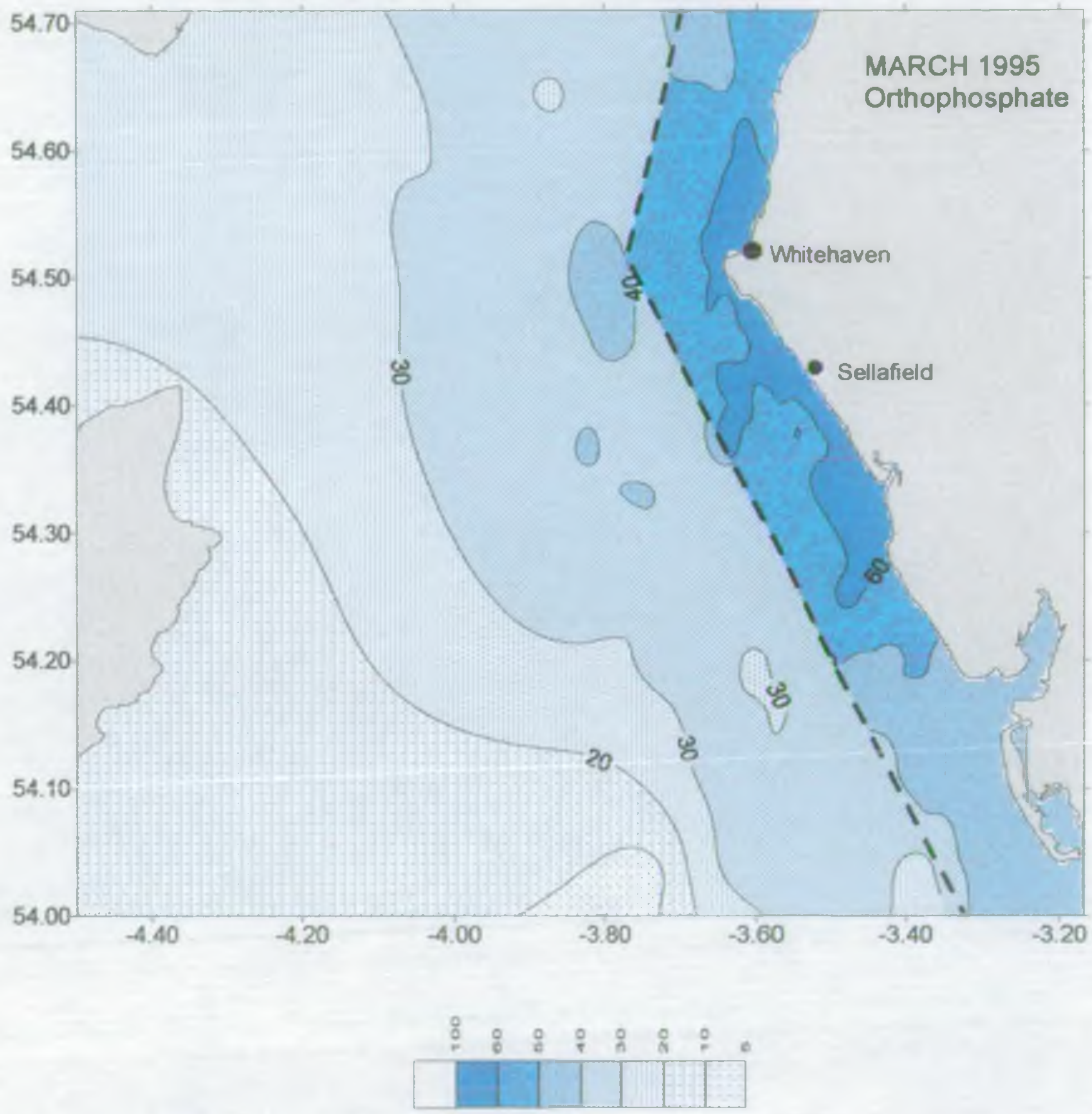


Fig. 17 Orthophosphate-P µg/l in the north east Irish Sea March 1995. Contours west of the dashed line are derived from PEML samples (02/03/95). Contours east of the dashed line are derived from NRA samples (20/03/95).

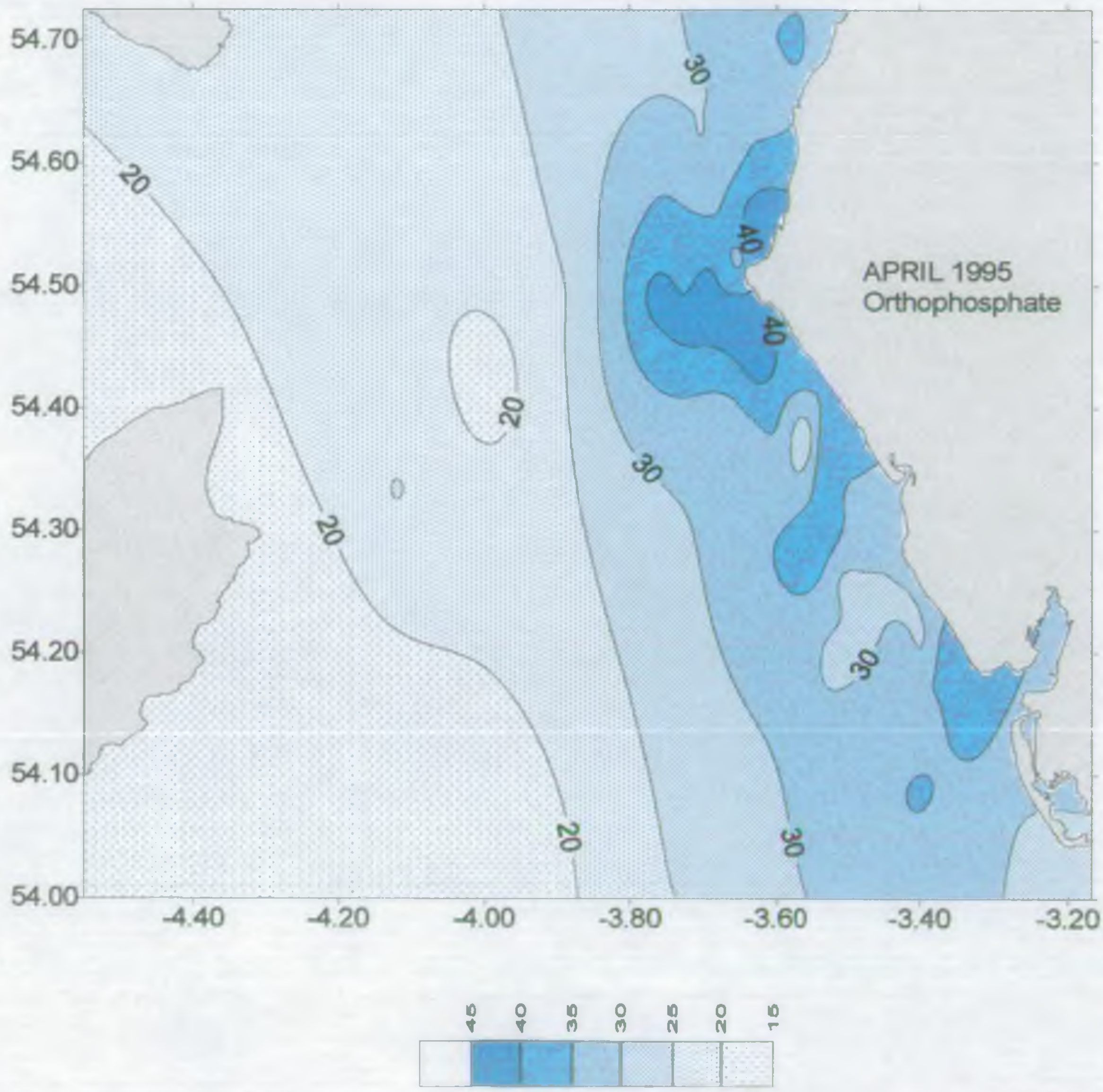


Fig. 18

Orthophosphate µg/l in the north east Irish Sea 3rd April 1995 (PEML samples).

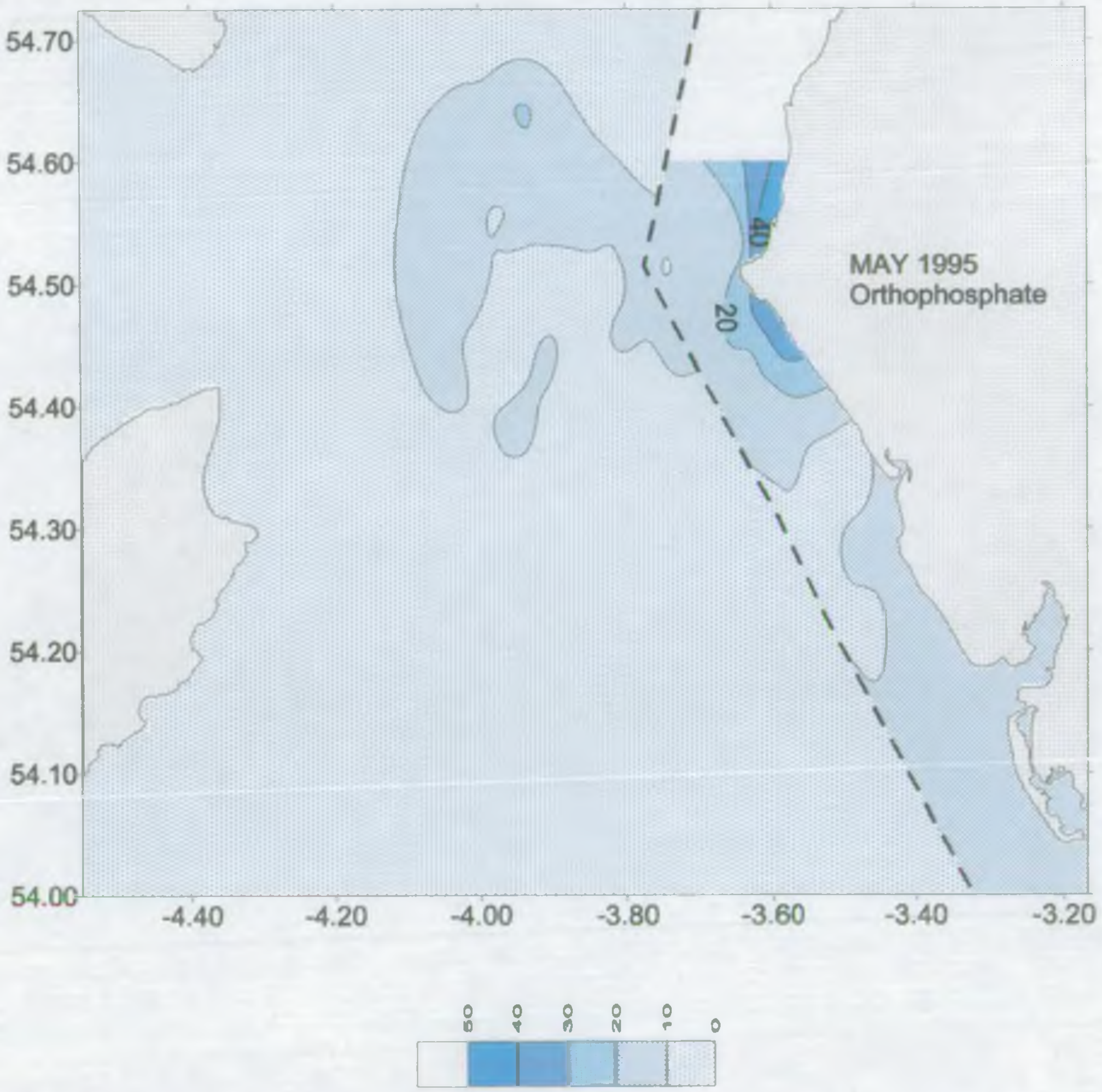


Fig. 19

Orthophosphate-P µg/l in the north east Irish Sea May 1995.
Contours west of the dashed line are derived fron PEML samples (23/05/95).
Contours east of the dashed line are derived from NRA samples (31/05/95).

