PRE-BLOOM PHYTOPLANKTON IN THE SURFACE WATERS OF THE CELTIC SEA AND SOME ADJACENT WATERS

C. Pybus

ABSTRACT

Surface water samples were collected from the Celtic Sea and adjacent waters during a two-week cruise in February/March 1985. Temperature, salinity, and nitrate-nitrogen were continuously monitored. Discrete samples were collected for chlorophyll *a* measurement and phytoplankton analysis. The results show distinct coastal and offshore water masses. Waters close to the Irish and Welsh coasts were characterised by low temperatures and salinities but high nitrate-nitrogen concentrations. Offshore waters were warmer and had higher salinities and lower concentrations of nitrate-N. However, although low chlorophyll *a* concentrations were generally found, they were highest in the coastal waters. Cryptophytes and other small flagellates were numerically dominant, but diatoms provided the larger contribution to both the chlorophyll *a* concentrations and the total volume of phytoplankton. The evenness and richness of diatom species was generally greatest off the south coast of Ireland. A list of species observed is given and is compared with published data for the same area. Most of the recorded diatom species have been shown by other workers to contribute to the spring bloom and to summer and autumn populations.

C. Pybus (e-mail: colin.pybus@gmit.ie), Department of Physical and Life Sciences, Galway–Mayo Institute of Technology, Dublin Road, Galway.

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INTRODUCTION

The Celtic Sea, which lies off the south coast of Ireland, is an easterly extension of the Atlantic Ocean (Fig. 1). The western boundary between it and the Atlantic Ocean is often taken as the 200m isobath, that is the edge of the continental shelf. The southern boundary is less well defined, but can be taken as the western approaches to the English Channel (about 49°N) or even as far south as 48°N. To the east, the Celtic Sea is bounded by the coasts of England and Wales and is confluent with the waters of the English Channel and the Bristol Channel. To the north-east it is connected to the Irish Sea by St Georges Channel, a deepwater channel with depths in excess of 100m that passes between the Irish and Welsh coasts.

The general physical environment of the area has been subject to several studies, and has been described by Pingree and Griffiths (1980) and Pingree and LeCann (1989). Mean winter surface water temperatures range from 10°C over the continental shelf to 8°C in the St Georges Channel and the southern Irish Sea (Lee and Ramster 1981). Lower values are found in the Bristol Channel. In the summer, mean surface temperatures range from 17.5°C to 14°C in St George's Channel. Much of the area has mean winter surface salinities in excess of 35 due to incursions of Atlantic water. In St Georges Channel and Cardigan Bay salinities fall to between 34 and 35, and salinity values are even less in the Bristol Channel (Lee and Ramster 1981). Lower values are found in the summer months. Residual surface currents in the centre of the Celtic Sea are usually weak, in the order of 1cm s^{-1}, but under strong winds they may exceed speeds of 30cm s^{-1} (Davies and Jones 1992). During the summer, the waters of the Celtic Sea stratify and thermal fronts develop in St George's Channel and in the English Channel between Cornwall and France (Pingree and Griffiths 1978; Pingree *et al*. 1978; Simpson *et al*. 1978; Simpson and Bowers 1979).

The phytoplankton of the western English Channel is well studied (Boalch *et al.* 1978; Pingree *et al*. 1978; Maddock *et al*. 1981; Boalch 1987) and the development and dynamics of the spring bloom have been examined at the Celtic Sea shelf edge (Rees *et al*. 1999), in the Celtic Sea (Pingree *et al*. 1976; Fasham *et al*. 1983), the Irish Sea (Savidge 1976), the western approaches to the English Channel (Pingree *et al*. 1975) and the western English Channel (Holligan and Harbour 1977). There are, however, few published records of the phytoplankton species composition and seasonal succession along the southern coast of Ireland (Marine Institute 1999) or the Celtic Sea, especially during the winter months. This paper presents data collected from the surface waters of the Celtic Sea and adjacent waters before the onset of the spring bloom during a two-week cruise in February/March 1985.

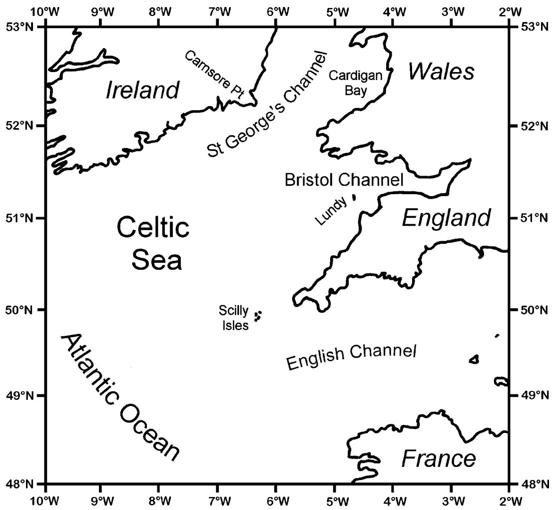

Fig. 1 — Geographical locations mentioned in text.

