KEY MESSAGES

- **The changes in chlorophyll observed in regional areas of the North-East Atlantic are also likely to have affected coastal areas around the British Isles and in the North Sea.**
- **The effects of eutrophication on European regional seas cannot be assessed without taking into account wider hydro-climatic influences on phytoplankton populations.**
- **The above changes have had marked effects on fish stocks, e.g. cod and salmon. If the International Panel on Climate Change (IPCC) predictions of a continuing rise in global temperatures prevail then it can be expected that the returns of salmon to home waters will continue to decline especially at the southern edge of its distribution in Spain and France and possibly in the UK.**
- **There is clear evidence for forcing by global warming in the signals seen in the plankton and the observed changes are likely to have a major impact on biogeochemical cycles and living marine resources and might ameliorate or exacerbate any contaminant or eutrophication impacts.**
- **It is unlikely that any changes in UK policy will make any difference to the climatic forcing parameters or to the plankton within one decade. A longer term view needs to be taken.**
- **The long time series of data and wide coverage of the CPR survey makes it possible to determine baseline conditions for a range of planktonic species and indices in terms of abundance, biomass and biodiversity.**
- **There are considerable spatial differences in the plankton communities around the UK as we are at a biogeographic node between warm temperate and boreal faunas. On the basis of this variability it is difficult to develop a target of what might be considered as a mean planktonic state for UK waters.**
- **Good information exists on most mesoplankton. In contrast, limited knowledge exists on gelatinous plankton and micro and ultraplankton.**
- **No time series of plankton production exist in UK waters. However, new methods and use of satellite data may make this possible in the near future.**

EXECUTIVE SUMMARY

Plankton are at the base of the food chain and are the source of food for all other marine organisms. The carrying capacity of ecosystems in terms of the size of fish resources and recruitment to individual stocks is highly dependent on variations in the abundance, timing and composition of the plankton. These organisms also play a crucial role in climate change through the export of the important greenhouse gas CO_2 to the deep ocean by carbon sequestration in what is known as the ‘biological pump’. Without this process concentrations of CO_2 would be much higher in the atmosphere and the climate of the world would be much warmer. Through the foresight of the UK government in maintaining funding for more than 70 years a comprehensive coverage of plankton variability has been obtained in the waters around the British Isles over this time by the Continuous Plankton Recorder (CPR) survey.

Assessment of the results from the CPR survey indicates that major biological changes have taken place in the plankton over the last few decades in the seas around the British Isles, apparently greater than at any time over the last 100 years. A pronounced stepwise change (regime shift) has occurred in marine ecosystems since the mid-

1980s that is reflected in all components of the ecosystem, e.g. plankton, benthos, fish, birds, nutrients and current fluxes. At about the same time there has been a northerly movement of warmer water plankton by 10° latitude in 40 years and a similar retreat of colder water plankton to the north. While direct causative mechanisms for these changes are at times not fully established, hydro-climatic variability appears to have played an important modulating role. This overriding natural variability, possibly forced by global climate change, needs to be considered in any assessment of the ecological state of UK coastal waters.

Against this background of ‘natural’ variability the plankton of the seas around the British Isles that are sampled by the CPR appear relatively pristine and apparently unaffected by anthropogenic inputs of contaminants or eutrophication. However, the CPR survey monitors in deeper water offshore. It is nearshore regions that are more likely to be affected by pollution and where there is a priority to distinguish between natural forcing and human impacts. At present there is in general no systematic sampling of plankton in nearshore waters, although this will be required in the future to comply with the EU Water Framework Directive and other international agreements. The evidence for the statement on eutrophication is provided by the similarity of the patterns of change seen in both coastal and offshore regions of the North Sea and areas to the west of Ireland in the ocean (Edwards *et al*., 2001). The changes in phytoplankton are primarily forced by physical factors. This does not mean that eutrophication does not occur in waters closer to the coast, where the CPR does not sample. Physical factors also clearly dominate the patterns of change in zooplankton. Overall there is no evidence for any impact from contaminants on the plankton at the regional scale. However, data from the CPR survey (Thompson *et al*., 2004) have shown a clear increase in the abundance of plastic particles in seawater, including in oceanic waters.

The seas around the British Isles are biologically diverse in terms of plankton, especially so as the UK is at the node of the limits of distribution of warm temperate and cold boreal faunas. This diversity is reflected in the productivity of the seas in terms of harvested resources. Our understanding of the diversity and ecology of certain members of the plankton, including coelenterates and other ‘jellies’ and the smaller components from micro to picoplankton is, however, far from complete. There have been clear changes in diversity in recent years as a consequence of the regime shift and the biogeographical shifts. The full consequences of these changes for biodiversity, biogeochemical cycles and living marine resources have still to be determined as have the potential impacts on the ‘biological pump’. Ecosystems around the UK appear to have moved into a warmer dynamic regime that is possibly leading to a greater transport of material to the benthos with a faster turnover in the plankton involving the microbial loop. Temperature appears to be a major factor in the composition of communities and in the timing (phenology) of populations.

Highly significant relationships have been found between plankton, salmon returns to home waters, cod and other demersal species and three indices of hydrometeorological forcing (Northern Hemisphere temperature (NHT), Sea Surface Temperature (SST) in the eastern Atlantic and the North Atlantic Oscillation (NAO)). These relationships have been reinforced by a strong link with NHT from the 1980s onwards. As the rapid rise in NHT has been attributed to increasing levels of greenhouse gases it is possible that the recent observed changes in the plankton are a response to global warming. If the predictions of the International Panel on Climate Change (IPCC) of a continuing rise in global temperatures prevail then it can be expected that returns of salmon to home waters will continue to decline, especially at the southern edge of their distribution in Spain and France and possibly in the UK. In recent decades North Sea cod stocks have undergone a pronounced decline as a consequence of overfishing. The radical switch that occurred in the plankton environment of larval/juvenile cod since ~1987 has exacerbated the impact of overfishing on cod as conditions have been highly unfavourable for the survival of young cod. The planktonic copepods that form the principal food of larval cod when they hatch from their eggs have changed in composition, with a reduction in size and biomass and a mismatch in the timing of occurrence of the cod larvae and their favoured planktonic food. Stocks of the boreal cod, as for the salmon, are also likely to decline if Northern Hemisphere temperatures continue to rise, although it should be remembered that a single year with good recruitment could lead to a rapid improvement in cod stocks.

Part of the sequence of changes that have occurred since the mid-1980s has been an apparent alteration in the current patterns in the North Atlantic, with an increased inflow of oceanic water into the North Sea from a more southerly source. Higher flows in the slope current are implicated. Possibly through increased nutrient supply from the ocean and higher temperatures, phytoplankton biomass and almost certainly production has increased in most UK waters, especially in the North Sea and in an area off the shelf to the west of Northern Ireland. Some idea of the scale of the change can be seen in the 90% increase in winter levels of Phytoplankton Colour (a visual index of chlorophyll) post 1987. Good calibration has recently been achieved between this index and SeaWiFS measures of chlorophyll reinforcing the message of the change. As the changes occur in both the North Sea and off the shelf they clearly cannot be attributed to eutrophication.

Because of the data rich nature of the CPR archive and the long period over which samples have been taken and analysed, it is possible to determine baseline conditions for a range of planktonic species and indices in terms of abundance, biomass and biodiversity. These indices may be calculated from mean results or changes since the beginning of the time series or from when important changes took place in the methodology of analysis. Results are presented for a set of proposed indicators of the state of UK marine waters. Four general indices of plankton have been selected to summarise the main patterns of change (Total Copepods, abundance of the copepod *Calanus finmarchicus*, Ratios of the copepods *Calanus finmarchicus* and *Calanus helgolandicus* and Phytoplankton Colour). In addition, seven assemblages of copepod plankton are outlined that reflect changes in water masses around the UK. Patterns of change are also described for 'Harmful Algal Bloom' species and introduced 'non-native species'.

Observed planktonic variability emphasises the need to develop an ecological approach to monitoring human impacts and also for a multi-scale approach that quantifies some degree of natural variability from a regional scale down to a local scale. Confidence in any assessment of anthropogenic impacts on the biological systems found in UK coastal waters will only be possible if wider pan-Atlantic influences and 'natural' variability through time are taken into consideration.

INTRODUCTION

THE ROLE OF PLANKTON IN THE OCEAN

The free-floating plant life of the sea (phytoplankton), at the base of the food web, provides food for the animal plankton (zooplankton), and in turn the fish and their predators, e.g. birds and marine mammals. Many of these tiny organisms exhibit spectacular patterns of shape and colour. For example, diatoms, the dominant group in the phytoplankton, are enclosed in two glass-like cups like an old-fashioned pill box, often with attached spines, and under the microscope are often iridescent and very beautiful. Copepods are the dominant zooplankton group in the North Atlantic. They are small (generally between 0.5 mm and ~8 mm long) crustaceans with long antennae at the front of a muscular body that may be bright red due to oily storage products. The successful development (recruitment) of larval fish to adult stocks after they hatch from their eggs is highly dependent on the abundance, composition and timing of occurrence of the zooplankton.

Light, nutrients and the degree to which the water is mixed are the main agents governing the growth of phytoplankton. Many of these factors in turn are dependent for example on wind strength/direction/frequency, cloudiness and precipitation and exert a strong influence on the upper 100 m of the water column. Even in clear tropical waters light only penetrates down to 100 m so most phytoplankton are found in the upper 40 m. Most zooplankton are also found in the upper layer of the water column, although some show patterns of daily vertical migration over hundreds of metres, apparently as a predator avoidance mechanism.

As well as forming the base of the food chain in the ocean, phytoplankton also influence other processes in the sea by at times occurring in huge concentrations (blooms) that may in part be due to increased human inputs of nutrients to the sea (eutrophication). Some of the species are toxic to humans and other marine animals forming 'Harmful Algal Blooms' and phytoplankton also play a key role in modulating climate change through a range of interactions. A key process is the photosynthetic uptake of CO_2 in the surface ocean and export of this carbon to the deep ocean in what is known as the 'biological pump'. At the surface, concentrations of CO_2 are generally in equilibrium with the atmosphere. The deep bottom water of the oceans, because of their colder temperature, can hold much higher concentrations of CO_2 and dissolved organic matter from settling plankton. Without this deep reservoir, concentrations of CO_2 in the atmosphere would be much higher. Any substantial change on a global scale of the composition or functioning of phytoplankton thus has considerable implications for climate change.

PLANKTON SAMPLING AROUND THE BRITISH ISLES

Studies of the variability of plankton sampled by simple cone-shaped nets were initiated in British waters in the 1890s. A more extensive, but semi-quantitative, study of spatial, seasonal and interannual variability of the plankton in British waters took place as part of the international collaborative surveys of the International Council for the Exploration of the Seas (ICES) in 1902 to 1908. Since then systematic and long-term studies of the plankton in British waters have been few and far between, with a number of time-series studies at single locations or covering small areas offshore (e.g. MBA Station E1 (Southward *et al*., in press) and the 'Flamborough Line' off the east coast (Cushing, 1975)). Many of these surveys were discontinued in the 1980s or earlier. Furthermore, many surveys took samples, but they have never been analysed. Exceptions to this generalisation are the time series of plankton measurements taken off Northumberland since 1968 (Clark and Frid, 2001), at Station L4 off Plymouth since 1988 (Rodriguez *et al*., 2000) and the weekly samples taken off Stonehaven by the Fisheries Research Services – Marine Laboratory Aberdeen (FRS-MLA) since 1997 (Steve Hay, *pers. comm.*). Routine samples, but with no systematic sampling strategy, are also taken each year for phytoplankton analysis by, for example, the Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA) for the assessment of toxic algal blooms. There has been no historical overview of planktonic research in UK nearshore waters that brings all this information together, other than the general information included on plankton in the Coastal Directories (Barne *et al*., 1996). While the following plankton report is very much based on CPR data and is biased towards offshore waters, the patterns of change demonstrated by the CPR survey are widespread and regional at the scale of the whole of the British Isles. It is unlikely, therefore, that nearshore areas, including marine conservation sites, will not be affected by the hydro-climatic signals that are detected by the CPR survey.

The main information on plankton variability around the British Isles derives from the CPR survey (Reid *et al*., 2003a). Since 1931 a monthly synoptic survey of the plankton has been carried out in UK waters and extending out into the Atlantic using the CPR machine. This survey is one of the longest running marine biological monitoring programmes in the world and the only one that operates on an ocean basin scale. The CPRs (Figure 2.1) are towed by ships of opportunity, at speeds of up to 25 knots, on standard routes, sampling the near surface plankton at a depth of about 5–10 m. The plankton is filtered by a continuously moving band of silk gauze, of 270 μm mesh, that moves through the instrument. Water enters the CPR through a small aperture at the front which expands to a rectangular cross-section (10 cm wide) across which passes the silk band that filters off the plankton (Figure 2.2). The silk slowly moves across the filtering area at a rate that is proportional to the speed of the towing ship so that six metres of silk is equivalent to 500 nautical miles of tow. In effect, the band of silk when unrolled is like a film roll of the changing plankton along the route of the towing ship. The silk is divided into sections representing 18 km (10 nautical miles) of tow for analysis under a microscope when the plankton are identified and counted. Over 450 different taxa of phytoplankton and zooplankton are identified and counted. Since the survey started in 1931, up to 2004, CPR machines have been towed for more than 5 million nautical miles (~8 million kilometres) and approximately 190,000 samples have been analysed.

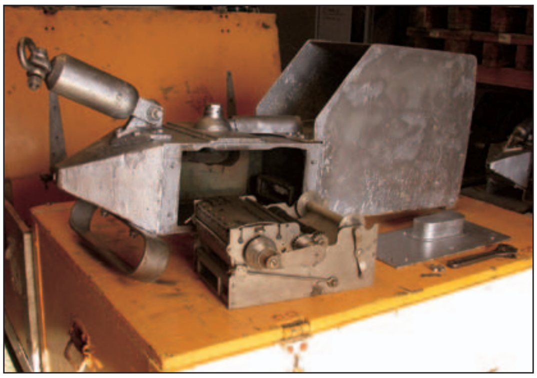

Figure 2.1. Photograph of a Continuous Plankton Recorder with the sampling cassette removed to show the silk spool and preservative storage tank. The cassette has been reversed to show the ingenious fusee tension mechanism on the side that takes up slack in the silk as it is wound on

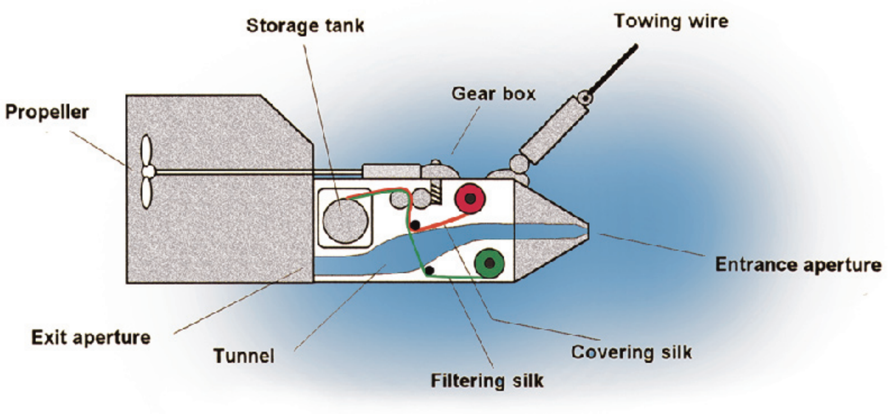

Figure 2.2. Schematic of the Continuous Plankton Recorder showing the water passing through the filtering silk (green) as it moves progressively through the machine at a rate that is proportional to the speed of the ship. The gearing mechanism is powered by an impeller that moves as the machine is dragged through the water. A second band of silk (red spool) covers the filtering mesh to form a sandwich that holds the plankton as it is wound onto a spool in a storage tank containing formaldehyde fixative and preservative

Sampling by the CPR in UK waters in every month of the year restarted after the Second World War in 1946. The route coverage has varied since then due to the changing vagaries of the shipping industry. Figure 2.3 gives representative coverage of routes in 1946, 1958, at the peak of the survey in 1970 and at the present day. A map of the sample coverage in the North Atlantic since January 1946 is given in Figure 2.4.