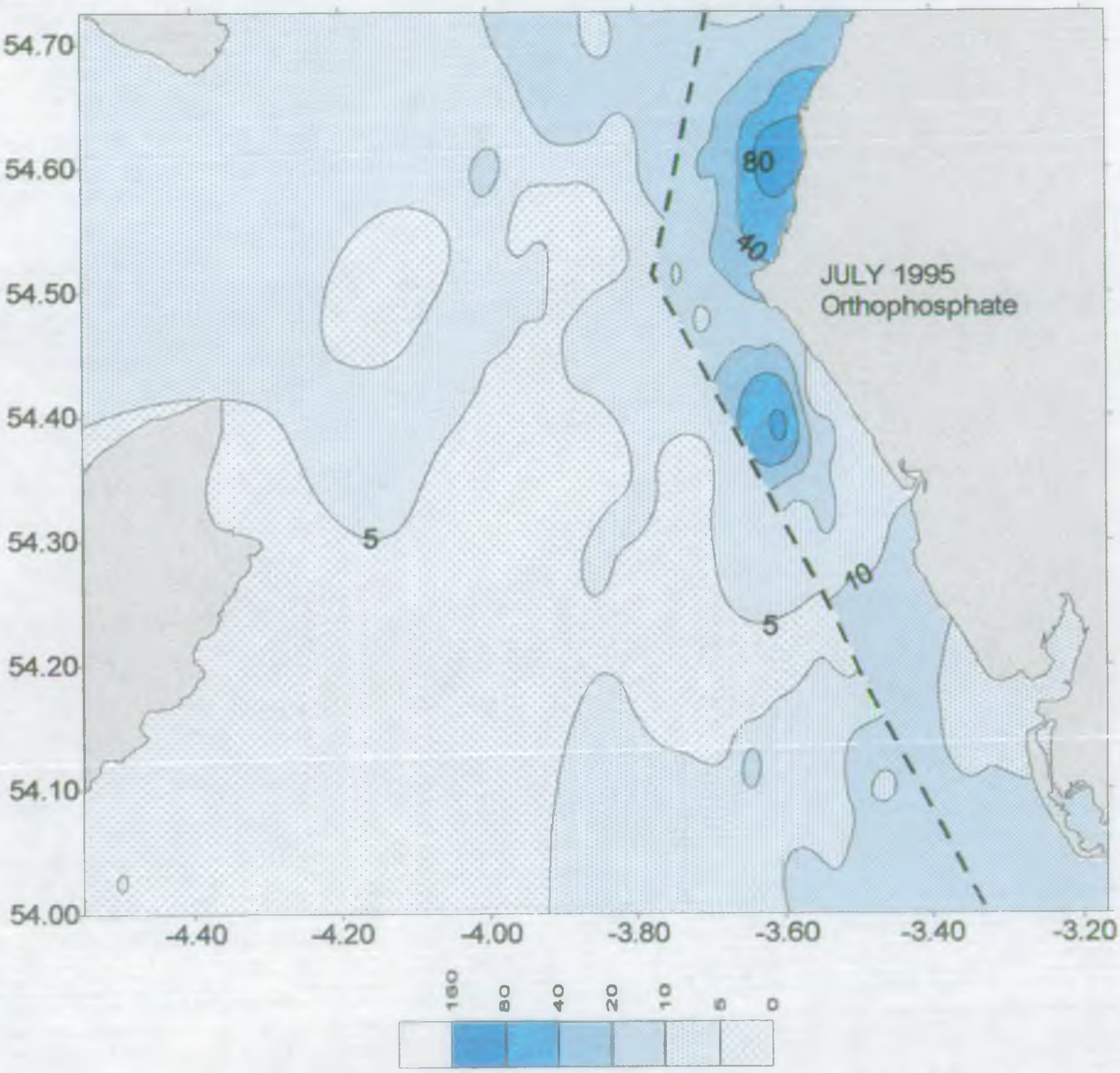


Fig. 20
Orthophosphate-P µg/l in the north east Irish Sea July 1995.
Contours west of the dashed line are derived from PEML samples (24/07/95).
Contours east of the dashed line are derived from NRA samples (24/07/95).

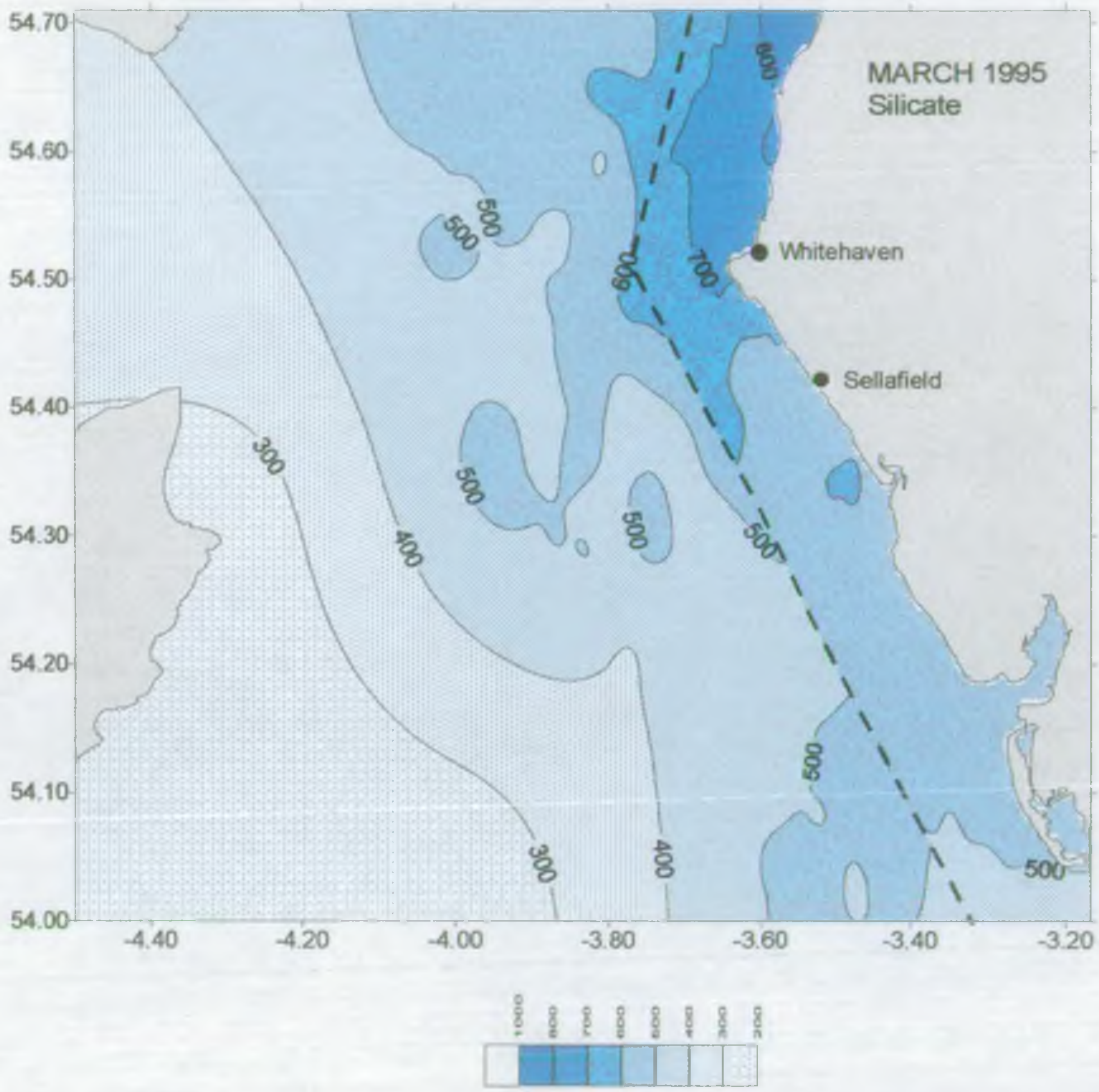


Fig. 21

Silicate-SiO2 µg/l in the north east Irish Sea March 1995.
Contours west of the dashed line are derived from PEML samples (02/03/95).
Contours east of the dashed line are derived from NRA samples (20/3/95).

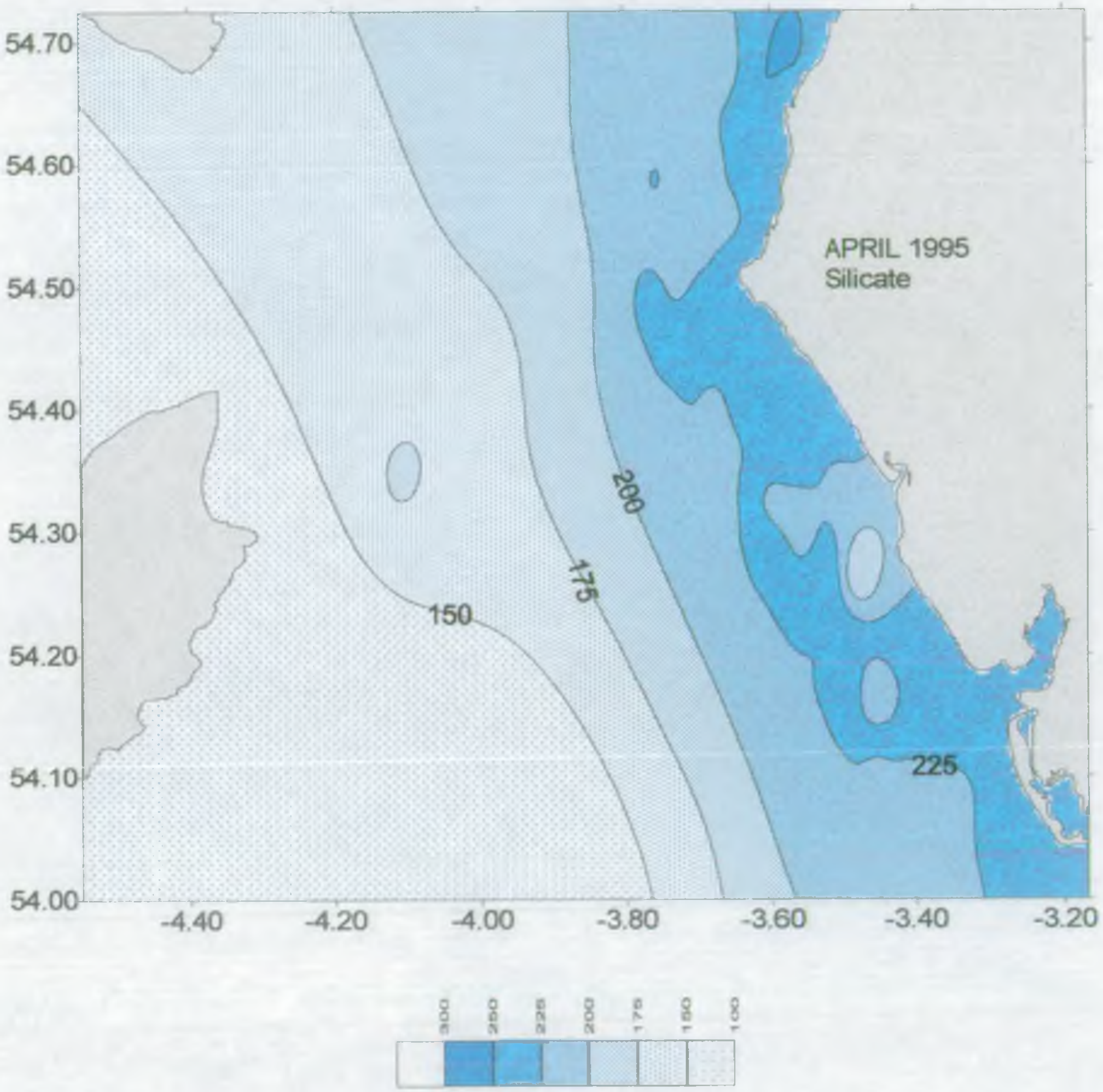


Fig. 22
Silicate-SiO2 µg/l in the north east Irish Sea April 1995.
Contours derived from PEML samples (03/04/95).

