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The Continuous Plankton Recorder Survey: a Long-Term, Basin-Scale Oceanic Time Series.

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Introduction

In the 1920s, before the advent of echosounders, fishery biologists were greatly concerned with assisting the fisherman to locate schools of pelagic fish. One of the approaches they developed was to relate the distribution of the planktonic food organisms to the presence of the schools of predators such as herring (Clupea harengus). The British planktologist, Alister Hardy, who had already carried out extensive studies on the feeding preferences of herring (Hardy, 1926a), initiated a programme to examine the fishermen's contention that herring schools avoided "green", i.e., phytoplankton-rich, water but could be correlated with high concentrations of zooplankton.

This practical programme was centred on the used of a specially developed instrument, the "Plankton Indicator", designed to be used by the fisherman to assist in the search for suitable waters. It had limited success in its main aim but, as a collecting device, it embodied several profoundly important features. It was a simple instrument which was robust enough to be deployed and recovered by the crew of commercial vessels (in this case fishing vessels) while they were underway.

The Indicator however, was no more than a high speed net which integrated the plankton over the area of sampling, but Hardy had also become interested in describing the patchiness of planktonic populations. He thus developed the Continuous Plankton Recorder (CPR) where he substituted the fixed filter screen of the Indicator by a continually moving length of silk mesh. The screen traversed at constant speed across the path of the incoming water and the trapped organisms were retained in place by sandwiching beneath an additional second mesh screen (Fig 1). Thus, knowing the speed of the towing vessel and the shooting and hauling positions, the spatial patterns of the plankton could be determined. Hardy took the first CPR to the Antarctic where he used it in the Southern Atlantic (Hardy, 1926b) and later deployed it in the North Sea to make some of the earliest contiguous records of plankton patchiness.

The Development of the CPR Survey

Hardy was not content with the mere description of the linear patchiness of plankton along a tow track, he was intrigued by the broader spatial patterns of plankton distributions and the temporal changes which occurred. He thus conceived the idea of deploying CPRs more or less simultaneously behind several towing vessels and, using the analogy of meteorological investigations of that time, would thereby gain a synoptic picture of temporal and spatial change in plankton populations. In his words "the idea underlying the initiation of this ecological survey was that of attempting to apply methods similar to those employed in meteorology to the study of the changing plankton distribution, its causes and effects" (Hardy, 1939). An improved version of the CPR was developed, the MK II, which incorporated an adjustable propeller to compensate for different towing speeds of commercial "ships of opportunity", had improved gearing and a mechanism to minimise the flattening of the captured organisms by the sandwiching silk meshes. A CPR Survey team was set up and a series of routes were developed in the North Sea between Britain and continental Europe. (Fig 2).

The present CPR survey was thus established over 60 years ago and, since then, has had a somewhat chequered history. It stopped operations during World War II, reached its zenith between 1965-1975 (Fig 3), nearly ceased in 1989 and became the responsibility of an independent Foundation in 1991. When reestablished after the War, sampling routes were developed to the west of Britain as well as across the North Sea. Initially routes were established to several weather ships in the eastern Atlantic with the first trans-Atlantic deployment, via Iceland to Newfoundland, taking place in 1959. At its height, in 1970, the CPR Survey included 4 trans-Atlantic Routes though, of these, only the UK-Iceland-Newfoundland-Cape May route remains (Fig 4). CPRs have been towed about 3.8 million nautical miles since the inception of the Survey, not including those deployed by NOAA/NMFS in the USA and CSIRO in Australia.

Until 1989 the Survey was financed directly by the UK government although occasional awards were made by other bodies such as the ONR of the USA and the Canadian Fisheries Department. Since April 1991 the Survey has been the responsibility of a new organisation, the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), which is an independent UK charity specifically formed to ensure the continuity of the CPR Survey and to promote and develop new long-term planktonic time series. SAHFOS is funded by an international consortium consisting of Canada, France, Iceland, Netherlands, United Kingdom, USA, the Council of European Communities and the Intergovernmental Oceanographic Commission.

Operations and Practices

The CPR used in 1991 has changed little from that designed by Hardy in the 1930s. There have been derivatives, which will be mentioned below, but the paramount need to maintain the integrity of the long-term database has necessitated an extremely conservative policy against unwarranted change. The same silk mesh size of 280μm is used, it traverses the sampling tunnel at the same rate and the Recorder is still towed at a nominal 10 m depth. Each sample, collected at a range of speeds between 10-24 knots, represents 10 nautical miles of tow equivalent to 3 m3 of water. As the main aim is to investigate the changing patterns of plankton populations, 391 different taxonomic entities are routinely identified (Table 1). In addition a "green-ness" index is estimated which relates to the amount of chlorophyll leached out of phytoplankton by the formaldehyde preservative and which subsequently stains the silk threads of the mesh.

Instrumentation for the CPRs has been developed (Aiken, 1980) and robust, self-contained packages can be attached to Recorders which can measure temperature, salinity, fluorescence, depth, downwelling and upwelling light at several wavelengths, transmittance and other parameters. Hardy himself realised that there were severe limitations to sampling at a single depth, the vertical migration of many of the zooplankton species being one, and he hoped that a vertically resolving Recorder would eventually become available (Hardy, 1956). This is now possible with the development of the Undulating Oceanographic Recorder (Aiken, 1985) which samples sinusoidally between the surface and 70 m and is capable of carrying both the instrumentation package and the CPR internal silk mesh sampling mechanism. It has been towed behind ships of opportunity (Robinson et al., 1986), but only when accompanied by scientific staff, hence it has not been deployed routinely on CPR tow routes.

Operationally the CPR Survey is a continuous exercise which breaks down into the usual four component parts of most scientific investigative operations: sample collection, sample analysis, data handling and data evaluation. The major procedural aspect is that all the processes occur simultaneously. At present SAHFOS operates 15 CPR routes on a monthly basis amounting to about 60,000 miles for the year. Sample collection currently requires the 360 shipments of CPR bodies between Plymouth and various ports each year.