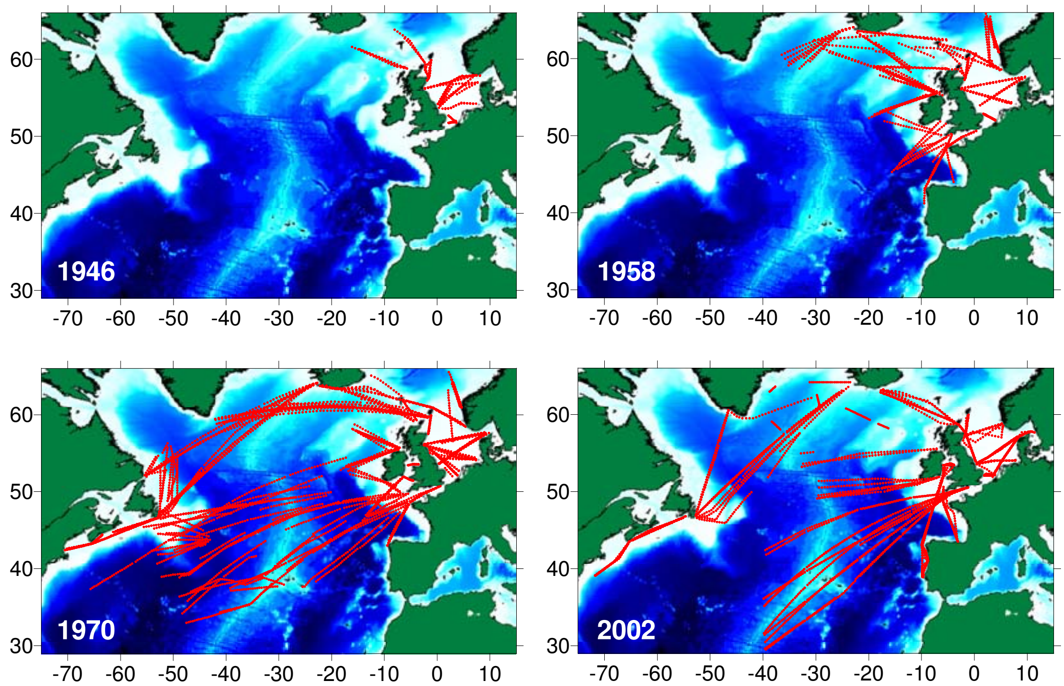

Figure 2.3. Coverage of routes in 1948, 1958, 1970 and 2002

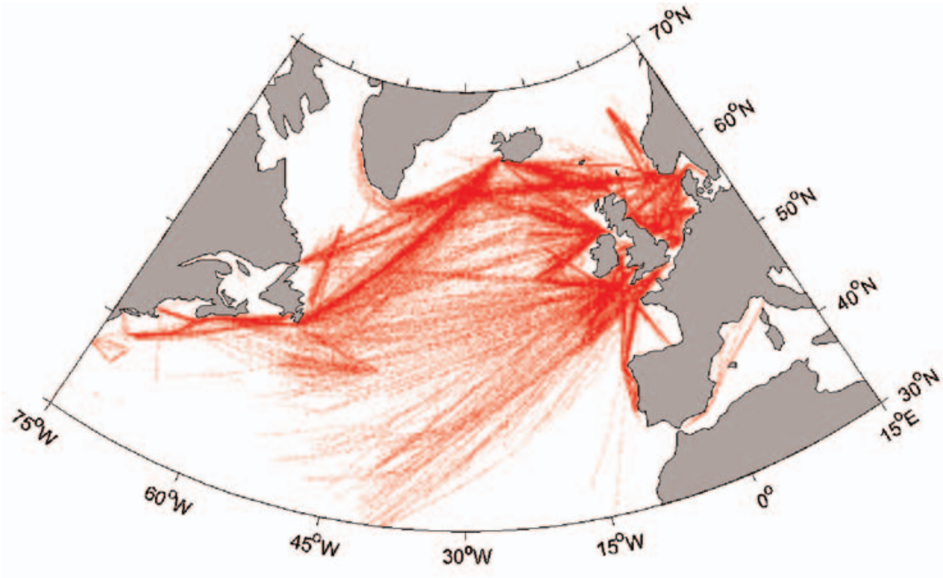

Figure 2.4. Map of the sample coverage in the North Atlantic January 1946 to December 2002. Each small red dot represents an analysed plankton sample

CURRENT STATE

The CPR survey is one of only a few long-term biological monitoring programmes and the only one at a spatial scale that gives a systematic coverage of the North-East Atlantic and UK shelf seas in space and time. Because this survey has a sufficient spatial extent to detect different regional responses to environmental variability it can be used to help to determine whether localised anthropogenic effects have a wider-scale impact and may help to separate anthropogenic and climatic signals from natural variability. New results from the CPR survey reinforce the message that natural atmospheric and hydrographic variability are the major contributors to ecosystem change in the shelf seas of North-West Europe. This overriding natural variability, possibly forced by global climate warming, needs to be considered in any assessment of the ecological state of UK coastal waters.

Because of the data-rich nature of the CPR archive and the long period over which samples have been taken and analysed it is possible to determine baseline conditions for a range of planktonic species and indices in terms of abundance, biomass and biodiversity. These indices may be calculated from mean results or changes since the beginning of the time series. Measurements of Phytoplankton Colour give a coarse visual assessment of phytoplankton biomass/chlorophyll. Preliminary studies have shown that the CPR Colour index compares well with satellite measurements of chlorophyll (Batten *et al*., 2003b). It is also possible to determine dominant patterns of change in the zooplankton and phytoplankton using multivariate statistics such as Principal Component Analysis. It was studies of this type that first showed that long-term trends in the plankton of the CPR were closely related to other measures of change in populations of seabird and fish across four trophic levels (Aebischer *et al*., 1990).

There has been increasing recognition of the uniqueness of the CPR time series as a 'barometer' against which climate change and the effects of pollution/eutrophication on the natural variability of marine populations can be assessed, and also as environmental input to interpretation of changes in fish stocks and fisheries assessments (Brander *et al*., 2003b). The results of the survey have been used to describe and analyse the biogeography, seasonal cycles and year-to-year variability of the plankton in relation to hydro- and meteorological change and fisheries. In a similar ecological vein, other recent applications of CPR data have provided information on harmful algal blooms, monitored and documented the spread of non-indigenous plankton species, and described changes in marine biodiversity. An overview of the last 70 years of work by the survey is presented in a special issue of *Progress in Oceanography* (Reid *et al*., 2003c).

The present chapter consists of two parts:

Firstly there is a series of case studies that provide a commentary on recent research based on CPR data that help understand and assess the current state of the marine environment in UK waters. A number of these studies have been focussed on the North Sea and further work is needed to extrapolate the findings to other areas around the UK. There is no equivalent sampling in nearshore waters that need to be monitored as part of the Water Framework Directive. It is these nearshore regions that are more likely to be affected by contaminants and eutrophication and where there is a priority to distinguish between natural forcing and human impacts. Urgent consideration should be given to establishing a similar extensive coastal plankton monitoring programme to the CPR survey further offshore. One possibility might be to tow CPRs at shallow depths behind the survey vessels of the public/government agencies when they are *en route* to or from their normal survey duties.

Secondly, we give an outline over time (when possible since 1946) and space (the seas around the British Isles) of a set of proposed indicators of the state of UK marine waters. Four general indices of plankton have been selected to summarise the main patterns of change (Total Copepods; abundance of the copepod *Calanus finmarchicus*; ratios of the copepods *Calanus finmarchicus* and *Calanus helgolandicus*; and Phytoplankton Colour, an index of phytoplankton biomass). In addition, seven assemblages of copepod plankton are outlined that reflect changes in water masses around the UK.

Results for the first four indicators are presented for six areas (Figure 2.5): two, the North Sea and Channel, covering Region II (the Greater North Sea) and three, the Malin, Irish and Celtic Seas, covering Region III (the Celtic Seas) as per the regional breakdown of OSPAR QSR 2000 (OSPAR Commission, 2000). To provide a comparison with oceanic conditions results for an area to the west of the British Isles are also presented.

Systematic monthly sampling in each of these regions started at different times ranging from January 1946 in the North Sea to October 1970 in the Irish Sea. As the methods of analysis for phytoplankton and for some zooplankton organisms changed in 1958 different periods of time are used in the presentation of results. The mean number of samples analysed per month for each of the six selected regions is plotted in Figure 2.6.

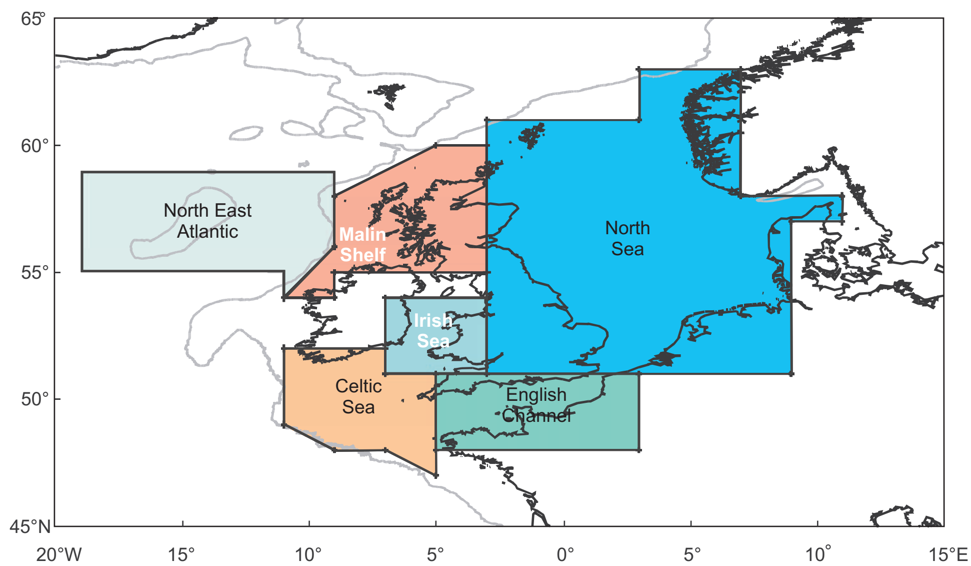

Figure 2.5. Map of the six areas for which plankton data has been averaged

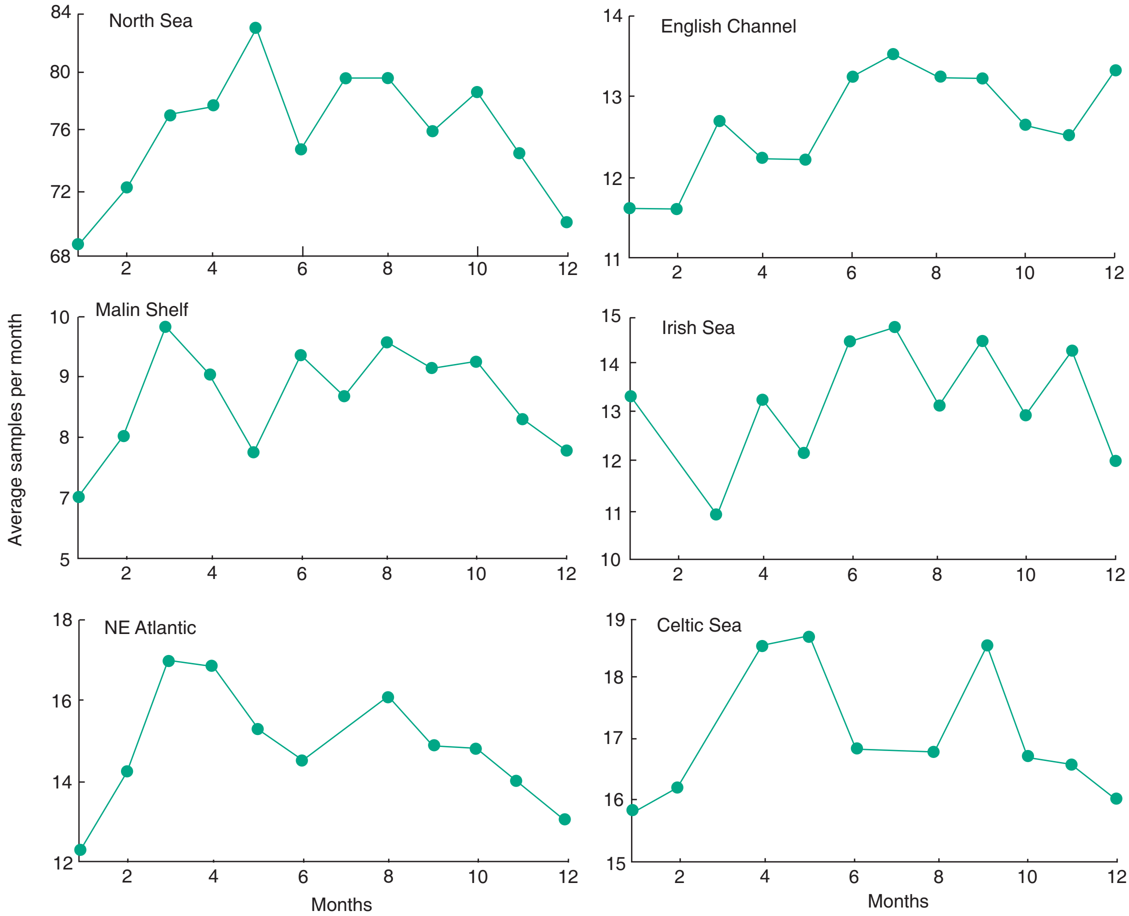

Figure 2.6. Mean number of samples analysed per month for each of the six regions

The number of samples available for the development of indicators in each of the six regions for two periods of time are given in Table 2.1. Maps of changes in the last group of indicators are provided for six associations of copepods over the period 1958 to 1999. Individual pixels in the maps give average information for a 50 × 50 nautical mile grid.

QUESTIONS ON CURRENT STATE

Can 'a real difference be made to planktonic ecosystems within one generation'?
On the basis of the evidence provided in this report the plankton of the seas around the British Isles that are sampled by the CPR are relatively pristine and unaffected by anthropogenic inputs of contaminants or eutrophication. The primary

Table 2.1. Analysed samples available for indicator development

UK Regional Seas	Total number of samples 1946-2002	Number of samples 1958-2001
North Sea	51914	41629
Irish Sea	5460	5433
Malin Shelf	5546	4249
NE Atlantic	8570	6526
English Channel	6032	5896
Celtic Sea	9804	9004

factor governing the changing seasonal and annual patterns appears to be hydroclimatic forcing. There is clear evidence for forcing by global climate change in the signals seen, and the changes observed are likely to have a major impact on biogeochemical cycles and living marine resources. They might also ameliorate or exacerbate any contaminant or eutrophication impacts. The observed environmental changes need to be taken into account when assessing potential policies that might be implemented 'to show a real difference in the marine environment within one generation'. It is unlikely that any changes in UK policy will make any difference to the climatic forcing parameters or to the plankton within one decade. A longer term view needs to be taken.

What is the measurement of performance against an overall target at a future date and research?

To a large extent only 70 years of measurement are available, primarily from the CPR survey. During this time there have been considerable changes with a pronounced regime shift in many ecosystems around the UK. There are also great spatial differences in the plankton communities around the UK, as it is at a biogeographic node between warm temperate and cold boreal faunas. On the basis of this large variability it is difficult to develop a target of what might be considered as a mean planktonic state for UK waters. Temperature variability seems to be a major factor in the composition of communities and it might be possible to determine an expected community structure for a given area in a given temperature band. There is a need for research in this area. Other research needs will be covered below.

Is the plankton around the UK productive and biologically diverse and can we measure it accurately?

It is clear from the evidence provided by the CPR that a rich and diverse fauna of plankton exists in UK waters, which is added to each year by varying inputs of different taxa from the Atlantic. The organisms identified by the CPR survey can be accurately quantified to include measures of diversity and can provide an index of productivity and of the state of health of pelagic ecosystems. The seas around the UK are some of the most productive in the world on the basis of harvested resources. The CPR gives an adequate overview of diversity in the larger components of the plankton with the exception of coelenterates, but we have very little understanding of this factor for most the vast majority of the micro-, nano- and picoplankton. Most measurements that are made on plankton are made at a single point in time. We also have little understanding of changes in production as there are no long-term measurements.

What is the description of the baseline productivity and diversity of marine life?

The results from the CPR survey identify more than 450 different taxa of phytoplankton and zooplankton in the North Atlantic, approximately half of which are identified to species. Baseline conditions can be accurately assessed using decadal means of the plankton species/communities/diversity in question. There are, however, some limitations to the available data because of the size of the filtering silk and the sampling methods (Batten *et al*., 2003a). There is limited information on the composition of the wider categories that are not identified to species and especially for the eggs and larvae of fish and the meroplanktonic larvae of benthic organisms. The CPR also only samples at ~5 to 10 m and does not therefore take into account many planktonic species that live at deeper depths. Gelatinous plankton may be important in the dynamics of marine systems, they are inadequately sampled by the CPR and we know very little about their variability. Finally, measurements of phytoplankton using inverted microscopy give a clearer picture of smaller components of the plankton. There has been no attempt to assess the variability of these organisms on a UK scale from the many analyses that have been made.

What is the evidence for current 'state' against a baseline condition?

