Plankton monitoring off the northeast coast of Scotland in 1997 and 1998
**Summary**

Sampling for hydrographic parameters, nutrient concentrations and abundances of phytoplankton and zooplankton species has been carried out on a weekly basis off Stonehaven on the northeast coast of Scotland since the beginning of 1997. The objective of the programme is to establish a monitoring base for assessing the status of the Scottish coastal waters ecosystem, and the responses to climate change. Results from the first two years of sampling are presented in this report.

Comparison of the results with archive regional data on temperature, salinity and nutrients and phytoplankton biomass, indicates that the site off Stonehaven provides a reasonable index of the state of the coastal waters. The biological data from 1997 and 1998 document the seasonal succession of plankton species and their abundances. The data indicate that conditions in 1998 supported higher stocks of plankton, and probably resulted in higher production than 1997. Particular species showed different responses and some of these can be related to oceanographic events, the major one being an influx of high salinity oceanic water in autumn 1997, which did not occur in 1998.
**Introduction**

Plankton are a sensitive indicator of the state of the marine ecosystem. The abundances of different categories of plankton, and the species composition of the categories, dictate the productivity of the ecosystem, and the amount of food that becomes available to support fish stocks. This report gives results from the first 2 years of a programme to monitor the North Sea plankton off Stonehaven on the northeast coast of Scotland. The purpose of the monitoring is to provide local information for Scottish waters on year-to-year variations in the state of the planktonic components of the ecosystem, and the timing of blooms. In time, the data will provide information on long term trends which may be related to climate change and/or human activities.
What is the ecosystem?

The ecosystem is a self-sustaining community of inter-dependent animals and plants and the nonliving resources upon which the community depends for survival. The essential constituents are:

- **Primary producers** - the plants and algae which utilise sunlight and inorganic nutrients to grow;
- **Secondary producers** - animals which feed on the plants and on other animals;
- **Microbes** - which decompose the droppings and corpses of animals and the remains of plants, releasing inorganic nutrients back into the environment.

The geographic boundaries of the ecosystem should be defined in terms of the distributions of the constituent species, though usually these will correspond to some distinctive physical boundaries. Ecosystem boundaries are often clear to see in terrestrial situations where the terrain and rainfall dictates vegetation types. However, ecosystems are less easily delineated in the oceans where water currents are continually transporting and mixing the various components of the system. Marine ecosystems tend to be defined in terms physical oceanographic characteristics as well as species composition. The North Sea is usually considered as a single ecosystem for fisheries purposes, though there are clear regional differences in terms of physical oceanographic features.

The marine ecosystem is often regarded as being two parts — the pelagic ecosystem and the benthic ecosystem (Fig. 1). The pelagic system is composed of animals and plants that live in the water column. These cover a very wide range of sizes, from microbes of 0.001 mm or less to whales many metres long. The smaller plants and animals, which have little or no sustained swimming ability and are carried by the water currents, are referred to as phytoplankton and zooplankton respectively. The benthic ecosystem includes all the plants and animals living on and in the seabed. In fact, the pelagic and benthic systems are closely linked, since the organic material upon which the benthic system depends is largely derived from the pelagic system. In addition, many benthic species produce young stages which live briefly in the water column, where many are eaten by the plankton.

Trophic relationships in the ecosystem

In describing the feeding links between the constituents of the ecosystem, species are often grouped into trophic levels. The lowest trophic level is the algae which capture energy from sunlight, and the highest is the birds and mammals which feed at the top of the food web. Species at intermediate trophic levels feed on lower levels (usually smaller species) and are themselves prey for higher levels (usually larger species). The efficiency with which energy or carbon is transferred from one trophic level to the next is referred to as the trophic efficiency and, as a rule of thumb, this is around 10% per trophic level. Thus, it takes around 1000 kg of phytoplankton production to support 1 kg of fish production in an ecosystem where fish occupy the third trophic level.

What are the main characteristics of the North Sea pelagic ecosystem?

The North Sea is similar to many other temperate continental shelf ecosystems. Seasonal production of algae dominates the development of the food web, and the herbivores are adapted to capitalise on this seasonal pulse of food. Away from the coasts, in water deeper than 10-20m, the microalgae
(phytoplankton) account for all of the primary production. The zooplankton are made up of a diverse mixture of herbivores, omnivores and carnivores, which in turn support stocks of pelagic fish (herring, sprat, sandeels), bottom living demersal fish (cod, haddock, flatfish), jellyfish, birds and mammals (seals and cetaceans). Our knowledge of the species which make up each trophic level is scant for the smallest organisms and increases with size. There are probably very many different species of bacteria, for example in the North Sea, but we are only able to resolve a few types with the instruments we have available today. On the other hand, all of the fish species in the North Sea have probably now been described.

**The phytoplankton:**

There are four main types of phytoplankton:

- **picoalgae** - very small (<0.002 mm) single cells, essentially photosynthetic bacteria;

- **flagellates** - small (<0.01 mm) single cells with limited swimming abilities;

- **diatoms** - 0.01-1 mm sized cells all of which have a hard silica outer casing (frustule) which contains the living plant material. The cells absorb the silica from the seawater. Some diatoms form chains of cells up to 1 cm in length;
dinoflagellates - 0.01-0.2 mm sized cells with limited swimming abilities. Many have rigid plates around the cell composed of cellulose material. Most dinoflagellates can consume other small plankton as well as being photosynthetic, so they really behave as both phytoplankton and zooplankton combined.

Diatoms dominate the North Sea plankton in spring, whilst dinoflagellates and flagellates dominate in the summer. Picoalgae are thought to be less numerous in shelf sea waters than in the open ocean. Identification of diatoms and dinoflagellates is routinely carried out by microscopy, but relatively little is known about the picoalgae.