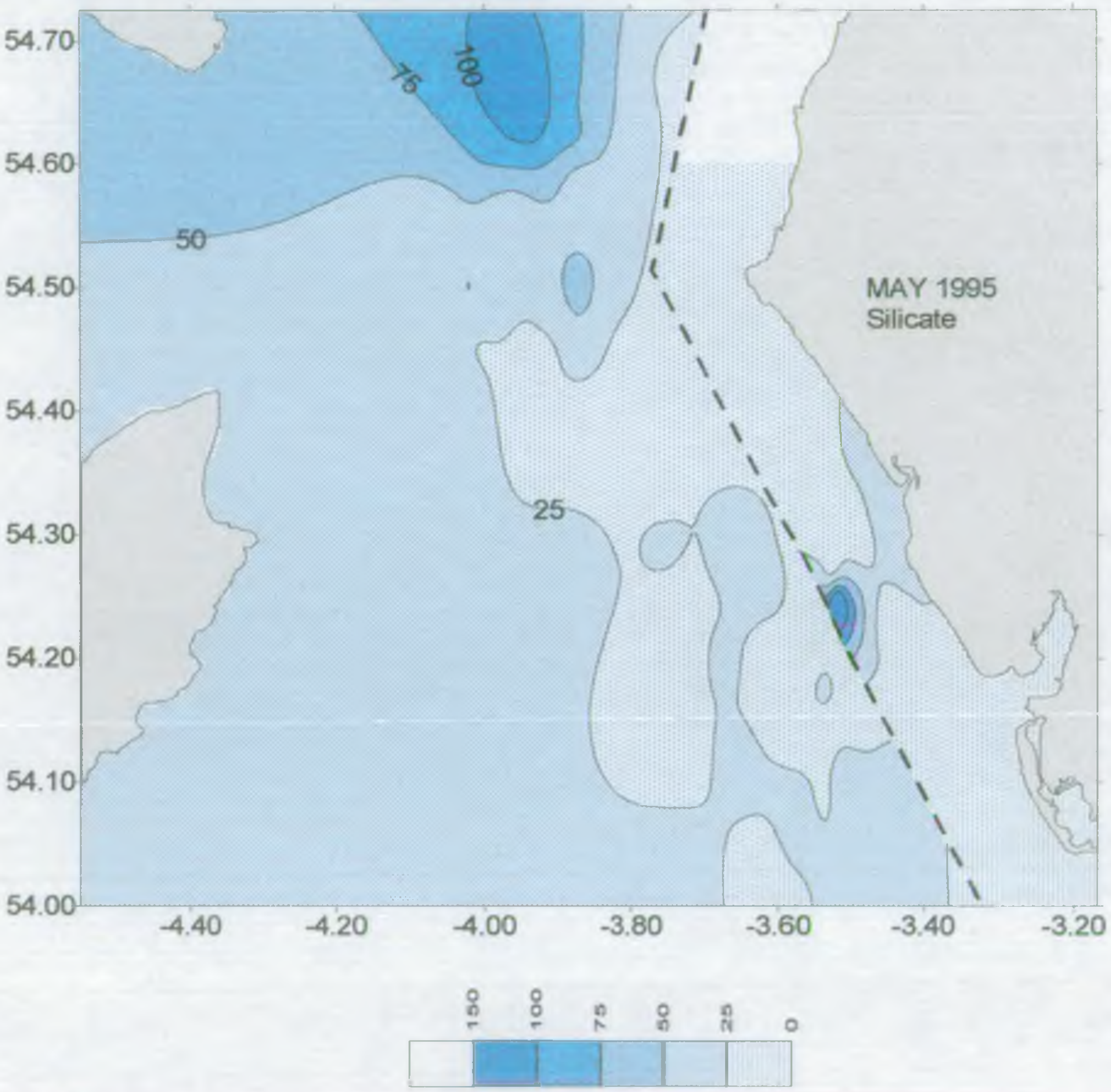


Fig. 23
Silicate-SiO2 µg/l in the north east Irish Sea May 1995.
Contours west of the dashed line are derived from PEML samples (23/05/95)
Contours east of the dashed line are derived from NRA samples (31/05/95).

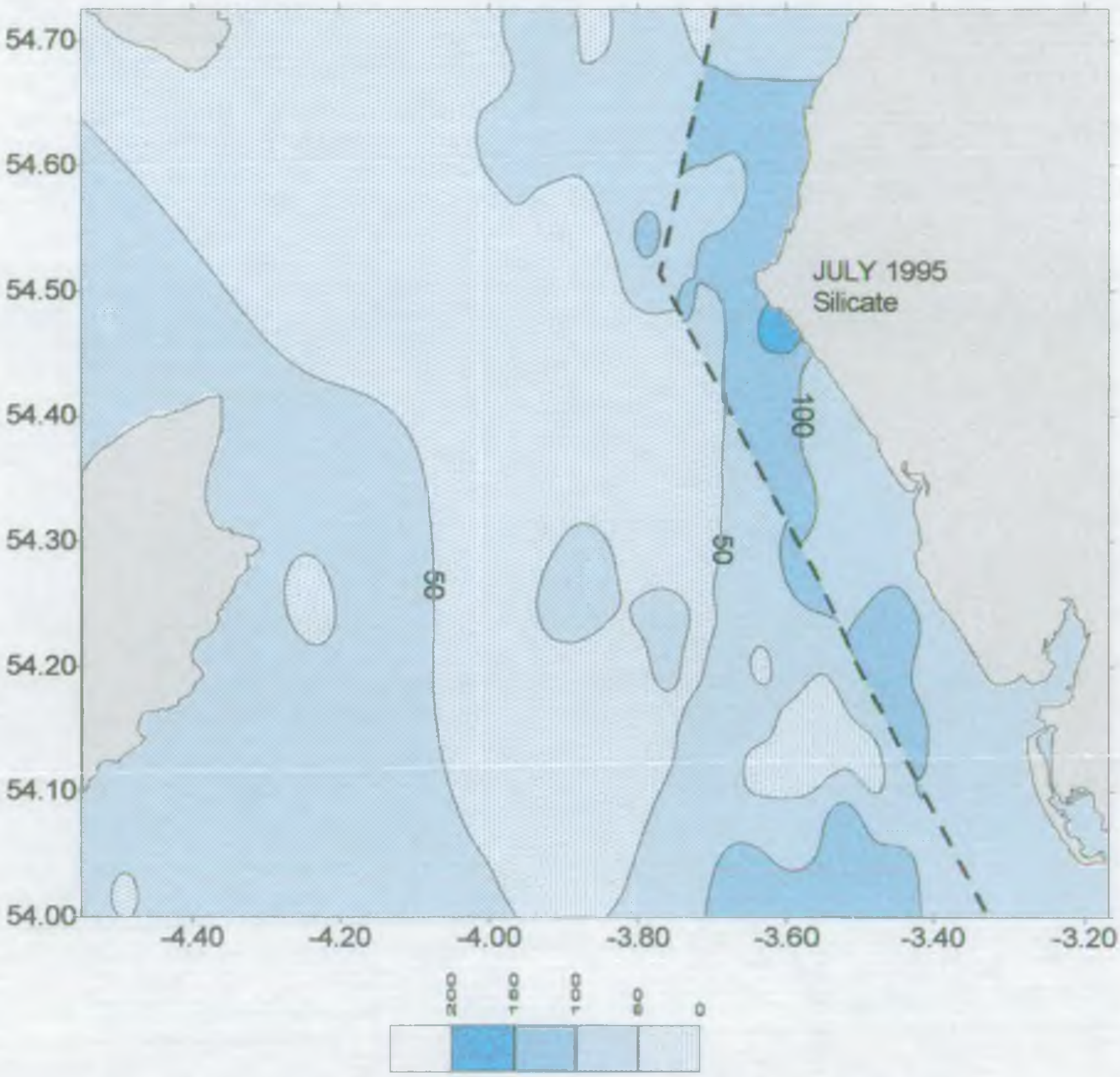


Fig. 24
Silicate-SiO2 µg/l in the north east Irish Sea July 1995.
Contours west of the dashed line are derived from PEML samples (24/07/95).
Contours east of the dashed line are derived from NRA samples (24/07/95).

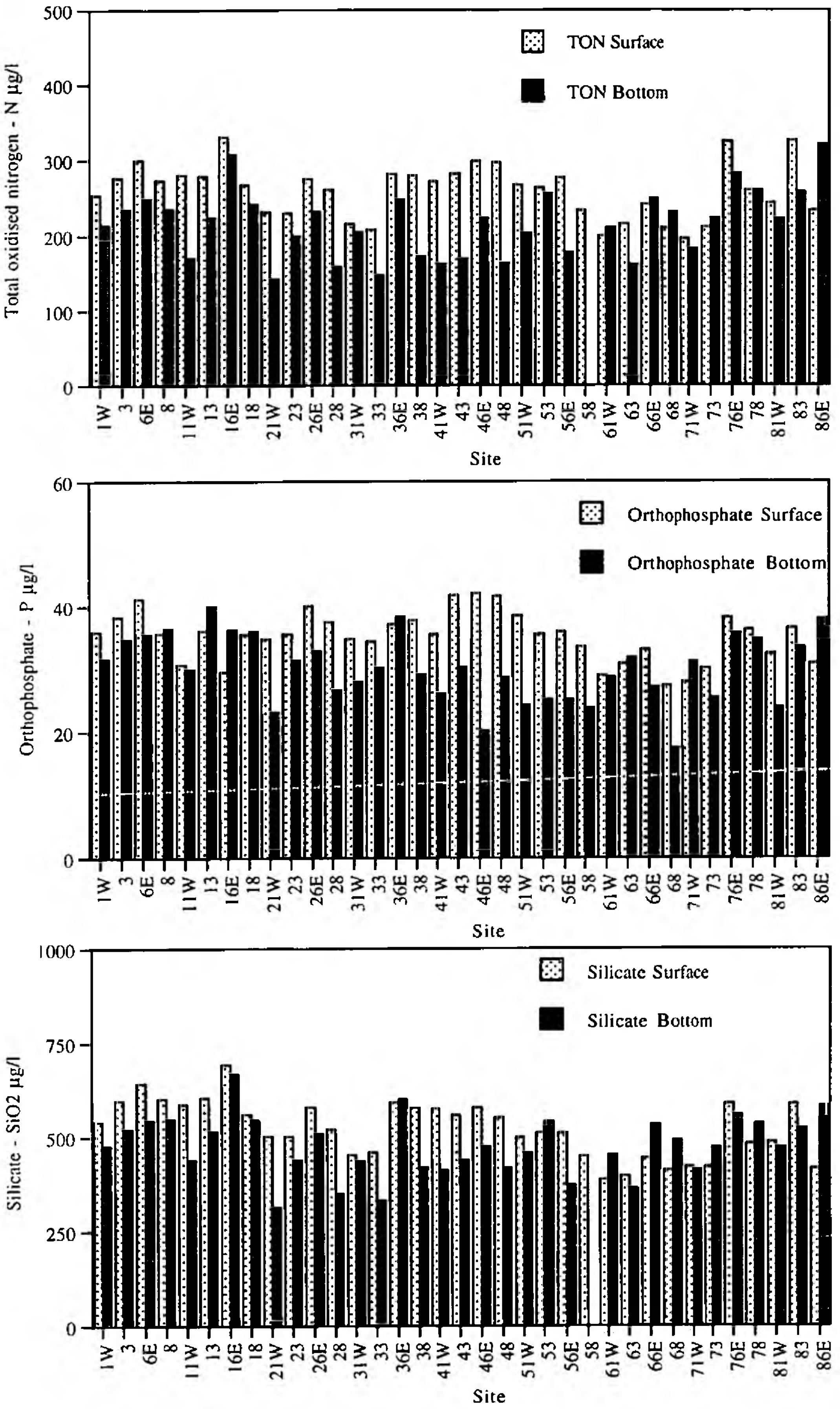


Fig. 25
Nutrients in surface and bottom samples, offshore Cumbrian coast grid, 2nd March 1995. For position of sample sites see fig. 3a.