MATERIALS AND METHODS

Sampling was carried out from the R.V. *Frederick Russell*. Seawater was pumped aboard continuously via the vessel's non-toxic supply from an intake approximately 2m beneath the sea surface. This supply then passed through the following instruments: Chem-Labs Autoanalyser, for nitrate analysis; Tuner Designs Model 5 Fluorimeter, for fluorescence measurement; and a Grundy Environmental Systems Model 66200 Thermo-salinograph, for the measurement of temperature and salinity. Outputs from these instruments were relayed to chart recorders.

Discrete water samples for calibration of the above instruments and phytoplankton examination were also collected from an outlet taken off the same seawater supply. A 100cm^3 sample of water was filtered through cellulose acetate paper for spectrophotometric chlorophyll *a* and phaeo-pigment analysis. These samples were placed in a freezer immediately after collection. A 250cm^3 sample of seawater was stored in glass medical flats fitted with polythene inserts and a screw-caps for later analysis in an inductive salinometer.

One cubic centimetre of Lugol's iodine was added as preservative to 100cm^3 of water. These samples were also stored in glass medical flats and subsequently examined for phytoplankton. Twenty cubic centimetres from each sample was placed in a 'Hydrobios' tube chamber and allowed to sediment overnight. Counts were then made using a 'Nikon Diavert' inverted microscope. For the small flagellates two transects of the chamber were counted. The entire chamber was scanned for the larger groups. Correction factors were applied to give estimates of numbers of cells per unit volume of seawater. Nomenclature generally follows Dodge (1982) and Tomas (1996).

After the counts, cells from each species of diatom and dinoflagellate were measured using an ocular micrometer and average dimensions were obtained. Cell volumes were then calculated using the formulae given by Edler (1979). For the cryptophytes and other flagellates average dimensions were based on a range of cell types.

Total species richness was estimated from the presence/absence data using a non-parametric estimator, the Chao index (Southward and Henderson 2000; Henderson 2003). This was calculated using the formula:

$$\hat{S}_{\max} = S_{obs} + \left(\frac{a^2}{2b}\right)$$

where S_{obs} is the number of species observed, a is the number of species found in one sample and b is the number of species found in two samples.

The variance of $\hat{S}_{\max}$ may then be calculated using the formula (Southward and Henderson 2000):

$$\mathrm{var}(\hat{S}_{\max}) = b\left[\left(\frac{a/b}{4}\right)^4 + \left(\frac{a}{b}\right)^3 + \left(\frac{a/b}{2}\right)^2\right]$$

The Berger-Parker index (D_{BP}) provides a dominance estimate (Magurran 2004) and is calculated from the total number of individuals in a sample (N) and the number of individuals in the most abundant species (N_{max}):

$$D_{BP} = \frac{N_{\max}}{N}$$

The reciprocal of the index ($1/D_{BP}$) is then calculated so that the lowest values indicate the greatest evenness within the samples. The highest values then represent those samples that are dominated by few species.

The Margalef Index (D_{Mg}) has also been used to examine phytoplankton distributions (Margalef 1978) and is a measure of species richness (Magurran 2004).

$$D_{Mg} = \frac{S - 1}{\ln N}$$

Here S is the number of species in the sample and N is the number of individuals.

The results calculated for the cell volume estimates and the Berger-Parker and Margalef indices were ranked and, for presentation purposes, were divided into quartiles. The quartiles were then coded and plotted.

RESULTS

The area studied, the cruise track taken by the vessel and the sampling locations are shown in

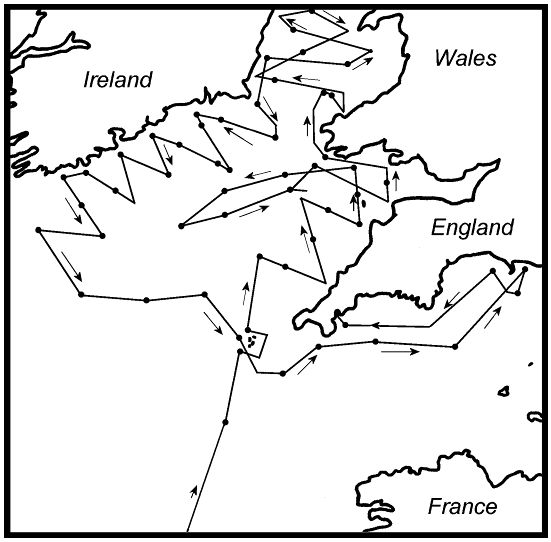

Fig. 2 — Cruise track taken during a two-week period in February and March 1985.