The zooplankton:
Like the phytoplankton, there is a wide range of sizes of animals in the zooplankton:

microzooplankton - small (<0.05 mm) unicellular organisms having a variety of forms, which feed by capturing other microzooplankton or phytoplankton cells and absorbing their cell contents;

mesozooplankton - (0.05-5 mm) metazoan (multicellular) organisms with advanced swimming and feeding abilities, able to stalk and capture other plankton animals and filter phytoplankton out of the water. Copepods, which are planktonic crustaceans, constitute a large fraction of the mesozooplankton;

macrozooplankton - (>5 mm) mostly carnivorous crustaceans which feed on the mesozooplankton;

gelatinous zooplankton - jellyfish which range in size from <1cm to 100cm diameter.

In the open ocean, microzooplankton are a major constituent of the zooplankton, especially in summer. Microzooplankton are certainly important in the North Sea, but most of the primary production, which is due mainly to diatoms on the spring, is consumed by copepods (mesozooplankton). Euphausiids (krill) are the main representatives of the macrozooplankton.

The planktivorous (plankton feeding) fish:
Fish which feed exclusively on plankton in the North Sea include herring, sandeels, Norway pout, sprat, pearl sides (Maurolicus) and gobies. Plankton is also an important component of the diet of some other species which are not exclusively planktivorous, such as mackerel, scad cod and whiting. In addition, all fish in the North Sea produce larvae which spend periods of between two weeks and several months as members of the plankton where they feed mainly on copepods. The adult migrations of some species of fish (herring and mackerel) may be adapted to the seasonal production patterns of zooplankton.

Seasons in the sea

Just as on the land, where seasonal changes in temperature and weather conditions are reflected in the vegetation and animal life, so in the sea there are seasonal changes in the plankton. Two main factors influence the production by phytoplankton in shelf waters. The first is sunlight, and the second is vertical mixing in the water column due to winds and tides. Vertical mixing can carry plankton cells to depths where the amount of light penetrating into the seawater is too little to support their growth. As mixing decreases, so the amount of time that an individual cell spends near the surface increases, thereby enabling growth. Mixing is generated by two main processes: the wind blowing across the surface, and tidal currents flowing over the seabed. In some areas, tidal currents are strong enough to keep the water completely mixed all year round, but where tides are weaker - usually in water deeper than 50-60m - then the water column becomes stratified in summer. This means that two layers develop, with the upper layer being warmer than the deeper one. These conditions greatly favour the growth of phytoplankton since the vertical mixing due to winds is then restricted to the thickness of the upper layer, which in the North Sea is usually around
Thus, each spring in the North Sea there is an outburst or bloom of phytoplankton triggered by increased sunlight, seasonal reductions in wind strength and warming of the surface waters.

The spring growth of phytoplankton in the sea has only a finite duration because it is limited by the amount of inorganic nutrient in the water upon which all algae rely. The concentrations of nitrate, phosphate and silicate dissolved in the seawater decrease as the phytoplankton increase in numbers, until one of these nutrients becomes so depleted that the algae can no longer obtain enough to support further growth. Then the bloom becomes starved of nutrients, the cells begin to decay and meanwhile the zooplankton populations develop through eating them. In the North Sea, diatoms usually dominate the spring bloom, and silicate and nitrate are the two nutrients which become limiting. Once the silicate is used up, the diatoms are unable to produce new silica frustules and they rapidly decline in abundance. The silica which has been incorporated into the diatom frustules takes several weeks to dissolve back into the water, so diatoms do not usually reappear in great numbers until the autumn. However, other types of algae do not require silica, so the spring diatom bloom is usually followed in the summer by a bloom of picoalgae, flagellates and dinoflagellates, supported by nitrogen released by bacterial degradation of the debris from the diatom bloom. In general, the algae use up nutrients as fast as they are being recycled throughout the summer, so nutrient concentrations in the water remain low. However, in the autumn the growth of phytoplankton slows down as sunlight decreases and storminess increases, so nutrient concentrations can increase again to their winter levels.

The phytoplankton are all unicellular organisms which grow by dividing into two. Under favourable conditions a cell can divide around once each day, and hence their numbers can increase very rapidly. Some microzooplankton also grow in this way and their numbers can respond very rapidly to the spring phytoplankton bloom. However the meso- and macrozooplankton are metazoans and have much longer and more complex life cycles involving generation times of between two and 10 weeks depending on the species. These animals have a variety of strategies for surviving through the winter months when phytoplankton are scarce in the water. Some herbivores produce resting eggs in the autumn which sink to the seabed and remain there until the following spring, when they hatch. Immature stages of other species go into a hibernation state in the autumn and can survive through the winter with little or no need to feed. Many omnivores survive through the winter by eating microzooplankton and detritus, reverting to phytoplankton food in the spring. In general, the abundance of herbivores and omnivores is highest in summer following on from the spring phytoplankton bloom, whilst the abundance of carnivores is highest in the autumn and decreases during the winter due to predation by fish.

Causes of long term change in the ecosystem

In addition to the strong seasonal changes in the North Sea ecosystem, other slower changes are taking place over periods of years. These are related to human activities such as fishing and runoff of nutrients from the land, and to climate changes. It is very difficult to predict how these factors affect the ecosystem because the interactions between all the species are very complicated. However, we do expect that an action which directly affects one component of the system, such as fish for example, will have repercussions elsewhere in the system. For example, we do not know what the North Sea ecosystem was like several hundred years ago before commercial large scale fishing operations began, but it might have contained fewer jellyfish or different zooplankton compared to the system we see today because a very different proportion of the resources in the system were consumed by fish.