Sample analysis consists of the routine systematic identification and enumeration of, usually, each alternate 10 miles of sampling along a given route. Analysis is carried out directly on cut lengths of silk representing 10 miles of tow. Large organisms are analysed by eye, mesozooplankton and phytoplankton at set microscope magnifications. The aim since the inception of the Survey has been to match consistency with efficient throughput of samples and the basic analytical techniques have not changed since the early 1960s (Rae, 1952 and Colebrook, 1960, 1964). Organisms are not counted but are assigned abundance categories which quickens the analytical procedure but does not, with an experienced analyst, lead to significant loss of precision (Colebrook 1960). Data are stored as abundance categories which are subsequently transformed, log(x+1), so as to standardise variances in subsequent averaging processes before being collated for evaluation.

Data handling procedures in the CPR Survey have evolved alongside the development of the laboratory computer with the database and retrieval systems being elaborated up as computer systems became more sophisticated. Currently the CPR database (including storage and access programs) extends to 64.4 Mb and recently has almost completely been transferred from a mainframe computer to an OS/2- based PC. The main data archive is file-based made up of four files annually. The first file contains navigational data and the length of silk filter mesh used for each tow. A second contains the sampling information for each tow detailing position (latitude, longitude and allocated "standard rectangle"), time, day or night and date. The third and fourth contain the plankton information for the tows made in a specific year; one with January to June data and the other the July to December data. Each tow within the files has been allocated a limited set of the sampling attributes; standard CPR rectangle co-ordinates and day or night allocation. The plankton information is held as coded abundance categories (see above).

The data for individual or grouped taxonomic entities can be retrieved in three ways:

1. Based on 1° latitude by 2° longitude "standard rectangles". The main use of the data extracted in this way is for producing distribution charts for biogeographical studies.
2. Based on defined groups of the standard rectangles into "standard areas" and used in the main for the analysis of large-scale variation in time and space. Such data has been used recently in the interpretation of possible effects of climatic/hydrographic interactions on plankton populations.
3. Based on any defined set of polygons (usually rectangles) which are most suitable for fine resolution analysis in restricted areas.

Results of the Survey

Over 400 publications have either resulted directly from the Survey or make substantial use of its data since its inception. Essentially the data evaluations fall into three broad perspectives; biogeographical, (including the recognition of new species), seasonal cycles and long- term, interannual trends. Biogeography can be divided into distributional mapping (a comprehensive atlas of North Atlantic and North Sea plankton was published by the Edinburgh Oceanographic Laboratory in 1973) and short-term changes relating to hydrography. The CPR Survey, for instance, established the spatial differentiation of the congeners Calanus finmarchicus and C. helgolandicus (Matthews, 1967)) in the North Atlantic (Fig 5). On a smaller scale there has been evidence of hydrographic incursions of Atlantic water into the North Sea as indicated by the recent increased prevalence of the predominantly Atlantic species, Corycaeus anglicus and Metridia lucens (Fig 6). These findings are supported by recent observations of exceptionally high salinity water in the northern North Sea in the winter of 1990-91 (Heath et al, 1991). The presence of doliolids in the German Bight of the North Sea in 1989 was further evidence of the same hydrographic event (Lindley et al, 1990). In some cases CPR observations have preceded hydrographic confirmation although the reverse has also been true, as the mid 1970 salinity anomaly in the North Sea has been used retrospectively to interpret CPR trends (J.M. Colebrook, pers. comm.).

In the context of JGOFS, it is appropriate to look at some of the CPR data in the vicinity of the recent UK BOFS operation around 60°N and 20°W. The time series of CPR data in each of the standard areas straddling this study site extend for 43 years in C5 to the east but only 8 years in the adjacent C6 to the west. The basic data, shown for C5 (Fig 7), which clearly shows the seasonal pulses, can be averaged into representative seasonal cycles for the two areas (Fig 8). It is apparent that there are differences in the trophic structure of the planktonic systems in the two areas. During the peak bloom period the more westerly area appeared to have less abundant grazing zooplankton populations and higher phytoplankton. It could be inferred that there would be an increased sink of ungrazed phytoplankton-fixed CO2 to the west of the study site. The greater proportion of grazing zooplankton in the east would presumably result in a greater level of metabolic remineralisation of CO2.

The short turnover time of planktonic trophic systems together with their inherent dependence on hydrographic conditions should make them ideal, rapid indicators of the effects of climate change. Two recent observations from the CPR Survey illustrate the consequences of both short and long-term climatic events on plankton populations.

Between 1986 and 1988 the abundance of several large species of dinoflagellates, Ceratium spp increased dramatically in the north-central North Sea (Fig 9). The preferred explanation for this increase (Dickson et al., in press) was that an anomalous south-easterly air stream had caused less saline water from the Baltic to spread away from its usual location close by the coast of Norway to cover a large area of the northern North Sea. The resultant stratification of the water column was highly favourable to the growth of the Ceratium spp. Recently this theory has been supported by information in Fraedrich and Müller (1992) which suggest that the south-easterly anomaly was a far reaching consequence of ENSO events being experienced in the eastern Atlantic.

Perhaps the most significant climatic aspect of the CPR time series is the recently evident change in the long term trends in abundance of groups of about 40 species of phytoplankton and zooplankton. Coherent patterns appear in the long term averages in each of 12 different areas suggesting in itself that pervasive factors relating to major atmospheric circulation events are involved in determining what happens to the plankton. Arguments have been presented which involve implicating changes in both westerly (Colebrook 1986) and northerly (Dickson et al. , 1988) wind patterns but interest has now shifted to a possible response of plankton to the current trend in global warming.

Figure 10 illustrates time-series for zooplankton and phytoplankton in the North Sea. Until the early 1980s the trend in both planktonic groups was consistently downwards, indeed concern was once expressed that such effects might have resulted from anthropogenic impact, but the trend, particularly in the zooplankton, has increased consistently since then. Comparable parallel trends are evident in the long-term variability of the position of the North Wall of the Gulf Stream (Taylor et al, in press), in changes in an index of coastal upwelling in the Atlantic (Bakun, in press) and in annual averages of North Atlantic water (Folland

and Parker, 1990) and global air temperatures (Kerr, 1990). Moreover, similar parallels have been drawn between North sea plankton, the abundance of herring and the breeding success of piscivorous seabird populations on the north east coast of Britain (Aebischer et al, 1990) indicating that pervasive changes affect several different trophic levels of the ecosystem. Such implications can only be drawn from correlations and more years of observation are required before the links with climate can be established with more certainty although the indications are presently becoming evident.