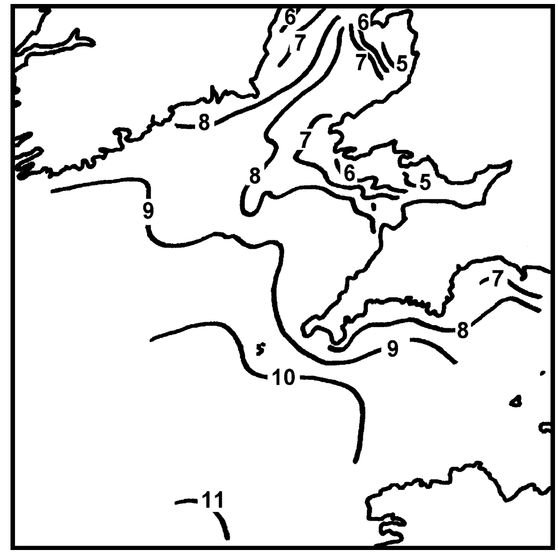

Fig. 4 — Surface water temperatures (°C).

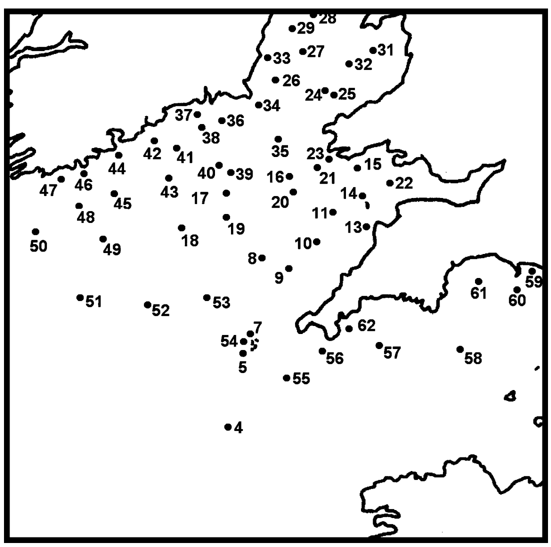

Fig. 3 — Stations where discrete water samples were collected for the examination of phytoplankton and chlorophyll *a* analysis.

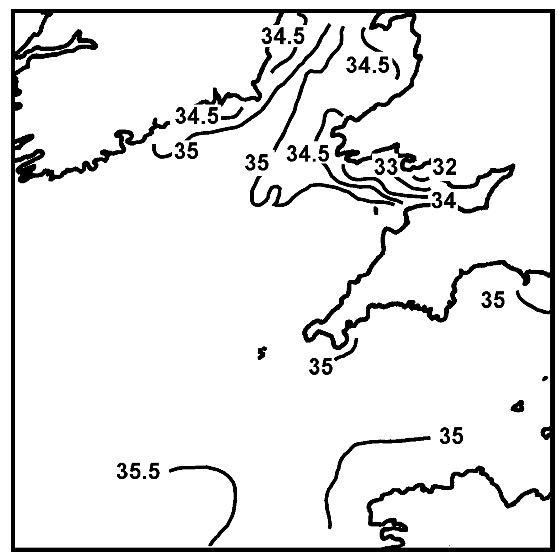

Fig. 5 — Surface salinities.

Figs 1–3. Samples 1 to 24 were taken during the period 26 February 1985 to 3 March 1985, and the remaining samples, 25 to 62, were taken during the period 4 March 1985 to 10 March 1985. Positions 1 to 3 are not shown but were located along a line south-west of position 4 at latitudes and longitudes 47°12′N, 7°27.7′W, 47°42′N, 7°15′W and 48°29′N, 6°57′W, respectively. There are no samples numbered 6 or 12. Surface isotherms (Fig. 4) and isohalines (Fig. 5) show a mass of warmer, high salinity water (>35) to be present in the south-west of the study area, with a tongue of high salinity water pushing up through St George's Channel towards the Irish Sea. Reduced salinities were found off the Welsh and Irish coasts. Highest concentrations of nitrate-N were located off the south and south-west Welsh coast (Fig. 6). Concentrations of chlorophyll *a* (reported in Garcia-Soto and Pingree 1998) were low throughout the area (Fig. 7). Highest values were recorded close to the Irish coast, in Cardigan Bay and off the south coast of England.