Climatic factors probably exert the biggest effects on the ecosystem. Individual species have an optimum temperature range for survival. Since mean temperatures decrease with latitude, each species will have a latitudinal range that it can occupy. The North Sea is located at the southern (warm) limit of the range for some species, at the optimum for others, and at the northern (cold) limit for still others. Thus, any warming or cooling trend above and beyond the seasonal fluctuations in temperature will naturally lead to subtle changes in species composition. Climate can also affect the ecosystem in other ways. The incidence and
seasonal timing of storms has changed significantly over the last 40 years, and this will have an impact on
the pattern of vertical mixing, and hence we would expect to see changes in the timing of the spring
phytoplankton bloom. Changes in winds and freshwater runoff have also had effects on the strength and
patterns of water currents and therefore on the way in which plankton and nutrients are transported across
the continental shelf. Given the interdependent nature of all the components of the ecosystem we can
expect such changes to propagate through the food web and impact even the highest trophic levels, but
the nature of the impact is very hard to predict at present.

**Why do we need to monitor the state of the ecosystem?**

Changes in the marine ecosystem are important because many of our economic activities depend on the
continuation of the current ecological situation. An extreme example of the consequences of major struc-
tural change in a marine ecosystem is the El Niño phenomena in the eastern Pacific, where large scale
alterations in the climate periodically lead to massive changes in the marine pelagic ecosystem due to
cessation of the supply of nutrients to the surface waters from deep in the Pacific. The consequences of El
Niño are collapse of fisheries for anchovies off Peru, death of coral reefs around the Galapagos Islands, and
breeding failures of seabird colonies. Closer to home, and on a less dramatic scale, there is a periodic
phenomenon in the English Channel in which the pelagic ecosystem flips between a cold water system
resembling the North Sea and dominated by a high abundance of mesozooplankton, herring and demersal
fish, and a warm water system resembling that in the Bay of Biscay and dominated by low plankton abun-
dance and high abundance of sardines. This phenomenon, which is known as the Russel Cycle, has been
related to Atlantic Ocean scale changes in atmospheric climate, in particular to the North Atlantic Oscilla-
tion (NAO), which is the Atlantic equivalent of the El Niño Southern Oscillation (ENSO) which has such a
dramatic effect on the Pacific ecosystem.

Structural changes in the North Sea ecosystem have been less obvious, at least in the last 60 years, but
have certainly occurred. Most importantly, the demersal fisheries of the North Sea during the 1960s were
apparently able to sustain significantly higher rates of exploitation that in the 1980s or 90s. Though there
may be several reasons for this, a number of factors point towards a structural change in the ecosystem
from a high to a low zooplankton abundance system. In order to take account of such phenomena in
fisheries management, we need adequate monitoring of the ecosystem, and a better understanding of how
the system functions.

**Existing monitoring programmes in the North Sea**

There are only a few places around the North Sea where regular sampling of the marine ecosystem is carried
out. There is a long-running sampling programme at the island of Helgoland in the German Bight of the
Southern North Sea, and similarly at the Dove Marine Laboratory on the northeast coast of England. Both of
these sites have been collecting data for around 30 years. In the open North Sea, zooplankton species
abundances have been monitored since 1948 by the Continuous Plankton Recorder (CPR) Surveys, now
based at the Sir Alister Hardy Foundation for Ocean Science in Plymouth, and fish species abundances have
been monitored at least annually since 1970 as part of an international effort coordinated by the Interna-
tional Council for the Exploration of the Sea (ICES) in Denmark. In this report, we present the first two
years of data collected by the FRS plankton and hydrographic monitoring programme off Stonehaven on the
northeast coast of Scotland.
Overview of changes in zooplankton sampled by the CPR

The CPR surveys collect monthly samples of zooplankton with a specially designed net which is towed behind cargo vessels and ferries plying regular routes in the North Sea and North Atlantic. Each sample contains the catch in a 10 mile section of the passage. There are a number of limitations. In particular, the samples are collected only from 7m and so may not be fully representative of the whole water column. The mesh size of the netting used to filter the water is coarse (350 microns) so that many of the small mesozooplankton and few of the microzooplankton or phytoplankton are quantitatively sampled, although an index of the overall amount of phytoplankton is obtained from the green staining of the filtering net which occurs during the sampling. Finally, no hydrographic or chemical data are available to complement the zooplankton collections. Nevertheless, the survey data give unique information on the seasonal and long term changes in the abundances of the species which are caught.

Briefly, the CPR data from the North Sea show a trend of increasing phytoplankton abundance since 1960, especially in the northern North Sea, although the index used to estimate phytoplankton may not detect some categories of algae (Fig. 2). On the other hand, copepods which are the major component of the zooplankton, have decreased in the northern and central North Sea (Fig. 3). In the southern North Sea there appears to be some direct correlation between the phytoplankton and copepods, but not in the northern North Sea.

Figure 2. Time series of phytoplankton abundance as measured by the colour index recorded by the Continuous Plankton Recorder, for the northern, central and southern North Sea. Data provided by the Sir Alister Hardy Foundation for Ocean Science, Plymouth, UK.
About the FRS monitoring programme

Rationale for the choice of sampling site

The key considerations in setting up the monitoring programme were that

- sampling must be maintained according to a regular schedule with a frequency adequate to resolve the important fluctuations in the components of the system;
- to facilitate frequent and regular sampling, the site should be accessible from the Marine Laboratory within 1-2 hours;
- the sampling site should be sufficiently far offshore to be outside the main influence of the freshwater plumes from the Rivers Dee and Don, and other smaller rivers flowing into the sea along the coast;
- the site should be representative of the wider region along the northeast coast.

A weekly sampling schedule was adopted, partly for practical reasons, and partly advised by knowledge of the time scales of hydrographic and biological variations at other sites.

