Technical Report TR_005

Technical report produced for

Strategic Environmental Assessment – SEA2

AN OVERVIEW OF PLANKTON ECOLOGY IN THE NORTH SEA

Produced by SAHFOS, August 2001

AN OVERVIEW OF PLANKTON ECOLOGY IN THE NORTH SEA

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CONTENTS

1. INTRODUCTION AND AIM OF STUDY

1.1 The purpose of this report is to give an overview of plankton ecology in the North Sea, and the processes that effect it, as derived from current research. The Sir Alister Hardy Foundation has extensive data for the North Sea area, and other sources have also been used to provide information for this report. Shortfalls in current research have also been highlighted. The information contained herein is to be contributed towards an information base for the Strategic Environmental Assessment.

1.2 The North Sea is an extension of the North Atlantic that has an area of 574,980 km^2. The deepest area is off the coast of Norway (660m), with a number of shallow areas, such as the Dogger Bank (15m). The North Sea represents a large source of hydrocarbons that have been exploited since the early 1970s. The aim of this study is to provide the Department of Trade and Industry with biological data on the planktonic community of the North Sea, as a contribution towards the Strategic Environmental Assessment (SEA 2). An overview of phyto- and zoo- plankton community composition, plankton blooms, *Calanus*, mero-, pico- and megaplankton, sensitivity to disturbance / contamination, phytodetritus and vertical fluxes and the resting stages of phytoplankton is made using the results of the survey database. Additional published literature has also been used, and gaps in available data have been highlighted.

1.3 The Continuous Plankton Recorder (CPR) survey provides a unique long-term dataset of plankton abundance in the North Atlantic and North Sea (Warner and Hays 1994). The survey has been running for almost 70 years, using ‘ships of opportunity’ to tow CPRs on regular, and incidental routes, sampling at a depth of 10 m. Each sample represents 18 km of tow and approximately 3 m^3 of filtered seawater. Over 400 taxa of plankton are routinely identified by a team of taxonomists. The samples are also compared to colour charts to give an indication of ‘greenness’, which provides a visual index of chlorophyll value (Reid *et al*., 1998). CPRs have been towed for over 4 million nautical miles, accumulating almost 200,000 samples. The design of the CPR has remained virtually unchanged since sampling started, thus providing a consistency of sampling that provides good historical comparisons. By systematically monitoring the plankton over a period, changes in abundance and long term trends can be distinguished. From this baseline data, inferences can be made, particularly concerning climate change and potential anthropogenic impacts.

2. BIOLOGICAL BACKGROUND

2.1 Plankton can be divided into phytoplankton and zooplankton, representing plants and animals generally. The majority of the plankton occurs in the top 20m of the sea, known as the photic zone (the layer that light penetrates to allow photosynthesis). The pycnocline is a zone of marked density gradient between stratified upper layers and mixed lower waters, which form in summer months in the northern North Sea and on the region of the Oyster Bank in the southern North Sea. Denser concentrations of plankton may accumulate in the pycnocline; this may extend up to the surface, forming a ‘front’. The vertical position of the pycnocline in the water column can vary throughout the year (Richardson *et al*., 1998).

2.2 The phytoplankton community can be divided into larger entities such as diatoms and dinoflagellates, and the smaller flagellates. The latter are often referred to as pico or nano plankton because of their small size, but can at times make up a large proportion of the phytoplankton community. Diatoms are characterised by having a siliceous test, comprising two valves, and being autotrophic (produce energy by photosynthesis). Dinoflagellates differ in having 2 flagella and a rigid test. They are usually heterotrophic (consume substances), but can also photosynthesize under certain conditions.

2.3 Diatoms typically 'bloom' in the spring, whilst dinoflagellates are more dominant during the summer months. Some diatoms can block intake filters of installations and vessels, and also foul fishing nets. The species' typically identified in these circumstances are *Coscinodiscus wailesii* and the larger *Odontella* species, and they produce copious quantities of mucilage when a bloom forms. The former species has been introduced to the North Sea, possibly through ballast water, and have rapidly spread throughout European waters (Edwards *et al*., 2001). *Phaeocystis pouchetii,* a colonial flagellate, is another species that produces large amounts of mucus in bloom conditions. It has been well studied as it can form large foam 'banks' on the seashore, especially in the southern North Sea (Riebesell, 1993, Jackson *et al*., 1991, Lancelot *et al*., 1987, Chang, 1983) and has been taken by some scientists as an indicator of eutrophication.

2.4 The most common group of organisms in the zooplankton community are the copepods (small, insect-like crustaceans which range from 0.5mm to 6mm). These are known to reach large concentrations, and they form the main food source for higher trophic levels.

2.5 The gelatinous members of the zooplankton include larvacea (small, tadpole like organisms living in a filtering 'house'), salps and doliolids (barrel – shaped organisms) and coelenterates (jellyfish). Salps and doliolids are known to produce huge swarms (Menard *et al*., 1997, Deibel, 1987), sometimes to such an extent as to clog ship intakes (Fraser, 1982). Siphonophores (colonial hydrozoa) can also reach large densities in the North Sea. In 1989 the species *Muggiaea atlantica* invaded the German Bight, reaching densities of 91 colonies per m^3 (Greve, 1993). The result of this was a decline in the small copepods (the species prey), and a consequential bloom in the phytoplankton.

2.6 Coelenterates are recorded as present / absent in the CPR database, and as their bodies disintegrate, along with most of the gelatinous entities on contact with the filter mechanism, an accurate account of their abundance is not known.

2.7 Meroplankton are the larval stages of benthic organisms that spend a short period of their lifecycle in a pelagic stage. An important group within this category are the echinodermata, whose larvae are the distributive stages of starfish and sea urchins, and they remain part of the plankton until they settle on the benthos. These organisms may be over a centimetre in diameter and are supported by skeletal calcareous rods. The skeletal rods and their attached cellular material have been found to reduce the porosity of filters in oil pipeline pressure tests (Reid and Hunt, 1986).

3. MAP OF STUDY AREAS

3.1 Figure 1 shows the areas examined for this study. It was felt that in order to have the maximum possible number of data points in the area of study, information from a slightly larger are has been included. The southern North Sea extends from 52^{o}N to 55^{o}N, 11^{o}E to 1^{o}W. The central and northern North Sea areas have been combined within the co-ordinates 56^{o}N to 62^{o}N, 11^{o}E to 1^{o}W.

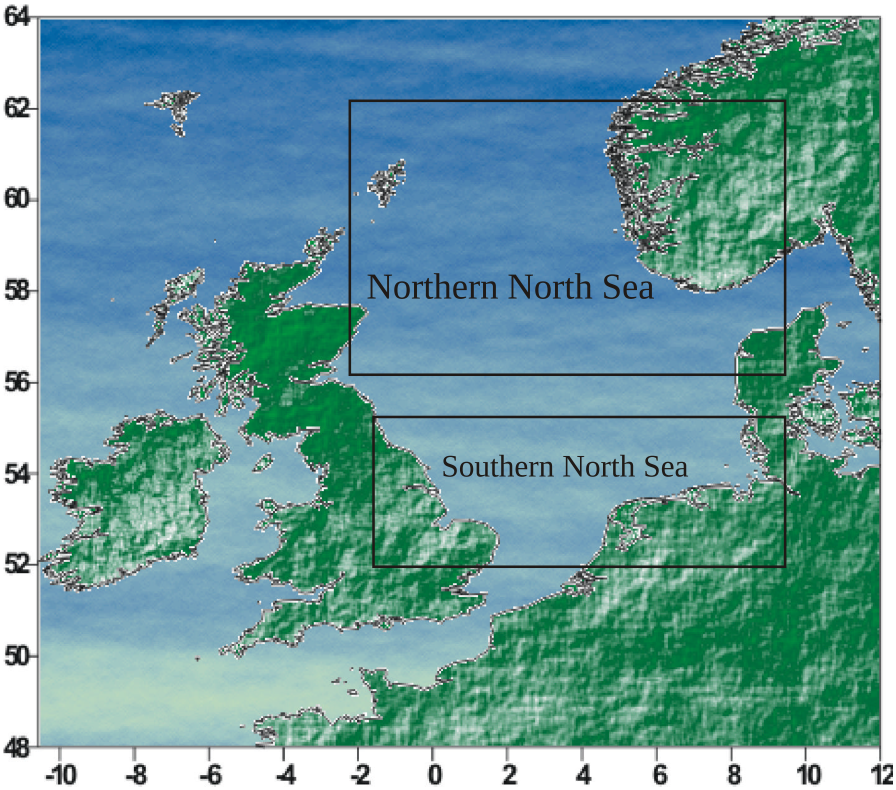

Figure 1. Map showing the areas used for this report

4. PHYTOPLANKTON AND ZOOPLANKTON COMMUNITY COMPOSITION

4.1 Results are presented for two areas representing the northern and southern North Sea. Using CPR data the ten most abundant groups of phytoplankton and zooplankton were established, and compared (see Table 1)

4.2 In the northern North Sea the dinoflagellate genera *Ceratia* dominates the phytoplankton community. The species are all fairly cosmopolitan in terms of temperature and salinity tolerances. If one was to examine the long-term changes in the community, there has been a gradual decrease in the abundance of the majority of diatom species (except *Thallasiosira* which has remained quite constant), whereas the dinoflagellate component has continued to increase. In the southern North Sea *Ceratia* again dominate, but there are higher numbers of the diatoms in the genera of *Chaetocera* (*Hyalochaete* and *Phaeoceros).* The same domination of the phytoplankton community by dinoflagellates has occurred in this area, as in the northern North Sea. Figure 2 shows the long - term changes in phytoplankton colour, an indicator of phytoplankton biomass. It is apparent that the level of phytoplankton biomass has increased over the last four decades over the majority of the North Sea.

4.3 It is a widely held opinion that this apparent increase in 'chlorophyll' is attributable to eutrophication, but this is largely restricted to coastal margins and areas with limited water exchange (Edwards *et al*., 2001). It is more likely that changes in environmental conditions (i.e. increased sea surface temperatures (SSTs)) have caused the phytoplankton community change, as similar changes have been seen to the west of the British Isles in oceanic waters, as opposed to an anthropogenic impact.