A list of phytoplankton species is given in Table 1. The occurrence of diatoms is given in Table 2, and other members of the phytoplankton in Table 3. Numbers were generally low. Some genera, for example *Chaetoceros*, *Thalassiosira*, *Nitzschia*, *Pseudo-nitzschia* and small, unarmoured

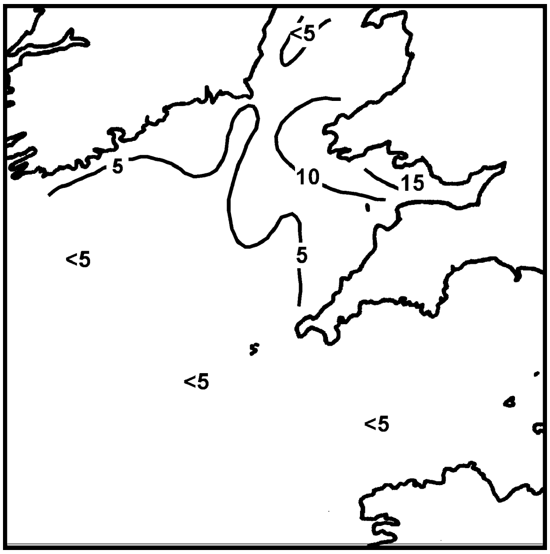

Fig. 6— Surface nitrate concentrations (as nitrate-N μM).

Fig. 7— Surface chlorophyll *a* concentrations (as μg dm^{-3}).

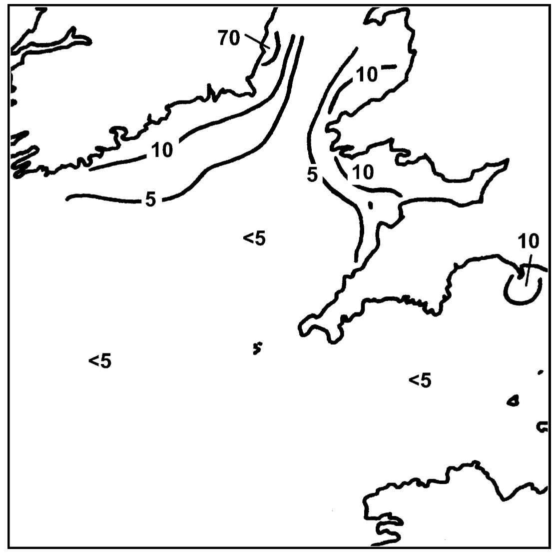

Fig. 8— Distribution of diatoms (unit = number of cells cm^{-3}).

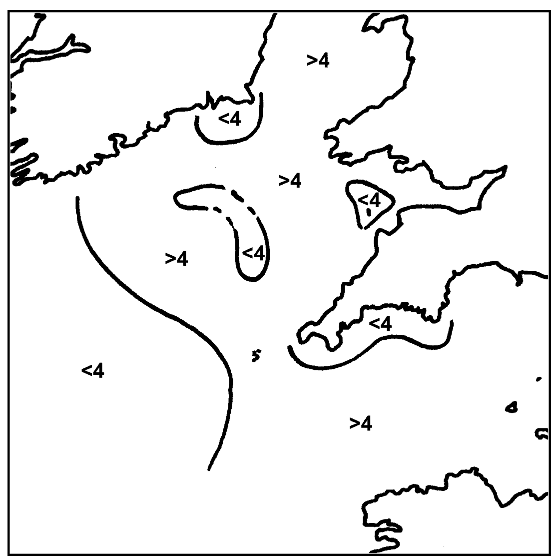

Fig. 9— Distribution of dinoflagellates (units = number of cells cm^{-3}).

dinoflagellates, were found throughout the area. Cryptophytes and other small flagellates occurred in every sample taken and, numerically, were the most abundant organisms recorded. The distributions of the diatoms, dinoflagellates, cryptophytes and other flagellates are presented in Figs 8–11. Diatoms (Fig. 8) generally show the clearest pattern. Lower numbers were found in the high salinity waters and higher numbers in coastal waters. Omitted from this diagram is one species of pennate diatom. This species was found in relatively high numbers (>10 cells cm^{-3}) over the Nymphe Bank and in the central parts of St George's Channel, but in lower numbers (<10 cells cm^{-3}) closer to the coasts and in the Atlantic Ocean and south Celtic Sea. Dinoflagellates (Fig. 9), especially small *Gymnodinium* and *Gyrodinium* species, were present throughout the study area but never abundant. Cryptophytes (Fig. 10), particularly *Plagioselmis* spp, were found throughout the study area. Higher densities (>100 cells ml^{-1}) occurred in much of the Celtic sea with lower densities (<100 cells ml^{-1}) occurring in the southern part of the study area and in some coastal areas, including the Bristol Channel and the central part of St Georges Channel. Other flagellates (Fig. 11) decreased in number from the open sea towards the coastal waters.