The chosen sampling site is at 56° 57.80' N 002° 06.20' W, 5km offshore from Stonehaven, which is a fishing harbour 28km to the south of Aberdeen (Fig. 4). The water depth at the site is 46m. Sampling is carried out from an 8m launch (RV Shuna) fitted with a winch and davit system, and based at Stonehaven (Fig. 5).
Figure 4. a) Map of Scotland showing the location of Stonehaven in relation to other features of the North Sea coastline. The box shown at Stonehaven is enlarged in Fig. 4b below.

b) Chart showing the seabed topography off Stonehaven and the location of the sampling site.
Sampling methods

Temperature measurements, and water samples for salinity and inorganic nutrient analysis, are collected using reversing thermometers and a Knudsen water bottle set just below the surface (12m depth) and 1m above the seabed (46m depth). An additional water sample for analysis of chlorophyll concentration (the photosynthetic pigments contained in phytoplankton) is collected from the sea surface.

Phytoplankton are collected with a hose having a non-return valve fitted at the outboard end. The end of the hose is lowered down through the water column to 45m depth, and in so doing free floods with water. The inboard end of the hose is then sealed with a tap and the hose recovered. The integrated sample from the water column is then drained off into a bucket and subsampled into a plastic jar containing iodine solution (Lugols iodine) as preservative.

Zooplankton are collected by a vertical haul with a pair of conical nets of different mesh sizes, referred to as a 'bongo net'. The nets are lowered to the seabed and then hauled to the surface collecting plankton on the way. One net has 0.2mm mesh, and the other 0.095mm mesh to capture different size categories of plankton. The samples are preserved in formaldehyde solution for return to the Laboratory.

Back in the Laboratory, the water sample for chlorophyll analysis is filtered through a glass fibre filter paper and frozen. The pigments are later analysed by extraction into 90% acetone and quantified by fluorescence.

Phytoplankton species are analysed by allowing all of the cells in 10 or 50ml of the preserved sample to settle onto a microscope slide in a special chamber, and then identifying the first 400 cells encountered during a scan of the slide under a microscope. All diatom and dinoflagellate cells were identified to species where possible. Flagellates and ciliate microzooplankton were counted but cannot be identified further by light microscopy.

Zooplankton species in the plankton samples are identified under a microscope and the numbers in the sample converted to numbers below 1m² of sea surface. A standard portfolio of species was identified on each occasion. Others were grouped into categories.

Nitrate, phosphate, silicate and ammonia concentrations are measured in each of the water samples collected for nutrient analysis, using standard wet chemical analysis techniques.

The salinity of the water samples is measured using a salinometer.
Performance of the sampling programme
The target was to collect samples each week throughout the year, which should yield 52 samples. The outcome was 45 samples in 1997 and 49 samples in 1998. Missed sampling weeks were due to weather conditions which prevented the launch from leaving harbour for safety reasons.

Results from the sampling programme

Hydrography
In both 1997 and 1998 the water column at the sampling site remained well mixed throughout the year apart from a 3 week period in August 1997 when warm calm weather conditions allowed slight stratification to develop.

The seasonal minimum temperature occurred in the last week of February/first week of March in both years. Following the warm summer of 1997, the minimum in 1998 was around 1°C higher in than in 1997. The seasonal maximum temperature at 45m depth occurred during the last week of August in both years. Despite the cooler atmospheric conditions in summer 1998, the maximum water temperatures were still 0.5 - 1.0°C higher in 1998 than 1997 (Fig. 6).
Figure 7. Nutrients concentrations during 1997 and 1998. 
a) nitrate, b) phosphate, c) ammonia, d) silicate, and e) the ratio of inorganic nitrogen to phosphorus (DIN/DIP).
Salinity showed a seasonal minimum in May each year of around 34.25 g.kg⁻¹. However, the data showed that during September and October 1997 salinity rose to values of 34.9 - 35.0 g.kg⁻¹, whilst this did not occur in 1998. The results indicate that a flow of water with a high Atlantic Ocean content passed down the Scottish east coast during autumn 1997. This event was not repeated in 1998 (Fig. 6).

**Nutrients**

In both 1997 and 1998, winter nitrate levels were typically between 7 and 11 mM m⁻³ until late March - early April when concentrations in both surface and bottom waters dropped to around 5 mM m⁻³ before falling to below 2 mM m⁻³ by May (Fig. 7). This decrease in spring coincided with the spring bloom of diatoms and also with the increase in chlorophyll concentration in the surface waters (Fig. 8). Nitrate levels remained low (1 - 2 mM m⁻³) until the beginning of September in 1998 and early October in 1997, when concentrations began to increase. By December, nitrate in both surface and bottom waters had increased to between 3 and 5 mM m⁻³. Throughout 1997, there was little difference in nitrate between surface and bottom waters, but there was more variability between surface and bottom in the spring of 1998.

In both years, concentrations of ammonia fluctuated between 0.5 and 1.5 mM m⁻³ for most of the year, but with a pulse of higher concentrations occurred (>3 mM m⁻³) between August and October (Fig. 7). This autumn peak was probably related to the degradation of the summer phytoplankton community and regeneration of nutrients by bacteria. There appeared to be considerable variability between bottom and surface waters in both years. Both the summer concentrations, and the autumn peak of ammonia appeared to be lower in 1998 than in 1997.

Phosphate concentrations were high (0.4 - 0.9 mM m⁻³) until the end of March in each year, after which concentrations in both surface and bottom water declined to between 0.2 and 0.3 mM m⁻³ (Fig. 7). In October 1997, phosphate increased in both surface and bottom waters to around 0.6 mM m⁻³. Phosphate did not appear to be depleted to the same extent as nitrate and silicate during the summer months, and this was more apparent in 1998. In both years there was relatively little variability between surface and bottom waters.