Table 1. 10 most abundant phyto- and zooplankton species in the North Sea (from CPR results)

	Northern North Sea	Southern North Sea
	Phytoplankton	
1.	*Ceratium fusus.*	*Ceratium fusus*
2.	*Ceratium furca*	*Ceratium furca*
3.	*Ceratium tripos*	*Ceratium tripos*
4.	*Ceratium macroceros*	*Phaeoceros* spp.
5.	*Ceratium longipes*	*Hyalochaete* spp.
6.	*Thalassiosira* spp.	*Ceratium macroceros*
7.	*Protoperidinium* spp.	*Thalassiosira* spp.
8.	*Ceratium horridum*	*Protoperidinium* spp
9.	*Hyalochaete* spp.	*Ceratium horridum*.
10.	*Phaeoceros* spp.	*Ceratium longipes*
	Zooplankton	
1.	Total copepods	Total copepods
2.	*Calanus* traverse	Echinoderm larvae
3.	*Calanus* I-IV	*Para-Pseudocalanus* spp.
4.	*Para-pseudocalanus* spp.	*Acartia* spp.
5.	Echinoderm larvae	*Temora longicornis*
6.	*Acartia* spp.	*Evadne* spp.
7.	Thecosomata spp.	*Pseudocalanus* adult.
8.	*Evadne* spp.	*Oithona* spp.
9.	*Oithona* spp.	*Calanus* traverse
10.	*Pseudocalanus* adult	*Podon* spp.

4.4 Looking at the zooplankton community, the northern North Sea and southern North Sea appear similar. Total copepods (all copepods recorded in a traverse section of analysis, representing all species under 2mm) have the highest abundance, but this represents an amalgamation of a number of smaller species. In general the smaller copepod species are more abundant, such as *Para-pseudocalanus* spp., *Acartia* and the younger stages of *Calanus*. In the southern North Sea echinoderm larvae are the second most abundant group recorded in the zooplankton from CPR records. The abundance is an order of magnitude higher than that found in the northern North Sea, and this is dealt with under section 7 Meroplankton. *Calanus* adults, of the species' *finmarchicus* and *helgolandicus*, are discussed in section 6.

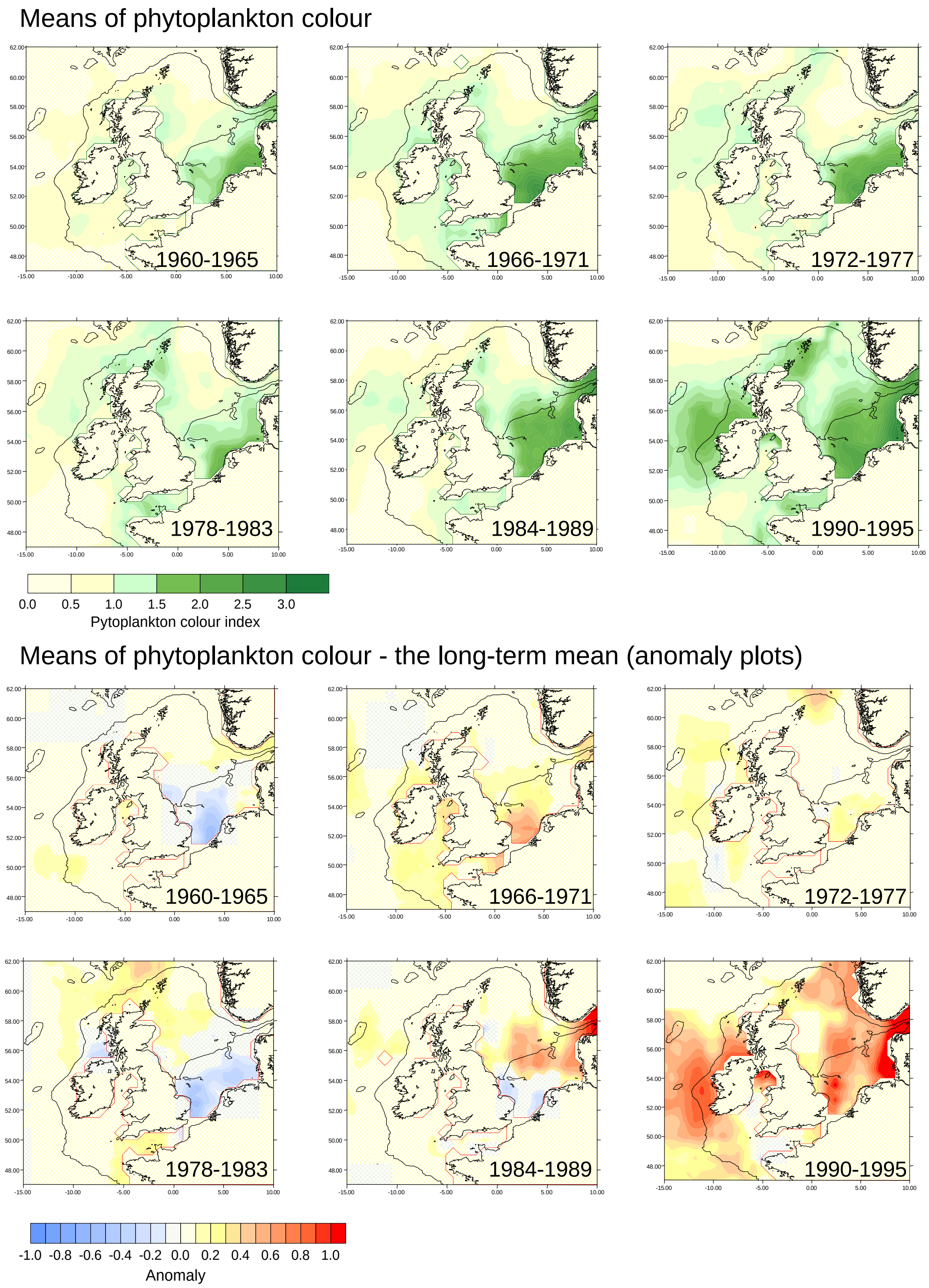

Figure 2. Geostatistical estimates of the mean spatial distribution of phytoplankton colour (the Continuous Plankton Recorder's estimate of phytoplankton biomass) in six-year period's form 1960-1995. Anomaly maps show the mean spatial distribution of phytoplankton (colour minus the long-term mean). From Edwards (2000) PhD University of Plymouth.

5. BLOOMS

5.1 In the North Sea, a 'bloom' of phytoplankton occurs every spring, often followed by a smaller peak in the autumn. The factors that initiate the spring bloom are vertical mixing and stratification of the water column, along with the length of photoperiod. During the winter months, in periods of low light, phytoplankton growth is inhibited. In this period, the nitrogen, phosphorus and silicate and ammonia nutrients increase in concentrations, as little or no primary production is taking place to utilise them. When the water becomes stratified in the spring, there follows a bloom of diatoms (Williams and Lindley, 1980). When silicate becomes limited (it is essential for diatom growth, being incorporated into their 'test'), other groups, such as flagellates, bloom, followed later by the dinoflagellates. This secondary part of the bloom is limited by the amount of phosphorus and nitrogen left after the initial diatom bloom. As the spring progresses to summer, surface waters warm and a more permanent thermocline develops. Colder, nutrient-rich waters sink away from the photic zone; primary production slows and tends to be largely confined to deeper layers in the pycnocline. The resulting phytoplankton community is one that can cope with reduced nutrient levels. With the onset of autumn, and the increase in wind strength, the sea becomes mixed once again, and at this time a secondary bloom of dinoflagellates may occur. As the light levels diminish in the latter part of the year, primary production once again decreases. The water then becomes mixed and this aids the distribution of nutrients throughout the water column. Based on CPR results (Edwards 2000), the late 1980s, and particularly 1989, were punctuated by a succession of exceptional phytoplankton blooms, with many species appearing up to two months earlier in their normal seasonal cycle. The phenomenon was connected with an ocean climate anomaly in which a combination of very mild atmospheric conditions and large oceanic inflow into the North Sea occurred (Edwards *et al*., 1999).

5.2 The above would be thought of as a natural event, a 'normal, annual bloom (Richardson 1989). But, under certain conditions blooms can occur at other times of the year, often consisting of a monoculture. The concentrations of organisms in these blooms can be very high, up to 100 x 10^6 l^{-1}, with chlorophyll concentrations around 2000mg chl m^{-3} (Reid *et al*., 1990). Many of these blooms involve nuisance or noxious species, particularly those consisting of dinoflagellate species, and can discolour the water, hence the popular term 'red tide'. The more correct description is a 'Harmful Algal Bloom (HAB)'. In the North Sea more than 30 taxa are recognised as occurring in bloom proportions, of which approximately one third may be toxic (Reid *et al*., 1990). Blooms can develop due to a combination of factors: the rapid reproduction of a species, reduced grazing pressures, favourable environmental factors (light, temperature, salinity and nutrient concentrations). Subsequent blooms can then cause a variety of detrimental effects, such as deoxygenation, foam formation, fish and marine mammal mortality, and a change to the ecosystem (Figure 3). Effects on humans can range from mild symptoms to life threatening toxicity, normally passed on via shellfish, as listed below (from the Intergovernmental Oceanographic Commission):

- Amnesic Shellfish Poisoning (ASP)
- Ciguatera Fish Poisoning (CFP)
- Diarrhetic Shellfish Poisoning (DSP)
- Neurotoxic Shellfish Poisoning (NSP)
- Paralytic Shellfish Poisoning (PSP)

5.3 There has been growing concern that blooms are on the increase, possibly due to a combination of climate variability and eutrophication. But the exact definition of an 'exceptional bloom' is open to debate (see ICES Symposia 1993), because using a minimal number of observations is not sufficient to draw long term conclusions (van Beusekom and Diel-Christiansen, 1993).

5.4 Recent studies (Kudela and Cochlan, 2000) have found that HABs can be forced by anthropogenic impacts, namely by the addition of urea (organic nitrogen compound derived from human urine). It was discovered that under certain situations, a dinoflagellate, *Lingulodinium polyedrum*, utilises urea and can rapidly form bloom concentrations.