Estimates of the expected maximum number of species calculated using Chao's Index (Henderson 2003) gave values of 44 (SD = 2.2) for diatoms and 32 (SD = 3.1) for dinoflagellates. The actual numbers recorded for diatoms was 42 and for dinoflagellates was 29. Although values might be expected to be higher than these estimates because in some genera, notably *Nitzschia*, *Chaetoceros*, *Thassiosira*, *Gymnodinium* and *Gyrodinium*, no attempt was made to identify to species level. These values indicate low species numbers.

Phytoplankton volumes (Fig. 12) estimated from the counts, ranged from 1.7×10^4 μm^3 cm^{-3} to 3.0×10^5 μm^3 cm^{-3}. The highest volumes were located in areas adjacent to the Irish and Welsh coasts, with intermediate values throughout much of the Celtic Sea. A few of the non-coastal samples showed values as great as those found in the coastal waters. Spearman rank correlation analysis (Zar 1996) indicated weak ($0.05 < p < 0.02$), significant and positive relationships between both the cell volumes of diatoms ($r_s = 0.329$) and total cell volume ($r_s = 0.338$). Diatoms, it would appear, contribute more to the total volumes of cells and chlorophyll *a* concentration at this time of year than any of the other groups of organisms examined.

Table 1 — Organisms identified from the phytoplankton. The codes are used for identification in Tables 2 and 3. Some unidentified diatoms have been omitted from this list.

Bacillariophyceae	*Code*	*Dinophyceae*	*Code*
Achnanthes taeniata Grunow in Cleve et Grunow	Achtae	*Ceratium fusus* (Ehrenberg) Dujardin	Cerfus
Asterionellopsis glacialis (Castracane) Round	Astegla	*Cochlodinium helicoides* Lebour	Cochel
Bacillaria paxillifera (O. F. Müller) Hendey	Bacpax	*Dinophysis* sp.	Dinsp
Cerataulina pelagica (Cleve) Hendey	Cerpel	*Gonyaulux digitale* (Pouchet) Kofoid	Gondig
Chaetoceros spp	Chaspp	*Gonyaulux* sp.	Gonsp
Coscinodiscus sp.	Cossp	*Gymnodinium* spp < 10μm	Gym10
Dactyliosolen fragilissimus (Bergon) Hasle	Dacfra	*Gymnodinium* spp < 20μm	Gym20
Ditylum brightwellii (West) Grunow in Van Heurck	Ditbri	*Gymnodinium* spp < 30μm	Gym30
Eucampia zodiacus Ehrenberg	Euczod	*Gymnodinium* spp > 30μm	Gym30+
Fragilariopsis pseudonana (Hasle) Hasle	Frapse	*Gyrodinium* spp < 10μm	Gyr10
Guinardia delicatula (Cleve) Hasle	Guidel	*Gyrodinium* spp < 20μm	Gyr20
Guinardia striata (Stolterfoth) Hasle	Guistr	*Gyrodinium* spp < 30μm	Gyr30
Leptocylindrus mediterraneus (H. Pergallo) Hasle	Lepmed	*Gyrodinium* spp > 30μm	Gyr30+
Leptocylindrus minimus Gran	Lepmin	*Gyrodinium fissum* (Levander) Kofoid et Swezy	Gyrfis
Navicula sp.	Navsp	*Gyrodinium lachryma* (Meunier) Kofoid et Swezy	Gyrlac
Nitzschia longissima (Brébisson, in Kützing) Ralfs in Pritchard	Nitlon	*Gyrodinium spirale* (Bergh) Kofoid et Swezy	Gyrsp
Nitzschia sp.	Nitsp	*Karenia mikimotoi* (Miyake et Kominami ex Oda) G.Hansen et Moestrup	Karmik
Odontella mobiliensis (Bailey) Grunow			
Odontella sinensis (Greville) Grunow	Odomob	*Katodinium glaucum* (Lebour) Loeblich III	Katgla
Pleurosigma spp	Odosin	*Katodinium* sp. 1	Katsp1
Pseudo-Nitzschia spp (*Nitzschia delicatissima* Complex)	Plespp	*Katodinium* sp. 2	Katsp2
Pseudo-Nitzschia spp (*Nitzschia seriata* Complex)	Nitdel	*Mesoporus perforatus* (Gran) Lillick	Mesper
Rhizosolenia hebetata Bailey f. hebetata	Nitser	*Prorocentrum balticum* (Lohmann) Loeblich III	Probal
Rhizosolenia hebetata f. *semispina* (Hensen) Gran	Rhiheb	*Protoperidinium bipes* (Paulsen) Balech	Probip
Rhizosolenia styliformis Brightwell	Rhisem	*Protoperidinium curvipes* (Ostenfeld) Balech	Procur
Skeletonema costatum (Greville) Cleve	Rhisty	*Prorocentrum micans* Ehrenberg	Promic
Thalassionema nitzschioides (Grunow) Mereschkowsky	Skecos	*Protoperidinium ovatum* Pouchet	Proova
Thalassiosira anguste-lineata (A. Schmidt) G. Fryxell	Thanit	*Protoperidinium* spp	Prospp
et Hasle	Thaang	*Scripsiella trochoidea* (Stein) Loeblich III	Scrtro
Thalassiosira spp 40–50μm	Tha40	*Torodinium robustum* Kofoid et Swezy	Torrob
Thallassiosira spp < 10μm	Tha10	Cryptophyceae	Cryptos
Thallassiosira spp < 20μm	Tha20	Other flagellate cells	Others
Unidentified pennate	Unipen		