There are no statutory monitoring programmes for marine plankton. In consequence, our present knowledge of plankton has been derived from a range of academic studies and from the few long-term studies that have fortuitously been maintained. The CPR survey provides the only long-term and wide spatial coverage of planktonic change in UK waters. After approximately 1986 the planktonic ecosystem moved from a cold temperate to a warmer dynamic regime around the UK. Natural variability is assumed to vary between ±2 standard deviations above or below the long-term mean. Large shifts greater than two standard deviations are used to assess anomalous periods and or anthropogenic influences within a multidecadal time series. If the high anomalies are sustained over a number of years this may signal a regime shift.

CASE STUDIES

NORTH SEA REGIME SHIFT

The planktonic ecosystem of the North Sea has undergone a sequence of changes over the last 50 years each represented by similar levels of plankton abundance and characteristic communities (Reid and Edwards, 2001). The most recent of these changes, around 1987, was sufficiently pronounced to be termed a regime shift (Reid *et al*., 2001a). In oceanography the term has been applied to pronounced stepwise changes in the abundance and composition of plankton and fish at decadal scales (e.g. Hare and Mantua, 2000). A theoretical basis for such changes in the dynamical equilibrium of plankton populations was proposed by Scheffer *et al*., (2001).

The change that took place around 1987 was first noticed in 'Phytoplankton Colour', a visual index of chlorophyll measured by eye on the CPR filtering silks. In the North Sea this index has shown a positive increasing trend with a convergence of the spring and autumn blooms until 1987 (Reid *et al*., 1998). After 1987 chlorophyll levels increased almost twofold throughout the year (Figure 2.7), especially in winter and summer months (Edwards *et al*., 2001a).

This pattern of change characterised a large area of the North Sea, other sea areas around the British Isles and oceanic waters out to approximately 20°W to the west of Ireland (Figure 2.8).

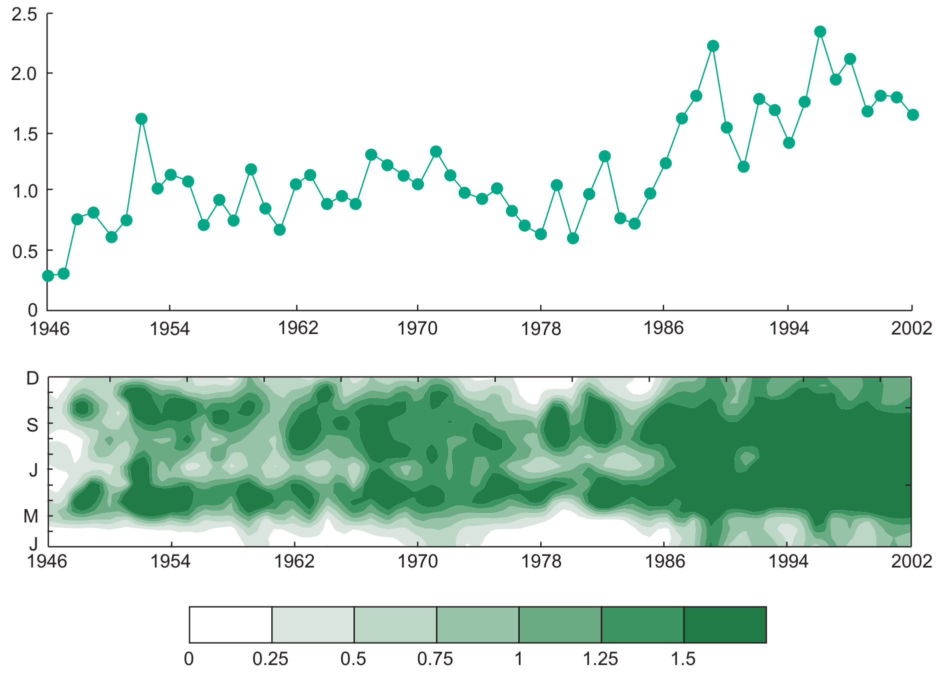

Figure 2.7. A contoured plot of monthly means of Phytoplankton Colour averaged for the North Sea (1946–2002) with above a graph of mean annual data. Updated from Reid *et al*. (1998)

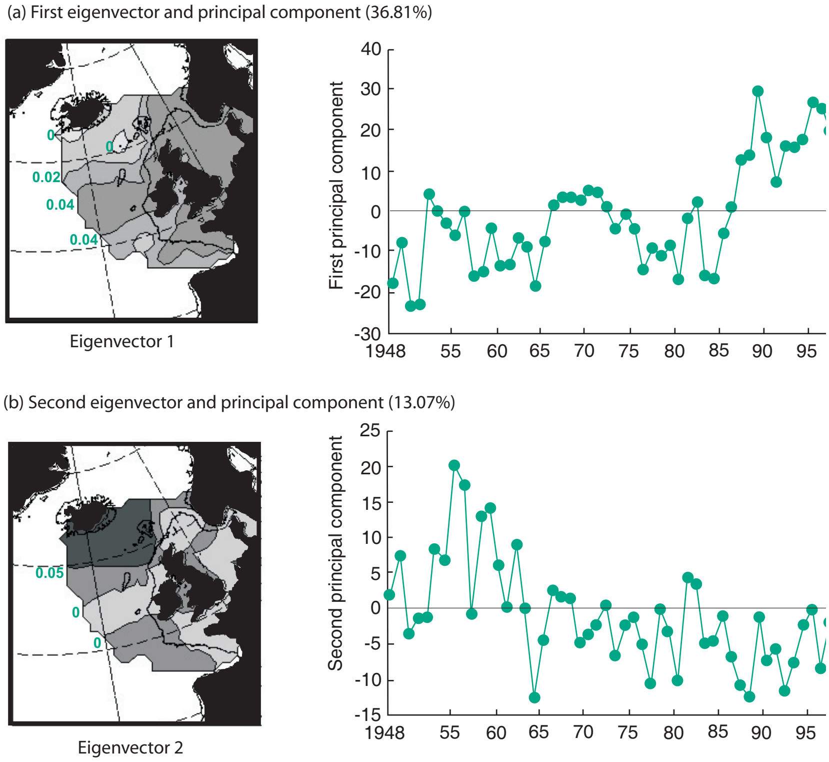

Figure 2.8. Long-term spatial changes in Phytoplankton Colour. Contoured map of the first and second eigenvector and graph of the first and second principal component from a principal component analysis of geographical variability over the period 1948 to 2000 (Beaugrand and Reid, 2003)

The composition of the dominant phytoplankton and zooplankton species sampled by the CPR and a range of other biological, physical and chemical variables showed changes approximately during the same period between the mid- and late 1980s (Beaugrand, 2004a) (Figure 2.9).

Benthic biomass doubled off the Friesian Islands (Krönke, *et al.*, 1998) (Figure 2.10) and the benthos monitored by the former Imperial Chemical Industry for titanium dioxide discharges off the Northumberland coast showed a stepwise change in diversity around 1987 (Warwick *et al.*, 2002).

Increases in oceanic inflow, in sea surface temperature and in the overall heat content of the North Sea occurred (Reid *et al.*, 2001a; Reid and Edwards, 2001; Beaugrand, 2004a). A substantial change in approximately 1989 was observed by Dahl and Danielson (1992) in nutrients (nitrate, orthophosphate, silicate) and oxygen in the deep waters of the Skagerrak. As the levels of nutrients increased (Figure 2.11) the concentration of oxygen decreased. Similar changes in nutrients and oxygen (starting in 1987) have also been described from the Helgoland time series in the German Bight (Hickel *et al.*, 1996).

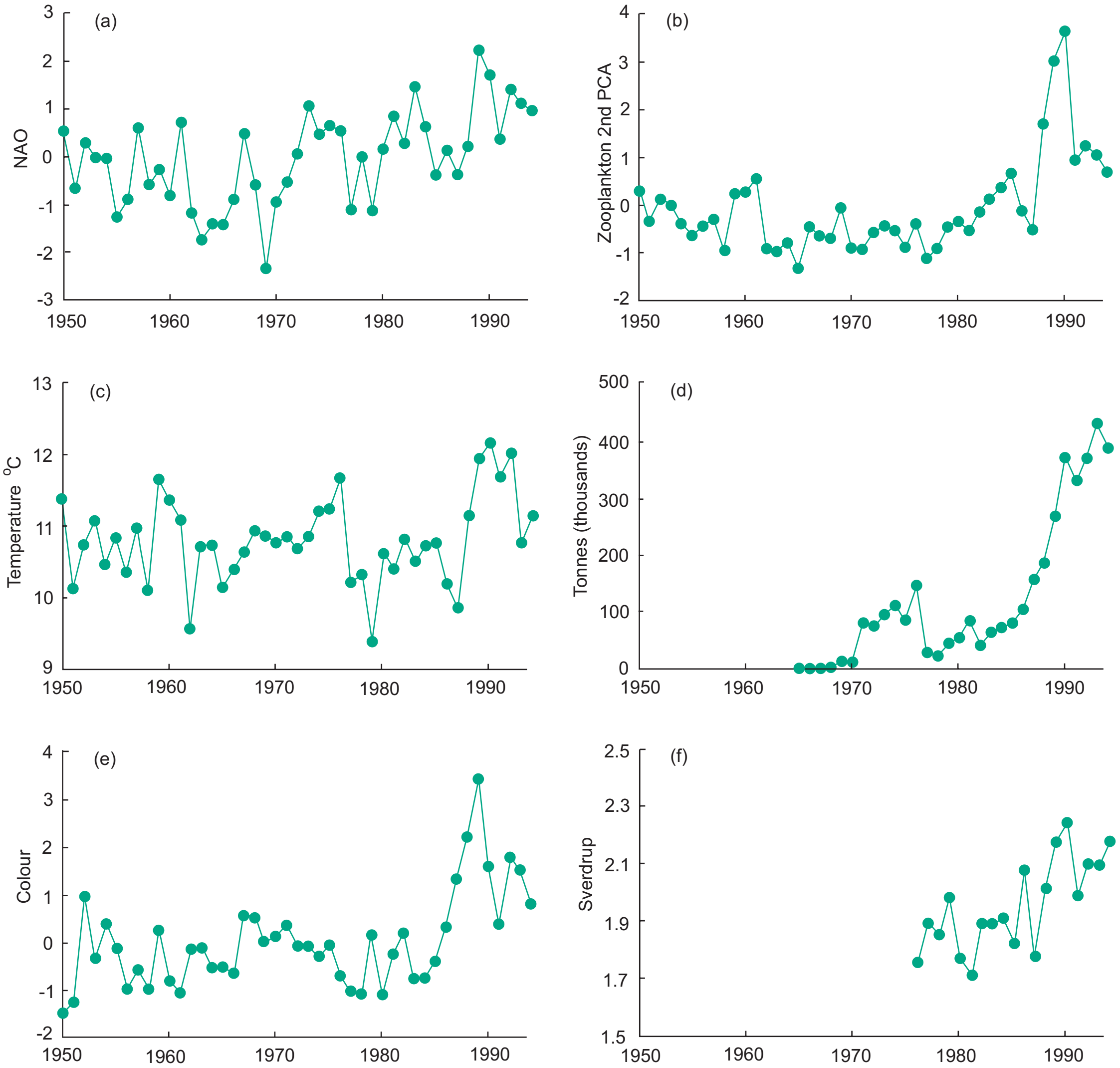

Figure 2.9. Annual mean graphs for: (a) A standardised plot of the North-Atlantic Oscillation, (b) Zooplankton (CPR, second principal component) for the North Sea, (c) Sea surface temperature for the North Sea (ICES data), (d) Horse mackerel landings from the North Atlantic between 45°N and 65°N (ICES data), (e) Phytoplankton Colour (CPR) for the North Sea and (f) Modelled inflow into the North Sea (IMS Bergen). Source: Reid and Edwards (2001)

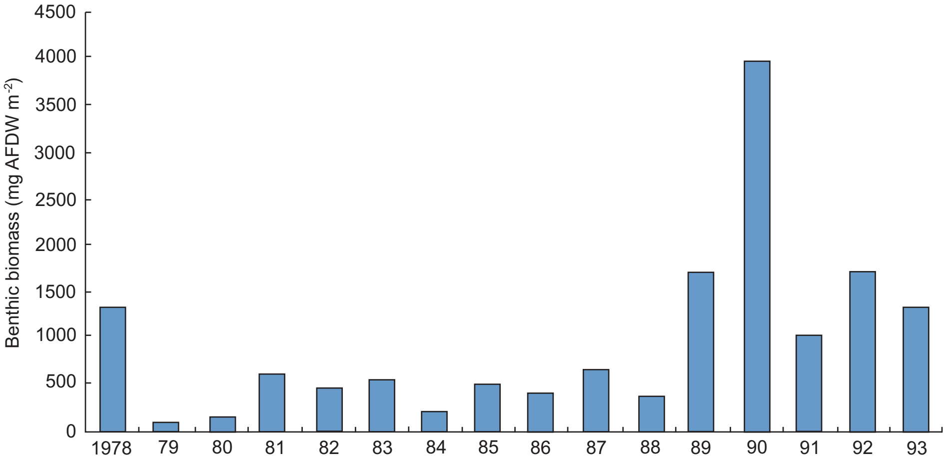

Figure 2.10. Second quarter means of benthic biomass from 1978–1993 recorded in the Norderney coastal zone (southern North Sea). Data from Kröncke, *pers. comm*.

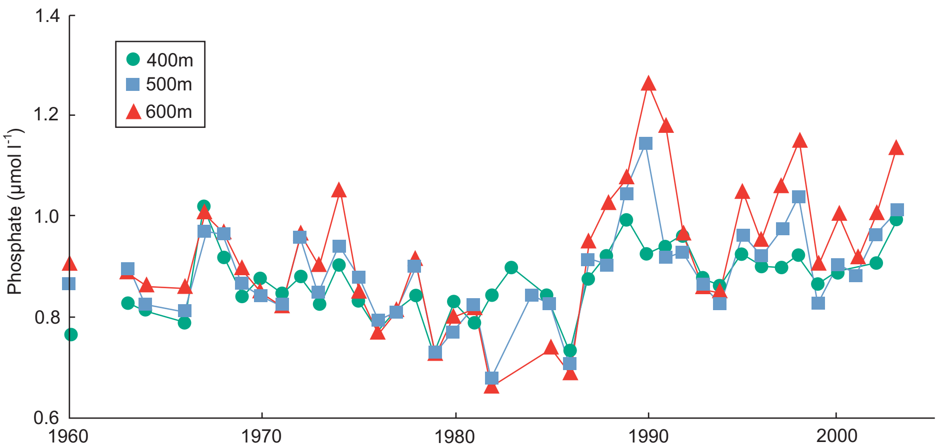

Figure 2.11. Time series of phosphate measurements averaged for three different depths in the Skagerrak. Source ICES database, courtesy of Dr H. Dooley

Observed changes in the abundance and distribution of some marine birds coincided with the regime shift, such as the appearance and expansion of the estuarine white egret (*Egretta garzetta*) in the UK from 1988. Some fish species have also shown marked changes in distribution and abundance, e.g. the horse mackerel (Reid *et al*., 2001a). The landings of horse mackerel by the Norwegian fishery were highly correlated with estimates of volume flux of oceanic water into the North Sea from a 3D mathematical model (Iversen *et al*., 1998; Reid *et al*., 2001a). Marked reductions circa 1987 are also seen in open ocean catches of salmon and in rates of return of salmon to home waters (Reid and Planque, 2000). Finally, the recruitment and biomass of cod dropped dramatically in the North Sea at the time of the regime shift (Beaugrand *et al*., 2003).

Evidence is accumulating to show that the regime shift is a much wider phenomenon characterising the North Sea and regions around and to the west of the British Isles out to ~20°W and that it started earlier in the Atlantic from ~1986 (Beaugrand and Reid, 2003). It also appears that this event is unique in the North Sea in at least the last 100 years (Reid *et al*., 2003b). In summary, post-1987 the North Sea appears to have become more productive and less of the plankton appears to be grazed, and instead there appears to have been an increase in the quantity of settling detritus helping to explain the higher biomass of the animals living on the bottom, lower oxygen levels and apparent recycling of nutrients in deeper waters of the Skagerrak. Levels of phosphate in seawater, instead of increasing, should have decreased as inputs of phosphate from rivers have reduced substantially. Measures to reduce phosphate levels by treatment in sewage plants and the introduction of phosphate-free detergents have led to substantial reductions in concentrations in rivers (Fourth North Sea Conference Progress Report, 1995).

NORTHERLY BIOGEOGRAPHICAL MOVEMENT

Recent research on the biodiversity of marine plankton has revealed a pronounced biogeographical shift in biodiversity, with a northward extension of more than 10° latitude of warm-water species in only 40 years (Figure 2.12) with a complementary reduction in the diversity of colder-water (cold-temperate, Subarctic and Arctic) species to the north (Beaugrand *et al*., 2002b).