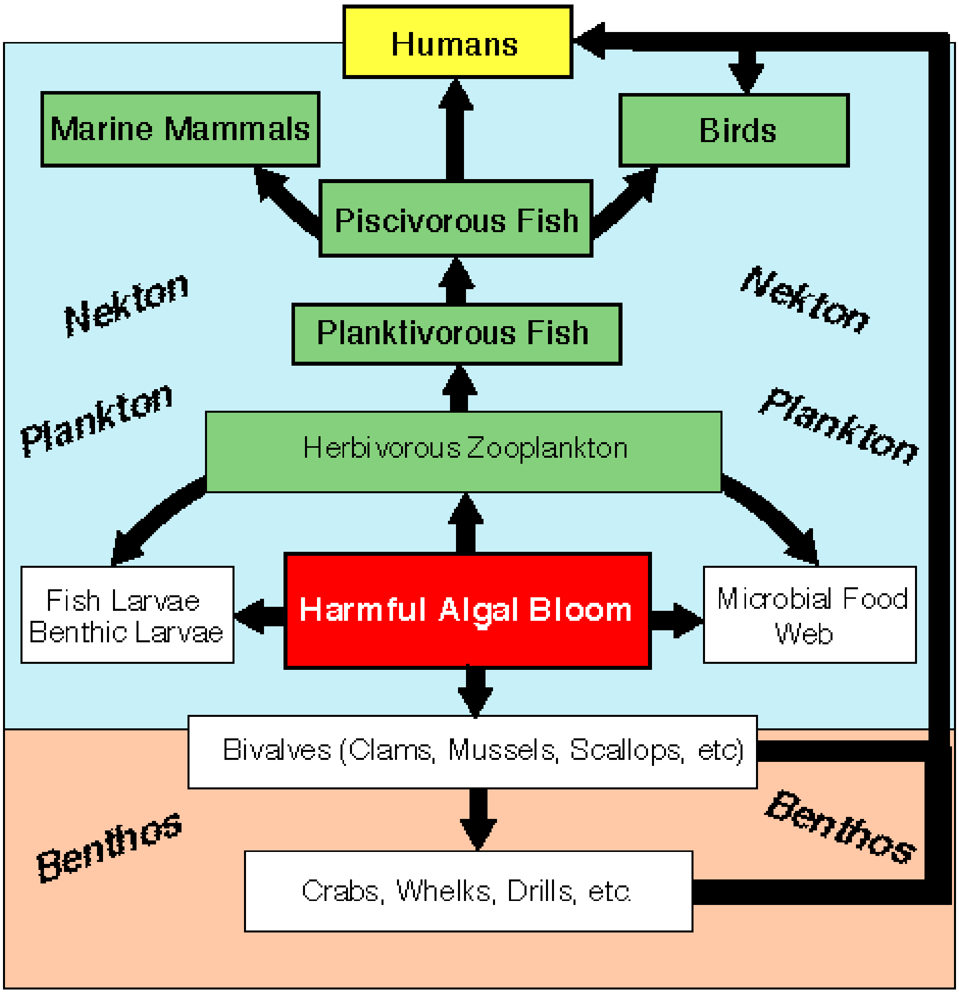

Figure 3. Model showing routes through which toxins impact different trophic levels. Sourced from http://www.redtide.whoi.edu/hab/foodweb/HABfoodweb.html

6. CALANUS *IN THE NORTH SEA*

6.1 Planktonic organisms, primarily copepods, constitute a major food resource for many commercial fish species, such as cod and herring (Brander, 1992). Changes in their populations are therefore of considerable importance, be it natural or anthropogenically forced. The dominant copepod genus in the North Atlantic is *Calanus*, which represents a major resource to the higher trophic levels, and is itself a strong grazer on phytoplankton (Planque, 1997). In the North Sea, the dominant species are *Calanus finmarchicus* and *Calanus helgolandicus*, and these species have been extensively studied for many years. *C. finmarchicus* was first identified in 1770 by Gunnerus, but was not separated from *C. helgolandicus* as a different species until 1958.

6.2 Section 13 describes the North Atlantic Oscillation (NAO) in more detail, but put concisely it is the alternation between the Icelandic low and the Azores high, as measured between the winter months (December to March). The index value is either positive (a lower Icelandic Low, and higher Azores High), or negative (the reverse situation). Figure 4 shows the correlation between the NAO index and *Calanus finmarchicus* abundance. The figure highlights the strong correlation, up until 1996, and shows how this relationship broke down afterwards. So the question is, why do *Calanus* respond to the NAO, and why did the relationship break down in 1996? The NAO is thought to drive the weather patterns over the North Atlantic, and specifically over the North Sea. In years of high NAO index, the westerly wind component is increased over the North Sea, bringing warmer air and therefore increasing the North Sea surface temperatures. In addition, this increase in wind is likely to reduce stratification of the surface waters, delaying the onset, or altering the community structure of the spring bloom. The timing of the bloom is critical to *Calanus* survival, as egg hatching is closely timed to the peak in primary production (Planque and Fromentin, 1996). It is possible that the combined factors: the timing of the spring bloom, sea surface temperature (SST) and phytoplankton community has effected the *Calanus* population. The trend towards a higher proportion of dinoflagellates in the phytoplankton community (Edwards 2000, Dickson *et al*., 1992) has also undoubtedly had a large impact on *Calanus*.

6.3 Recent research has concentrated on the biogeography of these two species that co-occur in the North Sea, and the changes that have occurred during the last few decades. Figures 5 and 6 show the distribution of the two species throughout the North Atlantic. Of particular interest to this report is the North Sea and here the greatest change has taken place. The two species are believed to have both responded to hydroclimatic conditions in the North Sea, driven by the North Atlantic Oscillation (NAO).

6.4 From Figure 5 it is apparent that *Calanus finmarchicus* has declined (it appears to have retreated north to colder waters) significantly in the North Sea during the late 1990s, whereas *Calanus helgolandicus* has increased in the North Sea (it has moved northwards as the SST has increased). It is likely that the reason for the decline in *C. finmarchicus* is also the cause of the increase in *C. helgolandicus*. It has been hypothesised that the breakdown in the relationship between the NAO index and *C. finmarchicus* abundance is because the population has reached such a low level that it is no longer responding to the signal of the NAO.

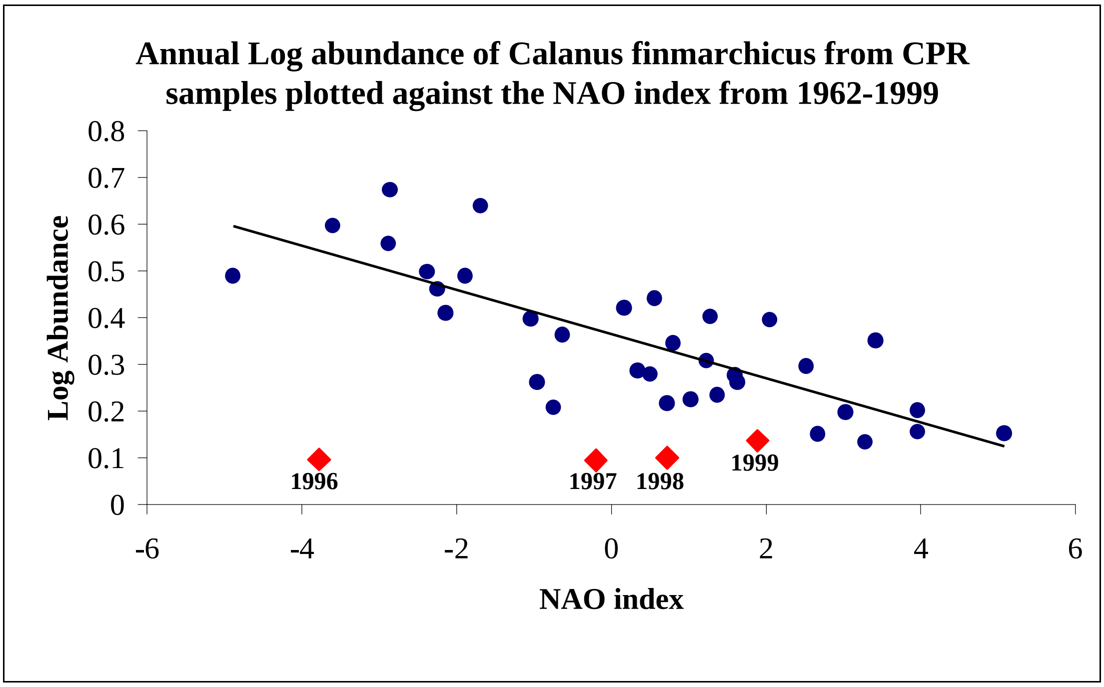

Figure 4.** **Graph showing negative correlation between NAO and** **Calanus finmarchicus** **in the North Sea. Note breakdown of relationship after 1996, when the NAO exhibited an extreme shift to a negative phase.

6.5 A number of hypotheses have been proposed to explain the switch in the relative abundance of the two *Calanus* species in the North Sea. For example, changes in sea temperature, food availability, inter-species competition, the transport of overwintering populations onto the shelf, and the flow and temperature of the shelf edge current (Reid and Beaugrand, In press). Another important aspect is the volume of the overwintering habitat in Norwegian Sea deep water, which has reduced, (Østerhus and Gammelsrød, 1999), because in the high NAO state convection is halted in the Greenland Sea, leading to a reduction of Norwegian Sea deep water.