The combined concentrations of ammonia and nitrate represents the total dissolved inorganic nitrogen (DIN) in the water. The ratio of this to the dissolved inorganic phosphate (DIP) is a measure of the potential for nitrogen limitation of the growth of phytoplankton. This ratio was around 15 in winter and declined to around 5 in summer, but was slightly lower (indicating more intense nitrogen limitation) in summer 1998 than in summer 1997 (Fig. 7).

In both 1997 and 1998, silicate concentrations were high (3 - 6 mM m⁻³) until April when depletion of silicate associated with the spring diatom bloom caused levels to decline to around 1 mM m⁻³ (Fig. 7). These low levels persisted through the summer, and in 1998, silicate levels in mid-May were extremely low. In 1997, levels did not begin to increase until September, as silicate from decaying diatoms was released back into the water column. In 1998, summer values were slightly higher and more variable. By December 1997, silicate concentrations had increased to around 3 mM m⁻³. There was relatively little variation in silicate between the surface and bottom waters in either year, apart for a short period during spring in 1998.

**Phytoplankton**

In both years, chlorophyll concentrations were low early in the year (< 1 mg m⁻³) until the onset of the spring bloom of diatoms was observed during April and May (Fig. 8). In 1997, the chlorophyll maximum was > 6 mg m⁻³ on 7 May. The maximum in 1998 was around the same date (11 May) but at a higher concentration (> 9 mg m⁻³). These maximum values coincided with the peak occurrences of diatoms, and the spring depletion of nitrate and silicate. The onset of the spring bloom, defined by the first incidence of chlorophyll concentrations (>1 mg m⁻³) was also around the same time in each year (2 April 1997 and 1 April 1998). In both years, chlorophyll fluctuated during summer months, although to a greater extent during the early summer of 1998. Levels in July and August were similar (<1 mg m⁻³) in both years, and smaller peaks
(2 - 3 mg m⁻³) occurred in autumn. The pattern in autumn was broadly similar in both years, although the autumn peak began and ended 2-3 weeks earlier in 1997 than in 1998. Chlorophyll declined to low levels (<1 mg m⁻³) over winter, due to decreasing daylength and increased mixing of the water column causing the decline of phytoplankton populations.

The seasonal trends in abundance of small flagellates varied between the two years (Fig. 9). In 1997, numbers were relatively low until early spring, then fluctuated throughout the year, with peak abundances (> 4x10⁶ cells l⁻¹) occurring during July and August. The seasonal trends were broadly similar between the dinoflagellates and flagellates. In 1998, flagellate abundance was generally higher than the previous year, with larger fluctuations in numbers occurring over a longer period. Maximum abundance occurred again in July (5.5x10⁶ cells l⁻¹), and high numbers (> 5x10⁶ cells l⁻¹) were observed into October. Whilst the abundance of flagellates generally matched the seasonal trends in dinoflagellates, the relationship was less clear than for 1997.

Diatoms were sparse in the early months of both years, until rapid increases in abundance were observed in April and May (Fig. 9). In 1997, numbers increased to around 2.25x10⁶ cells l⁻¹ late in May, whilst in 1998, the spring diatom bloom appeared slightly earlier, with maximum abundance (> 2.5x10⁶ cells l⁻¹) observed in April. In both years, the timing of the spring diatom blooms coincided with rapid declines in silicate and nitrate from the water column and increases in chlorophyll concentrations. By the end of May 1997, diatom numbers had fallen to less than 0.5x10⁶ cells l⁻¹, probably due to a combination of silicate and nitrate limitation, and grazing. Numbers remained low over the summer of 1997, before a smaller autumnal peak (> 1x10⁶ cells l⁻¹) appeared in September. This autumn peak, composed mainly of neritic species such as *Pseudonitzschia* spp. and *Leptocylindrus danicus*, coincided with gradually increasing silicate and nitrate in the water column. It may also have been linked to the flow of high salinity water that passed down the east coast during the autumn of 1997. In 1998 the seasonal pattern during summer and autumn was slightly different. Diatom numbers showed large fluctuations through May and June, before increasing to around 2x10⁶ cells l⁻¹ at the end of June. The decline in diatom numbers in early June may have been linked to very low silicate concentrations in mid-May. Diatom numbers fluctuated until late August, before declining into September and remaining very low until the end of the year. The autumnal peak in diatom numbers was less pronounced than in 1997, and the high salinity water observed during autumn that year was not present in 1998. In both years, diatom abundance appeared to be closely coupled to seasonal trends in nitrate and silicate concentrations.

The most commonly occurring diatom in both years was *Nitzschia longissima*, closely followed by *Chaetoceros* spp. In 1997, both occurred in ≥ 60% of all samples examined, but in 1998, only in between 40 and 50% of all samples. Pennate diatoms including *Pseudo-nitzschia* spp. and naviculoids were also frequently found in both years. Of the 27 identifiable species/taxonomic groups of diatoms, 78% of them were...
Figure 9. Concentrations of a) flagellates, b) diatoms and c) dinoflagellates at 1m depth during 1997 and 1998.
found more frequently in samples collected during 1997 than 1998. Fifty-nine percent taxa were on average more abundant in 1998 than in 1997. Chaetoceros spp. were the single most abundant diatom in 1998 and Leptocylindrus minimus in 1997. The diatom Skeletonema costatum was present in around 10% of samples in 1998, but absent in 1997 (Fig. 10).