An associated rapid rise, especially over the last decade, has occurred in the incidence of sub-tropical plankton species recorded around the British Isles. Of the nine species assemblages that characterise the northern North Atlantic, only six are found around the British Isles. The main shift in distribution took place from the early 1980s to the south-west of the British Isles and from the mid-1980s in the North Sea. All the biological assemblages show consistent long-term changes, including neritic species, which seem to have also moved slightly northwards. Examples of the changes in the distribution of the assemblages are given in the next section of this report on indicators. The changes in the plankton assemblages were correlated with Northern Hemisphere Temperature (NHT) anomalies and to a lesser extent with the winter NAO index (Beaugrand *et al*., 2002b), suggesting that global climate warming may be causally involved. There has been a similar northerly shift in the ranges, as yet poorly documented, of other marine organisms, e.g. the portunid crab and a number of marine fish species of southerly affinity, such as bass, horse mackerel, red mullet, pilchard sun fish and sardine (Brander *et al*., 2003a). New fisheries have started on some of these species in the North Sea. Combined together the evidence suggests that pelagic marine ecosystems have moved towards a warmer dynamic regime in the north-eastern North Atlantic. In terrestrial ecosystems of western Europe, similar changes in spatial distribution and phenology have been detected for many species of plants, butterflies, amphibians and birds and attributed to a warming climate.

There is some evidence that the slope current to the west of the British Isles has been more active since the 1980s with pulses of warmer water extending to the North in certain years (Holliday and Reid, 2001; Reid *et al*., 2001b). This current is used by fish such as the mackerel and horse mackerel as a migratory corridor and is also the primary route for the northerly expansion of some of the plankton assemblages in the above study. Variations in the water masses, temperature and volume flow of this current and its inflow onto the shelf and into the North Sea are likely to have a major impact on UK coastal waters. We have little understanding of this variability at the present time.

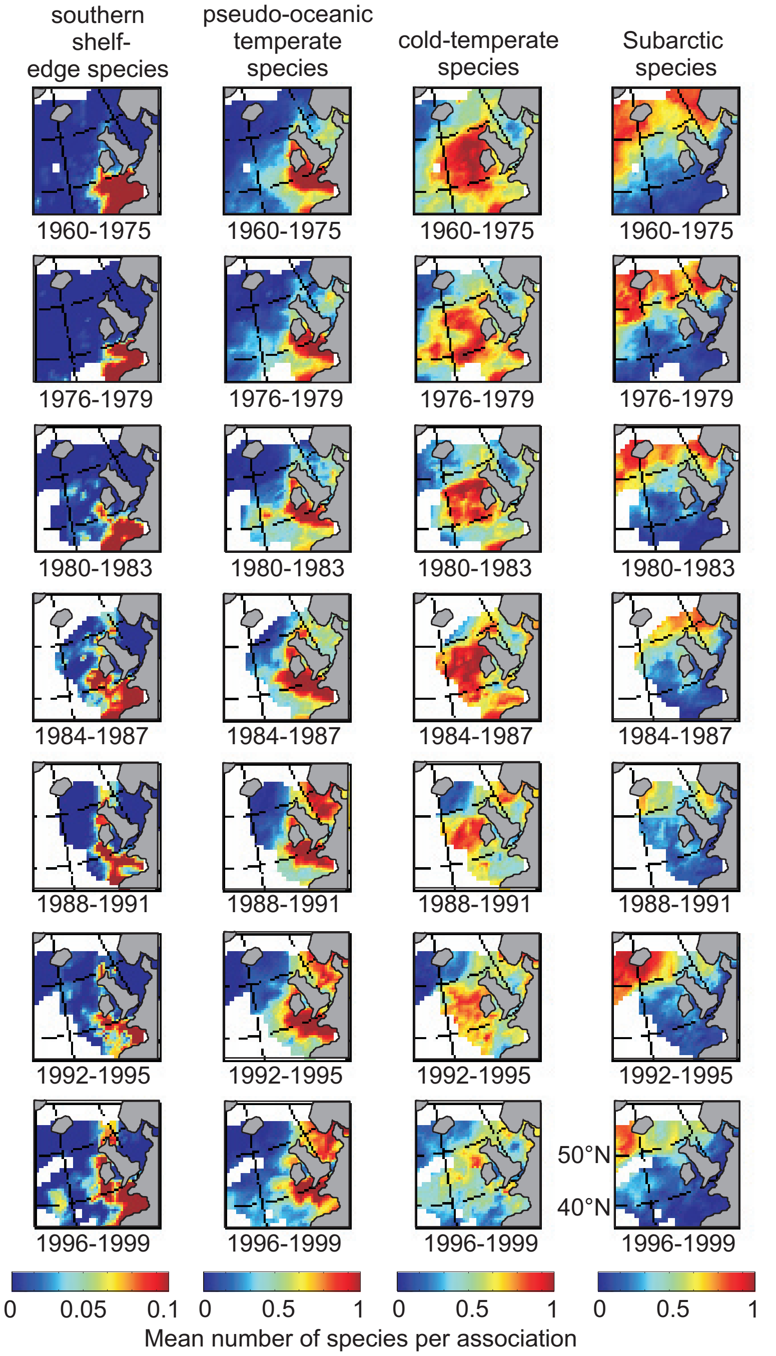

Figure 2.12. Long-term changes in the mean number of species for four planktonic copepod associations from 1960 to 1999. The mean of the four-year periods from 1960 to 1975 was calculated to reduce the number of maps. The spatial patterns seen in these two four-year periods were similar and consistent with the following period 1976–1979. Source Beaugrand *et al*. (2002a)

FISH, PLANKTON AND CLIMATE INTERACTIONS

Highly significant relationships (Figure 2.13) were found between Phytoplankton Colour (as an index of primary production), three measures of secondary zooplankton production (total small copepods, the large copepod *Calanus finmarchicus* and Euphausiids from the CPR),

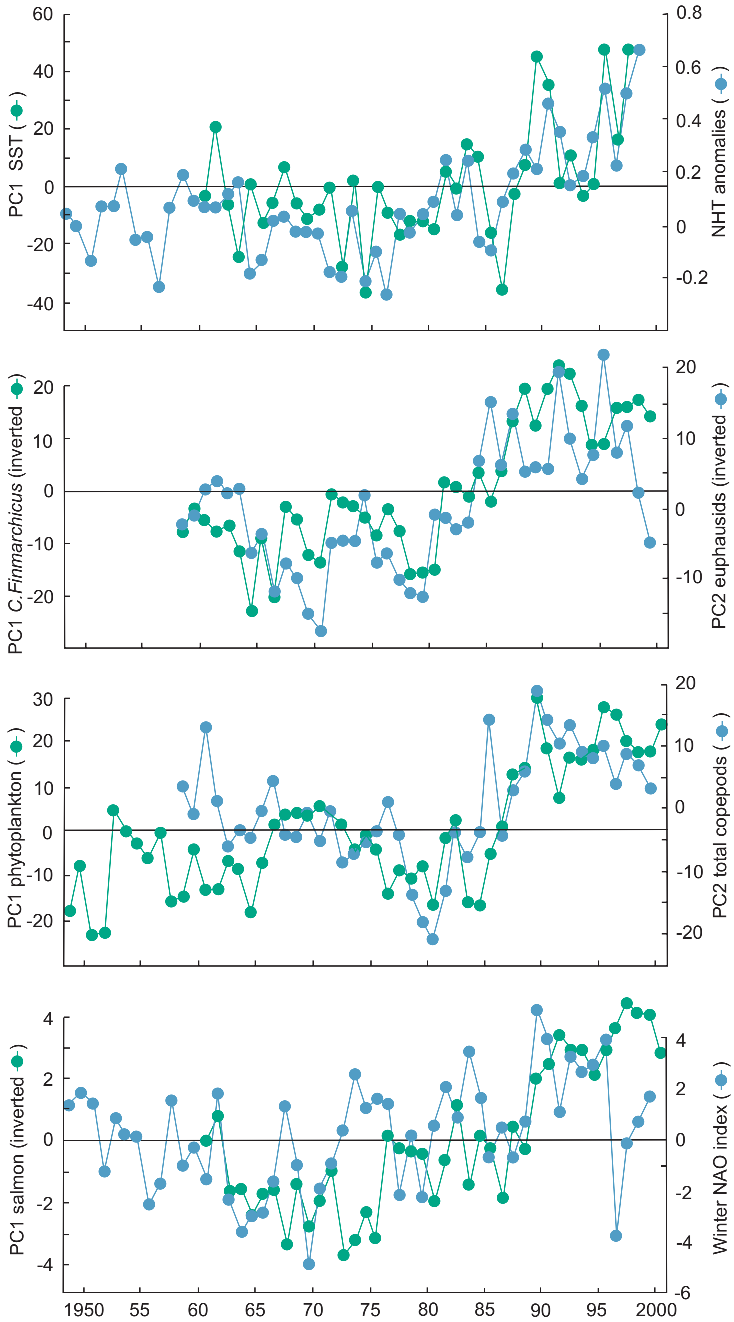

Figure 2.13. Long-term changes in CPR plankton, salmon returns to home waters, sea surface temperature and the large-scale hydro-climatic variables, Northern Hemisphere temperature (NHT) and the North Atlantic Oscillation (NAO). PC1: first principal component. PC2: second principal component. Areas related to the principal components correspond approximately to the area exhibited by eigenvector 1. Source: Beaugrand and Reid (2003)

salmon returns to home waters from 14 locations in the North-East Atlantic and three indices of hydro-meteorological forcing (Northern Hemisphere Temperatures (NHT), Sea Surface Temperature (SST) in the North Atlantic and the North Atlantic Oscillation (NAO)) in a study of long-term change by Beaugrand and Reid (2003). Superimposed on the linear relationships was a stepwise change that appears to have been initiated after an increase in Northern Hemisphere temperatures at the end of the 1970s, culminating in the regime shift of 1986/88, which again appears to be associated with a sharp increase in NHT, SST and the NAO. The biological variables responded in a cascade that started with Euphausiids (reduction) in 1982, Total Copepods (increase) in 1984 Phytoplankton Colour (increase) and *C. finmarchicus* (reduction) in 1986 and salmon returns to home waters (reduction) in 1989.

To understand the regional forcing behind the hydrometeorological change, correlations were made between two climatically contrasting periods: 1960–1978 and 1979–1997 (Figure 2.14). These analyses showed that the pattern of forcing on SST generated by the NAO remained very similar through both periods, especially in the winter and spring. The situation was very different for NHT, with no significant pattern of correlation in the first period, whereas the second period showed high correlation between SST and NHT in the eastern North Atlantic, around the British Isles and in the North Sea, especially in the autumn, winter and spring months of the year. It is likely that the high temperatures experienced in the North Sea and British waters in recent years, after the regime shift, are generated by the combined effect of a generally highly positive NAO and high and increasing NHT. If the IPCC predictions of a continuing rise in global temperatures prevail then it can be expected that the returns of salmon to home waters will continue to decline, especially at the southern edge of its distribution in Spain and France and possibly in the UK.

In recent decades cod stocks and recruitment have undergone a pronounced decline as a consequence of overfishing. Using data from the CPR survey Beaugrand *et al*. (2003) have shown that, in addition to the effects of overfishing, fluctuations in plankton have resulted in long-term changes in cod recruitment in the North Sea. Six quantitative parameters representative of the diet of cod larvae and juveniles were produced for the study, total biomass and mean size of calanoid copepods, abundance of the two dominant large copepods *Calanus finmarchicus* and *C. helgolandicus*, *Pseudocalanus* spp. and euphausiids. Long-term changes in cod recruitment were seen to covary significantly with the plankton indices (Figure 2.15).

The radical switch that occurred in the plankton environment of larval/juvenile cod after the regime shift has been highly unfavourable for the survival of young cod. Since ~1987 the planktonic copepods that form the principal food of the young larval cod when they hatch from their eggs have changed in composition, with a reduction in size and biomass. For example, the mean size of copepods decreased by a factor of two after the beginning of the 1980s. Euphausiids, which are an important food source for cod later in the year also declined in abundance. These organisms have a high-energy content and are an important source of vitamin A for cod, which cannot synthesize this vitamin. The timing of occurrence of the main peak in the abundance of the copepods has also changed to later in the year, a time when the fish larvae have grown and can no longer utilise these small prey organisms. This mismatch in the abundance and timing of their prey means that fewer cod larvae are developing into adult cod. In contrast, at a time between 1963 and 1983, known as the ‘gadoid outburst’ when cod stocks reached unprecedented high levels, the type, quantity and timing of planktonic food available to cod larvae precisely matched their requirements (Beaugrand *et al*., 2003).

The higher temperatures that are associated with the post regime shift period and which have contributed to the changes in plankton will also have a higher metabolic cost for cod growth. Cod are boreal animals and are at the southerly limits of their distribution in British waters. The warmer waters have caused a northerly retreat of their favourite food organisms and are almost certainly linked to the general changes in their planktonic food. Clearly, links between the temperatures in the North Sea and rising trends in the Northern Hemisphere attributed to global climate warming, suggest that North Sea cod stocks are unlikely to recover in the near future, even with a zero ban on fishing.

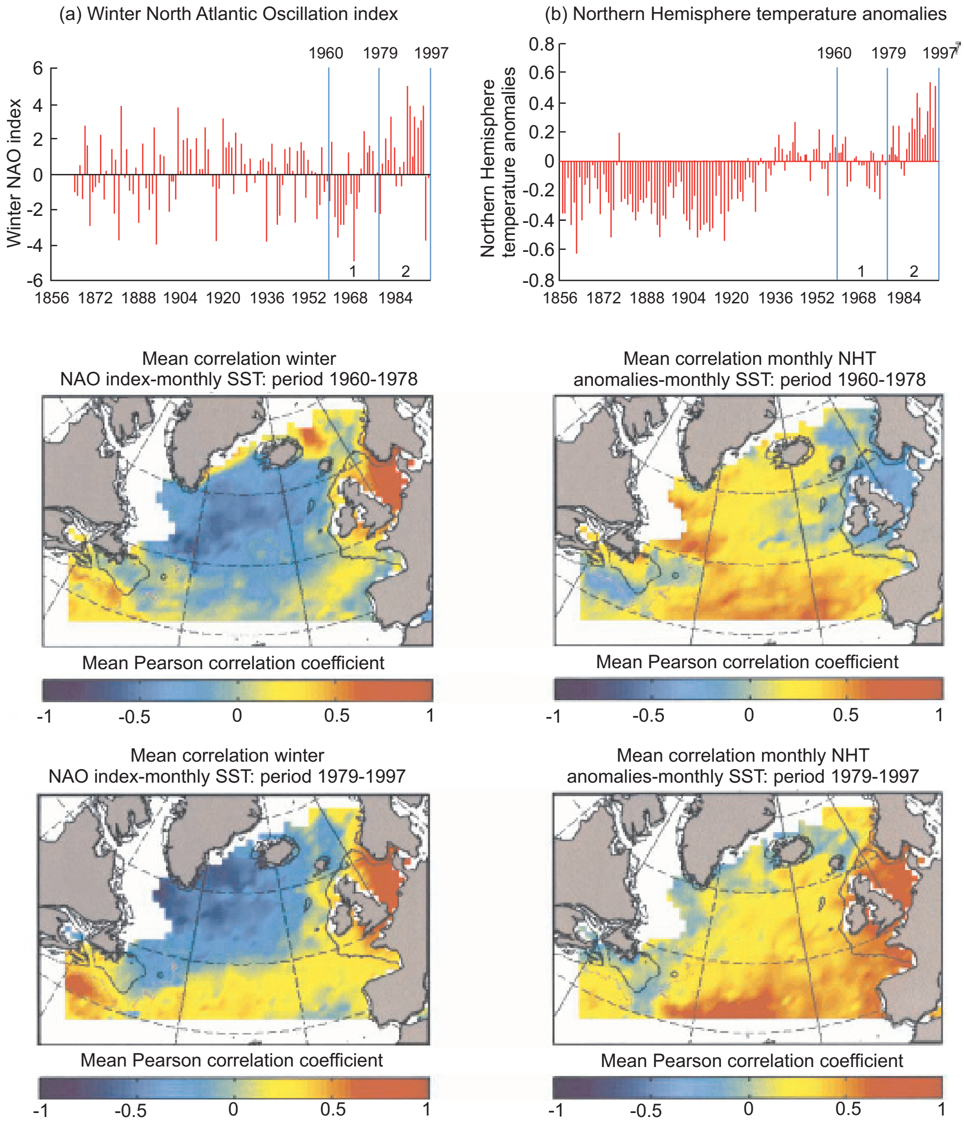

Figure 2.14. Long-term changes in the winter North Atlantic Oscillation (NAO) index (a) and monthly Northern Hemisphere Temperature (NHT) anomalies (b). Maps of correlations were produced for each between the winter NAO index and monthly SST (left map) and between monthly NHT anomalies and monthly SST (right map). The maps present the average of all monthly correlation maps for two 19-year periods: 1960–1978 and 1979–1978. From Beaugrand and Reid (2003)