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Table 1. Summary of taxonomic entities identified routinely in the Continuous Plankton Recorder Survey

	Phytoplankton	Zooplankton
Species	119	118
Genus	42	63
Family	1	6
Sub-Order	1	3
Order	-	16
Class	2	14
Phylum	-	6
Total	165	226

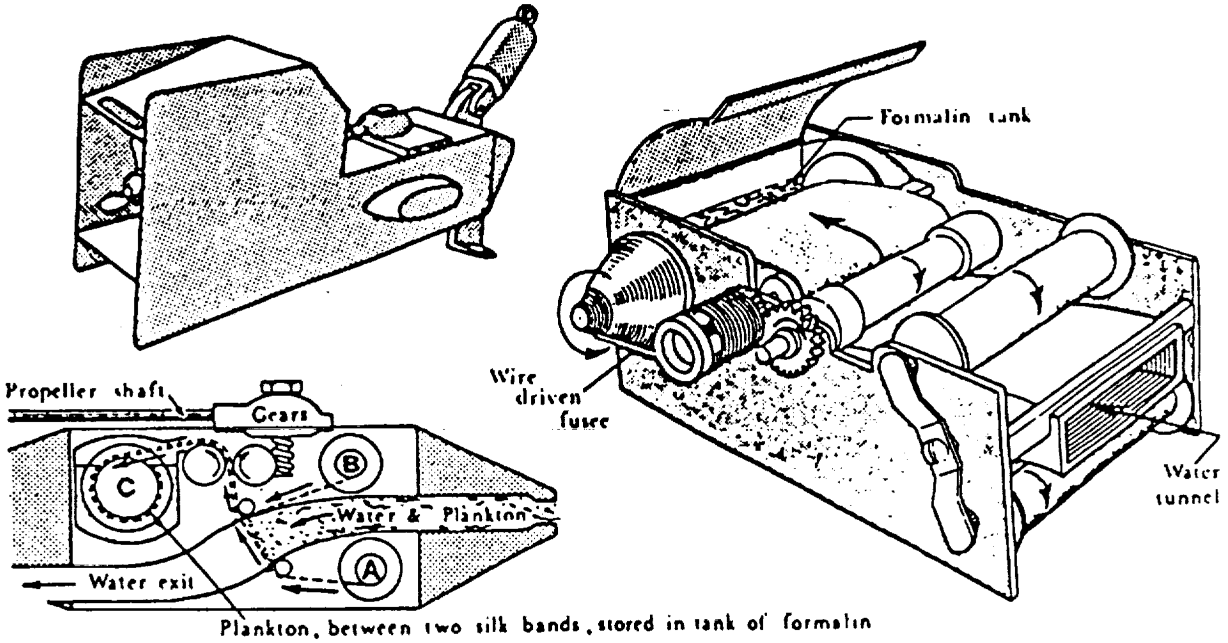


Figure 1. Schematic representation of the Continuous Plankton Recorder. The entire instrument is approximately 1 m in length.

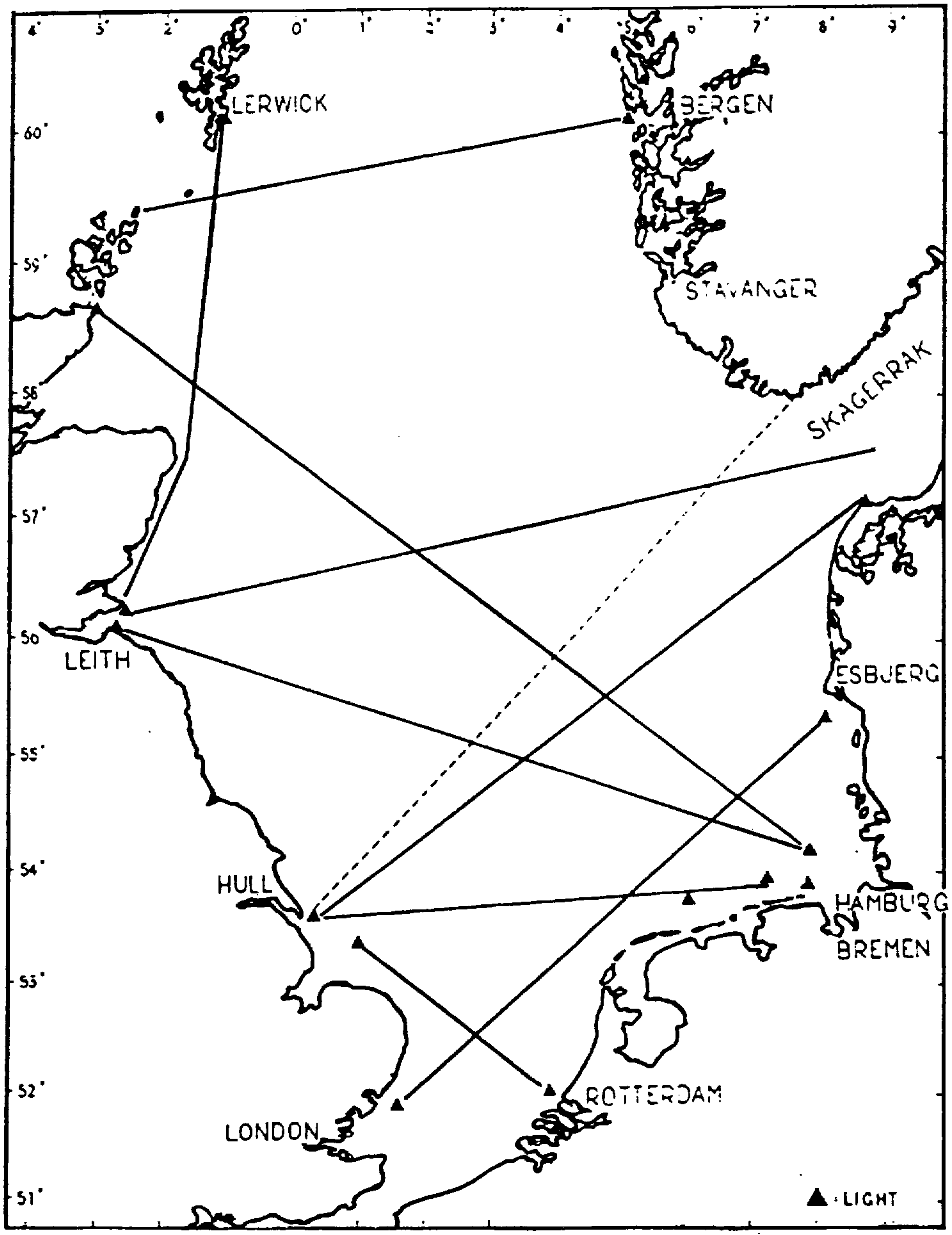


Figure 2. Monthly Continuous PLankton Recorder Survey routes in the North Sea in 1938 from Hardy, 1939).