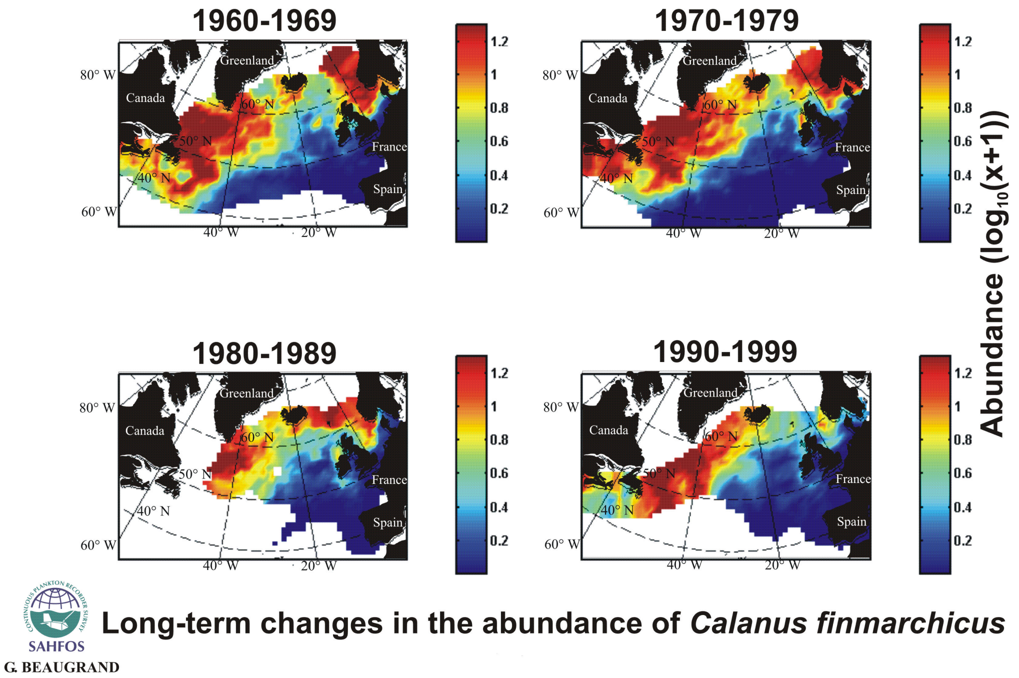

***Figure 5.** Long term changes in* Calanus finmarchicus *abundance, as determined from CPR data.*

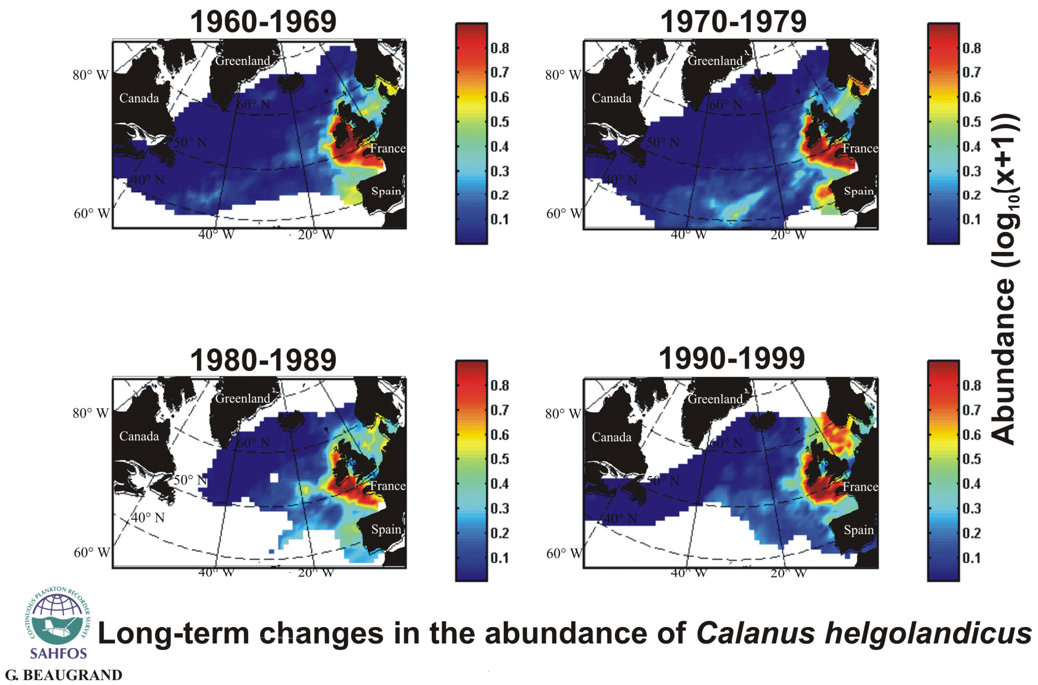

***Figure 6.** Long term changes in* Calanus helgolandicus *abundance, as determined from CPR data.*

7. MEROPLANKTON

7.1 The term meroplankton applies to temporary members of the plankton community that have a pelagic (larval) stage followed by a benthic (adult) stage. Meroplankton constitute an important and often dominant (sometimes over 50% of the biomass can consist of decapod larvae) part of the planktonic community (Lindley, 1998). Examples of meroplankton would be decapod larvae and echinodermata larvae, both of which spend a period in the plankton before settling to the benthos. The larval stages of some fish would also be included in this category.

7.2 Decapod larvae are not speciated in the CPR survey as a general rule, but they are well sampled. Section 4 details the composition of the zooplankton community in both the southern and northern North Sea, and it is apparent that echinoderm larvae are also an important part of the biomass.

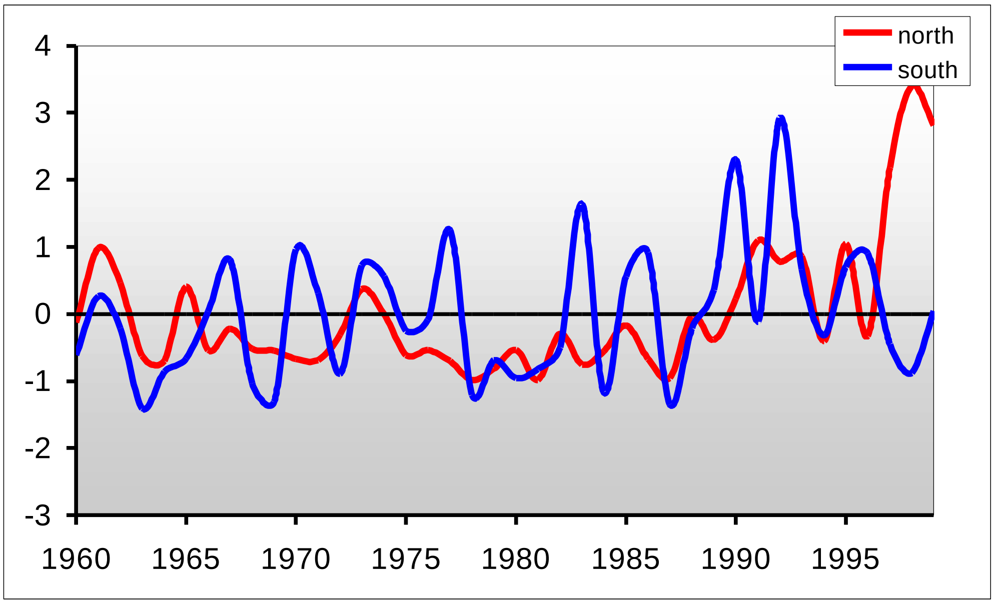

Figure 7. Graph showing standardised abundance of decapod larvae (from the CPR survey). Red line indicates northern North Sea; blue indicates southern North Sea.

7.3 Figure 7 shows the standardised abundance of decapod larvae in both areas of the North Sea. The areas show different trends to each other, with the northern part increasing dramatically in 1998, after a steady rise since the late 1980s. The northern area shows a pronounced oscillation over the last 40 years.

7.4 The northern part of the North Sea shows a clear response in the decapod larvae to the 1998 inflow event (Edwards *et al*. 1999). Abundance rose to over 3 standard deviations above the long-term mean, and remained high for the following year.

7.5 The southern part of the North Sea has shown a general increase in abundance, though no pronounced increase in 1998 as in the northern area (possibly due to a lag in a signal developing).

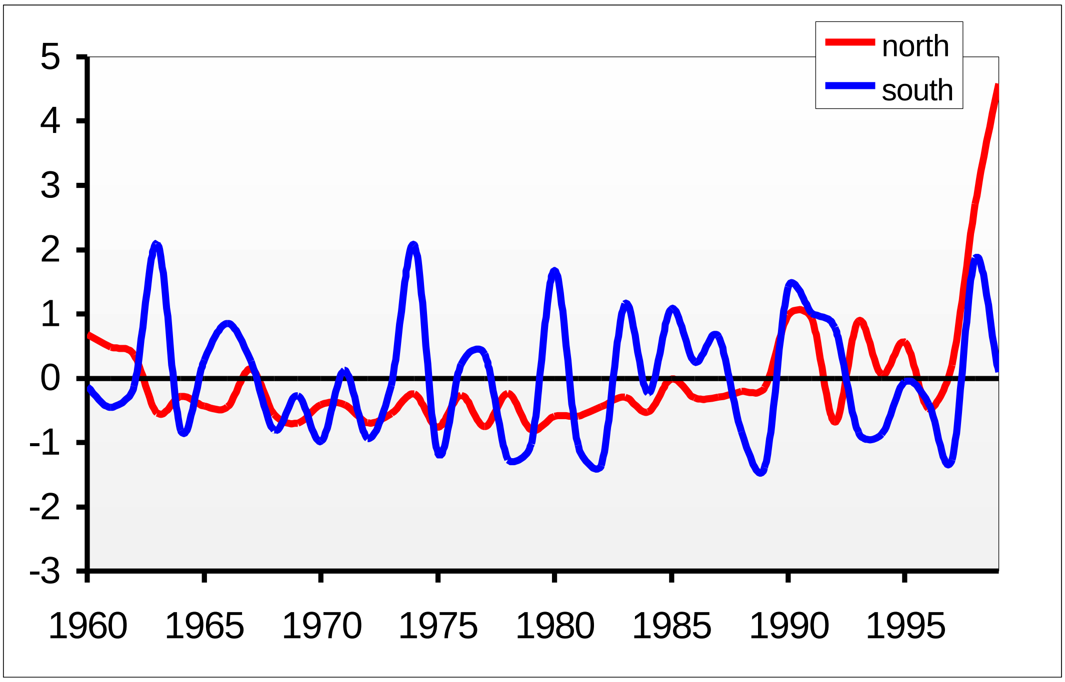

Figure 8. Graph showing standardised abundance of echinoderm larvae (from the CPR survey). Red line indicates northern North Sea; blue indicates southern North Sea.