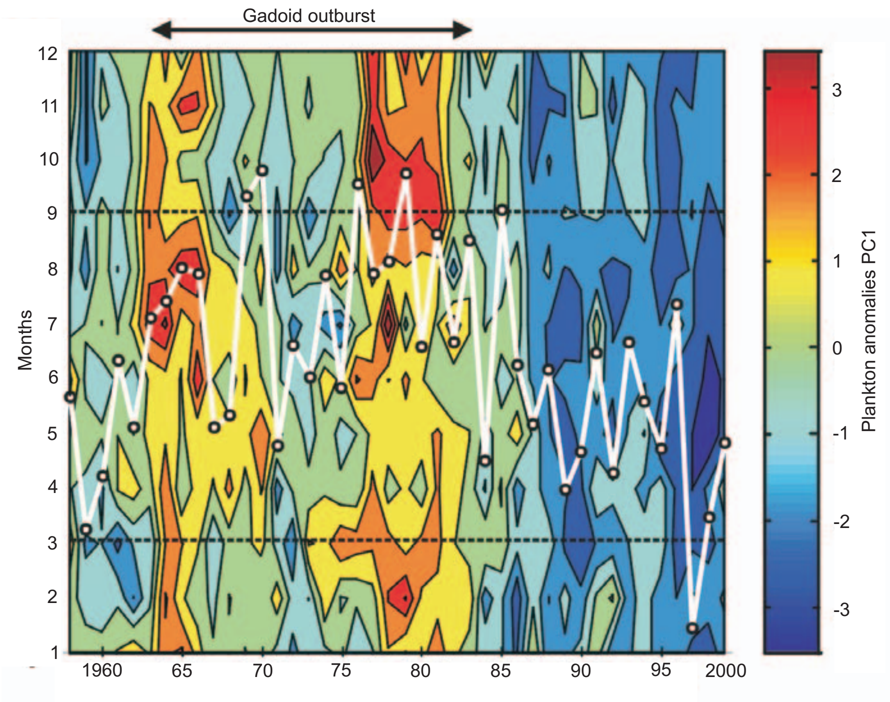

Figure 2.15. Long-term monthly changes (1958–1999) in the plankton (as the first principal component, 33.78% of the total variability), resulting from analysis of a year–month table of a set of biological indicators. The main variables related to this first principal component were, in order of importance, mean abundance (as mean number of individuals per CPR sample) of ***Calanus finmarchicus*** **(normalised first eigenvector), euphausiids), mean size of calanoid copepods,** ***Calanus helgolandicus*****, calanoid copepod biomass and the genus** ***Pseudocalanus*** **spp. A negative anomaly in the first principal component indicates a low value for all biological parameters with the exception of** ***C. helgolandicus*** **(opposite pattern) and** ***Pseudocalanus*** **spp. (no relationship). Cod recruitment (one-year-olds; in decimal logarithm) in the North Sea (curve in white) is superimposed with a lag of one year. The period of the 'gadoid outburst' is indicated at the top of the diagram. Horizontal dashed lines indicate the period (March–September) when larval cod occur most commonly in the North Sea. Source (Beaugrand** ***et al*****., 2003)**

EUTROPHICATION VERSUS NATURAL VARIABILITY

There has been a considerable increase in phytoplankton biomass (Phytoplankton Colour index) over the last decade in certain regions of the North-East Atlantic and North Sea. Particularly high stepwise increases were seen after the mid-1980s in the North Sea (Figure 2.7) and west of Ireland between 52°N and 58°N (Reid *et al.*, 1998). An inverse pattern of change (decreasing trend) in phytoplankton biomass occurred in the oceanic area north-west of the British Isles, but has increased again in the late 1990s (Reid and Beaugrand, 2002). The increase in phytoplankton biomass was in the region of 3–4 standard deviations above the long-term mean (1960–1995) which included a >90% rise in phytoplankton biomass over the winter months (Edwards *et al.*, 2001a). The late 1980s/early 1990s also saw an increase in phytoplankton abundance, with many species occurring up to one to two months earlier than their normal seasonal cycle. This apparent stepwise increase in chlorophyll levels in the North Sea in the late 1980s could, at face value, be taken as evidence of eutrophication. However, the exact same pattern and increase was also seen in oceanic waters to the west of the British Isles. Therefore, it must be assumed that a strong overriding climatic signal is showing through in the phytoplankton data recorded by the CPR survey, which is not only evident in regional areas of the North-East Atlantic, but is also likely to have affected coastal areas around the British Isles and in the North Sea. Many published studies on decadal biological changes that have previously been ascribed to signs of eutrophication have later been found to be primarily driven by hydro-climatic changes (Edwards *et al*., 2002). It should also be noted that climate has an equally important role in modifying marine nutrient concentrations. Edwards and Reid (2001) concluded that the effects of eutrophication on European regional seas cannot be assessed without taking into account wider hydro-climatic influences on phytoplankton populations.

Long-term signals in phytoplankton biomass and phytoplankton community shifts are correlated with Sea Surface Temperatures (SST) in the eastern North Atlantic, Northern Hemisphere Temperature (NHT) and changes in the North Atlantic Oscillation (NAO) index (Edwards *et al*., 2001a; Beaugrand and Reid, 2003). It has been suggested that the ratio between diatoms and dinoflagellates may provide a good indicator for both regional environmental changes, such as eutrophication, and wider scale climatic changes, as these two groups show consistent patterns of ecological succession and distinct eutrophication responses. The CPR data has shown that there has been a general increase in dinoflagellates from the 1960s to the 1990s which is associated with an increase in temperature.

BIODIVERSITY

By monitoring the diversity of the pelagic ecosystem (Figure 2.16) the CPR survey contributes towards the commitments of the UK government under the 1992 *Convention on Biological Diversity*. Information and data are necessary for the development of policies for sustainable use of marine resources (Article 6), identifying and monitoring components of biodiversity (Article 7) and providing data relevant to management of biological resources (Articles 8 and 10).

Total species richness (γ-diversity) is higher in the northern North Sea than the southern North Sea (Lindley and Batten, 2002). However, diversity per sample (α-diversity) of copepods is higher in the southern North Sea (Beaugrand *et al*., 2000). This apparent contradiction is due to the different ecological characteristics of the areas. The composition of the community in the northern North Sea is much more seasonally variable (Beaugrand *et al*., 2001) being influenced by boreal and warmer oceanic waters coming from the shelf edge bringing diverse oceanic and shelf edge communities into the area.

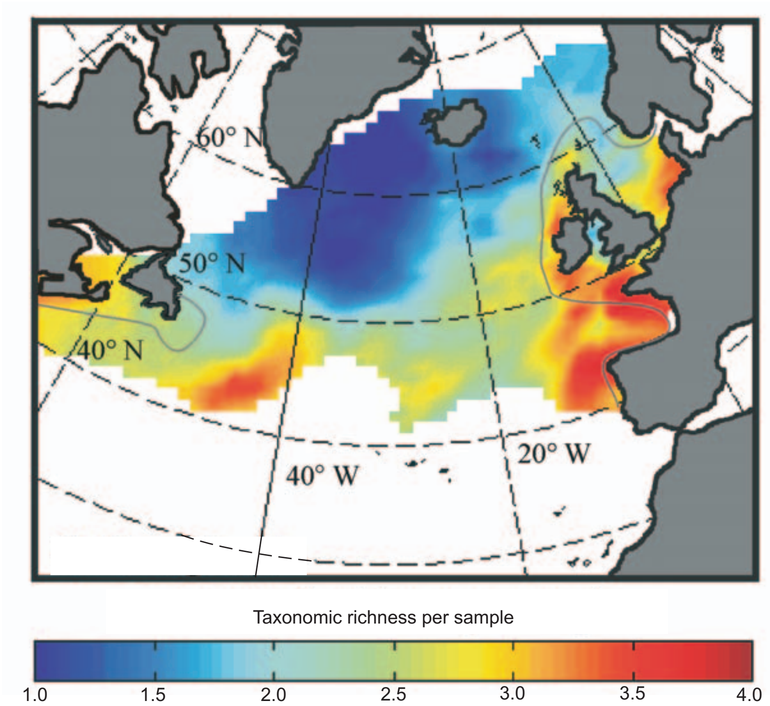

Figure 2.16. Biodiversity of marine copepods in the North Atlantic as measured by taxonomic richness. Source: Beaugrand *et al*. (2000)

Diversity, measured both as species richness and dominance, has increased in the northern North Sea (Lindley and Batten, 2002; Beaugrand, 2003), and this can be related to changes in the distributions of communities described by Beaugrand *et al*. (2002b). These distributional changes appear to be related to climatic variability on an ocean basin scale rather than localised phenomena. The changes have included an increase in the relative and absolute importance of the meroplankton (Lindley and Batten, 2002) and the replacement of the cold water copepod *Calanus finmarchicus* as a key species in the North Sea by its sibling *Calanus helgolandicus*. Also, the high diversity warmer water communities contain a larger proportion of small species than do the colder water communities. Although the most detailed work on the effects on biodiversity of long-term changes has been focussed in the North Sea, comparable patterns of change can be expected throughout the survey area.

NON-NATIVE SPECIES

One of the biggest threats to marine planktonic biodiversity is thought to be the introduction of non-native species and has only recently been recognised as being a serious problem in the oceans. There is now considerable concern about the inadvertent trans-oceanic transfer of planktonic organisms in the ballast water of ships. Many of these introductions can have important ecological and large economic consequences by out-competing native species and/or causing nuisance blooms. The effects of each new introduction are extremely unpredictable and efforts to assess and monitor invasive species are at best fragmented.

One case history, however, based on CPR data has provided a unique insight into the progressive expansion of an invasive plankton species (*Coscinodiscus wailesii*). The geographical expansion of this species has been followed from its initial introduction into European shelf seas to the present day (Figure 2.17), during which time it has become a persistent and significant member of the plankton community (Edwards *et al*., 2001b). When this species first appeared in the North Atlantic it had a detrimental effect on fishing operations and has subsequently become, at times, a dominant member of the phytoplankton community in competition with other indigenous species. This information has provided an invaluable model of how the pattern and rate of spread of an introduced species is

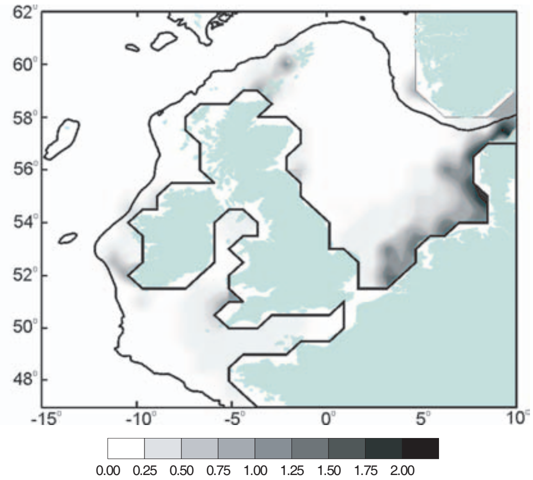

Figure 2.17. Geostatistical estimates of the mean log abundance of the diatom *Coscinodiscus wailesii* in the North-East Atlantic from 1985–1995. Source: Edwards *et al*. (2001b)

likely to evolve in European waters. This type of analysis is essential if we are to establish the effectiveness of any management strategy that may be deployed to limit such invasions, such as controls on ballast water exchange.

PHENOLOGICAL CHANGES

Figure 2.18 shows the annual peak in the seasonal abundance of decapod larvae from 1948–2000 in the central North Sea (Edwards *et al*. (2004) and Richardson submitted). There is

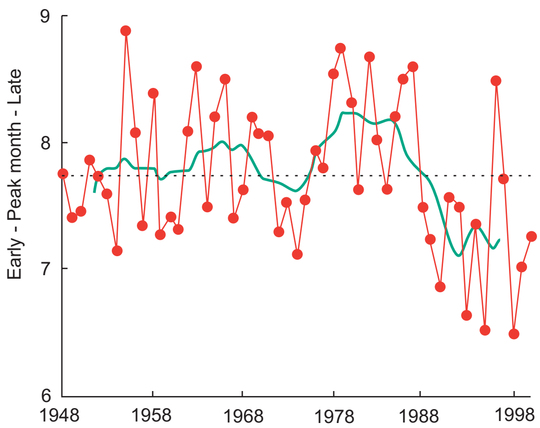

Figure 2.18. Inter-annual variability (light line) in the peak development of decapod larvae in the central North Sea from 1948–2000 (dark line: 3 year running mean; dashed line: baseline mean 1948–2000). Source Edwards *et al*. (2004)

a strong relationship between winter sea surface temperature and the early/late development of the decapod seasonal cycle (r = 0.67; $p < 0.01$). Although there is considerable inter-annual variability in the period 1948–2000, a major pattern has emerged over the last decade. Since 1988, with the exception of 1996, the seasonal development of decapod larvae has been much earlier than the long-term average (baseline mean: 1948–2000). The peak seasonal appearance of echinoderm larvae shows the same pattern and is correlated with the trend in decapod larvae. The pronounced trend towards an earlier seasonal appearance of meroplanktonic larvae during the 1990s parallels equivalent changes in the climate of the North Atlantic. The 1990s in the Northern Hemisphere, for example, were the warmest decade since records began in 1860, having 9 out of the 10 warmest years on record (Hadley Centre, UK climate database). Many other plankton species are occurring earlier in the season, including dinoflagellates, which has important implications for the monitoring and study of Harmful Algal Blooms.

Overall marine pelagic production is thought to be largely dependent on the temporal synchrony between primary, secondary and tertiary production (Cushing, 1990). The inter-annual variability in the timing and degree of overlap between trophic production curves is presumed to govern larval survival rates of meroplankton and fish during their early life stages and the eventual year-class strength of commercially important fish and shellfish species (Platt *et al*., 2003). In the marine environment, varying responses to climate change across functional groups and multiple trophic levels could lead, in theory, to a mismatch in timing and decoupling of phenological relationships. This in turn could have repercussions for trophic interactions, food web structure and eventually changes at an ecosystem-level (Beaugrand *et al*., 2003; Edwards and Richardson, 2004)).

HARMFUL ALGAL BLOOMS (HABS)

As well as providing an index of phytoplankton biomass (Phytoplankton Colour), the CPR survey identifies approximately 170 phytoplankton

Table 2.2. Known harmful and detrimental phytoplankton taxa recorded by the CPR survey in the North Atlantic and around UK coastal waters at a temporal resolution of one month

Species/genus	Associated harmful/detrimental effects	Time-series
Ceratium furca	Hypoxia/anoxia	1948 –
Coscinodiscus wailesii	Production of mucilage.	First recorded in 1977 (invasive)
Dinophysis spp	Diarrhectic shellfish poisoning (DSP).	1948 –
Gonyaulax spp	Unspecified toxicity.	1965 –
Noctiluca scintillans	Discolouration and hypoxia/anoxia.	1981 –
Phaeocystis spp	Production of foam and mucilage. Hypoxia/anoxia.	1946 – (presence/absence)
Prorocentrum micans	Diarrhectic shellfish poisoning (DSP). Discolouration and hypoxia/anoxia	1948 –
Pseudo-nitzschia spp	Amnesic shellfish poisoning (ASP)	1948 –
Nitzschia closterium (now *Cylindrotheca*)	Production of foam and mucilage.	1948 –
Chaetoceros spp	Gill clogging	1948 –
Skeletonema costatum	Gill clogging	1948 –

taxa. Within the database a number of taxa that have been identified as potentially harmful or detrimental have been recognised and are listed in Table 2.2. One of the most studied HABs in the North Sea is the foam alga *Phaeocystis*. Massive developments of this alga regularly occur in the southern North Sea. The long-term monthly variability of *Phaeocystis*, averaged for the North Sea, is shown in Figure 2.19.

Whereas it was particularly common in the 1950s it began a process of decline which lasted through the 1960s and 1970s. Since the mid-1980s, however, the occurrence of *Phaeocystis* has increased in the North Sea and has been frequently recorded over the last few years. In particular, 1999 stands out as an exceptional year with a number of large blooms. It has been suggested that increases in *Phaeocystis* could be attributed to an increase in nitrogen and phosphorus inputs (Lancelot *et al*., 1987). However, similar patterns of occurrence are found in other non-eutrophic regions of the North-East Atlantic, suggesting that the patterns are climatically forced, mirroring what is seen for phytoplankton biomass. Remarkably similar decadal patterns of abundance have also been observed for *Noctiluca scintillans* from the Helgoland Roads, which have been related to winter SST (Heyen *et al*., 1999). At this site, water samples for plankton are taken five days in every week. Some of the most exceptional phytoplankton blooms recorded by the CPR survey have also been associated with ocean climate anomalies and oceanic incursions into the North Sea (Edwards *et al*., 2002). Bloom events recorded by the CPR survey also show strong similarities with other phytoplankton surveys (Kat, 1982; Zevenboom *et al*., 1990). Without the aid of inter-regional comparisons, many blooms in the past have been wrongly used as supporting evidence for eutrophication.