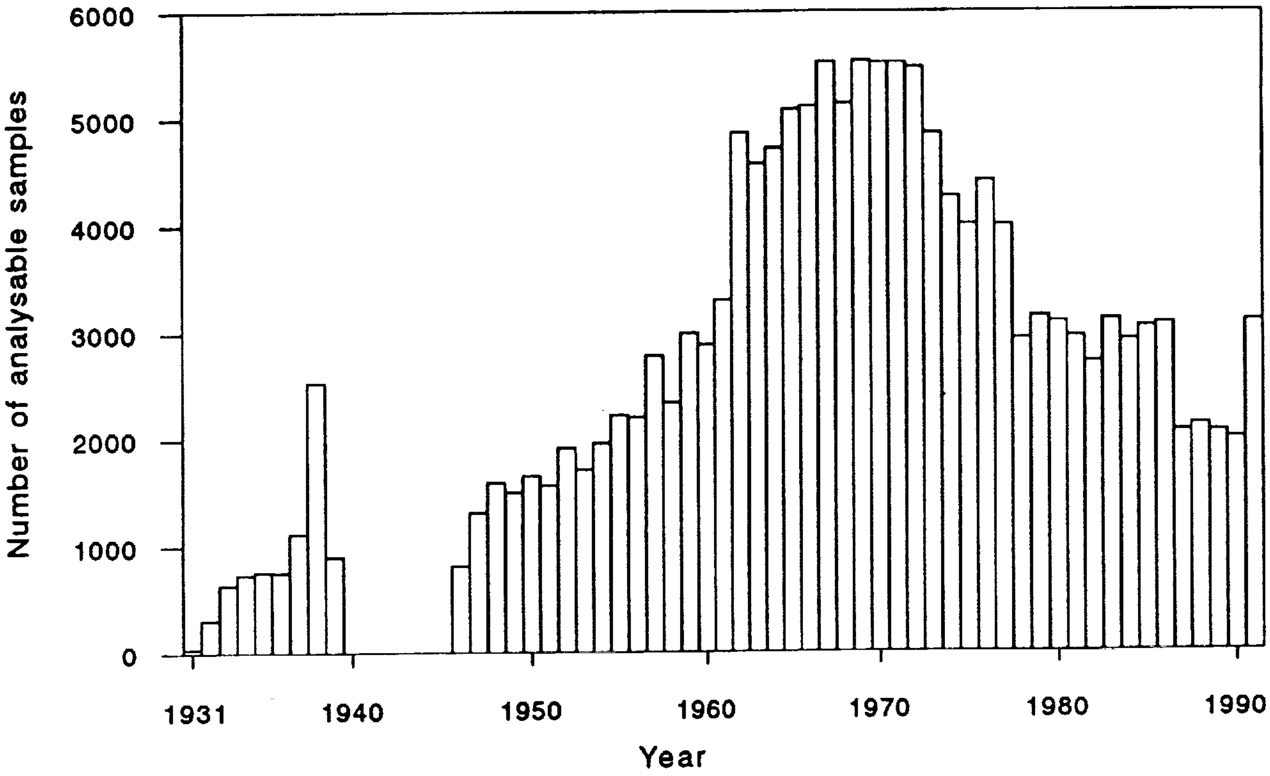
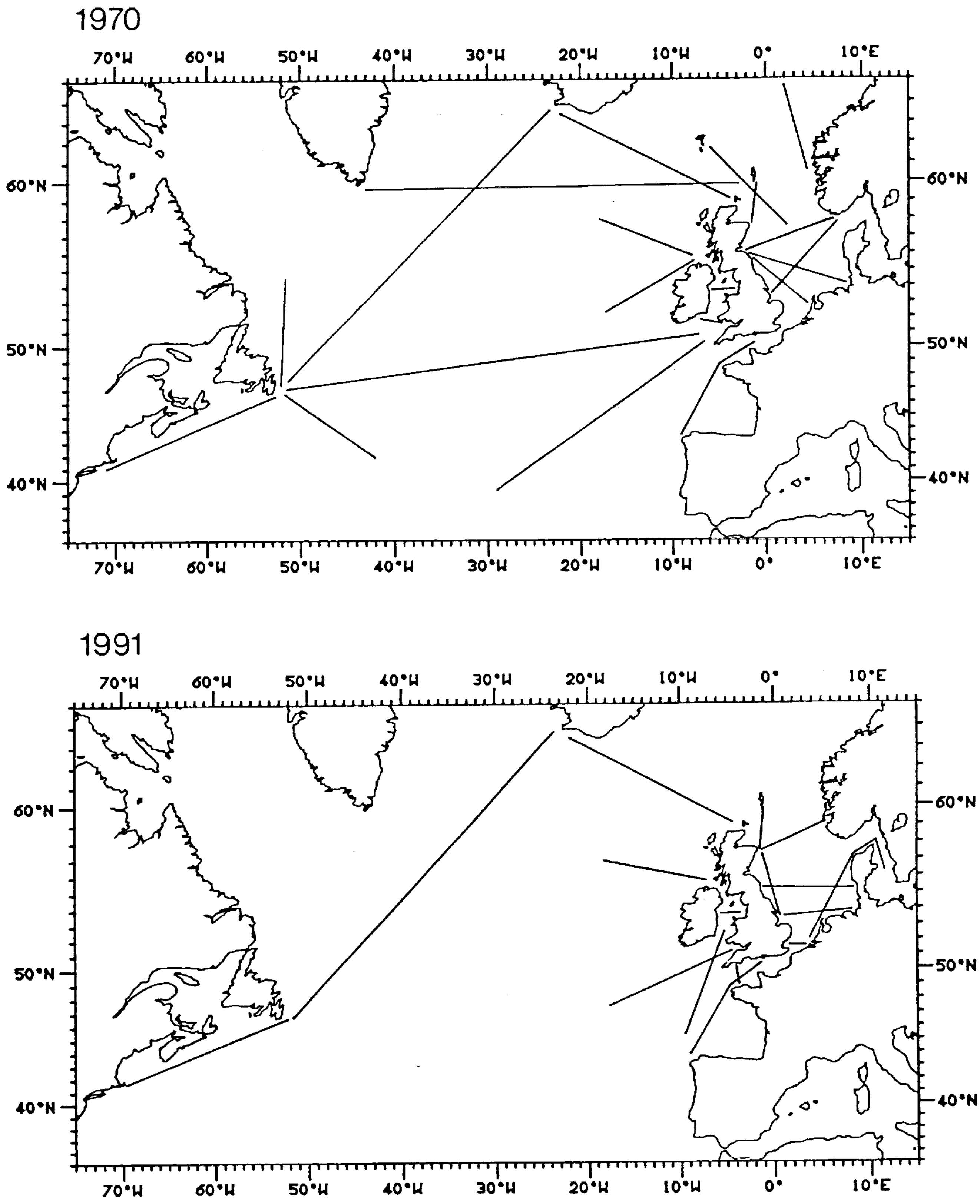
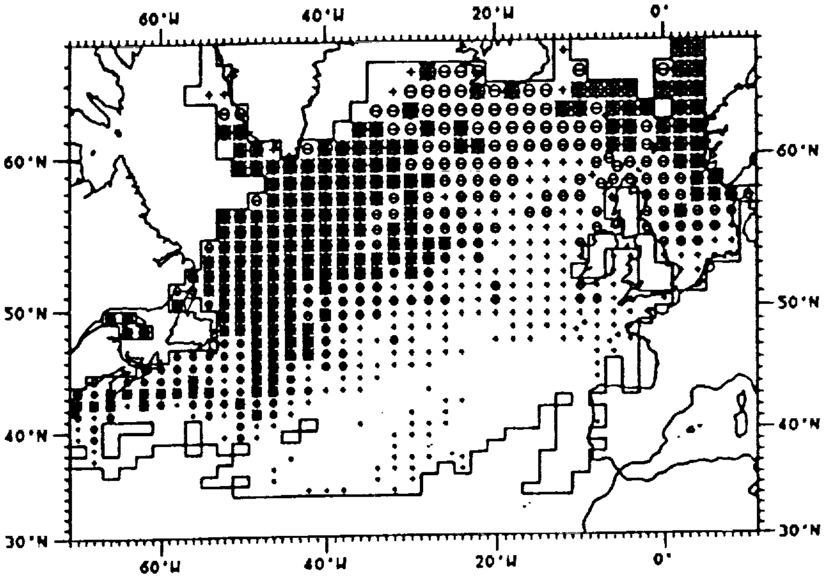