In both years, dinoflagellates were virtually absent until March, and then fluctuated between zero and 20,000 cells l⁻¹ from April until late June (Fig. 9). In 1997, abundance increased into July and peaked in
early August at almost 120,000 cells l⁻¹. This was largely attributable to a bloom of *Ceratium lineatum*, which formed approximately 70% of total dinoflagellate numbers. Abundance slowly declined through September, and fluctuated between zero and approximately 10,000 cells l⁻¹ from early October to the end of the year. There was clear succession of taxa with diatoms dominating during spring, and dinoflagellates being more abundant during summer months. In 1998, seasonal trends in dinoflagellate abundance were quite different. In terms of total abundance, the situation was broadly similar to 1997 until May. During summer however, the maximum abundance was observed earlier but was of much smaller magnitude (approximately 55,000 cells l⁻¹) - there was no evidence of a bloom of *Ceratium lineatum* of similar magnitude to the 1997 event.
Of the 18 species/taxonomic groups of dinoflagellates encountered, only 6% were found more frequently in 1997 than 1998 (Fig. 11). The most commonly occurring dinoflagellates were unidentifiable naked dinoflagellates, found in 24% (1997) and 32% (1998) of all samples. *Ceratium lineatum* which formed a large bloom in 1997 was found in 18% (1997) and 22% (1998) of all samples. *Dinophysis acuta*, thought to be associated with Diarrhetic Shellfish Poison (DSP) was found in 16% of samples in 1998, but not observed in 1997. *Alexandrium* spp., thought to be linked to Paralytic Shellfish Poison (PSP), was found in both years in <4% of samples. 72% of the dinoflagellate species/groups were more abundant in 1997 than 1998. *Ceratium lineatum* was on average the most abundant dinoflagellate in 1997 whilst in 1998, small naked species were more numerous.

In summary, although dinoflagellate species were found much more commonly in 1998, the species were on average less numerous than in 1997. Conversely, diatoms were found more frequently in 1997, but were more numerous in 1998. This may be linked to the prevailing weather conditions in 1998, a particularly wet and stormy year. Any increased mixing in the water column may have led to conditions unfavourable for large populations of dinoflagellates to accumulate. Of particular note was the chain-forming diatom *Skeletonema coastorum*, which was found in just over 10% of samples in 1998 when it was the third most abundant diatom, but was not found at all in 1997. The appearance of this species is usually restricted to a brief period in the spring when it may dominate the phytoplankton, especially in inshore waters to the west of Scotland. We do not yet know whether or not its absence off Stonehaven in 1997 was an unusual event.

**Microzooplankton**

Ciliates were the only category of microzooplankton analysed in the samples, and their abundance followed a similar pattern in both years (Fig. 12). When found, the concentrations of these organisms was similar in 1997 and 1998, but they were found more frequently in 1997.

**Mesozooplankton**

**General Patterns of Species Abundance**

Table 1 and Figure 13 indicates the main species and analysis groups of the mesozooplankton (middlesized, approx. 0.05-5 mm) found in the samples collected with the 0.2 mm mesh net during 1997 and 1998, and their mean incidence over the two years of sampling. Larger species are probably under-sampled because they may avoid the net more easily than small species. Conversely the smallest zooplankton will pass through the net’s meshes.
Table 1. Mesozooplankton groups used in analysis of samples, their constituent species, approximate sizes and mean frequency of occurrence in samples during 1997 and 1998

<table>
<thead>
<tr>
<th>Type</th>
<th>Individual Species</th>
<th>Size mm</th>
<th>Groups identified</th>
<th>% incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Crustacea</td>
<td>Calanus finmarchicus</td>
<td>2.5</td>
<td>Calanus finmarchicus</td>
<td>20.2</td>
</tr>
<tr>
<td>Copepoda</td>
<td>Calanus helgolandicus</td>
<td>2.5</td>
<td>Calanus helgolandicus</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>Calanus C I – IV</td>
<td>0.5 – 2.5</td>
<td>Calanus juveniles</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Metridia lucens</td>
<td>0.4 – 1.1</td>
<td>Metridia lucens</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>Oithona similis</td>
<td>0.2 – 0.8</td>
<td>Oithona similis</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>Candacia armata</td>
<td>0.4 – 1.9</td>
<td>Other Copepod Species*</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Pseudocalanus elongatus</td>
<td>0.35 – 0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paracalanus parvus</td>
<td>0.25 – 0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temora longicornis</td>
<td>0.35 – 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acartia clausi</td>
<td>0.35 – 0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centropages hamatus</td>
<td>0.25 – 1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centropages typicus</td>
<td>0.3 – 1.4</td>
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<td></td>
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<tr>
<td></td>
<td>Anomalocera pattersoni</td>
<td>0.5 – 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pareuchaeta norvegica</td>
<td>0.5 – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harpacticoida</td>
<td>0.25 – 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Crustacea</td>
<td>Evadne nordmanni</td>
<td>0.2 – 1.0</td>
<td>Cladocera</td>
<td>8.3</td>
</tr>
<tr>
<td>Cladocera</td>
<td>Podon sp.</td>
<td>0.2 – 1.2</td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Crustacea</td>
<td>Amphipoda (benthic)</td>
<td>0.5 – 5.0</td>
<td>Large Crustacea</td>
<td>67.9</td>
</tr>
<tr>
<td></td>
<td>Parathemisto abyssorum</td>
<td>0.5 – 5.0</td>
<td>Parathemisto spp</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Euphausidacea</td>
<td>3.0 – 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thysanoessa sp</td>
<td>3.0 – 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Euphausid furcilia</td>
<td>0.5 – 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mysidacea</td>
<td>2.0 – 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decapod larvae</td>
<td>0.5 – 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larvae of benthic</td>
<td>Gastropod larvae</td>
<td>0.1 – 1.0</td>
<td>Mollusc larvae</td>
<td>55.5</td>
</tr>
<tr>
<td>(bottom living)</td>
<td>Bivalve larvae</td>
<td>0.1 – 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>invertebrates</td>
<td>Polychaete larvae</td>
<td>0.2 – 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cyphonautae larvae</td>
<td>0.2 – 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Echinoderm larvae</td>
<td>0.2 – 0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cirripedia nauplii</td>
<td>0.2 – 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cirripedia cypris</td>
<td>0.3 – 0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arrow worms</td>
<td>Sagitta elegans</td>
<td>1.0 – 12.0</td>
<td>Chaetognatha</td>
<td>77.1</td>
</tr>
<tr>
<td>Jellyfish</td>
<td>Hydromedusae species</td>
<td>2.0 – 12.5</td>
<td>Coelenterata</td>
<td>47.7</td>
</tr>
<tr>
<td></td>
<td>Pleurobrachia pileus</td>
<td>1.0 – 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muggiaea atlantica</td>
<td>1.0 – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendicularia</td>
<td>0.5 – 2.0</td>
<td>Appendicularia</td>
<td>12.5</td>
</tr>
<tr>
<td>Urochordates</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Fish</td>
<td>Fish larvae</td>
<td>2.5 – 15.0</td>
<td>Fish larvae</td>
<td>16.5</td>
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<tr>
<td></td>
<td>Fish eggs</td>
<td>0.75 – 2.5</td>
<td>Fish eggs</td>
<td>6.4</td>
</tr>
</tbody>
</table>