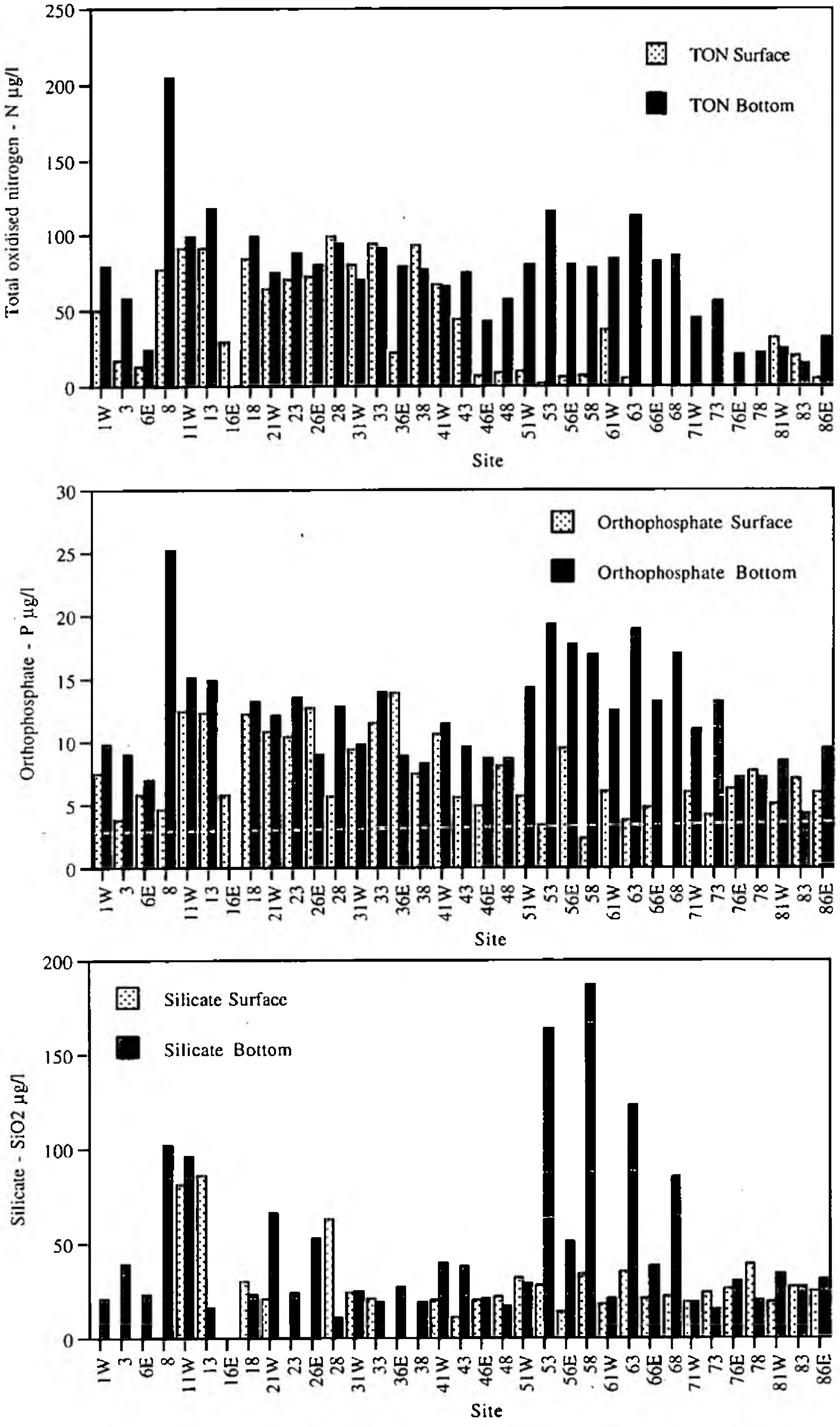


Fig. 26
Nutrients in surface and bottom samples, offshore Cumbrian coast grid, 23rd May 1995. Note there are no zero values, blank columns are due to missing values. For position of sample sites see fig. 3a

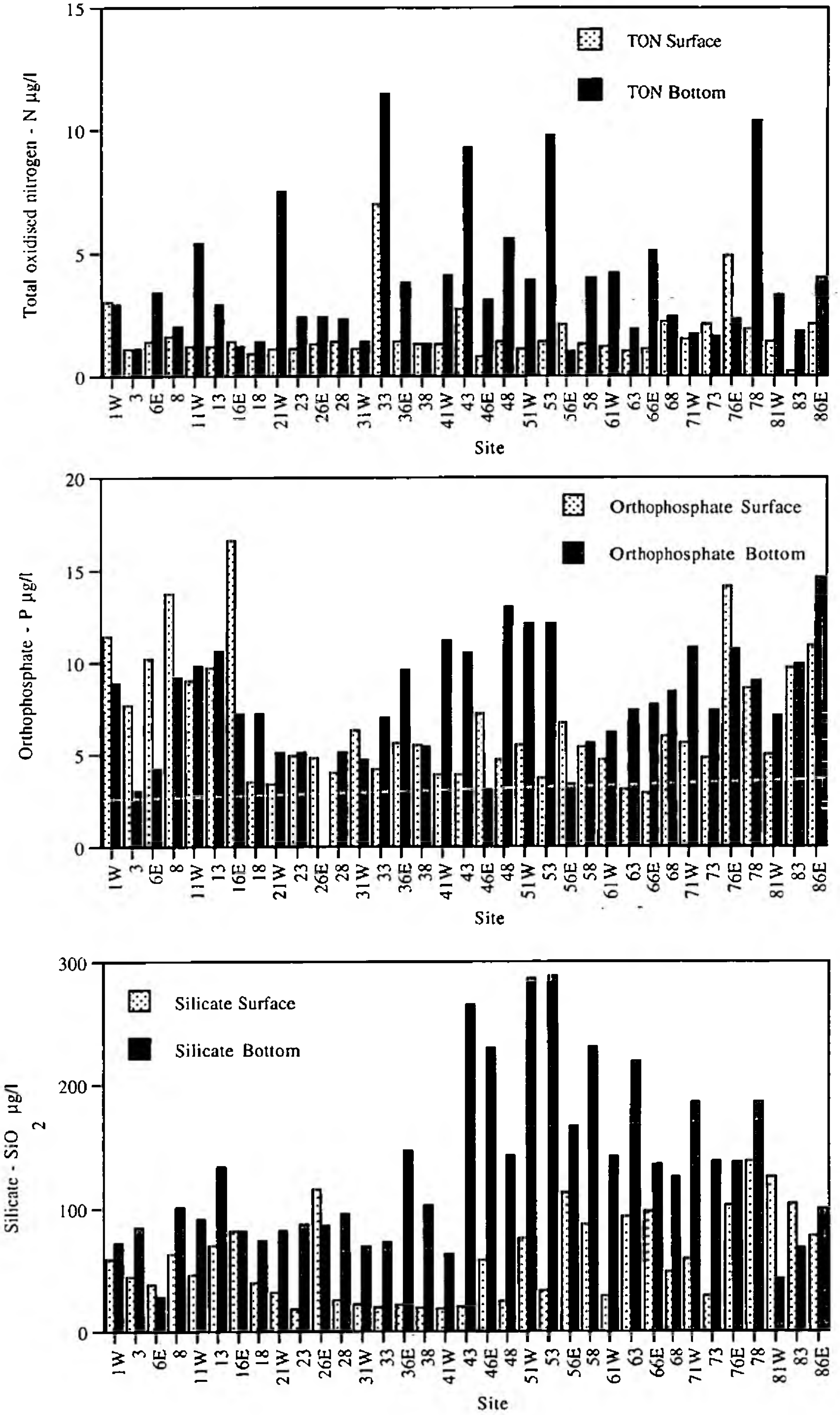


Fig. 27
Nutrients in surface and bottom samples, offshore Cumbrian coast grid, 24th July 1995. For position of sample sites see fig. 3a

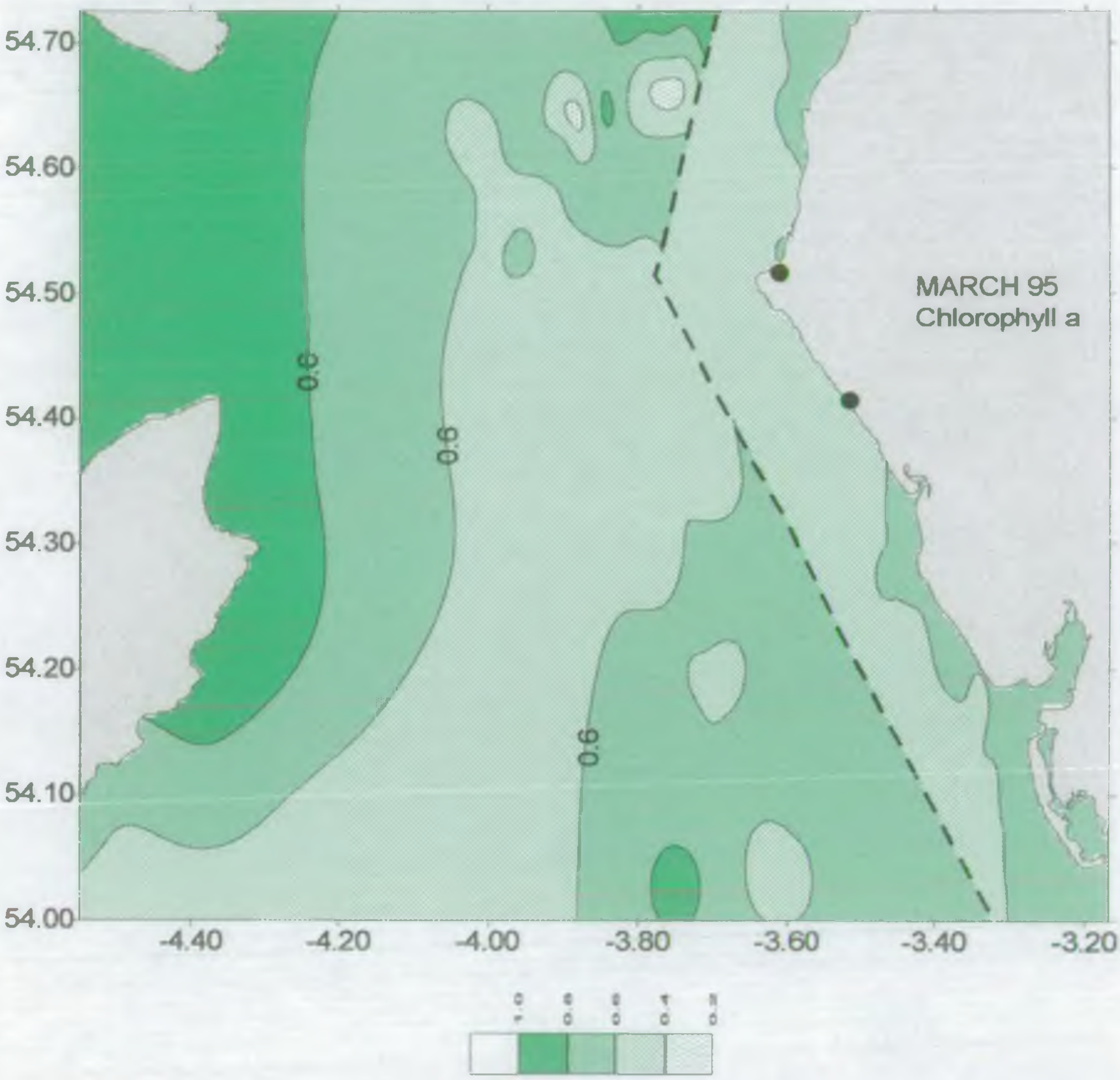


Fig. 28

Chlorophyll a µg/l in the north east Irish Sea March 1995 (fluorometer readings, surface water).
Contours west of the dashed line are derived from PEML readings (02/03/95).
Contours east of the dashed line are derived from NRA readings (20/03/95).