Figure 3. Number of samples collected by the Continuous Plankton Recorder Survey since 1931.

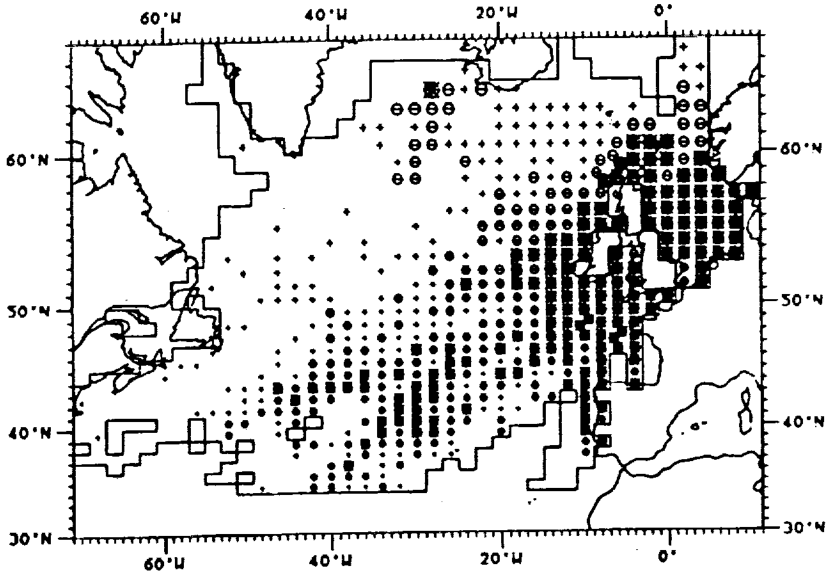

1970

1991

Figure 4 . Tow routes of Continuous Plankton Recorders in 1970 and 1991.



Calanus fin. finmarchicus



Calanus helgolandicus

Figure 5. Distribution patterns of the copepods Calanus finmarchicus and Calanus helgolandicus in the North Atlantic province as determined by the Continuous Plankton Recorder Survey. Symbols represent relative population densities within each species (see Edinburgh Oceanographic Laboratory, 1973, for further details).