(* Mostly small coastal water species)
Though many species are common throughout the year, most have periods or seasons in which their abundance peaks and they become dominant in the community. Amongst the mesozooplankton, the copepods are usually the most abundant. However, at certain times the larvae of bottom living (benthic) invertebrates such as molluscs, worms, starfish, barnacles or crabs may dominate the zooplankton community. These are the meroplankton or temporary plankton which, if they survive, will eventually settle onto the seabed. Many of the benthic animals producing these larvae have a short spawning season of only a few weeks, so they tend to occur as brief pulses of abundance.

Figure 13. a) Annual frequency of occurrence, and b) Annual abundance of meso-zooplankton categories during 1997 and 1998.
The spring peak of copepod abundance in 1997 (Fig. 15) was composed largely of *Pseudocalanus*, with a mix of less abundant species including *Acartia clausi*, *Temora longicornis* and *Paracalanus parvus* whereas the later peak in autumn was mostly of *Acartia* with fewer of the other species present. During winter most of these species are rare in the water, but the small cyclopoid copepod *Oithona similis* (Fig. 16) is found in the plankton throughout the winter. Among plankton species two basic strategies of egg laying are found. When food is abundant females of some species lay many eggs and simply broadcast these into the sea, while other species invest in fewer, more yolk-rich eggs which the females carry in a sac beneath the abdomen. For example, *Pseudocalanus* and *Oithona* have egg sacs whereas *Acartia*, *Temora* and the larger *Calanus* species are broadcast spawners. The eggs of some species (*Acartia* and *Temora*) are able to settle to the seabed sediments and survive through the winter to hatch in spring.

During winter the abundance of most herbivorous zooplankton species is much reduced due to the cool temperatures, the lack of food, and the cumulative effects of carnivorous predator populations. Populations of predators such as the arrow worms (*Chaetognatha*) and small jellyfish (Fig. 17) grow in abundance through the summer and autumn. Locally, their feeding may outpace the population growth of their prey. Other predators include the large crustaceans (Fig. 18). This category contains such organisms as the Euphausiids and Mysids, small shrimp-like creatures, which may grow to two or three centimetres long and
often shoal together. These are not sampled quantitatively by the small net used off Stonehaven, but catches indicate that they are quite common in the summer months.

Each plankton species has its own strategy for surviving winter and this may involve hibernation as juveniles living on reserves of fatty lipids (*Pseudocalanus* & *Calanus*), or the laying of eggs which survive in the seabed through the winter. Some species such as *Oithona similis* survive winter at low population levels simply by eating what they can. Most copepods are omnivores to varying extents and feed on phytoplankton, other smaller zooplankton and on dead material (detritus). They are all selective feeders, sensitive to taste and vibration in the water and with a range of feeding appendages which allow them to grasp individual food items or to select from a stream of particles generated by the fanning of their feeding apparatus. Some have, for example, been shown to avoid particular phytoplankton species which produce toxins to deter grazers.

This copepod genus *Calanus* has species in all the world’s oceans and is particularly important across the North Atlantic and Norwegian Sea, and up to the Arctic. In the North Sea *Calanus* can constitute up to 70%
of the biomass of mesozooplankton at certain times, and is an important part of the diet of very many fish species. There are two main species in the North Sea; *Calanus finmarchicus* which has a sub-Arctic distribution and is dominant in the northern North Sea, and *Calanus helgolandicus* which is a southern temperate species and dominates in the southern North Sea. The Scottish coast is an area where the distributions of these two species overlap. *Calanus finmarchicus* hibernates during the winter, mostly as late stage juveniles (copepodite stage V) in the cold deep water off the edge of the continental shelf further north and west of Scotland, and reinvades the North Sea each spring where it spawns in April and May. In contrast, *Calanus helgolandicus* is found in the North Sea throughout the year and spawns mainly during the summer and autumn. The early juveniles of *Calanus finmarchicus* and *Calanus helgolandicus* cannot be distinguished even by microscopic examination.

The abundances of juvenile *Calanus* (copepodite stages I-IV), later stages of *Calanus finmarchicus* (copepodite stage V and adult) and *Calanus helgolandicus* off Stonehaven are shown in Figure 19. Late stages of *Calanus finmarchicus* was overall less abundant than *Calanus helgolandicus* and occurred mainly in the spring, whereas *Calanus helgolandicus* was dominant in the autumn and winter. Very few of either species were present in June and July. We do not know why there are so few *Calanus* in the summer, but possible reasons are that the water is too warm for *Calanus finmarchicus*, or that the large diatoms which they depend on for food are insufficiently abundant, having been superceded by dinoflagellates and microflagellates (Fig. 9).