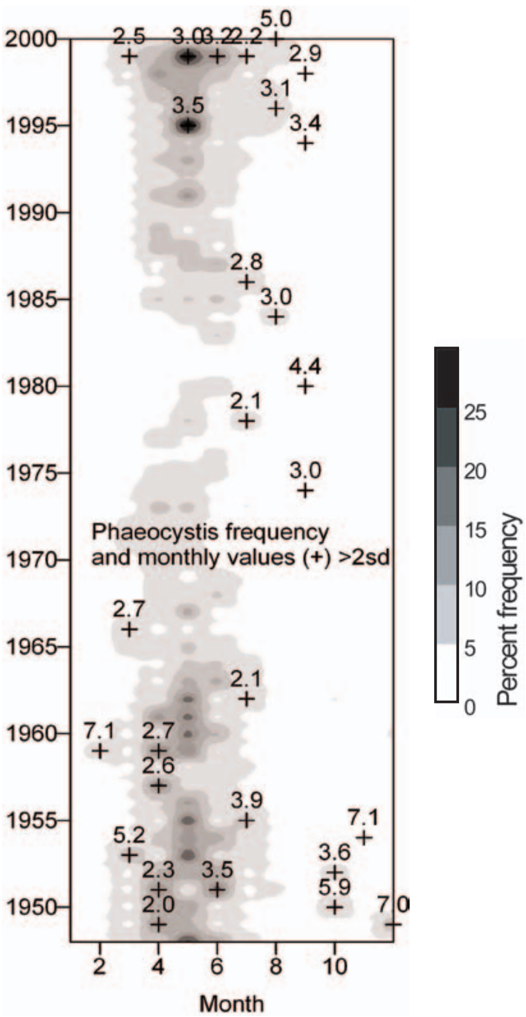

Figure 2.19. Long-term monthly variability of *Phaeocystis* from CPR records averaged for the North Sea. Source: Edwards (unpublished)

Shellfish for human consumption are monitored for algal toxins under the requirements of the EC Shellfish Hygiene Directive by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), the Fisheries Research Services and the Department of Agriculture and Rural Development, Northern Ireland. Some phytoplankton samples are taken to help identify the causative organisms. Records obtained are coordinated by CEFAS as part of a UK Toxic phytoplankton monitoring programme. Non-routine sampling of phytoplankton blooms or other algal/scum concentrations is also undertaken by the Environment Agency and Scottish Environmental Protection Agency.

GAPS IN KNOWLEDGE OF THE STATE OF THE MARINE PLANKTONIC ECOSYSTEM

- An historical overview of planktonic research in UK waters that brings all information on UK and international monitoring and research together is long overdue. Such an overview would help to clarify gaps in knowledge and prioritise issues for study in the future.

- There has been no attempt to integrate single point samples and small surveys using nets or water samples with the geographically more extensive CPR survey. Developing a web-based Geographical Information System that could include data from many different surveys would have considerable management uses.

- There are a number of geographical gaps in sampling in UK waters, especially on a synoptic monthly level. Sampling by the CPR is very limited or does not occur (for example in west Scotland and its sea lochs, in the northern Irish Sea and in the Clyde estuary) and is poor in the Atlantic to the west of the UK.

- Perhaps equally important are more distant waters such as the Labrador, Greenland and Norwegian Seas that may show early signs of changes that could later affect the ecosystems around the UK and which are highly sensitive to change in climate.

- At present there is no systematic monitoring of phytoplankton or other plankton in nearshore and estuarine regions out to 1 or 3 nautical miles. This is a very large linear band of water that will need to be sampled on a regular basis as part of the Water Framework Directive. Developing a shallow towed CPR survey in this region would enable comparisons with the long-term data that exists from further offshore.

- Given the large variability that is evident in plankton, our understanding of what is a baseline/normal ecosystem state is limited.

- Groups of plankton that are particularly poorly known and sampled are the coelenterates and other ‘jellies’ and the microplankton to picoplankton. Especially large changes in abundance of meroplankton have been evident in the North Sea in recent years. There is a poor understanding of the causes of these increases and of interactions between the benthos and pelagos.

- Only limited work has been undertaken on relationships between plankton and hydro-meteorological variables especially at the scale of the seas around the UK. A number of past studies have focussed on the North Sea and further work is needed to extrapolate the findings to other areas around the UK.

- The pronounced temperature increase that coincided with and has continued since the regime shift in the mid-1980s seems to be a key parameter governing the dynamic equilibrium of marine ecosystems over a wide region around the British Isles with likely, but at present largely unknown, consequences for biogeochemical processes, fisheries and the ‘biological pump’.

- Variations in the water masses, temperature and volume flow of the slope current to the west of the British Isles and its inflow onto the shelf in the North and adjacent Seas are likely to have a major impact on UK coastal waters. We have little understanding of this variability at present.

- Until recently there has been minimal use of plankton data in ecosystem and climatic models. There is considerable scope for research in this area to examine the process behind recent changes. Future development of these studies holds the prospect of improving our knowledge of the mechanisms by which climate change and plankton productivity are linked and of working towards a truly predictive capacity.

- The same situation applies to understanding relationships between plankton and fish recruitment. A demonstrated clear linkage has only become evident in recent work on cod (Beaugrand *et al*., 2003). Options also exist for including CPR and other plankton and environmental data in future new approaches to fish stock management.

- Temperature variability seems to be a major factor in the composition of communities and it might be possible to determine an expected community structure (mean planktonic state) for a given area in a given temperature band. There is a need for research in this area.

- We are still far from understanding relationships and the relative importance of human impacts such as contamination and eutrophication on plankton against natural and climatic change. This applies especially to nearshore waters and to organic contaminants.

FUTURE CHANGES TO RESEARCH PROGRAMME

Data sources

- An overview of UK plankton research and assessment of available datasets should be initiated. Many datasets are still in paper form and inaccessible. They need to be digitised and placed in a national archive as part of a data archaeology project. Pre-Second World War studies are particularly important to provide a longer term perspective on recently observed planktonic changes.

Design of plankton monitoring programmes

- A study should be initiated to look at appropriate sampling regimes for plankton to establish true spatial and temporal variability. Such a study could provide useful information on the number of samples that needs to be analysed in a given area and could be used in the design of a UK plankton monitoring programme for the Water Framework Directive.

Indicator development

- Further work needs to be carried out on the development of phytoplankton indicators and other sensitive ecological indicators.

Target performance

- There is a need for further work to be undertaken on the relationship of plankton to basic physical factors such as temperature and salinity. The expected composition of plankton communities in a given area against temperature bands should be determined.

Introduced species

- Introductions of new species should be recorded and their spread recorded in a national data centre.

Plankton satellite comparisons

- Data from the CPR survey should be used to provide sea-truthing of satellite data and a calibration in return of the in situ plankton results.

Modelling

- A range of modelling initiatives could be envisaged from ecosystem modelling built on 3D hydrodynamic models, to use of CPR plankton data in climate models. Modelling to take into account oceanic inflow and the role of the slope current should be progressed.

Instrumentation

- Wherever possible, additional hydrographic information should be obtained at the same time as plankton sampling is undertaken. Where ships of opportunity are used in Ferry Box and CO_2 studies, CPR machines should be towed on the same vessel.

Genetics

- There is enormous potential to apply new genetic tools to studies of populations and their variability through time and space using archived samples.

Resting stages

- Many planktonic organisms include a dormant resting egg or cyst stage as part of their life cycle. The role that this stage plays in the ecology of plankton is poorly known. The resting cysts of some toxic phytoplankton are often concentrated in seed beds in fine sediments on the bottom. It is not known how the distribution of these beds will be affected by climate change.

Filling gaps in UK sampling

- New CPR type programmes should be established in near coastal waters using the traditional methodologies so that a comparison can be made with the long datasets that occur offshore.

INDICATORS OF STATE

The only established marine planktonic indicators used by the UK up to now have been the abundance of the boreal copepod *Calanus finmarchicus* and total small copepods in the North Sea. These indicators were chosen respectively because of the inverse relationship between C. finmarchicus and the North Atlantic Oscillation discovered by Fromentin and Planque (1996) and the correlation found by Taylor (Taylor, 1995) and the position of the North Wall of the Gulf Stream (Gulf Stream index). Since at least 1996 (Planque and Reid, 1998), and probably 1987, the relationship with the NAO has broken down and the species has become much less abundant in UK waters as a consequence of the changes described above in the Case Studies section.

In addition to the abundance of *Calanus finmarchicus* and Total Copepods two new indicators are proposed here, all four indicators are averaged for six areas around the British Isles (Figure 2.5). The first new indicator is Phytoplankton Colour to represent algal growth. Ratios between *Calanus finmarchicus* and its congeneric *Calanus helgolandicus* are used for the second new indicator of environmental change. A second series of seven indicators, based on assemblages of copepods after the methodology of Beaugrand *et al.*, (2002a, 2003) and Beaugrand (2004b) is also included. Maps showing changes in four of these copepod species associations in the North Atlantic, east of 20°W (averaged for pixels of 50 × 50 nautical miles) were presented earlier in Figure 2.12. These results and three other assemblages (Arctic, Shelf Sea Neritic and Coastal Neritic) also found around the British Isles are summarised below for two time periods: 1958–1981 and 1982–1999. The assemblages were determined using three criteria: (1) the spatial distribution of species, (2) the similarity in the seasonal variability of species and (3) diel and ontogenetic variation.

Proposed indicators:

- Total Copepods: Measured total abundance of mostly small copepods
- Abundance of Calanus finmarchicus
- Ratios of *Calanus finmarchicus* and *Calanus helgolandicus*, showing changes in the relative importance of two of the main large copepods that represent respectively, boreal and warm temperate water in British waters
- Phytoplankton Colour, an index of phytoplankton biomass, and
- Seven species assemblage indicators based on calanoid copepods, showing variability in the abundance of groups of copepods that characterise different water masses (based on 108 species).

    1. Arctic
    2. Subarctic
    3. Cold-temperate mixed water
    4. Shelf Sea Neritic
    5. Coastal Neritic
    6. Temperate Pseudo-oceanic
    7. Warm-temperate Pseudo-oceanic

TOTAL COPEPODS

Specific indicator: Total copepod abundance is the sum of the number of copepods, identified during the traverse stage of analysis, sampled (per 3 m^3) by the CPR survey. Copepods numerically dominate the zooplankton community. The method of counting this category in the survey has remained unchanged since January 1946.

Objective: To provide a measure of the total abundance of copepods for areas around the UK.

Relevance: Marine copepods form an important part of the diet of commercially exploited fish species and are the link between the base of the food web and higher trophic levels. There is increasing evidence that patterns in the abundance of copepods integrate a great deal of hydro-climatic variability and are particularly sensitive to ocean currents and changes in sea temperatures. They are therefore useful for monitoring environmental change in the marine environment.

Sensitivity of the index: Copepods can multiply rapidly when environmental conditions are optimal for growth and reproduction and consequently populations fluctuate readily in response to changing conditions. Two commonly used climate indices have generally been used to examine the relationship between environmental change and copepods at a large scale and over decadal periods of time. the first being the Gulf Stream index (GSI) and the second the North Atlantic Oscillation index (NAO). The GSI (available only since 1966) measures the position of the North Wall of the Gulf Stream, such that high values indicate a northerly path. In the past, the total number of copepods was positively correlated with the Gulf Stream position in April and copepods tended to be more numerous when the Gulf Stream followed a northerly path (Taylor, 1995). The relationship between the northerly path of the Gulf Stream and copepod abundance is thought to be via downstream atmospheric changes that affect the timing of spring stratification and the formation of a warmer surface layer in the sea.

Change over time and space: Figure 2.20 shows the annual mean levels of total traverse copepods averaged for each of the six areas:

- North Sea
- Malin Shelf
- North-East Atlantic
- Irish Sea
- Celtic Sea
- English Channel

Apart from the decline in *Calanus finmarchicus*, which is discussed below, the most evident feature of total copepod abundance in the areas around the British Isles is a general long-term decline. The taxa that most strongly showed this decline were the small copepod species *Para-Pseudocalanus* spp., *Oithona* spp. and *Pseudocalanus* adults. In the North Sea, for example, the abundance has dropped by half during the last few years compared with the abundance in the 1940s and 1950s.

Interpretation: An adequate explanation for the general decline in total copepod abundance has not yet been formalised. As total copepod abundance is the sum of all the species observed in CPR traverse it is difficult to interpret the observed change. Apart from the decline in *Calanus finmarchicus*, which is discussed below, the most evident feature of total copepod abundance in the areas around the British Isles is a general long-term decline. In the North Sea the taxa that most strongly showed this decline were the small copepod species *Para-Pseudocalanus* spp., *Oithona* spp. and *Pseudocalanus* adults. Some of these species will have adapted to boreal conditions and others to temperate conditions. There is a need therefore, to examine inter-species patterns to ascertain how each species is responding to changing climatic conditions. Over the last few years the decline has begun to stabilise, at least for the North Sea, but the

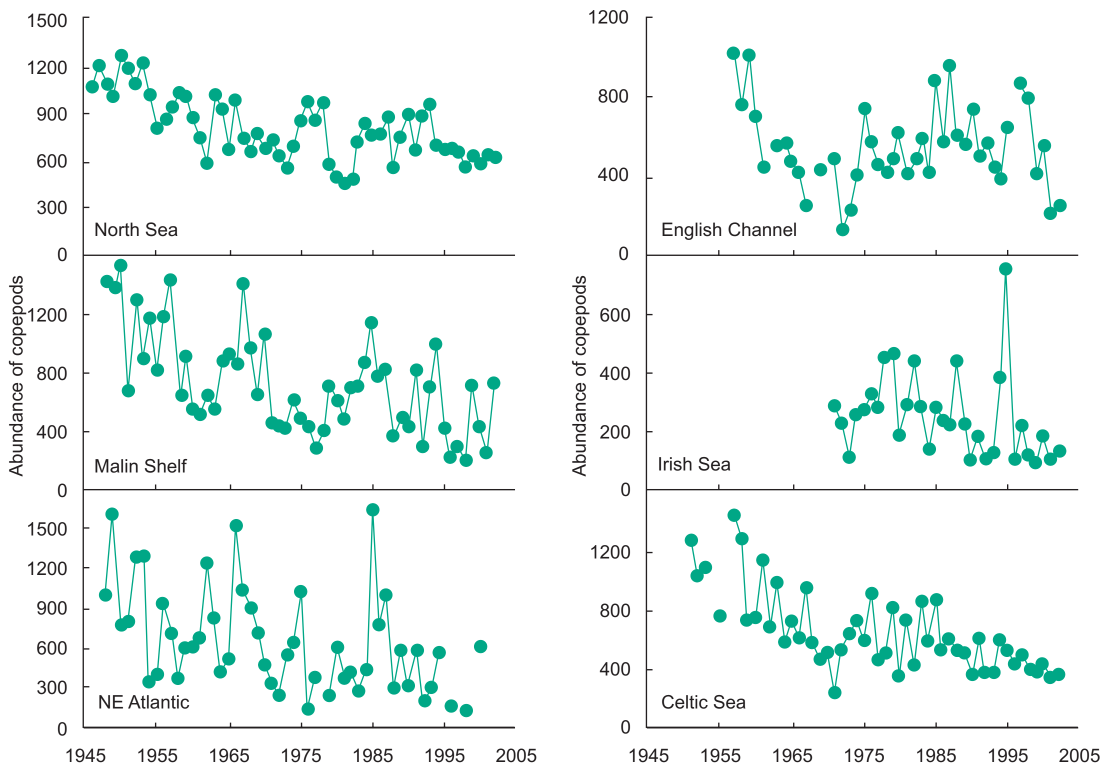

Figure 2.20. Plots of annual mean total traverse copepods averaged for the six areas defined in Figure 2.5

previously observed statistical relationship with the Gulf Stream is no longer evident. This is a similar pattern to the breakdown in the relationship between *Calanus finmarchicus* abundance and the North Atlantic Oscillation index since 1996 (see below). A general conclusion is that whatever is causing the decline in total copepods it is a large-scale phenomenon encompassing all the shelf seas around the UK, and is therefore likely to be modulated by large-scale hydro-climatic changes.

Further work: The decline in total copepod abundance needs to be examined in more detail as it has important consequences for higher trophic levels.