7.6 Figure 8 shows the abundance of echinoderm larvae in the two areas of the North Sea. As with the decapod larvae, there was a steep rise in abundance in the northern North Sea in the late 1990s, again a possible response to the 1998 inflow event. The southern North Sea population shows no real change over time, oscillating around the long-term mean. This appears to be similar to decapod larvae variations in the same area.

8. PICOPLANKTON

8.1 The term picoplankton refers to the very small plankton, that which is between 0.2 and 2.0 microns in diameter (Carrick and Schelske, 1997). As such it presents a challenge to sample, and the mesh that the CPR survey uses is far too coarse.

8.2 Much of the picoplankton consists of bacteria, such as Proteobacteria and others from the Cytophage / Flavobacterium / Bacteroides (CFB) group (Uphoff *et al*., 2001). Another important group is the picocyanobacteria, or blue – green algae, which play a significant role in primary production in the ocean.

8.3 The contribution of picoplankton to the overall plankton biomass has been estimated at between 15 and 33% (Klinkenberg and Schumann, 1995). Picoplankton below 3 microns have been estimated to account for 6.6 to 57.5% of the total phytoplankton chlorophyll-a biomass (Iriarte and Purdie, 1993). In fact, in a study by Savidge *et al*. (1995) in the northeast Atlantic, the spring bloom was dominated by the >1 – 5 micron fraction of the plankton community, almost entirely displacing the larger diatoms more typical of a bloom.

8.4 The picoplankton community in the North Sea undoubtedly represents an important, understated part of the ecosystem. This is evident in the relative lack of research into this part of the plankton community, despite its contribution to the total plankton biomass and chlorophyll production. Research is only in its early stages, with the contribution of picoplankton to the aquatic ecosystem only becoming evident over the past decade (Carrick and Schelske, 1997).

9. MEGAPLANKTON

9.1 Megaplankton, in terms of the CPR survey, consists of euphausiids, thaliacea (salps and doliolids) and siphonophores. Larger organisms, such as coelenterata (i.e. jellyfish) and ctenophores are poorly sampled in the CPR survey due to the fragile gelatinous nature of their bodies. But an indication can be gained from the CPR results, and it can be seen that the organisms are more abundant in the latter part of the summer and autumn, this is in agreement with Williams and Conway (1981). Their work was to describe the seasonal abundance of a coelenterate species in the North Sea, and it was found that peak abundance occurred in June, July and September. In these months the concentration of individuals reached up to 40 per m^3 and accounted for over 80% of the dry weight biomass. Coelenterata can occur in vast numbers under ideal hydro-climatic conditions, and there is no doubt that their nature means they are greatly undersampled, both by the CPR and other surveys.

9.2 Salps and doliolids (distribution shown in Fig. 9), collectively known as *Thaliacea,* are known to peak in abundance in the North Sea in late summer to October (Fraser, 1982). They are known to produce huge swarms (Menard *et al*., 1997, Deibel, 1987), sometimes to such an extent as to clog ship intakes (Fraser, 1982). Doliolids are predominately oceanic temperate water species, and generally, it is thought that there are no known cold water species. Because of this, their presence in British waters acts as an indicator of oceanic inflow into the North Sea (Edwards *et al.,* 1999). The species *Doliolum gegenbauri* is one of the more hardy ones, and is the main species identified in British waters. *D. nationalis* and *D.mulleri* occur to a lesser extent, and rarely *D.krohni* and *D.intermedium* enter British waters. The fact that doliolids have such a fast reproduction rate means that they can respond quickly to favourable conditions. However, the increasing population can rapidly deplete the food stock, resulting in an inverse relationship between the doliolids and their food. There would be an obvious effect on the plankton community locally in such an event, and work has been done in an attempt to model this (see Haskell *et al.,* 1999).

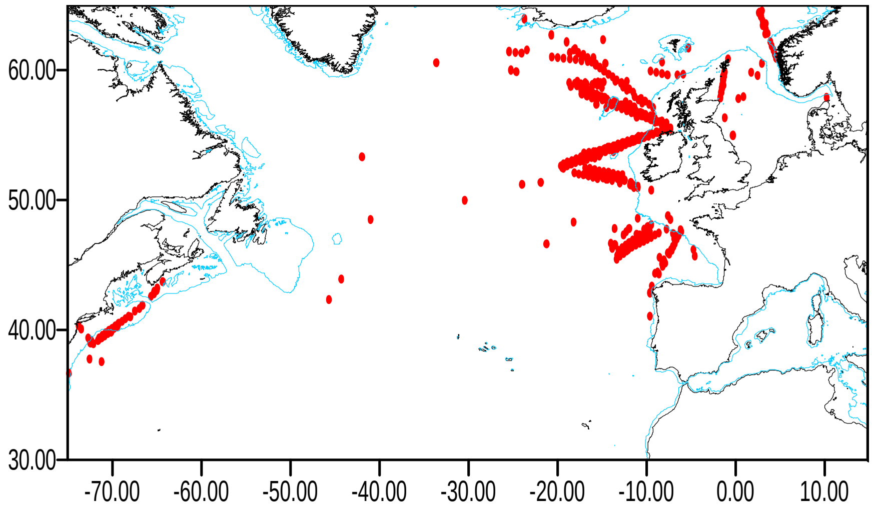

Figure 9. Records of Thaliacea in CPR samples (1948-1997).

9.3 Salps are larger than doliolids, though superficially similar. The main difference is that the muscle bands on a salp are discontinuous ventrally, as opposed to being a continual band on a doliolid. This pattern in the muscle bands is one of the identifying features. As with doliolids, salps have a capacity to rapidly form enormous swarms, which by their grazing can severely limit the food available to other herbivores in the plankton. This in turn affects carnivorous zooplankton, and subsequently higher trophic levels (Fraser 1982).

9.4 Siphonophores (colonial hydrozoa) can also reach large densities in the North Sea. In 1989 populations of the species *Muggiaea atlantica* grew to enormous concentrations in the German Bight, reaching densities of 91 colonies per m^3, after a possible oceanic introduction the previous autumn (Greve, 1993). The result of this was a decline in the small copepods (the species prey), and a consequential bloom of the phytoplankton.

9.5 Euphausiids, or 'krill' as they are more commonly termed, are well sampled and very abundant throughout the North Sea, though not routinely identified to species level in the CPR survey. Figure 10 shows the long-term abundance of euphausiids in the CPR survey, from the southern and northern North Sea. The graph highlights the cold boreal inflow event of the late 1970s, when the decrease in the North Atlantic current allowed an influx of colder water from the Norwegian Sea, including boreal plankton such as the euphausiids. In contrast to this boreal event, the peak in the southern North Sea in the early 1990s is likely linked to the increase in Atlantic water inflow. At the same time as this event occurred, phytoplankton colour, benthic biomass and the catch of Horse mackerel (*Trachurus trachurus*) increased significantly (Reid *et al*., 2001), in what has been termed a 'regime shift'.

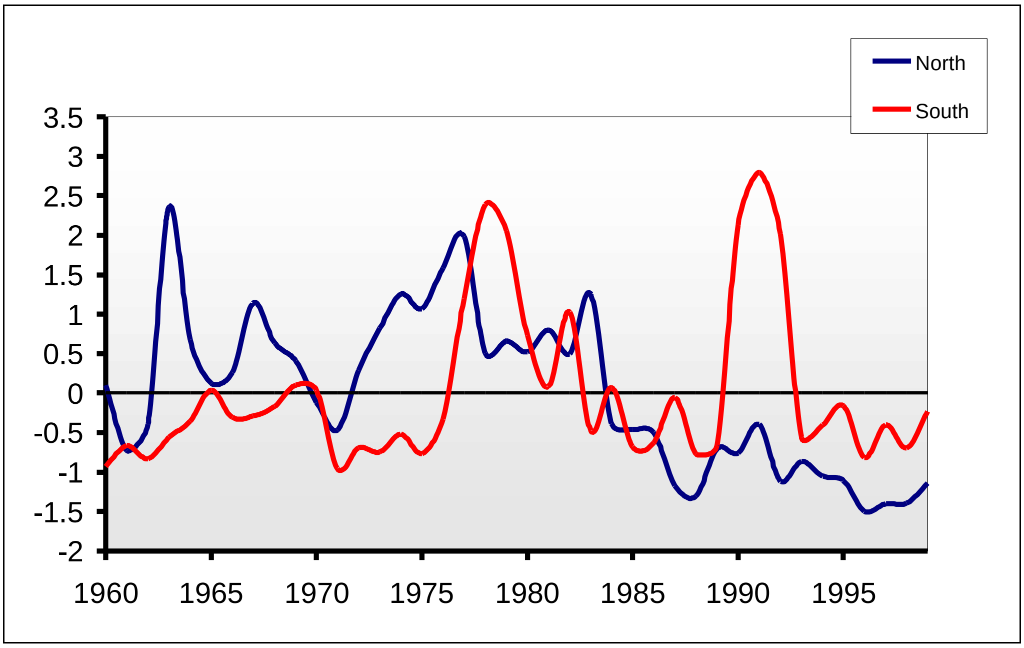

Figure 10. ***Graph showing standardised abundance of euphausiids (from the CPR survey). Red line indicates southern North Sea; blue line indicates northern North Sea.***

9.6 As aforementioned, euphausiid are not speciated routinely within the CPR survey, but there are a number of well-researched species. Of particular importance is *Meganyctiphanes norvegica*, a large krill that has a wide distribution and tolerance to climatic conditions (Lass *et al*., 2001). It is a major consumer of smaller zooplankton, as well as being a primary food source for fish and whales. Another dominant species is the smaller *Thysanoessa inermis*, which was the focus for the Fladen Ground Experiment (FLEX) in 1976. During the experiment the examined population consumed 10mg C m^{-2} d^{-1} in the upper 100m, which represented only 1.5% of the daily primary production (Lindley and Williams, 1980).