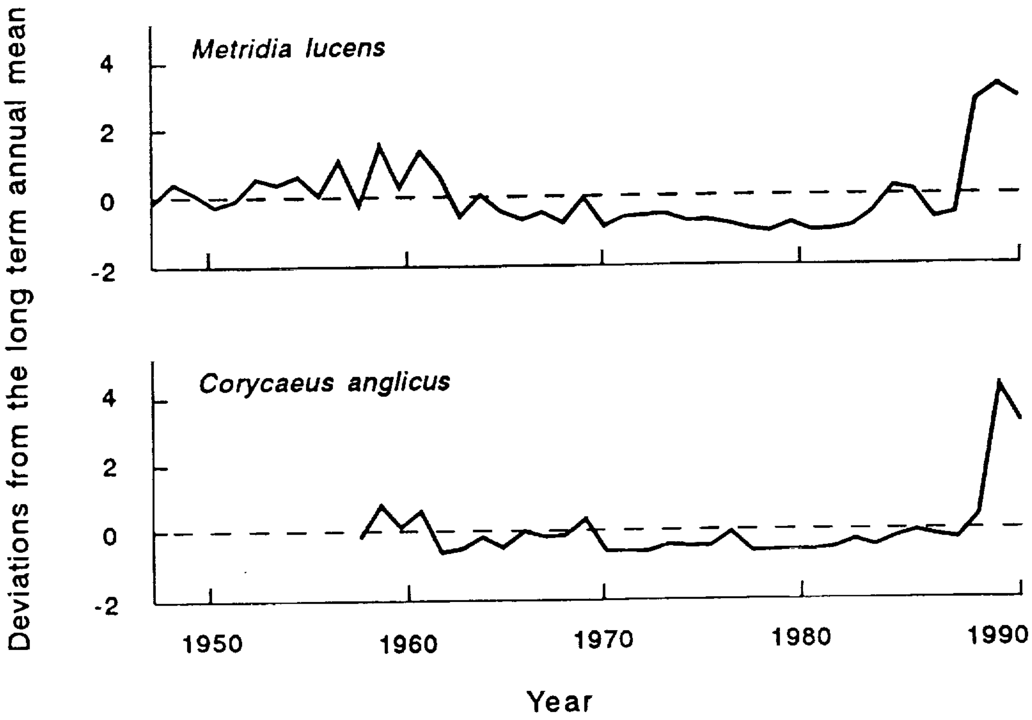
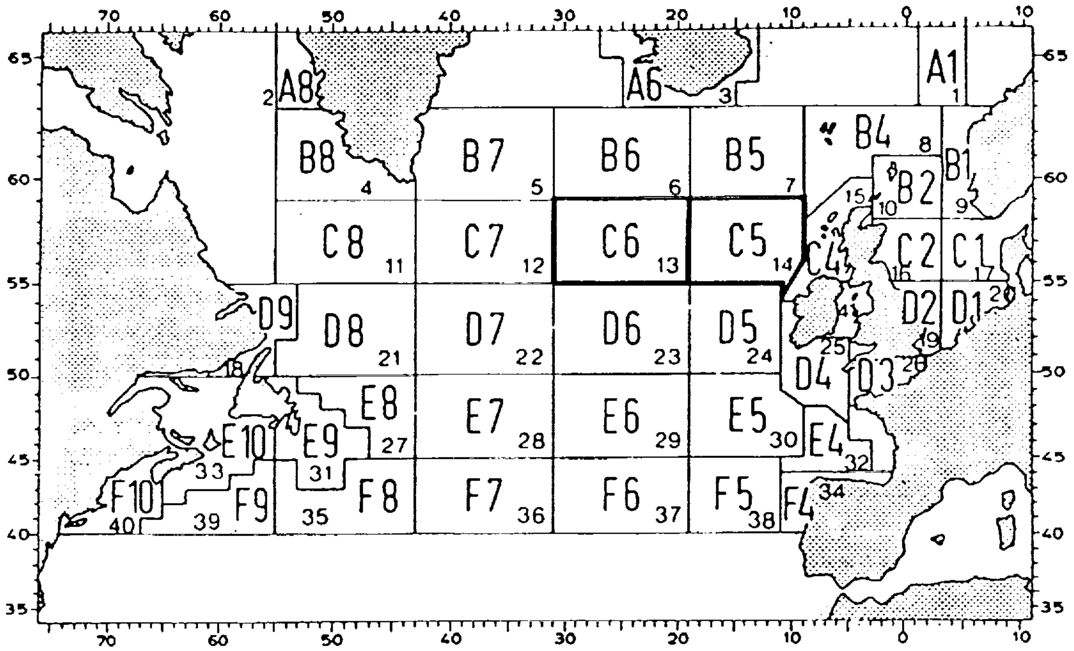


Figure 6. Summaries of the long term fluctuations in the abundance (in standard deviation units) of the copepods Metridia lucens and Metridia anglicus in the North Sea.