Data source: Sir Alister Hardy Foundation for Ocean Science, The Laboratory, Citadel Hill, Plymouth, PL1 2PB.

ABUNDANCE OF *CALANUS FINMARCHICUS*

Specific indicator: *Calanus finmarchicus* is an index of the abundance of boreal copepods determined from samples taken by the Continuous Plankton Recorder that represent a section along 10 nautical miles of sea. This species was not distinguished from the congeneric *C. helgolandicus* until January 1958. Results are only presented from this date, since when the methodology has remained unchanged.

Objective: To provide an index of the importance of boreal waters around the UK.

Relevance: Marine zooplankton are the food source of fish and many other marine organisms. Their abundance and timing are crucially important for the development of fish larvae, the recruitment of young fish and thus the size of fish stocks. *Calanus finmarchicus* is especially important as a food for fish larvae and for adult pelagic fish species such as the herring due to its size and its content of nutritious lipid oils. As a boreal organism they also provide an indication of the changing position of the boundary between boreal and temperate plankton. Since they diapause (hibernate) over the winter in the deep waters of the Norwegian Sea their abundance may also be an index of the volume of this water, which is an essential component of the 'global conveyor belt'.

Sensitivity of the index: The occurrence and abundance of this species in the shelf seas around the British Isles is dependent on yearly advection of seed populations from overwintering (diapause) populations in deep waters of the Norwegian Sea and possibly the Norwegian trench. In most years the species does not appear to be able to survive over the winter on the shelf. The highest concentrations of overwintering *Calanus* that are the source for North Sea populations appear to occur in the Faroe–Shetland Channel. Since the 1960s the volume of cold bottom water in this channel has decreased, possibly due to global climate change. In consequence, the annual supply of *Calanus* to restock the North Sea has dwindled, with important effects on recruitment of cod and other species. As a boreal organism *C. finmarchicus* prefers colder water; rising temperatures are likely to have reinforced its reduction in the North Sea. Until approximately 1987 this species was shown to be highly inversely correlated with the North Atlantic Oscillation (NAO) in waters around the British Isles (the NAO index measures the difference between the dominating atmospheric pressure systems in the North Atlantic: the Azores high and the Icelandic low). Many factors are likely to have contributed to this relationship, such as temperature, precipitation, strength of inflow from the ocean and wind strength, which are all known to be related to the NAO. The breakdown in the plankton NAO relationship shows the complexity of marine pelagic systems and the need to undertake more research on this sensitive species to environmental change to determine the key factors forcing changes in abundance and distribution.

Change over time and space: This species primarily occurs in the spring/summer months of the year (typically April, July) in the more northerly waters around the British Isles after the spring bloom of phytoplankton and normally declines to a low level in the autumn. It is found in much smaller numbers in the Channel and the Celtic and Irish Seas.

Figure 2.21 shows the annual mean levels of *Calanus finmarchicus* averaged for each of the six areas:

- North Sea
- Malin Shelf
- North-East Atlantic
- Irish Sea
- Celtic Sea
- English Channel

Interpretation: This species diapauses in deep water of the Norwegian Sea during the winter months of the year and re-invades UK shelf waters in the spring each year. Much research has been carried out on this process of invasion and it is believed that part of the reason for the decline in the species is attributable to the decrease in the volume of the cold deep water in the Norwegian Sea (Heath *et al*., 1999). Higher temperatures, and possible increased flows in the slope current may also have been unfavourable to the recolonisation of shelf seas like the North Sea. Interpretation of this species has been complicated by the breakdown in the clear statistical relationship with the NAO that existed until at least prior to 1988.

Further work: The breakdown in the *C. finmarchicus*: NAO relationship shows the complexity of marine pelagic systems and the need to undertake more research on this sensitive species to environmental change to determine the key factors forcing changes in abundance and distribution. Further work also needs to be undertaken on the invasion routes of the species onto the shelf and the forcing factors that promote different routes.

Data source: Sir Alister Hardy Foundation for Ocean Science, The Laboratory, Citadel Hill, Plymouth, PL1 2PB. North Atlantic Oscillation data can be obtained from http://tao.atmos.washington.edu/data_sets/nao/ and Northern Hemisphere temperatures from the Hadley Centre for Climate Research.

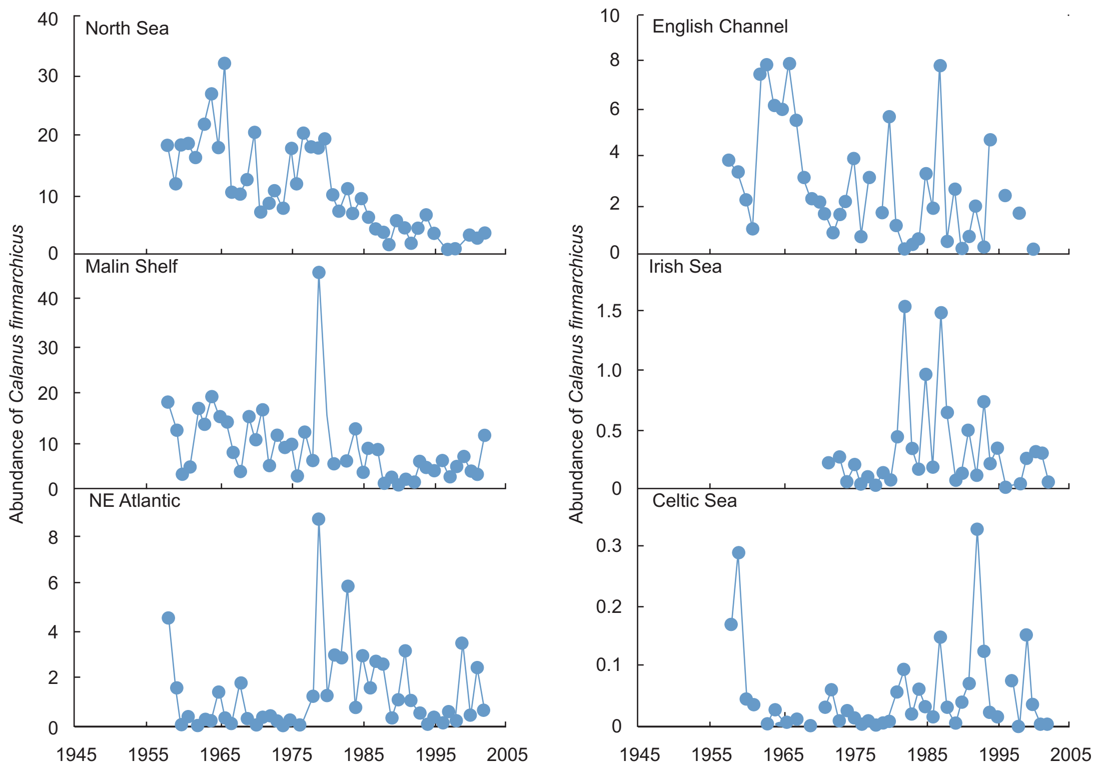

Figure 2.21. Plots of annual mean *Calanus finmarchicus* averaged for the six areas defined in Figure 2.5

RATIOS OF *CALANUS FINMARCHICUS* AND *CALANUS HELGOLANDICUS*

Specific indicator: There are no systematic or long-term current measurements of oceanic inflow into the North Sea so the only ways of estimating inflow are from modelling studies and by the use of indicator plankton. Changes seen in the plankton, and in particular *Calanus finmarchicus* and *Calanus helgolandicus* in the North Sea have been shown to be associated with variability in inflow and North Sea temperature. The patterns of change are especially clear when the relative abundance of these two copepods are expressed as ratios. Modelled monthly estimates of inflow for a section across the northern North Sea forced by monthly wind fields confirmed this relationship (Reid *et al*., 2003b). The main pattern of change in the inflows was also highly correlated with the North Atlantic Oscillation (NAO) reinforcing the dominant contribution that this mode of atmospheric variability has on the hydro-meteorological variability of the North Sea. While the ratios were originally determined for the North Sea they are presented here for six areas to reflect potential oceanic incursions on to the shelf with the eastern North Atlantic area as a possible control.

Objective: Development of a biological indicator of the relative importance and source of oceanic inflow onto the shelf around the UK and characterisation of cold/warm events.

Relevance: Oceanic inflow is estimated to contribute more than 90% of the nutrient input into the North Sea (NSTF, 1993). Temperature is also a key parameter influencing physiological processes and community composition of marine organisms. Together, variability in temperature and the volume, chemical properties, biological content and source of inflowing oceanic water are likely to have a considerable effect on all aspects of marine ecosystems around the British Isles, including the carrying capacity for fish resources and in turn the composition and tonnage of fish landings.

Sensitivity of the index: Appears to be a highly sensitive index to changing sources of oceanic water flowing into the North Sea and to the temperature conditions in the North Sea.

Change over time and space: Graphs of two different ratios between the large copepods *Calanus finmarchicus* and *Calanus helgolandicus* as annual means (Figure 2.22), are averaged for each of the six areas:

- North Sea
- Malin Shelf
- North-East Atlantic
- Irish Sea
- Celtic Sea
- English Channel

For the North Sea the different ratios of *C. helgolandicus* and *C. finmarchicus* distinguish three periods: a warm period subsequent to 1988 and two ‘cold’ biological events between ~1978 and 1982 and between ~1962 and 1967. However, it should be noted that the relative abundances of the two species in the North Sea are very different with *C. finmarchicus* being six times as abundant as its sister species. On the Malin shelf these two species again alternate in abundance in a similar way to the North Sea although numbers of *C. finmarchicus* are much lower. The major peaks in abundance appear to be delayed compared to the North Sea by one to two years.

In the other three more southerly areas the two species again alternate in relative abundance. The pattern of change is very different for the Celtic Sea compared to the North Sea with a warm period between 1973 and 1977 followed by a long period when *C. finmarchicus* dominates to 1993. What is of interest is that *C. finmarchicus* is also more abundant in 1999 and 2001, although numbers are much lower than in the North Sea. The Irish Sea shows a similar general pattern to the Celtic Sea, with one high peak in the *C. finmarchicus* to *C. helgolandicus* ratio in 1996. There is no clear pattern to the results from the English Channel other than a temperate phase between 1973 and 1980 in the general cold period in the North Sea and as for the Celtic Sea some higher peaks in the ratio *C. finmarchicus* to *C. helgolandicus* in recent years.

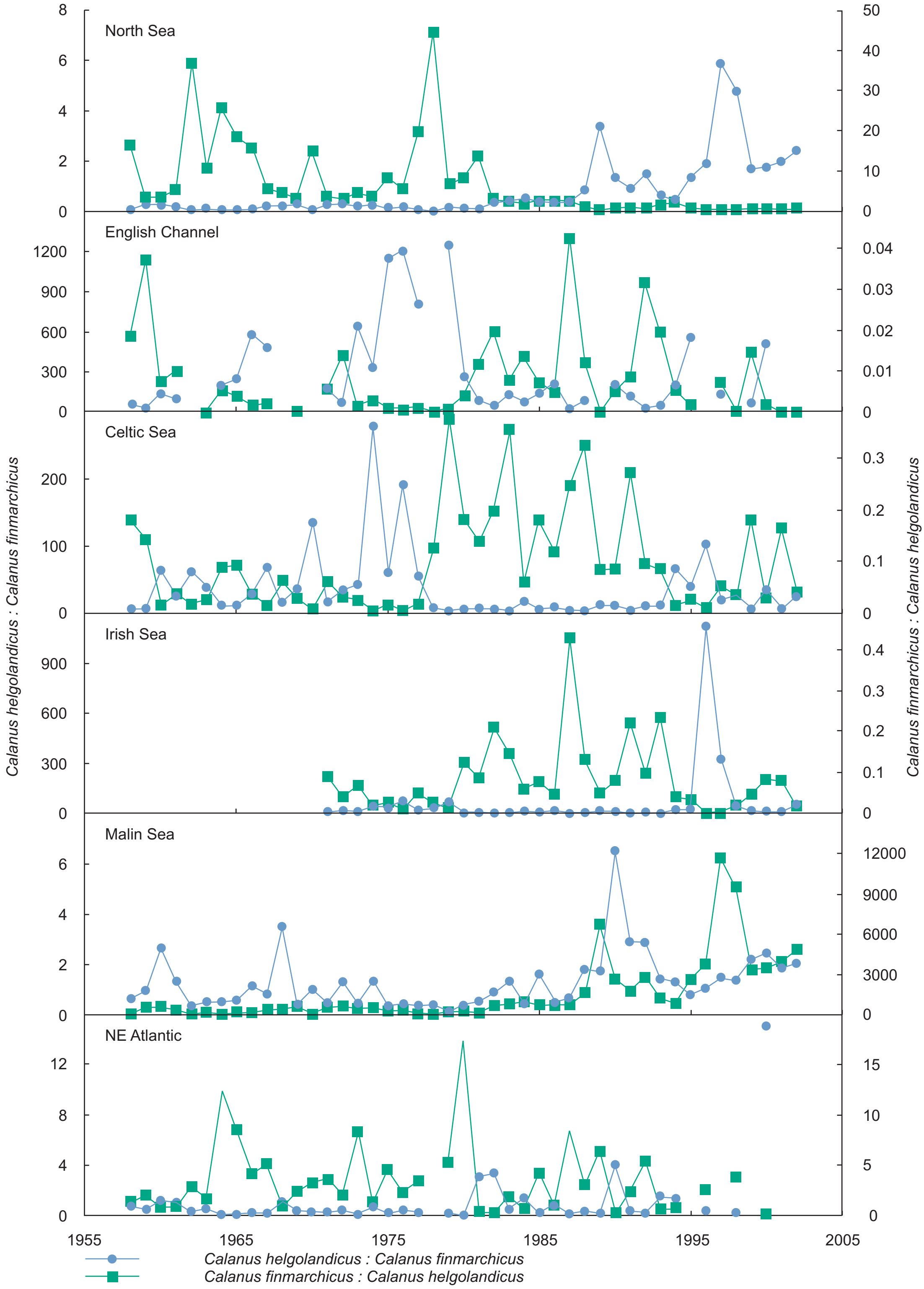

Figure 2.22. Plots of *Calanus finmarchicus*:*Calanus helgolandicus* ratios averaged for the six areas defined in Figure 2.5

Interpretation: In the North Sea abundance of the boreal copepod *C. finmarchicus* and warm temperate *C. helgolandicus* has shown a systematic alternation over the last 40 years (Reid *et al*., 2003b). In part, this reflects the inverse correlations that the two species show with the North Atlantic Oscillation (Fromentin and Planque, 1996), but also includes a temperature component as *C. helgolandicus* is strongly correlated with Sea Surface Temperature (Lindley and Reid, 2002). Varying inflows of oceanic water and the depth and seasonal timing of their occurrence, again related to the NAO, are a third important contributor bringing in seed populations. Inflows in the warmer periods appear to have a southerly source and be linked to higher flows in the slope current to the west of the British Isles (Holliday and Reid, 2001; Reid *et al*., 2001b). Inflows in the cold periods are important at lower depths, bringing in seed populations of *C. finmarchicus* from diapausing populations in deep water.

In the plot for the North Sea the 1988 regime shift identified by Reid *et al*. (2001a) is clearly distinguished. This event is shown, on the basis of 3D modelling, to be associated with an increased inflow of oceanic water. Peaks in the abundance of *C. helgolandicus* centred on 1989 and 1997 coincide with the two major oceanic incursions indicated by intrusion of southerly plankton into the North Sea (Edwards *et al*., 2001a; Holliday and Reid, 2001). The second of the cold events (~1978 to 1982) had a profound effect on North Sea ecosystems and fisheries with a marked reduction in the abundance of plankton and fish stocks (Edwards *et al*., 2002).

Further work: The breakdown in the *C. finmarchicus*:NAO relationship shows the complexity of marine pelagic systems and the need to undertake more research on this sensitive species to environmental change to determine the key factors forcing changes in abundance and distribution. The relationship between *C. helgolandicus* and the NAO was less clear. It is not known if this pattern has also broken down. Further work also needs to be undertaken on the invasion routes of the species onto the shelf and the forcing factors that promote different routes. In the past the two species were recorded in the Celtic Sea respectively above and below the thermocline. Vertical sampling in this area needs to be carried out to determine if a relict population of *C. finmarchicus* still exists in this area, and if so where it and its congeneric species overwinters.

Data source: Sir Alister Hardy Foundation for Ocean Science, The Laboratory, Citadel Hill, Plymouth, PL1 2PB. North Atlantic Oscillation data can be obtained from http://tao.atmos.washington.edu/data_sets/nao/.