Two indices of diversity, the Berger-Parker Index and the Margalef Index, were calculated for the diatom populations. The Berger-Parker Index provided consistently high values off the south coast of Ireland (Fig. 13). Samples from these stations were dominated by few species. The Margalef Index (Fig. 14), a species-richness estimate, indicated rich populations off the Irish coast and in Cardigan Bay. This index showed a significant positive correlation with cell volume ($r_s = 0.389$, $p > 0.01$) and with diatom volumes ($r_s = 0.584$, $p > 0.001$). There was, however, no correlation with chlorophyll *a* concentrations, even though the highest chlorophyll *a* values were recorded off the Irish coast and in Cardigan Bay (Fig. 7).

DISCUSSION

Based on the temperature and salinity data, different water masses can be identified: a mass of warm (>9°C), high salinity (>35) ocean water occupying the western margins of the Celtic Sea; a cooler (8°C–9°C) tongue of high salinity (>35) water in St George's Channel; and cool (<8°C), lower salinity (<35) coastal waters along the Welsh and Irish coasts. The low salinities and temperatures of the coastal waters on the eastern side of the area are caused by the outflow from the river Severn and on the western side by various Irish rivers whose waters are entrained in a geostrophic flow around the coast. The highest concentrations of nitrate-N

Table 2 — Distribution of diatoms. Full names for the species codes listed in the first column are given in Table 1. See Fig. 3 for the locations of the stations.

Station	1	2	3	4	5	7	8	9	10	11	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Achtae													★													★
Astegla																					★					
Bacpax																							★			
Cerpel		★																								
Chaspp		★	★	★			★				★		★	★			★	★		★	★					
Cossp											★															★
Dacfra			★																		★			★	★	
Ditbri			★			★			★		★	★	★	★												
Euczod													★													
Frapse													★										★		★	
Guidel				★			★				★		★			★	★	★	★				★			
Guistr		★	★																							
Lepmed																										
Lepmin	★																				★					★
Navspa																		★				★				
Nitdel									★				★	★	★						★	★		★	★	
Nitlon	★	★		★	★	★	★	★		★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★
Nitser	★	★	★	★			★						★		★	★	★	★	★	★	★	★	★	★	★	
Nitsp	★	★	★		★	★	★			★		★	★		★	★	★	★	★	★	★	★	★	★	★	★
Odomob													★			★	★					★	★	★		★
Odosin													★								★					
Plespp		★		★	★					★	★		★	★	★	★	★		★	★	★	★		★	★	
Rhiheb							★																			
Rhisem			★							★																
Rhisty																										
Skecos													★						★	★	★	★	★	★		★
Tha10	★	★	★				★			★	★	★	★		★			★				★		★	★	★
Tha20				★						★									★		★	★		★	★	
Tha40							★						★				★	★	★				★			
Thaang																										
Thanit				★	★	★	★		★			★	★		★	★	★				★		★	★		★
Unipen				★						★			★	★										★	★	★

were also associated with the Severn plume in the Bristol and St George's Channels.

Though chlorophyll *a* concentrations were low throughout the area, the highest values were all recorded in coastal waters. A similar situation has also been reported from the English Channel (Pingree *et al*. 1986), where higher chlorophyll concentrations located off the French coast were associated with water influenced by the River Seine. It has also been shown that the waters of the western English Channel are dominated by cryptophytes and other small flagellates until March, when the chlorophyll *a* concentrations are low (Pingree *et al*. 1986). In the Celtic Sea, cryptophytes and other small flagellates were numerically dominant in the spring of 1985, but diatoms contributed more to both the volume of plankton and the chlorophyll *a* concentrations.