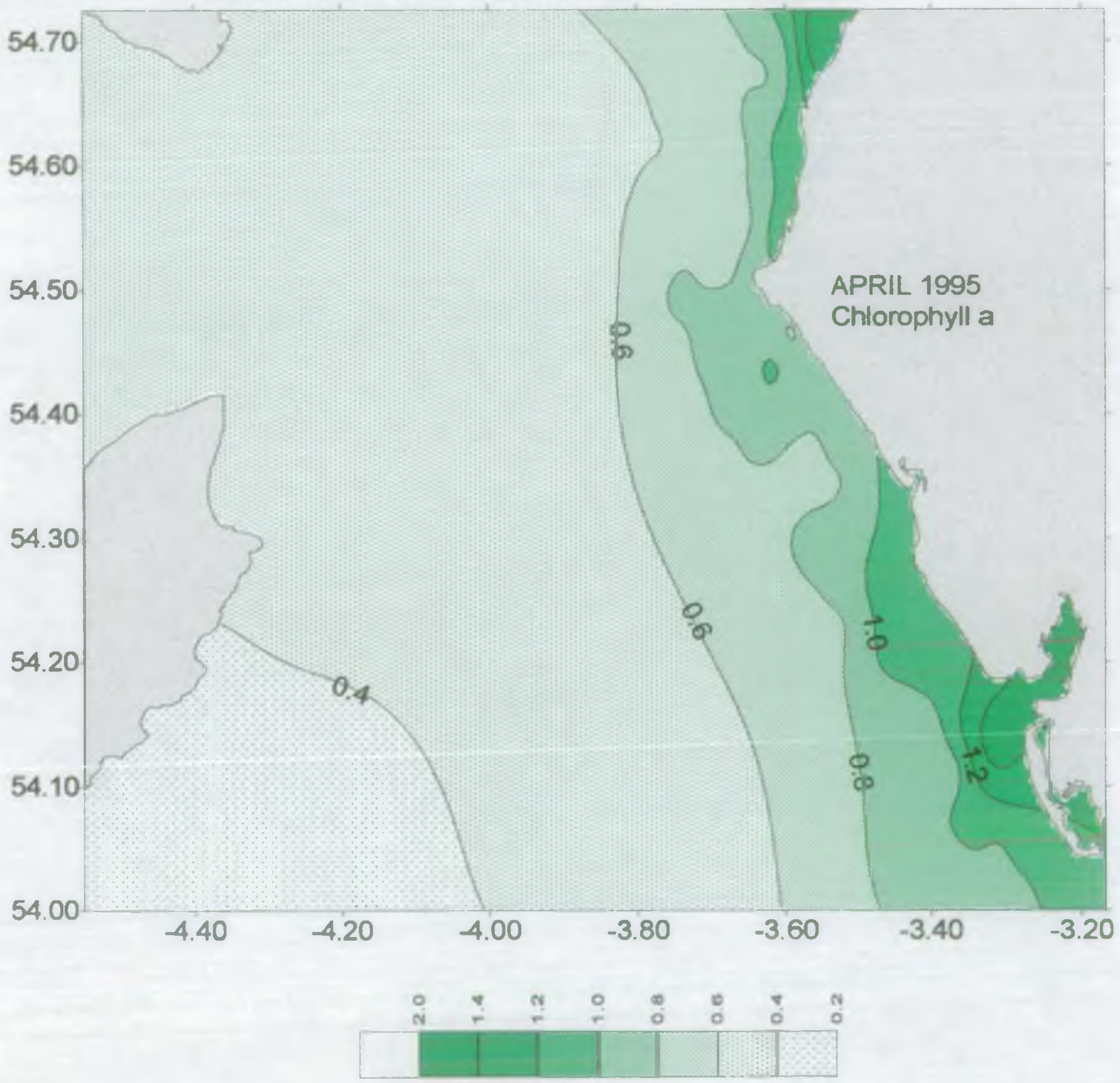


Fig. 29
Chlorophyll a µg/l (fluorescence) in the north east Irish Sea, 3rd April 1995 (PEML samples).

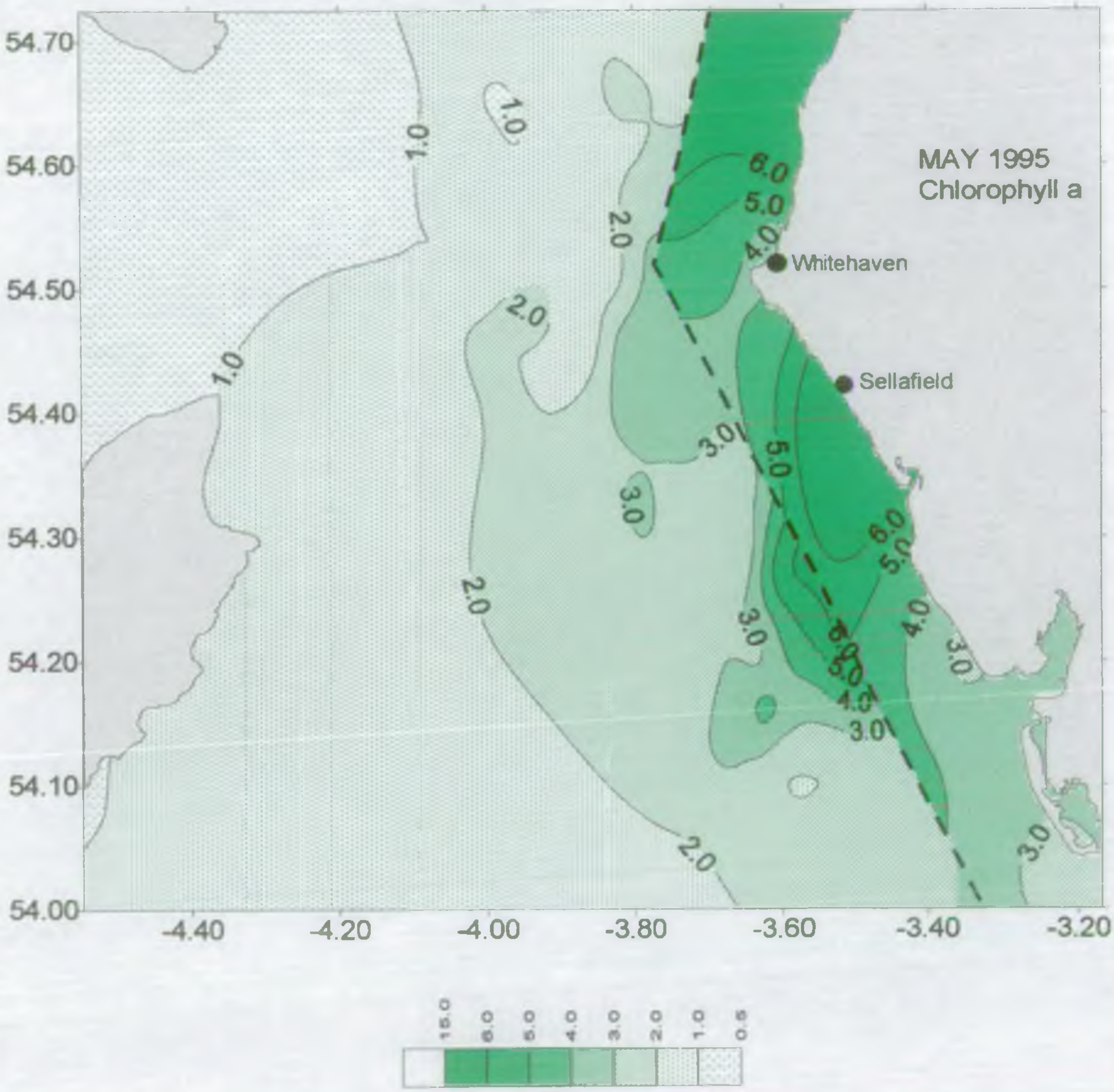


Fig. 30
Chlorophyll µg/l in the north east Irish Sea May 1995.
Contours west of the dashed line are derived from PEML readings (fluorimeter readings, 24/5/95)
Contours east of the dashed line are derived from NRA samples (acetone extraction, 31/5/95)

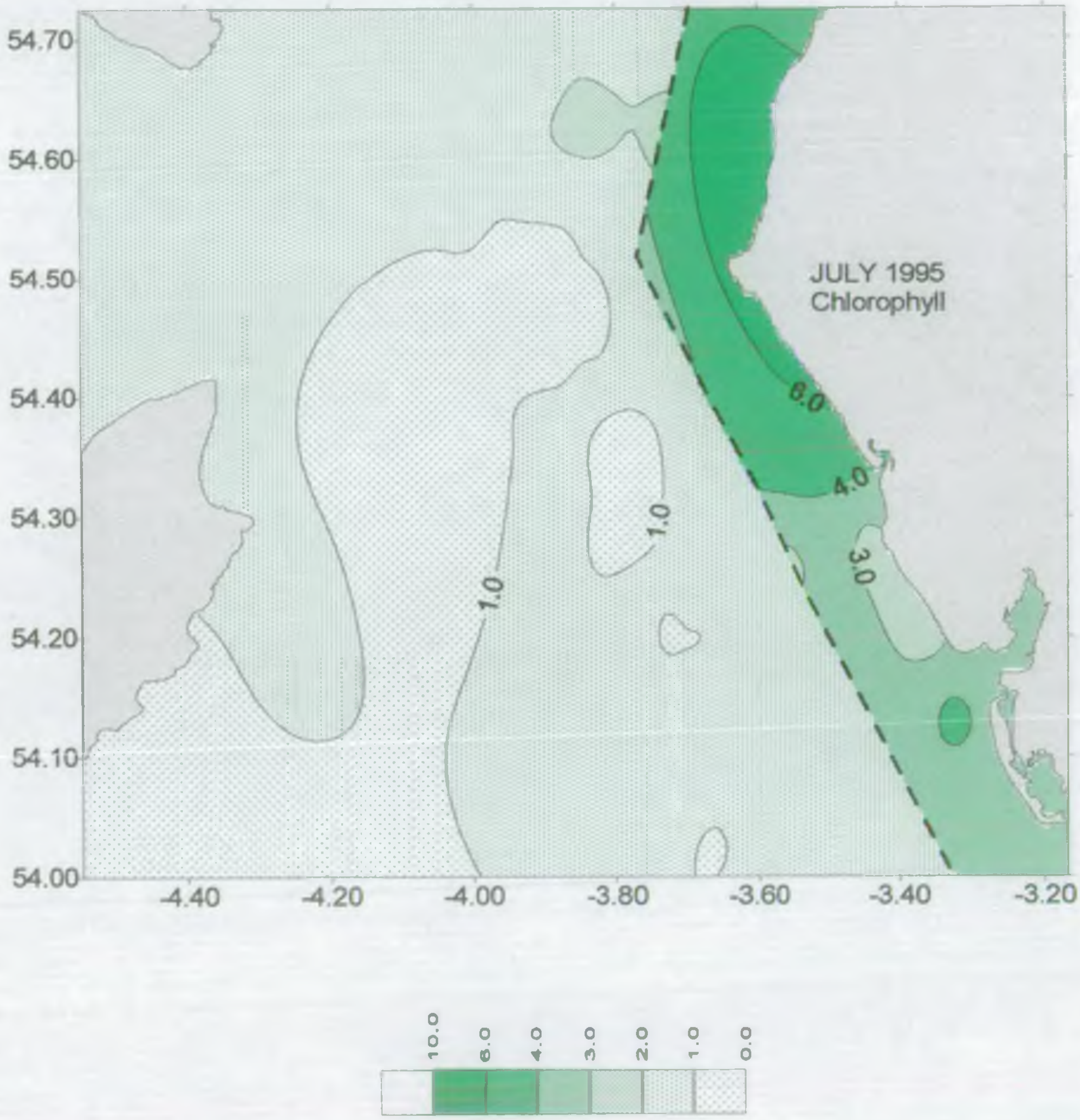


Fig. 31
Chlorophyll a µg/l in the north east Irish Sea July 1995.
Contours west of the dashed line are derived from PEML readings (fluorimeter readings 24/07/95).
Contours east of the dashed line are derived from NRA samples (acetone extraction 24/07/95).