10. SENSITIVITY TO DISTURBANCE/CONTAMINATION

10.1 The North Sea supports a high volume of ship traffic (especially tankers), and therefore the risk of an environmental disaster is particularly high. The effect of a spillage of hydrocarbons on higher trophic levels (i.e. fish, sea birds and cetaceans) has been widely investigated (Elmgren *et al*., 1983), but effects at the lower trophic levels are less well understood.

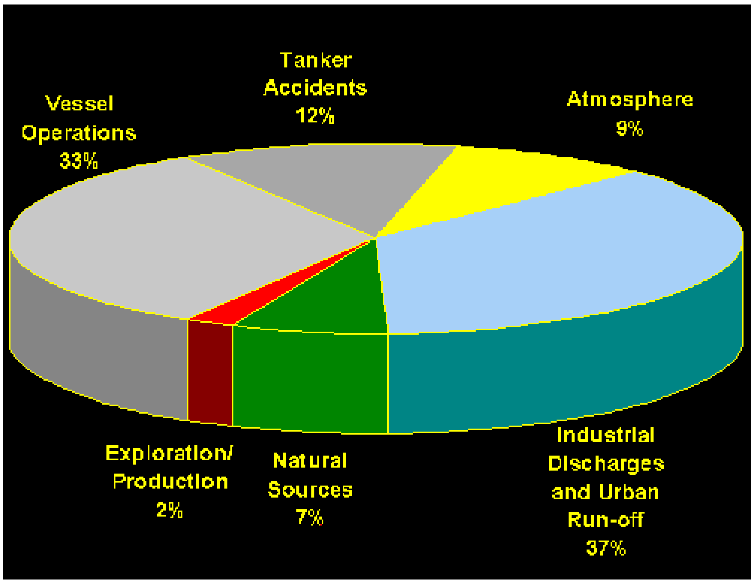

Figure 11. ***Sources of oil pollution, sourced from: www.soton.ac.uk/~engenvir/environment/water/oil.sources.html***

10.2 Figure 11 shows a simplified pie chart detailing possible entry sources of oil into the marine environment. Oil pollution from exploration/production forms a small percentage of the total. Over the last two decades there have been a number of large oil spills from tankers, such as those listed below:

Oil Spilled:

Torrey Canyon (Scilly Isles, 1967)	117,000 tonnes
Amoco Cadiz (Brittany, 1978)	223,000 tonnes
Braer (Shetland Isles, 1993)	84,000 tonnes
Sea Empress (S W Wales, 1996)	71,800 tonnes
Erika (North Biscay, 1999)	26,000 tonnes

Note that none of the above occurred in the North Sea area, but it is useful to compare the effects of these spills on the local environments.

10.3 It is important to examine the effect on the whole plankton community, and not simply the dominant species, which may prove relatively insensitive to hydrocarbon pollution (Batten *et al*., 1998, Elmgren *et al*., 1980). In fact, according to Dale (1987) and Frithsen et al (1985), the addition of oil, in conjunction with high nutrient concentrations, can benefit certain ciliates, such as tintinnids. But such situations are liable to cause a monospecific bloom. Work by Batten et al (1998) on the after effects of the Sea Empress failed to find any significant effects on the plankton of the southern Irish Sea, suggesting that there were no changes to either the phytoplankton or zooplankton communities. But the scope of this work does not take into account ingested pollutants, and the possible accumulation and ‘passing on’ of these up the trophic levels. Mackie *et al.* (1978) and Gajbhiye *et al.* (1995) both found levels of aromatic hydrocarbons in zooplankton species near the site of an oil spill. Research carried out after oil spills has found that benthic species are particularly susceptible to hydrocarbon pollution, due to the trapping of substances in subtidal sediments (Poggiale and Dauvin 2001, Frithsen *et al*., 1985).

10.4 The WWF International Report 1994 (van Beusekom and Diel-Christiansen, 1993) states how zooplankton communities are affected by oil both directly through the hydrocarbon content of their food and indirectly via a change in the ecosystem. Egg production and egg fecundity are lowered, as well as offspring mortality, and there is a strong suggestion that dispersant treated oil has a more pronounced effect. Any possible long-term genetic changes, through the disruption of internal chemical signals, are effects that are hard to recognise, and likely to be subtle.

10.5 Despite the detrimental effects that an oil spillage can cause, in less major spills bacteria can play an important role in removing the oil. Davis et al. (1979) and Gearing et al. (1980) both commented on the increase in bacteria after a spill, and estimated that between 80 and 90% of the oil held in sediments was affected by microbial biodegradation.

11. PHYTODETRITUS AND VERTICAL FLUXES

11.1 Detritus, or non-living particulate organic matter (POM), in the sea is estimated to exceed plankton mass by 10:1 (Verity *et al*., 2000). It is composed of a variety of organic substances, the major constituents being carbonate tests, opaline shells and other particulate organic matter (cellular and amorphous) (Honjo *et al*., 1982). The POM sinks through the vertical column, and the carbon contained within is often utilised for primary production in the sub-surface layers (Richardson *et al*., 2000).

11.2 Faecal pellets constitute a major source of nitrogen removed from the upper layers, and pass through the water column, providing nitrogen flux (Hays *et al*., 1997). Hays also proposed an ‘active’ N-flux, involving zooplankton feeding above the thermocline during the night, and descending below the thermocline in the day, where nitrogen is released via excretion.

11.3 Sediment rates of POM vary according to the dominant hydrodynamic characteristics of an area. In a shallow area of the North Sea (Oyster Grounds, 45m deep), Van Raaphorst et al (1998) noted that the accumulation of sediment over a 14 day study period was 75g m^{-2}. Re - suspension of sediment takes place in such shallow areas of the North Sea as part of the spring / neap tidal cycle and elsewhere in strong wind events.

11.4 Sediment traps can be used to measure an estimate of vertical flux (Bale 1998), though positioning and design of the trap must take into account hydrodynamic forces. Using this method, Billen et al. (1990) estimated POM sedimentation of about 10 – 40 g C / m^2 yr.

11.5 Sedimentation of POM is known to increase during bloom conditions (Riebesell *et al*., 1995, Vanderwall *et al*., 1995), but not due to an increase in phytodetritus. In most cases it is the contribution from grazing species, via faecal pellet production, that causes the increase in POM.

11.6 The recent high increase in levels of phytoplankton colour seen as part of the circa 1988 regime shift coincides with a doubling of the benthic biomass off the Friesian Islands (Reid and Edwards, In press). This correlation suggests that much of the phytoplankton is not being utilized by the zooplankton and an increasing proportion is settling to the benthos in recent years.

12. RESTING STAGES

12.1 Certain species of both phytoplankton and zooplankton groups form resting cysts or eggs that sink to the bottom sediment until they are re-suspended or the right conditions return for them to re-emerge. These resting stages are small, typically between 40 – 80 microns in diameter, at times with appendages, and are preferentially concentrated in silt / mud sediment. They may be concentrated in faecal pellets and are found in high numbers in the floc that is found near the surface of sediments.

12.2 For the zooplankton, the most common egg forming taxa are neritic copepods such as the genera *Acartia* and *Centropages*. In the case of the microplankton a wide range of groups are known to form resting cysts, of which the most common and abundant group is the dinoflagellates.

12.3 Surveys of the distribution of dinoflagellate cysts around the British Isles in the late 1960s showed a change in species assemblages from one part of the coast to another that reflected hydrographic provinces, the positions of fronts and evidence for oceanic influence. These early observations are now being applied in Quaternary stratigraphy (Mudie and Harland, 1996) and are known to reflect the changing climate of Europe. A recent re-examination of dinoflagellates in coastal sediments (Helen McCall, pers.comm.) indicates that the assemblages of the late 1990s are different to those found 30 years earlier.

12.4 Unpublished work (Reid, unpublished) off Plymouth (near the Eddystone lighthouse) based on 12 months of bi-weekly sediment traps has shown that dinoflagellate cysts show a seasonal succession in their occurrence in the water column. This may be reflecting the succession of motile species in the plankton, but may also represent differing timing triggers of encystment in species.

12.5 Some of the most toxic dinoflagellates, causing for example PSP, form large numbers of resting cysts. They can easily be transported in fine bottom sediments at the bottom of ballast water tanks. tanks. Tropical species may also be carried in this way and could pose an invasive threat.

13. HYDRO-CLIMATIC CHANGES IN THE NORTH SEA

13.1 When considering an area such as the North Sea, it is essential to examine dominant weather systems that could effect the local biota. Of particular interest is the North Atlantic Oscillation (NAO), a large-scale alternation of atmospheric mass with centres near the Icelandic Low and the Azores High (Stein, 2000). The NAO is the dominant, recurrent atmospheric phenomenon in the North Atlantic, and accounts for over one-third of the total variance in sea-level pressure (Dickson and Turrell, 2000). The NAO index is known to alternate between a 'high' state, typified by an intense Iceland Low and strong Azores High, and a 'low' state where these pressure cells are reversed (index shown in Figure 12). The NAO, by driving the weather patterns in the North Atlantic, is known to have an influence on the plankton community (Edwards *et al.,* 2001, Planque and Fromentin, 1996). The NAO has been in a predominately positive state for the last few decades, and there is a suggestion that global warming is in fact 'forcing' the NAO (Paeth and Hense, 1999). It is hypothesised that if the 'greenhouse effect' is to manifest itself, it will do so through existing climate patterns (Morton 1998).