Communities of phytoplankton are often dominated by a few species, with many others occurring in lower numbers. Patchiness of some species can also affect patterns of abundance. In a pre-bloom situation no single species would be expected to dominate the populations and all species should occur in low numbers. This was the situation in most of the area examined, but in those areas with higher chlorophyll *a* concentrations and biovolumes the increasing dominance of a few species is indicated by the prevalence of high Berger-Parker indices. This is particularly noticeable along the southern coast of Ireland. These species might be expected to form the

29	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
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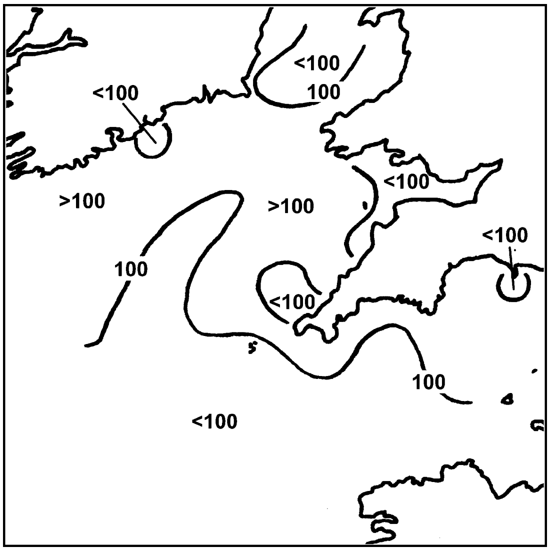

Fig. 10—Distribution of cryptophytes (unit = number of cells cm^{-3}).

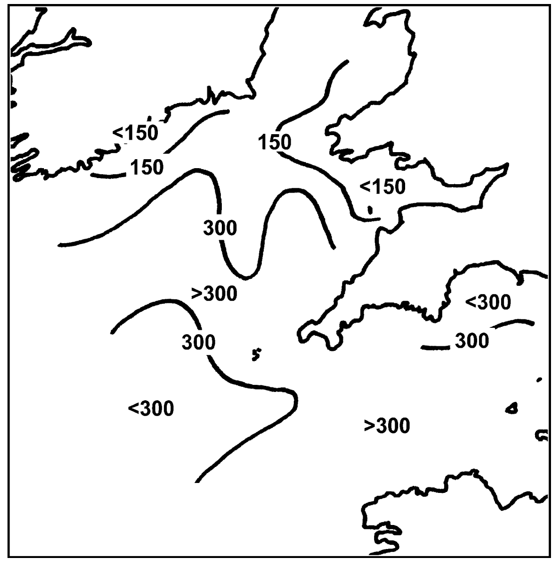

Fig. 11—Distribution of other flagellates (unit = number of cells cm^{-3}).

Table 3—Distribution of dinoflagellates. Full names for the species codes listed in the first column are given in Table 1. See Fig. 3 for the locations of the stations.

Station	1	2	3	4	5	7	8	9	10	11	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Cerfus										★																
Cochel						★	★								★	★	★	★				★			★	
Dinsp					★			★																		
Gondig																										
Gonsp																										
Gym10	★	★	★	★			★	★					★	★	★	★		★								★
Gym20					★		★	★		★				★		★	★	★		★		★	★	★	★	★
Gym30				★		★																★				
Gym30+		★																								
Gyr10						★	★	★					★	★												
Gyr20	★	★	★	★	★	★			★	★		★		★	★	★	★	★	★							★
Gyr30						★																				
Gyr30+		★		★													★									★
Gyrfis																										
Gyrlac								★	★			★			★					★	★					
Gyrsp	★	★	★	★	★					★				★		★	★	★		★		★				
Karmik									★								★	★	★			★			★	
Katgla							★				★	★														
Katsp1	★			★		★		★	★																	
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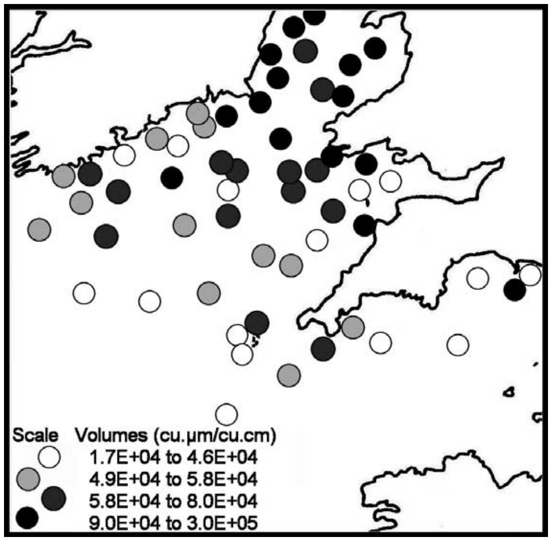

Fig. 12 — Estimated total cell volumes for each station.