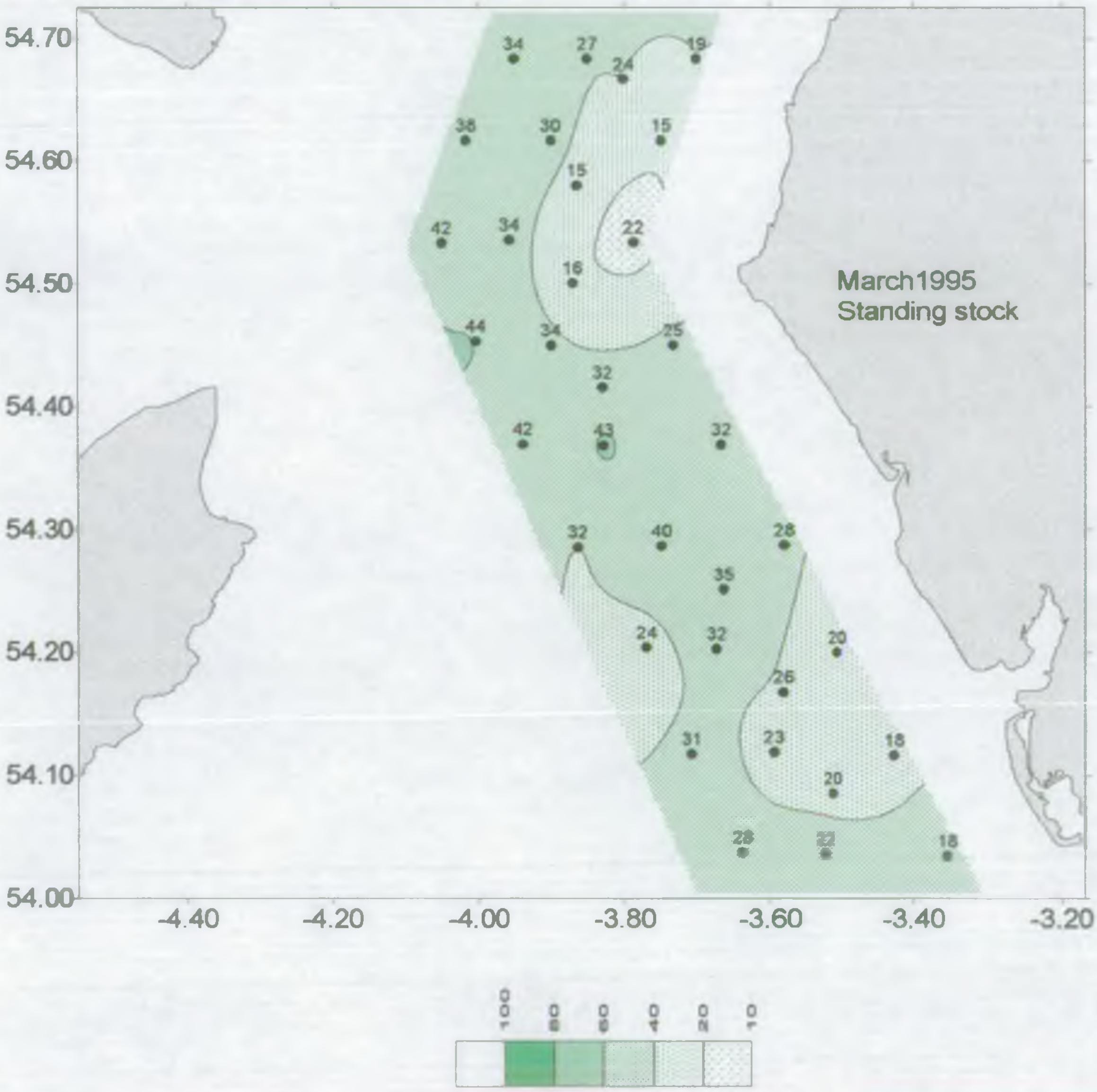


Fig. 32
Standing stock (chlorophyll a mg/m2) on the offshore grid calculated from CTD (fluorometer) casts 3rd March 1995. Sites and depth (m) of each cast is indicated.

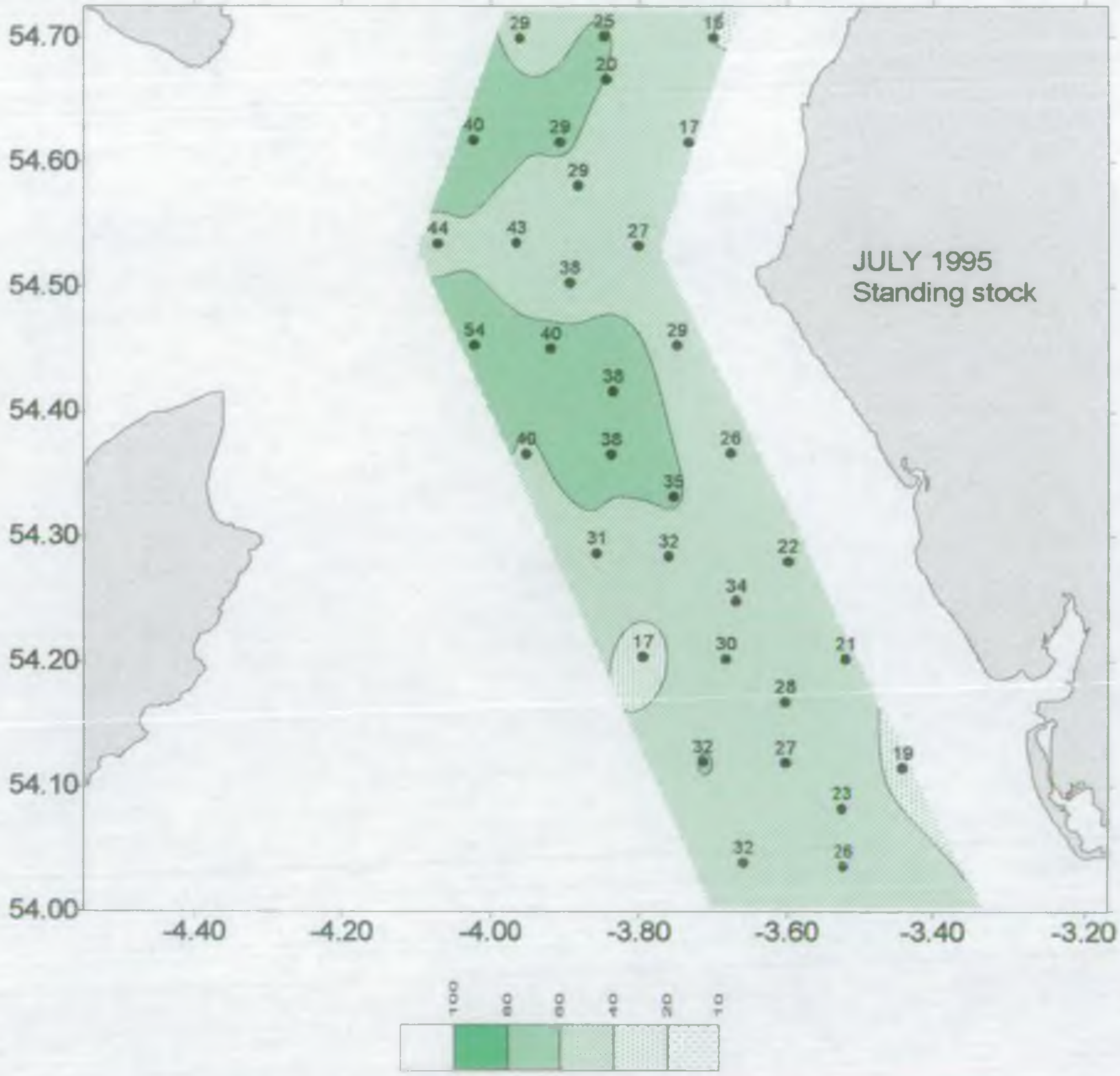
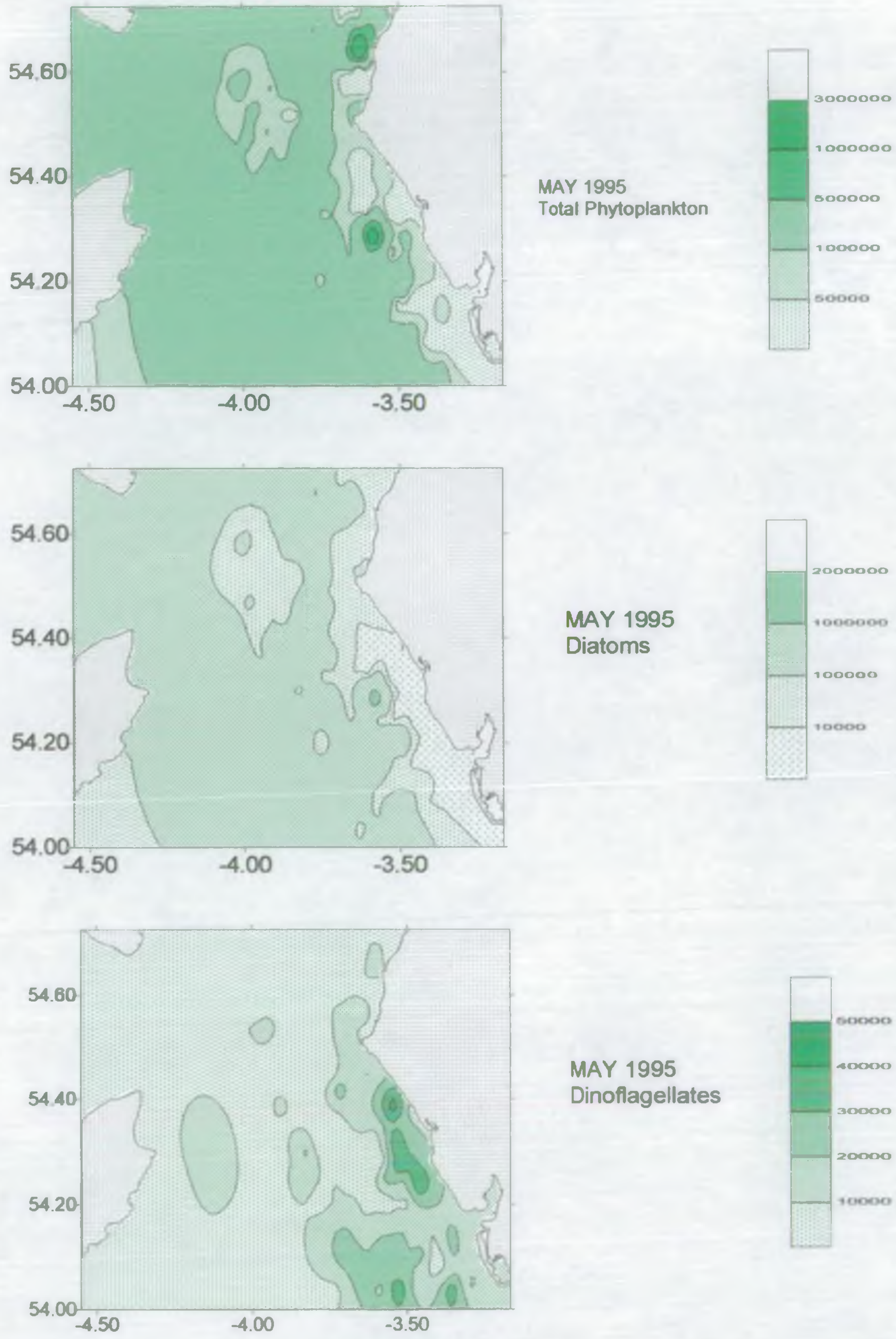


Fig. 33
Standing stock (chlorophyll a mg/m2) on the offshore grid, calculated from CTD (fluorometer) casts 24th & 25th July 1995. Sites and depth (m) of each cast is indicated.



MAY 1995
Total Phytoplankton

MAY 1995
Diatoms

MAY 1995
Dinoflagellates

Fig 34
Total phytoplankton, diatom and dinoflagellate cell counts (cells/l) in the north east Irish Sea, surface water, May 23rd (offshore sites) and 31st (inshore sites).