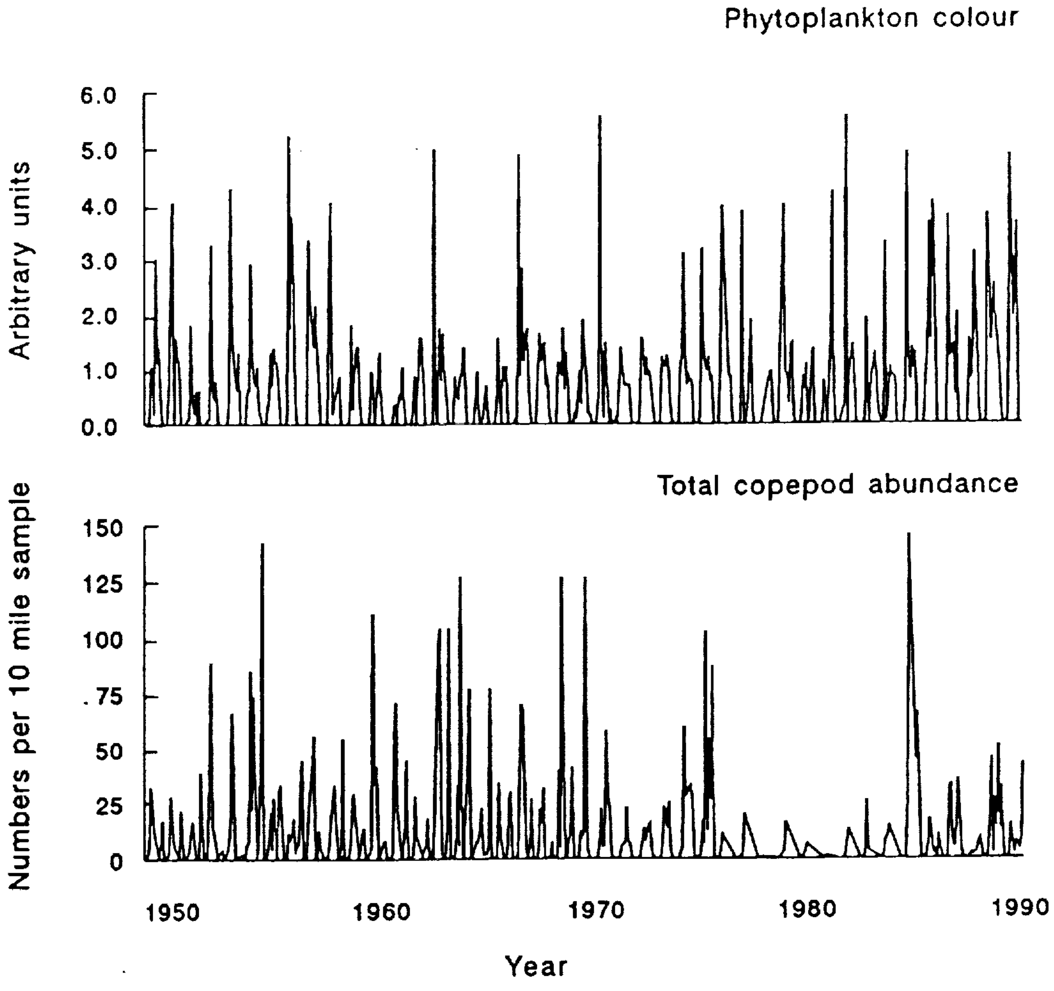


Figure 7. Annual variation in phytoplankton colour index and total copepod abundance in the NE Atlantic area C5 situated to the north west of the British Isles.

C-4

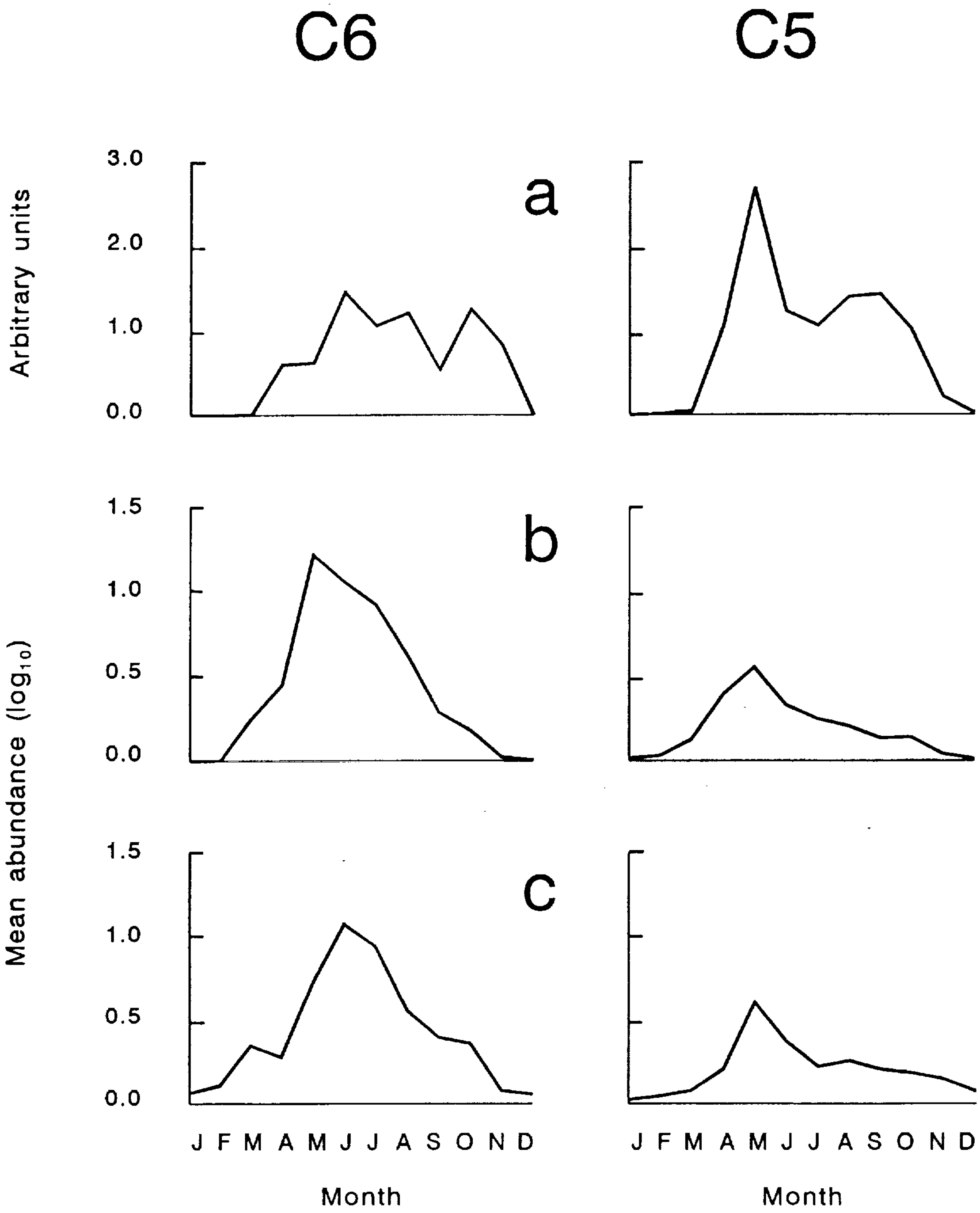


Figure 8. Averaged seasonal variation in (a) the phytoplankton colour index, (b) abundance of Calanus finmarchicus and (c) abundance of Euphausiacea in the NE Atlantic areas C5 and C6 (see Figure 7).