PHYTOPLANKTON COLOUR

Specific indicator: CPRs have been towed behind merchant ships to monitor the plankton on a number of routes across the North Sea each month since January 1946. A six metre band of the filtering silk used in these instruments provides a 'film' of the plankton along a transect of ~500 nautical miles. Phytoplankton Colour is a simple index of chlorophyll (a basic measure of phytoplankton biomass) determined from a visual assessment, into four categories, of the colour of the CPR sampling silk. The methodology used has not changed since January 1946. Data for this index are available on the SAHFOS web site averaged for 41 Standard Areas covering the northern North Atlantic.

Objective: To provide an index of long-term variability in phytoplankton biomass and possibly production for sea areas around the UK.

Relevance: Phytoplankton forms the base of the food chain; variations in its composition, biomass and production are thus crucial for all other marine life. This variability also defines the carrying capacity of the living marine resources of an ecosystem/regional sea. Phytoplankton are sensitive indicators of environmental change and can be used to help distinguish anthropogenic from natural variability especially with respect to eutrophication and climate change. Measuring primary production is expensive and complicated; the Colour biomass index used here is a simple proxy for this production. The microscopic plants of the sea play a key role in climate change through the biological pump and in modulating gaseous exchanges with the atmosphere. Some of the species are toxic, causing Harmful Algal Blooms (HAB); information on natural change from the CPR helps to interpret the mechanisms behind HAB and develop management strategies. Finally the colour index provides sea-truthing for satellite measurements of phytoplankton biomass.

Sensitivity of the index: The spring bloom heralds the beginning of the growing year; its timing as well as subsequent successional changes in composition and abundance are known to be highly linked to meteorological (e.g. sunshine, wind) and hydrographic (e.g. currents, stability of the water column) variability as well as grazing from the zooplankton. Temperature is a key variable in phytoplankton growth and development as well as strongly influencing their physical environment through for example the development of water column stability. Evidence from the CPR has shown that Phytoplankton Colour is significantly correlated with both Sea Surface Temperature (SST) and Northern Hemisphere Temperature (NHT) in both the North Sea and much of the eastern North Atlantic. A weak relationship has also been found between Colour and the North Atlantic Oscillation (NAO).

Change over time and space: The predominant pattern of change for Phytoplankton Colour in a large area comprising the North Sea, sea areas around the British Isles and oceanic waters out to approximately 20°W to the west of Ireland over the last ~50 years has been an increasing linear trend, with a sharp stepwise increase after 1986 (Beaugrand and Reid, 2003; Edwards *et al*., 2001a; Reid *et al*., 1998). This pattern is most evident in the North Sea and less clear in some of the other five areas selected for this study. Pronounced changes have also occurred in the seasonal occurrence of the index.

Phytoplankton Colour in the North Sea (Figure 2.7) has shown pronounced changes over time with a stepwise increase in the index after about 1987, which reflects a much earlier and longer growing season as well as higher levels of Colour in the summer months of the year.

Graph Figure 2.23 shows the annual mean levels of Phytoplankton Colour averaged for each of the six areas:

- North Sea
- Malin Shelf
- North-East Atlantic
- Irish Sea
- Celtic Sea
- English Channel

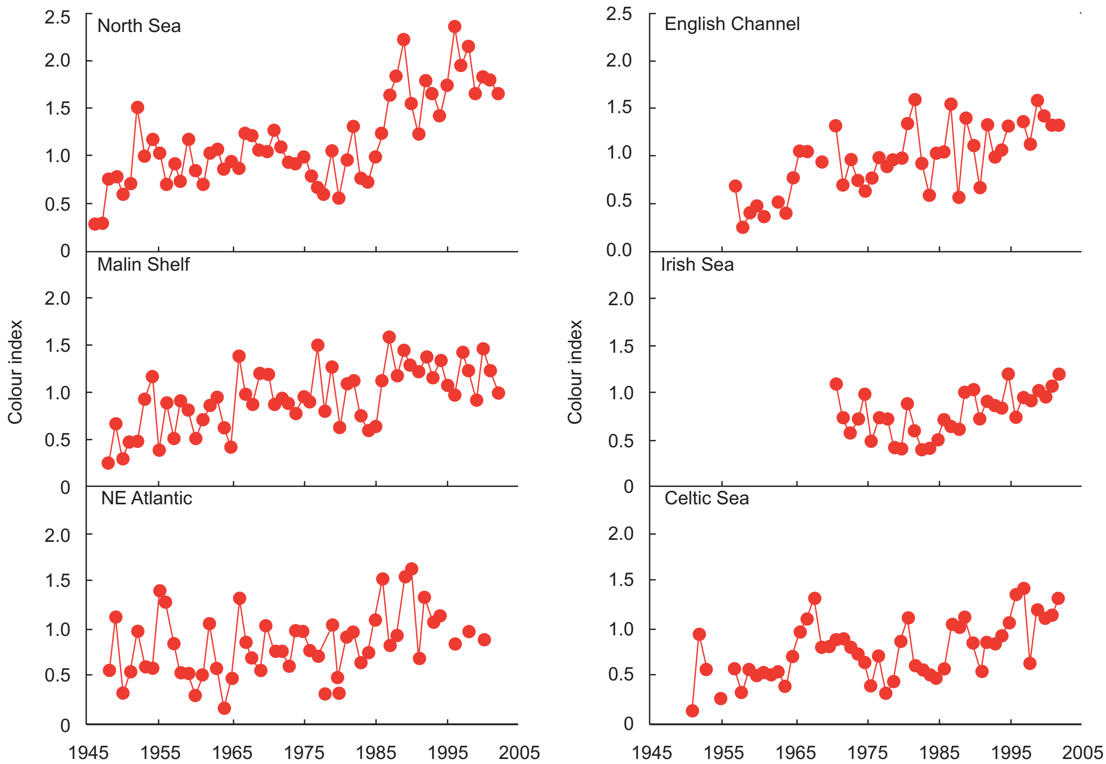

Figure 2.23. Plots of annual mean Phytoplankton Colour averaged for the six areas defined in Figure 2.5

In the North Sea, Phytoplankton Colour measurements were initiated in January 1946. At this time they were at a low level, especially considering that most of the routes were in the southern North Sea at this time. Levels increased, oscillating around a mean of 1 until 1988 when they jumped to a new mean level of ~1.7 units. Sampling in the Malin Sea started in a systematic way in January 1948; interannual changes and the mean level until 1987 were similar to the North Sea. An equivalent increase occurred in 1988 to the North Sea, but the mean level was much less. In the central eastern North Atlantic there has been a progressive upward trend since sampling started in 1948 with a general increase to higher levels from 1986. Sampling in this region has been more intermittent in the last decade.

Sampling in the Celtic Sea started from 1950, since when there has been a progressive rise in Colour to generally higher levels post 1987. Higher levels of Colour were also seen between 1968 and 1975. Systematic results were obtained in the Irish Sea from October 1970. Over this period the pattern of change is similar to the Celtic Sea, with the rise to higher levels occurring in 1989. In the English Channel the time series has been broken a number of times for short periods. The pattern is again one of a rising trend, with high levels of Colour occurring as early as 1982.

Interpretation: The changing patterns of Colour in the wider region that includes the six areas outlined here has been shown, after removal of temporal autocorrelation, to be significantly correlated with SST (averaged for the same area) and NHT (Beaugrand and Reid, 2003). Edwards *et al*. (2001a) also found a moderately significant correlation with the NAO. In the North Sea the changes in Colour as part of a regime shift are reflected in other trophic levels of the plankton in the biomass and diversity of the benthos (animals living in and on the bottom) in fish catches, recruitment and biomass, in nutrient concentrations, in inflow of oceanic water into the North Sea and even in the number of times that the Thames barrage has been closed to prevent tidal surges. Inflow of oceanic water has been shown to be highly related to the North Atlantic Oscillation and as the major source of nutrients to the North Sea has an important impact on productivity.

The similarity in pattern between the North Sea and the ocean to the west of Ireland indicates that the same processes are operating both on and off the shelf. These relationships suggest that the dominant factor contributing to the year-to-year variability in Phytoplankton Colour is physical hydroclimatic forcing, and that eutrophication in the areas sampled by the CPR, is a minor factor in the change. It is possible, however, that post regime shift changes may well have reinforced eutrophication symptoms in nearshore waters. Preliminary positive correlations between Phytoplankton Colour and satellite derived measurements of chlorophyll biomass help to reinforce the message that the observed changes are real and substantial. Colour in the North Sea at least appears to be responding to higher temperatures generated by the combined forcing of the NHT and NAO. The projected continuing rise in global temperatures by the International Panel on Climate Change (IPCC) implies that Colour levels may well continue to rise with a progressive change in the composition and seasonal occurrence of the species contributing to the index.

Further work: Some caution needs to be taken in the interpretation of the results for areas outside the North Sea where sampling has been less systematic through time. A statistical re-analysis of the data is needed that takes sampling into account.

Data source: Sir Alister Hardy Foundation for Ocean Science, The Laboratory, Citadel Hill, Plymouth, PL1 2PB. North Atlantic Oscillation data can be obtained from http://tao.atmos.washington.edu/data_sets/nao/ and Northern Hemisphere temperatures from the Hadley Centre for Climate Research.

COPEPOD INDICATOR ASSEMBLAGES

Specific indicator: Seven indicator assemblages of copepods have been produced based on the mean number of species in each assemblage (Beaugrand *et al*., 2002a,c). These associations determined from 108 species show variability in the abundance of groups of copepods that characterise different water masses. Here results have been averaged for two periods of years: 1958–1981 and 1982–1999.

Indicator associations

1. Arctic
2. Subarctic
3. Cold temperate mixed water
4. Shelf Sea Neritic
5. Coastal Neritic
6. Temperate Pseudo oceanic
7. Warm-temperate Pseudo-oceanic

Beaugrand *et al*., (2002a) decomposed the diversity of calanoid copepods, the most abundant taxonomic group in the plankton and best sampled by the CPR survey, into a number of species assemblages (Beaugrand *et al*., 2002b). At the scale of the North Atlantic basin and a spatial resolution approaching the meso-scale, nine species assemblages were identified using three criteria: (1) spatial distribution of species, (2) similarity in the seasonal variability of species and (3) their diel and ontogenic variations. The nine species assemblages were found to be closely related to geographical location and water mass. The indicator maps presented here (Figure 2.24) have been recalculated for two periods: 1958–1981 and 1982–1999. Only the seven associations that occur in waters adjacent to the UK are shown.

Objective: To produce a set of indicators that can be used to monitor modifications in the structural organisation of North Atlantic marine ecosystems linked to climate change.

Relevance: Provides an easily visualised and measured dataset of planktonic change at a scale of 50 × 50 nautical mile pixels. It enables the rates of biogeographic movement in planktonic assemblages to be measured.

Sensitivity of the index: These indices are constructed from time series of 108 species of copepods from the whole CPR database. The large amount of information included makes them especially sensitive to change.

Change over time and space: In the north-eastern North Atlantic and European seas, maps of the mean number of species for all associations in the area demonstrate that major biogeographical shifts have occurred in all seven species assemblages. This change has occurred since the early 1980s to the south-west of the British Isles and from the mid 1980s in the North Sea. The number of warm-water species has increased northwards by 10° of latitude, while the diversity of colder-temperate and subarctic species has decreased. All biological assemblages show consistent patterns of change, which may reflect a movement of marine ecosystems towards a warmer dynamical equilibrium.

Interpretation: Changes in these indices have been shown to be highly correlated with Northern Hemisphere Temperature (NHT) change and the North Atlantic Oscillation (NAO).

Further work: There is considerable scope to expand the use of these indicators to the examination of variability along particular stretches of the UK coast. The processes that are contributing to the distinction of the different associations and their change through time need to be examined.

Data source: Sir Alister Hardy Foundation for Ocean Science, The Laboratory, Citadel Hill, Plymouth, PL1 2PB. North Atlantic Oscillation (NAO) data can be obtained from http://tao.atmos.washington.edu/data_sets/nao/ and Northern Hemisphere temperatures from the Hadley Centre for Climate Research.

FUTURE RECOMMENDATIONS

- The environmental changes reported here need to be taken into account when assessing potential policies that might be implemented 'to show a real difference in the marine environment within one generation'.

- Consideration should be given to establishing a similar extensive inshore plankton survey to the Continuous Plankton Recorder (CPR) survey. One possibility might be to tow CPRs at shallow depths behind the survey vessels of the EA and SEPA when they are en route to complete other surveys.

- Temperature variability seems to be a major factor in the composition of communities and it might be possible to determine an expected community structure for a given area in a given temperature band. There is a need for research in this area.

- Some biological monitoring for plankton should be included in statutory monitoring programmes.

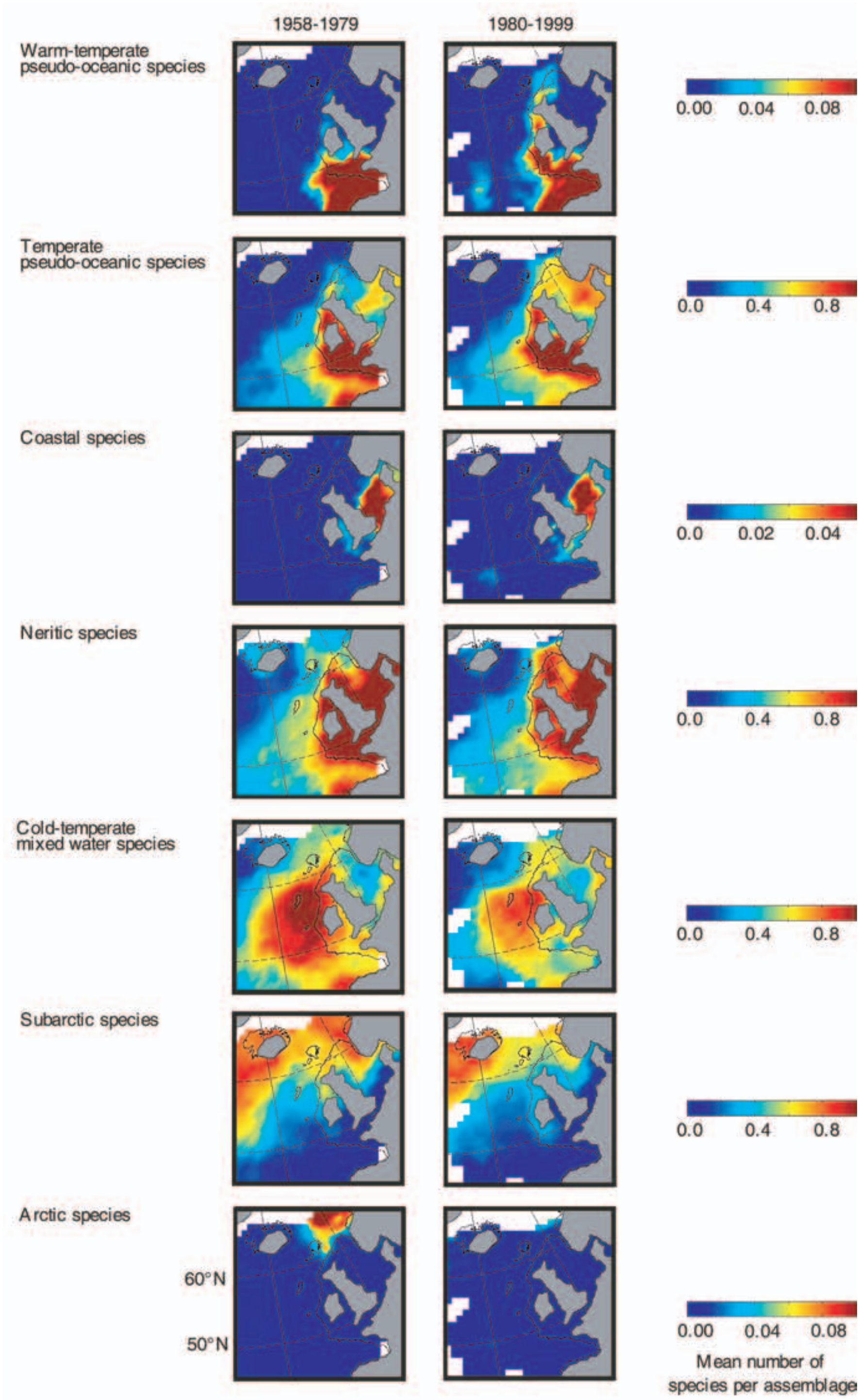

Figure 2.24. Maps of the Indicator Associations: Arctic, Subarctic, Cold temperate mixed water, Shelf Sea Neritic, Coastal Neritic, Temperate pseudo-oceanic and Warm temperate pseudo-oceanic averaged for the periods 1958–1979 and 1980–1999. Legend otherwise as per Figure 2.12 from Beaugrand *et al*. (2002a)

- Methods used in long-term plankton surveys should be standardised and maintained over long periods.

- An historical overview should be undertaken of past planktonic research in UK waters that brings together information from single point time series, one off surveys and the results of the Continuous Plankton Recorder (CPR) programme.

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