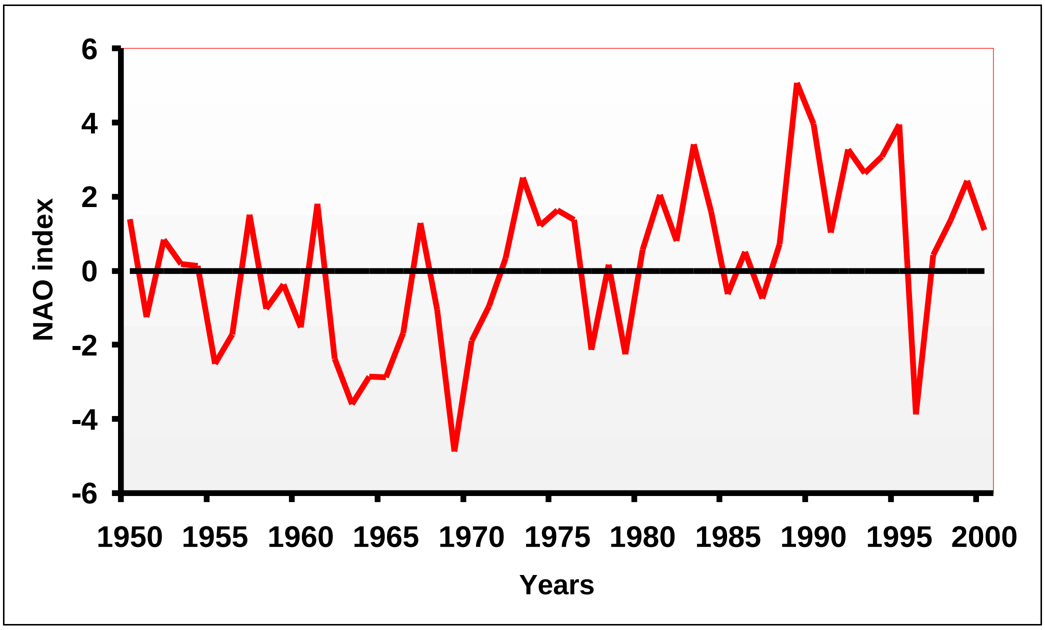

Figure 12. The NAO index

13.2 Changes in the plankton community in the North Sea have been particularly evident over the last few decades. As mentioned in section 6, the population composition of *Calanus* has changed markedly over the last 10 years. There has also been a considerable increase in phytoplankton colour over the last decade in most areas of the North Sea, with particularly high step-wise increases seen after the mid – 1980s (Edwards *et al*., 2001). Over the same time period there has also been an increase in sea surface temperature (SST) in the Northeast Atlantic, linked to the state of the NAO (Fig. 13). In the North Sea, high SSTs are closely correlated to high NAO values and high phytoplankton colour. The general trend over recent years has seen a rise in temperatures, and this has not only manifested itself in the plankton community, there has been an increase in the active growing season of some species of terrestrial plants (Myneni *et al*., 1997), and the earlier laying of eggs by birds in the British Isles (Crick *et al*., 1997). What is not known exactly are the mechanisms involved in connecting these variables, but it is likely to be related to wind mixing and stratification.

13.3 In addition to the general trend in increasing SSTs, there have been episodic inflow events into the North Sea. In these cases water of differing salinity and/or temperature entered the area and changed the local ecosystem to some extent. In the late 1970s a pulse of cold, low salinity water was detected in the North Sea, known as the 'Great Salinity Anomaly'. This body of water was first detected in the East Greenland Sea in 1960s, and reached the British Isles in 1975 (Dickson *et al*., 1988). The effect of this pulse was to delay, and lower the primary production of the spring bloom. Conversely, in the late 1980s and then again in the late 1990s warm, more saline oceanic water entered the North Sea, and its presence was detected by 'oceanic indicator species' recorded in the CPR survey (such as *Doliolum nationalis, Rhincalanus nasutus, Dadayiella ganymedes* and *Zoothamnium pelagicum*).

13.4 Recent research has suggested that inflow into the North Sea is becoming more persistent, rather than episodic. These events are thought to have an effect throughout all trophic levels, causing a 'regime' shift (Reid *et al*., 2001). This is notable in the phytoplankton community, with diatoms decreasing in abundance over the last decade, and dinoflagellates becoming more abundant. This could have important ramifications, as many dinoflagellate (and flagellate) species are noxious to other organisms.

13.5 It is therefore apparent that hydro-climatic events are important in altering the ecosystem of the North Sea. Current research would seem to suggest that these events have a greater impact on the biota of the North Sea than the anthropogenic impact of eutrophication. This must be taken into account when looking at the potential effect of pollutants, as the baseline plankton community has not been to be stable over the last few decades due to changing hydroclimatic forcing.

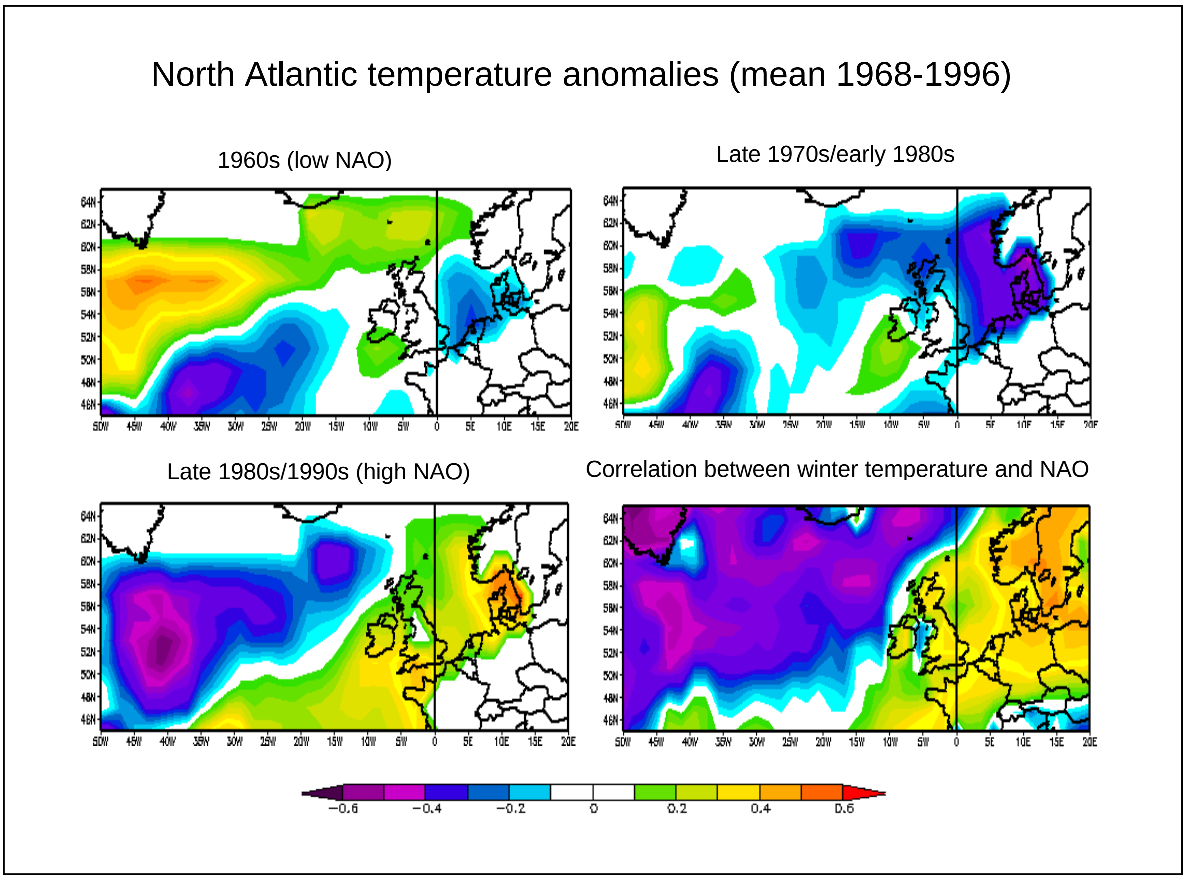

Figure 13: ***Reconstructed Reynolds Sea Surface Temperature anomalies (2-degree gridded data) for the North Atlantic. Anomalies are deviations from the long-term mean temperature in the North Atlantic from 1968-1996. Four plots have been constructed showing the SST anomalies in the 1960s (low NAO index), late 1970s/early 1980s, late 1980s/early 1990s (high NAO index) and the correlation between SST and the NAO index. Note when the NAO index is high Western Europe has positive temperature anomalies and when the NAO index is low Western Europe has negative temperature anomalies. The opposite response is seen in the northern and western North Atlantic. Reconstructed Reynolds SST data provided by the National Oceanographic and Atmospheric Administration, Climate Diagnostics Centre, Colorado, USA. From Edwards (2000) PhD University of Plymouth.***

14. BALLAST WATER AND INVASIVE SPECIES

14.1 Over the last few decades ballast water discharges have increased throughout the world in most of the major ports. The discharge volumes of ballast water can be considerable, and the probability of the successful establishment of self-sustaining populations of exotic species is expected to increase with greater volumes of ballast water and reduced ship transit times (Rosenthal *et al*., 1998). Ships, with their large volumes of ballast water, have been recognised as a major vector for the introduction of non-indigenous and harmful organisms. Ostenfeld (1908), who noticed the large diatom *Odontella sinensis* in the North Sea, a species previously known from the Pacific Ocean, initially suggested the idea of invasive species. Since then a number of planktonic organisms have been identified in the North Sea and Baltic Sea (see Figure 15), comprehensive lists of which can be found in Nehring (1998), Elbrachter (1999) and Reisse *et al*. (1999).

14.2 Such species can have a detrimental effect on an ecosystem, but exact information is difficult to obtain, and to quantify. Past records have shown that such invasions can take place, and can occur rapidly under suitable conditions. Edwards *et al.* (2001) examined the case history of the non-indigenous diatom *Coscinodiscus wailesii,* suspected of being introduced via ballast water. The organism was initially identified in the English Channel in 1977, and has spread successfully throughout European shelf seas (as far north as Trondheim) to become an established, and significant, member of the planktonic community (Figure 14). This species had an initial detrimental effect on fisheries (Boalch and Harbour, 1977), because although being non-toxic, it produces copious amounts of mucilage during bloom conditions that can clog fishing gear.