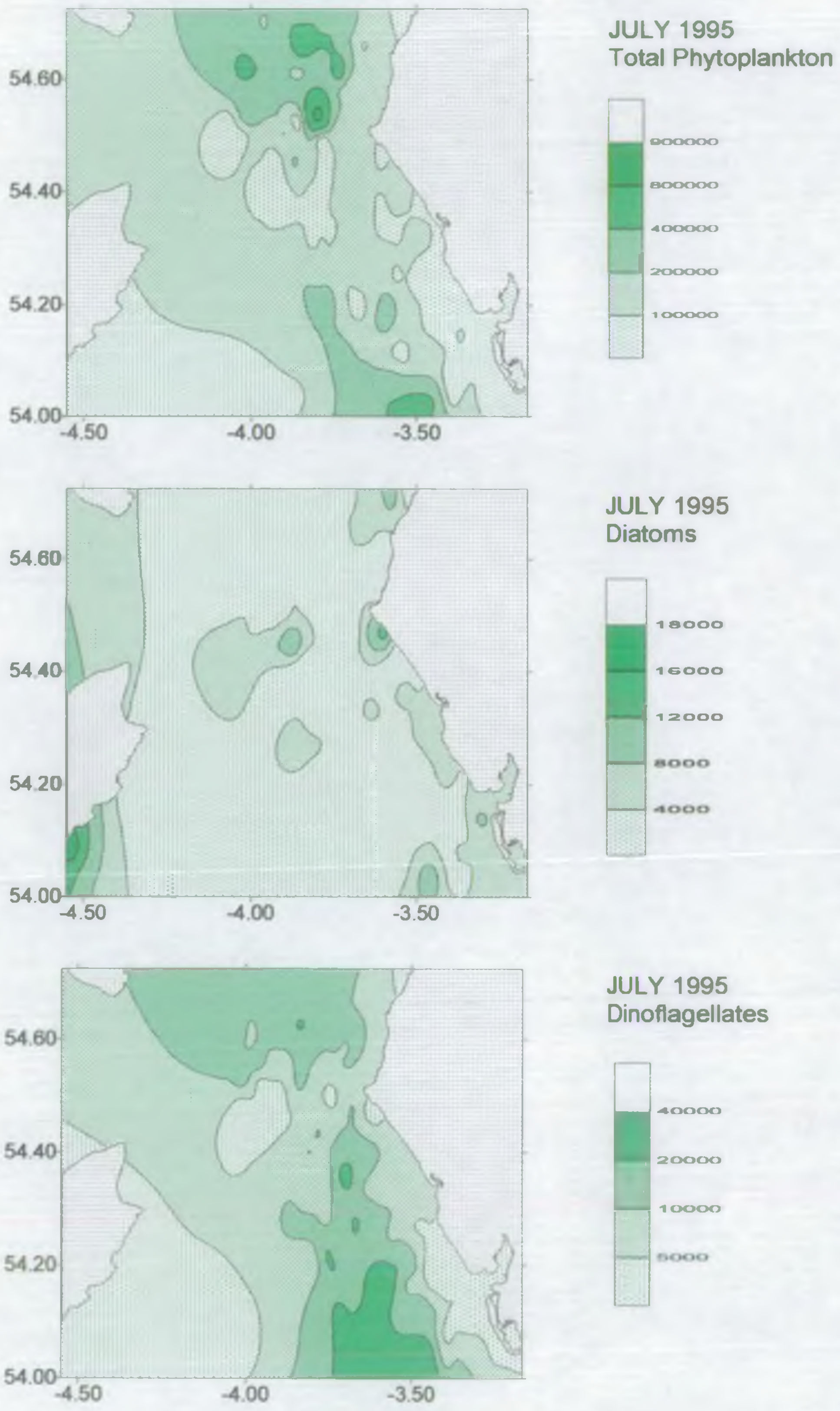


Fig. 35
Total phytoplankton, diatom and dinoflagellate cell counts (cells/l) in the north east Irish Sea, surface water, July 24th.

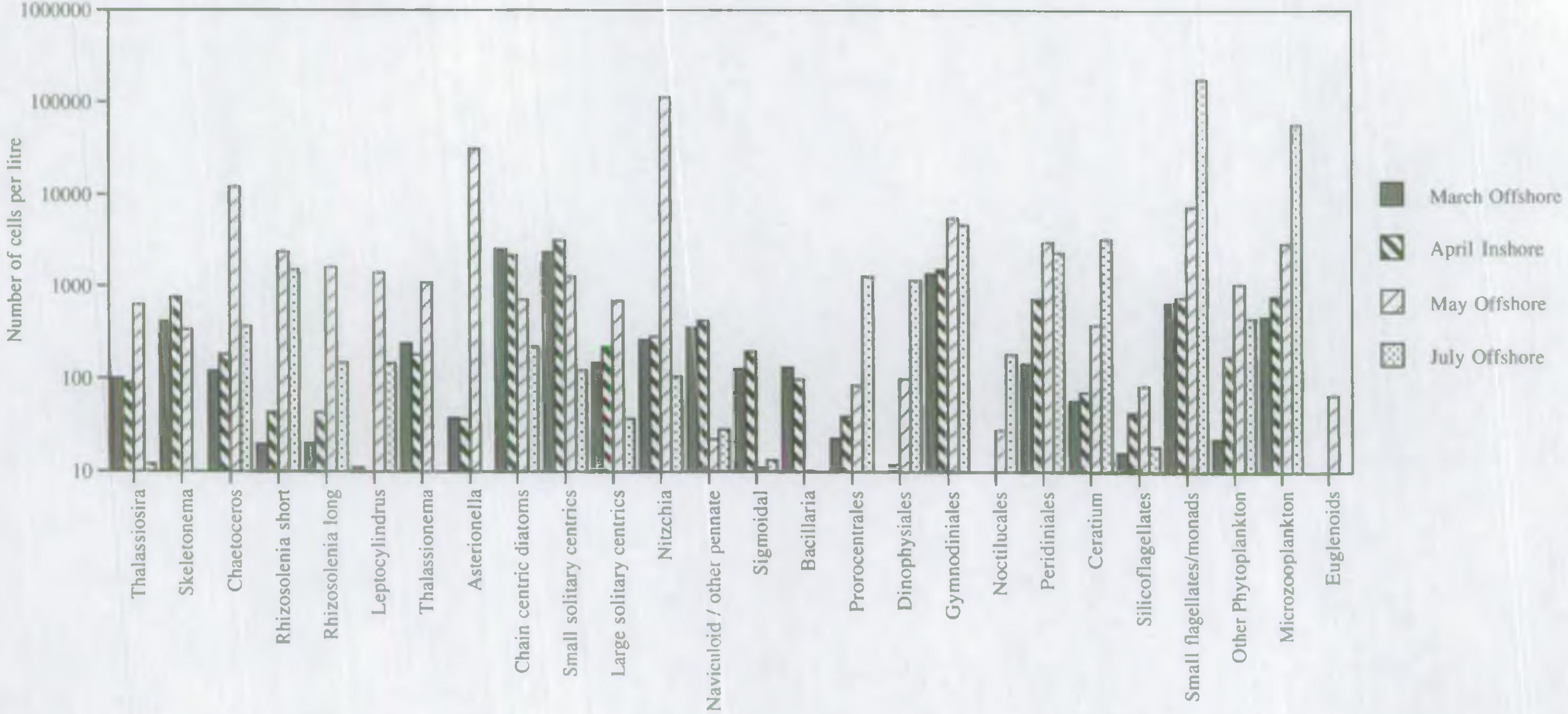


Fig. 36
Seasonal changes in mean plankton cell densities in offshore surface samples.

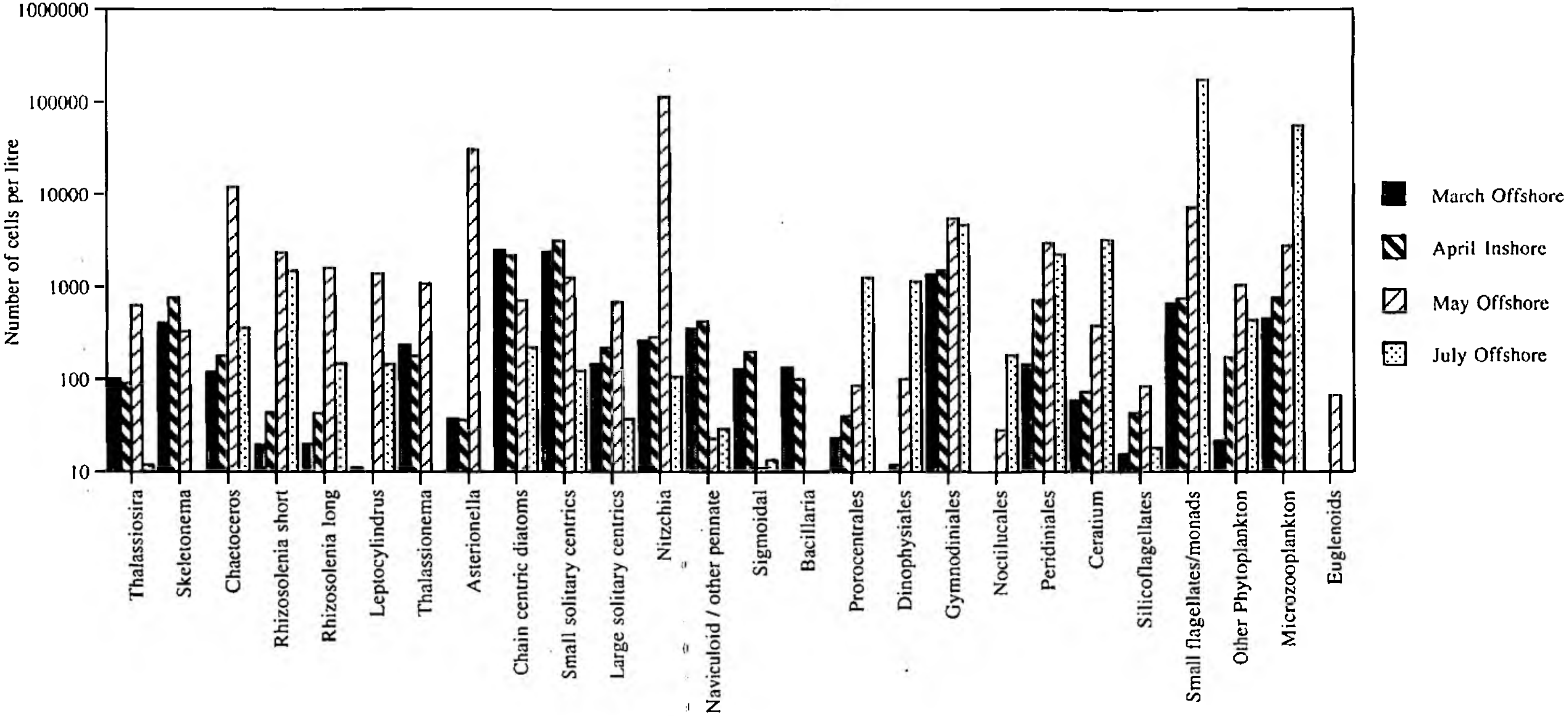


Fig. 36
Seasonal changes in mean plankton cell densities in offshore surface samples.

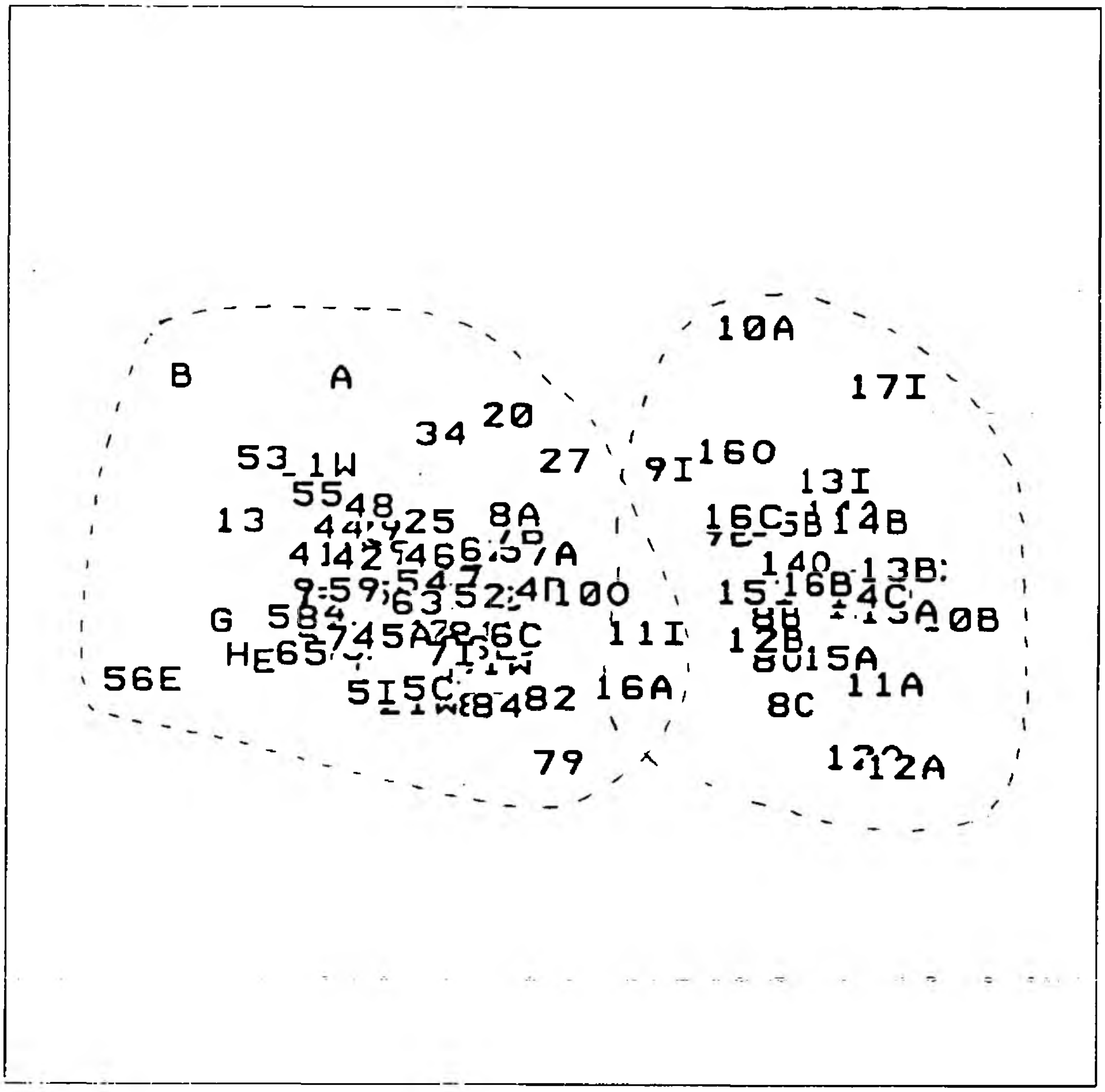


Fig. 37
MDS plot of phytoplankton communities from both inshore and offshore samples, May 1995. Stress = 0.117