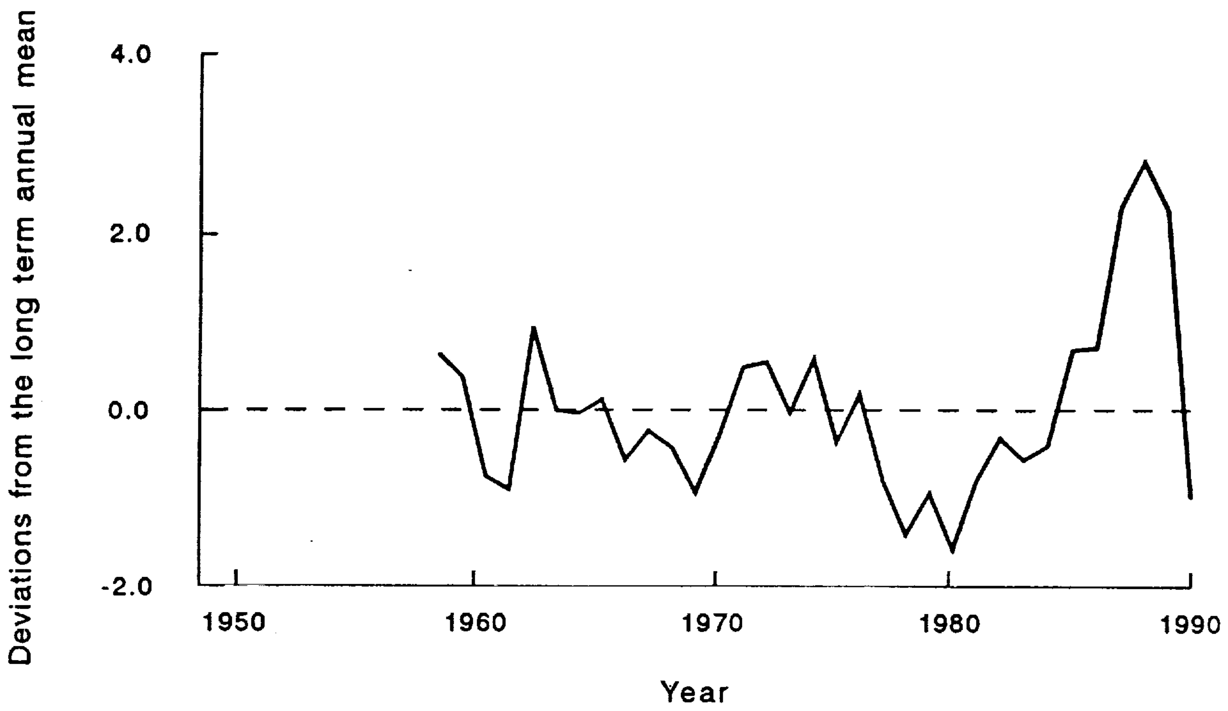


Figure 9. Summary of the long term fluctuations in abundance (in standard deviation units) of Ceratium species in the northern North Sea for the years 1958-1990.

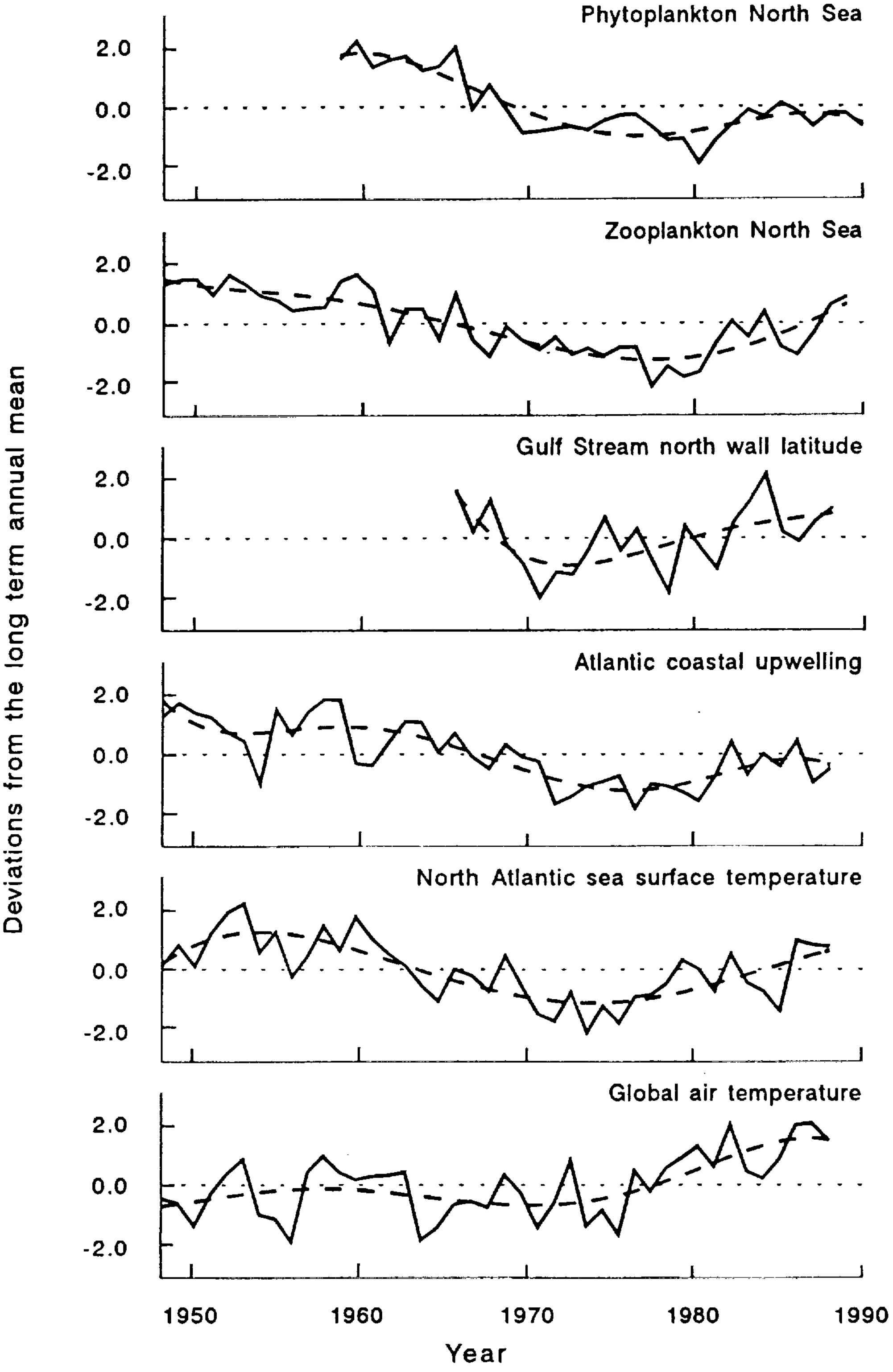


Figure 10. Summaries of the long term fluctuations in the abundance (in standard deviation units) of phytoplankton and zooplankton in the North Sea compared to long term indices of hydrographic and temperature changes.