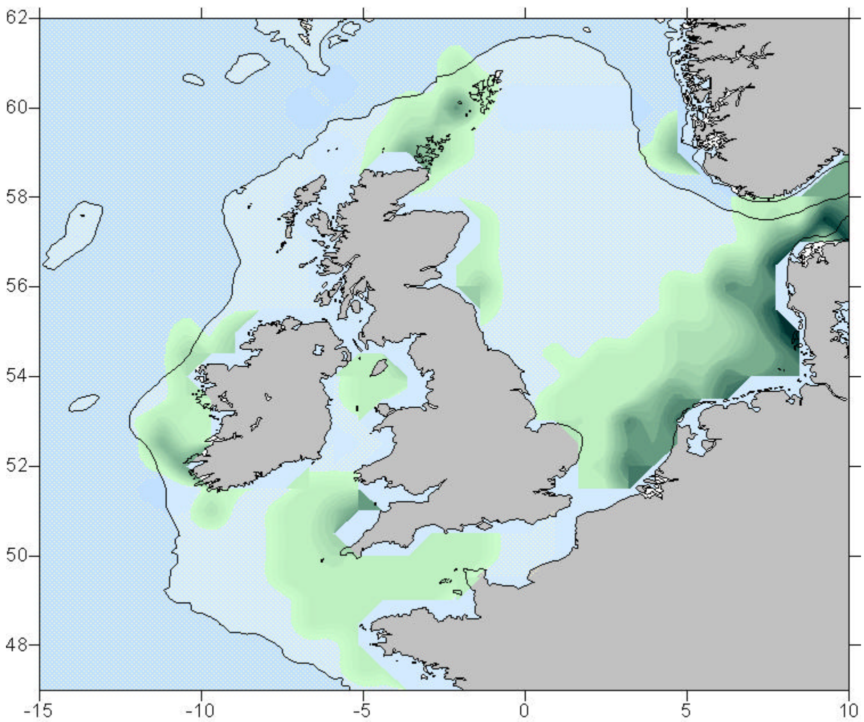

Figure 14. Geostatistical estimates of the mean log abundance of C. wailesii in the northeast Atlantic between 1985-1995 (Edwards et al., 2001).

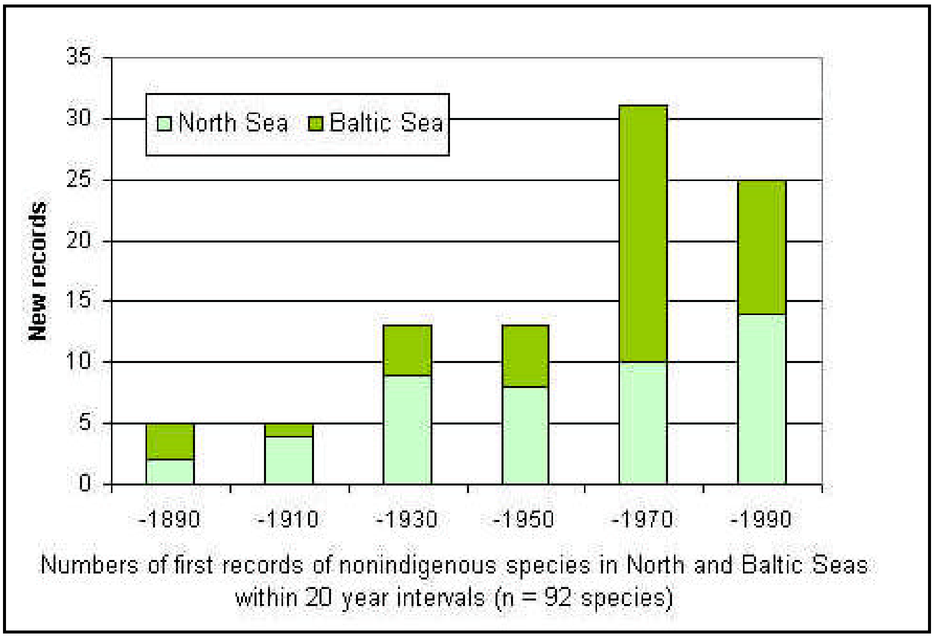

Figure 15. Alien species recorded in the North Sea and Baltic since 1890. Sourced from http://members.aol.com/sgollasch/sgollasch/index.htm#Exotics in North and Baltic Seas.

14.3 Zooplankton invasion via ballast water is not as well documented as that of phytoplankton. A number of species have been recorded in the North Sea for the first time in the last few years (the cladoceran *Penilia avirostris* and the stomatopod *Meisoquilla desmaresti* (Johns, unpublished)). But these species are most probably responding to a biogeographic change due to a variation in the hydro-climatic conditions (i.e. increased SSTs). But, in the case of *Penilia*, resting eggs may have 'seeded' the North Sea from ballast water, and responded to favourable conditions (in 1999 the species was recorded for the first time, in very large numbers).

14.4 There is a growing concern considering the risk of alien species, and the importance of protecting native bio-diversity. Recent publications (Sutherland *et al*., 2001, Wonham *et al*., 2001) address this topic, the former advocating the use of ultraviolet radiation, followed by a period of darkness to prevent photorepair. The latter report states that over 50% of taxa and 98% of organisms did not survive a trans-Atlantic crossing, and this mortality was further enhanced by a mid-ocean exchange (the most common form of preventing invasion). The International Maritime Organisation (IMO) has suggested voluntary guidelines for the control and management of ships' ballast water in Agenda 21 at the United Nations Conference on Environment and Development (UNCED) in 1992. This was adopted in Resolution A.868 (20) Agenda item 11, in 1997, further details of which can be found at the website http://globallast.imo.org. Furthermore, the United Nations Development Program plans to execute a project by IMO (under GEF International Waters portfolio), over $10 million, that will run from 2000 to 2003 to address the following points:

- assist developing countries to reduce the transfer of harmful organisms from ships' ballast water.
- increase adherence by these countries to the current IMO voluntary guidelines on ballast water management,

- assist these countries to prepare for the implementation of the IMO mandatory regime when it comes into force.

See also ICES Code of Practice on the Introduction and Transfer of Marine Organisms (1994).

15. CONCLUSIONS

15.1 There have been recent biogeographical changes in the plankton community of the North Sea that are irrefutable. Over the last decade sea surface temperatures have risen, inflow events of oceanic water have become more common, and the occurrence of warm temperate species has increased in the North Sea. In contrast, the occurrence of cold – boreal species has declined. The recent trend of rising SSTs in the North Sea, due in part to the protracted positive phase of the NAO, could be linked to a global scale rise in temperatures, due to global warming.

15.2 Anthropogenic impacts on the marine environment are hard to distinguish from the background noise of hydro-climatic variations. Even with small-scale events, such as petrochemical spillages, it is difficult to quantify the effects. The visibility of oil after a spill provokes an initial reaction that could be unnecessary, as it appears that microbial degradation of oil occurs very quickly, and the addition of chemical cleaning agents appears to be more harmful to marine organisms.

15.3 Invasion by non-indigenous plankton species via ballast water has occurred a number of times in the 20th Century. The increase in exploitation of North Sea oil reserves could mean an increase in shipping traffic, with a potential increase in ‘alien’ species invasions. This, combined with the aforementioned rise in SST, could lead to a substantial change in the plankton community, with further effects on higher trophic levels. Legislation to control ballast water changes in coastal waters is currently underway, but the addition of further control methods (such as ultraviolet irradiation) would be beneficial. As yet, the impact of non-indigenous species in the North Sea has been relatively benign, but it must be remembered that the accidental introduction of the zebra mussel into American lakes costs the local economies $500 million annually.

15.4 Following on from invasive species, one must consider the implication of resting cysts. Although many native species encyst to avoid unfavourable conditions, it is the risk of non – indigenous plankton being transported into the North Sea that is important. Any aspect of marine work in the North Sea that could provide a vector for cyst introduction from foreign waters (such as ballast waters with sediments) needs to be closely monitored, with a system in place to prevent invasion.

15.5 Picoplankton play an important role in marine ecosystem dynamics, but one that is under-researched due to the difficulties involved in study. Estimates of the contribution of picoplankton towards the total plankton biomass are between 15 and 33%, and this represents a sizeable portion of the total primary production. It is an area that clearly requires further research.

15.6 Harmful algal blooms (HAB) occur frequently in the North Sea area, resulting in Paralytic Shellfish Poisoning, Amnesic Shellfish Poisoning, Diarrhetic Shellfish Poisoning in humans, and animal and plant mortalities. These events are caused primarily by a monospecific bloom, often involving dinoflagellate species. Anthropogenic impacts can influence the frequency and extent of HABs, through the addition of carbon / nitrogen compounds (primarily from urban run – off).

15.7 The recent rise in phytoplankton colour in the CPR survey in the North Sea has coincided with a doubling of the benthic biomass off the Friesian Islands. It has been suggested that the rise in phytoplankton colour (and therefore increase in phytoplankton biomass) has resulted in an increase in phytodetritus reaching the benthos. Further studies on vertical fluxes would be beneficial in the North Sea, to determine its role as a sink for introduced substances.

15.8 Plankton communities studied in the North Sea have changed markedly over the past decade or more (regime shift of 1988). It is apparent that hydro – climatic events have so far proved more of a large-scale effect on the ecosystem than anthropogenic factors. It would not be possible to categorically state which is the most important, but it is likely that the two will combine to form a greater influence (i.e. increased SST with eutrophication will have a greater impact).

15.9 Research into higher trophic levels, particularly marine mammals, has showed a downward trend in abundance. The work by Thompson *et al*. (2001) concerned marine pinnipeds in the North Sea, and found that in 1998 shore – based counts of adults and pups were only 16 – 36% of counts made between 1984 and 1987. Herein lies the problem with many similar studies, in that comparisons are made over very short time scales, which could prove inaccurate. Furthermore, linking species decline with anthropogenic impact is tenuous. Wolff's (2000) research into the loss of vertebrate fauna during the past 2000 years from the south – eastern North Sea suggests the disappearance of 31 species of marine mammals, marine and coastal birds and marine and anadromous fish. Approximately two thirds of these disappearances have been due to over fishing, with the remaining number due to destruction and / or pollution of the respective environments. One would suggest that the changes in the driving hydro – climatic forces will prove to be equally as important as anthropogenic effects.

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