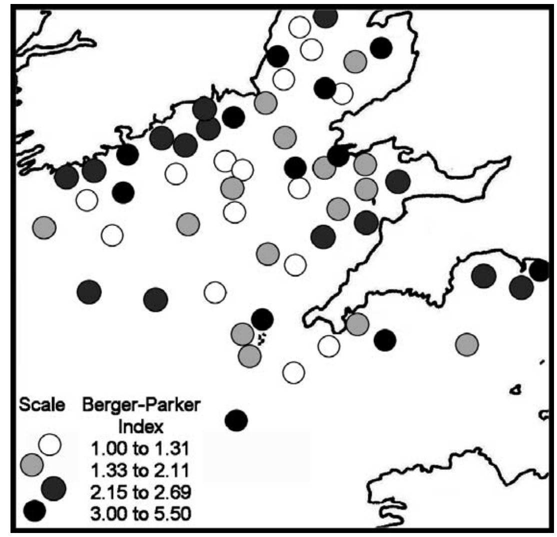

Fig. 13 — Berger-Parker diversity indices for each station (diatoms only).

29	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
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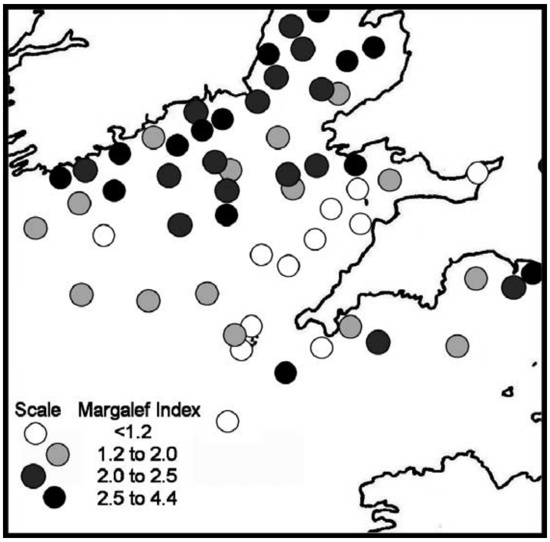

Fig. 14—Margalef diversity indices for each station (diatoms only).

core species of the spring bloom which, off Kinsale in February 1980, contained species of *Chaetoceros*, *Guinardia*, *Skeletonema*, *Pseudo-Nitzschia* and *Thalassiosira* (Pybus 1981). These organisms were also recorded during the 1985 cruise.

With few exceptions, the highest cell volumes and chlorophyll *a* concentrations were found in the cooler, low-salinity coastal waters and the lowest cell volumes were found in the central Celtic Sea area. In April 1994, Rees *et al*. (1999) working at the shelf edge, showed that when the chlorophyll *a* concentration was low (<0.7 $\mu g\ l^{-1}$) the picophytoplankton ($<2\mu m$ fraction) were responsible for 42% of primary production. In the pre-bloom populations in 1985 cryptophytes and other flagellates (although $>2\mu m$) were numerically dominant, but the diatoms made the most significant contribution to both volume of phytoplankton and chlorophyll *a* concentrations.

Rees *et al*. (1999) also found that the increasing chlorophyll *a* concentrations of the spring bloom were associated with cells greater than 2μm in size and with developing diatom populations, which were dominated by *Nitzschia* (*Pseudo-Nitzschia*), *Thalassionema* and *Chaetoceros*. These and the main diatom species recorded in the May bloom by Pingree *et al*. (1977)—*Chaetoceros* spp and *Guinardia delicatula* (=*Rhizosolenia delicatula*)—were seen in many of the samples examined here. As the populations developed and changed during the summer of 1977, other species became prominent. Most were recorded in the pre-bloom samples taken in 1985. By late summer and early autumn, populations of dinoflagellates become more pronounced (Pingree *et al*. 1976). Again similar species were recorded in the pre-bloom populations in 1985.

An initial inoculum is a prerequisite for development of any phytoplankton bloom. The source may be derived from dormant cells or cysts, in suspension or in the sediments. Sedimentary sources are quite likely in lakes and shallow seas, where sediments may be disturbed by water movements. This is less likely in deeper water, so some cells must remain in suspension ready to take advantages of the beneficial conditions that occur in spring. However the cell densities become so low during the winter months that it is not easy to prove the presence of many of those species even when their cells are quite large. That large cells may escape detection by routine sampling was demonstrated for a freshwater dinoflagellate, *Ceratium hirudinella*, in Lake Windermere (Heaney *et al*. 1988), when it was found that the examination of up to 50 litres of water was needed before the presence of *C. hirudinella* could be proven. Rarely would routine sampling involve such large volumes of water, so it is interesting to note that most of the dominant species recorded by other workers during the later blooms in the Celtic Sea area are already present in the early vernal surface water samples examined here.

Blooms are likely to develop earlier in the coastal waters where nutrients are most abundant and conditions necessary for bloom formation, particularly those related to mixing of the water column can occur earlier than in the deeper waters. The marginally higher chlorophyll *a* concentrations off the Irish, Welsh and southern English coasts would support this hypothesis.

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