Samples are represented by site codes (see fig 3a). Distance between samples on the two dimensional plot represents the degree of similarity in phytoplankton communities. Sites having similar species assemblages are placed close together. Two community types are apparent (enclosed by dashed line), with some degree of overlap. The group to the left is diatom dominated, while the group to the right of the plot (mainly southern inshore sites) is more dinoflagellate dominated.

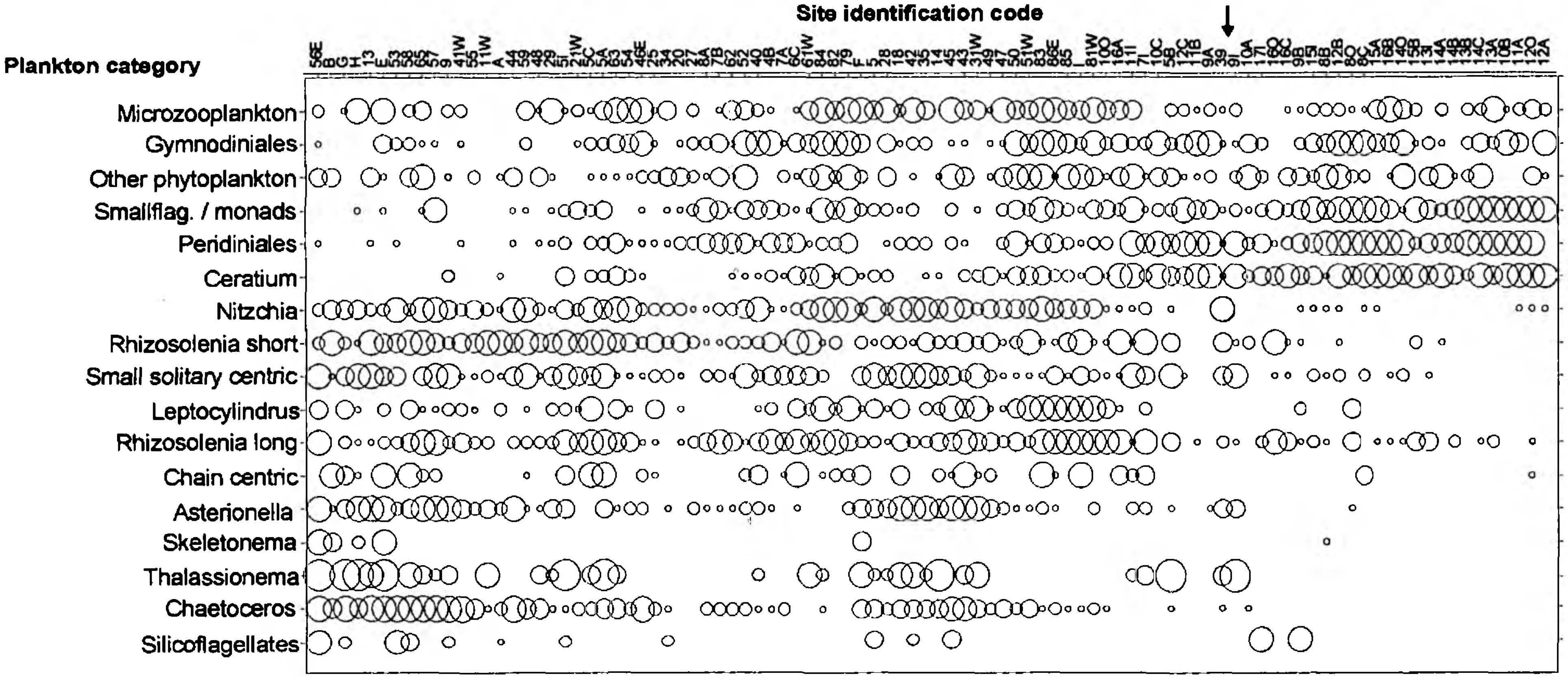


Fig. 38
Shade diagram illustrating major trends in abundance of phytoplankton and microzooplankton at inshore and offshore sites May 1995. Symbols are sized according to abundance, scale varies according to species, no symbol indicates lowest abundance class. Sites to the right of the arrow are all to the south of the inshore grid.

APPENDIX

Appendix table A. Site codes and nominal positions of sites on offshore and inshore Cumbrian coast grids.

	Offshore Grid			Inshore Grid	
Site Identifier	Decimal Latitude	Decimal Longitude	Site Identifier	Decimal Latitude	Decimal Longitude
A	54.087	4.530	1	54.723	3.534
B	54.168	4.374	1A	54.712	3.576
C	54.251	4.250	1B	54.695	3.619
D	54.332	4.144	1C	54.680	3.664
E	54.421	4.053	2	54.666	3.710
F	54.500	4.023	2A	54.653	3.667
G	54.584	3.999	2B	54.640	3.624
H	54.668	3.976	3	54.623	3.584
1W	54.699	3.960	3A	54.613	3.623
2	54.700	3.913	3B	54.603	3.665
3	54.701	3.847	3C	54.595	3.707
4	54.701	3.799	4	54.584	3.749
5	54.700	3.747	4A	54.571	3.698
6E	54.700	3.699	4B	54.553	3.650
7	54.679	3.769	5	54.544	3.609
8	54.666	3.844	5A	54.535	3.650
9	54.653	3.893	5B	54.524	3.698
10	54.641	3.944	5C	54.511	3.747
11W	54.618	4.023	6	54.500	3.792
12	54.620	3.984	6A	54.490	3.736
13	54.616	3.906	6B	54.480	3.685
14	54.621	3.858	6C	54.468	3.633
15	54.624	3.811	7	54.460	3.589
16E	54.616	3.732	7A	54.442	3.657
17	54.608	3.777	7B	54.430	3.705
18	54.581	3.882	8	54.418	3.750
19	54.568	3.930	8A	54.404	3.661
20	54.562	3.965	8B	54.395	3.604
21W	54.535	4.070	8C	54.385	3.546
22	54.534	4.011	9	54.378	3.495
23	54.535	3.965	9A	54.363	3.542
24	54.535	3.925	9B	54.349	3.593
25	54.533	3.865	10	54.333	3.643
26E	54.533	3.801	10A	54.327	3.597
27	54.519	3.842	10B	54.317	3.546
28	54.503	3.893	10C	54.310	3.492
29	54.482	3.940	11	54.300	3.449
30	54.465	3.989	11A	54.287	3.486
31W	54.453	4.022	11B	54.270	3.525
32	54.453	3.978	12	54.250	3.563
33	54.451	3.919	12A	54.240	3.507
34	54.451	3.873	12B	54.231	3.461
35	54.451	3.817	12C	54.219	3.410
36E	54.453	3.748	13	54.211	3.364
37	54.441	3.780	13A	54.198	3.410
38	54.416	3.835	13B	54.180	3.460
39	54.400	3.868	14	54.168	3.509
40	54.379	3.918	14A	54.163	3.469
41W	54.366	3.951	14B	54.153	3.422

Appendix table A continued

Offshore Grid			Inshore Grid		
Site Identifier	Decimal Latitude	Decimal Longitude	Site Identifier	Decimal Latitude	Decimal Longitude
42	54.365	3.922	14C	54.143	3.372
43	54.365	3.837	15	54.135	3.330
44	54.367	3.801	15A	54.118	3.356
45	54.367	3.751	15B	54.101	3.388
46E	54.367	3.675	16	54.084	3.408
47	54.359	3.697	16A	54.072	3.374
48	54.332	3.753	16B	54.059	3.340
49	54.319	3.782	16C	54.046	3.302
50	54.300	3.821	17	54.035	3.266
51W	54.286	3.857			
52	54.285	3.812			
53	54.284	3.760			
54	54.284	3.716			
55	54.282	3.661			
56E	54.280	3.599			
57	54.270	3.618			
58	54.249	3.668			
59	54.235	3.710			
60	54.217	3.760			
61W	54.204	3.794			
62	54.203	3.737			
63	54.202	3.681			
64	54.202	3.635			
65	54.204	3.591			
66E	54.202	3.516			
67	54.188	3.554			
68	54.167	3.603			
69	54.153	3.643			
70	54.133	3.685			
71W	54.120	3.713			
72	54.122	3.652			
73	54.119	3.602			
74	54.116	3.552			
75	54.117	3.491			
76E	54.115	3.440			
77	54.107	3.463			
78	54.082	3.522			
79	54.072	3.480			
80	54.060	3.440			
81W	54.039	3.658			
82	54.037	3.585			
83	54.036	3.520			
84	54.038	3.460			
85	54.037	3.402			
86E	54.037	3.364			
I	54.041	3.850			
J	54.043	3.989			
K	54.031	4.262			
L	54.031	4.495			

Appendix table B Categories for plankton enumeration

Thalassiosira
Skeletonema
Chaetoceros
Rhizosolenia short
Rhizosolenia long
Leptocylindrus
Thalassionema
Asterionella
Chain centric diatoms
Small solitary centrics <50µm diameter
Large solitary centrics >50µm diameter
Nitzchia
Naviculoid / other pennate
Sigmoidal
Bacillaria
Prorocentrales
Dinophysiales
Gymnodiniales
Noctilucales
Peridiniales
Ceratium
Silicoflagellates
Small flagellates/monads 5 to 15 µm length
Other Phytoplankton
Microzooplankton

Presence of phaeocystis colonies is noted

Appendix table C **PEML performance in WRc Aquacheck distributions (saline waters) during period of survey.**

Distribution number	Date of run	Data set	Operator	Z-scores TON	Silicate	Nitrite	Ammonia	SRP
83	20/3/95	Saline waters	Lab	0.20	0.76	0.10	**-5.12**	-0.20
			1	0.20	0.76	0.10	**-5.12**	-0.20
			2	0.64	*	-0.08	**-5.03**	-0.27
	NB:- WRc highlighted a problem with the stability of ammonia and a separate problem with silicate in sample provided. Flags were therefore removed for both these determinands in distribution 83. For further info. see Aquacheck summary of results.							
87	19/6/95	Saline waters	Lab	-0.47	0.22	0.38	**-2.10**	0.36
			1	-0.47	0.22	0.38	**-2.10**	0.36
			2	-0.46	0.78	-0.17	**-2.02**	-0.69

Z-score - (mean result-reference value)/error threshold

error threshold - 0.85C or 17%, whichever is the greater

C - concentration unit

>1 - flagged (fail) result. Bold indicates flagged result.

1 - acceptable limit. Barely acceptable result indicated in italics.

<1 - acceptable

* - no results