Two peaks in juvenile *Calanus* abundance were observed during the year, one in the spring the other in the autumn. Based on the association between juveniles and adults, the spring peak in juveniles probably arose from spawning of the adult *Calanus finmarchicus*, and the second from the *Calanus helgolandicus*.
Figure 19. Abundances of Calanus species and stages during 1997 and 1998.
a) juvenile stage CI-CIV, b) stage CV-CVI C. finmarchicus, c) stage CV-CVI C. helgolandicus.
Differences Between Years

The data show considerable differences in the mesozooplankton between years, some of which can be related to differences in the environment. A striking feature of the *Calanus* data is the very much greater abundance of juveniles relative to adults in 1998 compared to 1997, especially in the spring. It appears that the reproductive success of both species, but *Calanus finmarchicus* in particular, was poor in 1997. The reasons for this are not immediately obvious. The environmental feature which most strongly influenced the plankton development in the two years was the influx in autumn of mixed coastal and oceanic water from the north, which is a regular feature of the Scottish northeast coast. In autumn 1997 the influx was of relatively high salinity water, suggesting strong oceanic influence, and carried with it large numbers of the small transparent bells of the siphonophore *Muggiaea atlantica*. This is an oceanic species common in the northeast Atlantic Ocean but seldom abundant in inshore waters and is included in the small jellyfish analysis category which showed a large peak in abundance in autumn 1997 but not in 1998 (Fig. 17).

Other differences between years were higher abundances of some species groups in the summer and autumn of 1998 than in 1997. Examples include the small copepod species, *Oithona similis*, mollusc larvae and Arrow worms. For *Calanus helgolandicus*, although the initial population increase in August/September was greater in 1998 than in 1997, the numbers remaining at the end of the year were slightly lower.

In conclusion, the overall patterns of species composition, seasonal abundance and life cycles of zooplankton were similar in the two years and typical of a temperate coastal sea area. However, there was variability between years in species composition and in the timing and success of population growth and production in the plankton. Differences in the influx of oceanic water were partly responsible, but other factors must also have been involved, including wind mixing, solar heating, freshwater runoff and the abundance of predators including fish species.
Summary of differences between 1997 and 1998 at Stonehaven

Sea temperatures off Stonehaven were warmer in winter and spring 1998 than in 1997, but summer and autumn temperatures were cooler, reflecting the more stormy conditions. The main oceanographic difference was that in 1997 a flow of high salinity water passed down the coast between August and November, which was not repeated in 1998.

Summer and winter nutrient concentrations were similar in both years, although nitrate was drawn down to low levels (<1 mM m\(^{-3}\)) for longer during summer 1997 than summer 1998, reflecting the calmer and warmer weather conditions in 1997. Ammonia concentrations resulting from the degradation of organic matter, were higher in autumn 1997 than 1998.

Chlorophyll concentrations, reflecting phytoplankton biomass, were higher during the spring bloom of 1998 than 1997, and the period during the year of concentrations >1mg m\(^{-3}\) was 2-3 weeks longer. 1998 was a year which favoured dinoflagellates, whereas conditions in 1997 favoured flagellates and diatoms. There were significant species differented between years as well. Species which were present in one of the years, but not in the other included the diatom *Skeletonema costatum*, and the dinoflagellate *Dinophysis acuta*. The dominant species were also different in each year.

Among the zooplankton, most categories were more abundant in 1998 than 1997. In particular, both species of *Calanus* in the area, but especially *Calanus finmarchicus*, had more successful recruitment in 1998 than in 1997. An exception was the abundance of jellyfish, since the strong inflow of oceanic water in autumn 1997 introduced large numbers of the siphonophore *Muggiaea atlantica* to the area, which is thought to be a relatively rare event.

Overall, conditions in 1998 seem to have supported higher stocks of plankton than in 1997, and the year as a whole was probably more productive.

Stonehaven data compared to observations from a wider area off the Scottish northeast coast

The data collected off Stonehaven were compared with data accumulated from surveys in the North Sea carried out by FRS between 1960 and 1990, to determine the extent to which the Stonehaven data are representative of a wider area. The North Sea has been divided into a number of sub-regions based mainly on hydrographic considerations. The various regions are considered to be relatively homogeneous with respect to temperature, salinity and stratification. One of these regions covers a strip along the east coast of Scotland extending out to between 30 and 60 miles offshore, referred to as Scottish Coastal Zones (Fig. 20).

Between 1960 and 1990, FRS has collected temperature, salinity, nutrient and chlorophyll observations from the East Coast Inshore Waters region as part of a wide variety of surveys and studies, as shown in Table 2. These data were grouped by the week number (1-52) during the year in which they were collected and the geometric mean and standard deviations calculated. In each case, the majority of data collected off Stonehaven fell within the range of the historical observations from the Scottish Coastal Zones (Fig. 21-23). Hence, we conclude that the measurements, of these parameters at least, off Stonehaven are a good indicator of the state of the ecosystem in the wider area off the Scottish east coast.
Table 2. Number of observations of various parameters from the Scottish east coast region during the period 1960-1990, in the FRS hydro-chemical database.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of observations 1960-1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>12011</td>
</tr>
<tr>
<td>Salinity</td>
<td>12011</td>
</tr>
<tr>
<td>Nitrate</td>
<td>4237</td>
</tr>
<tr>
<td>Phosphate</td>
<td>3959</td>
</tr>
<tr>
<td>Silicate</td>
<td>3713</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1733</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>2316</td>
</tr>
</tbody>
</table>
Figure 21. Long-term (1960-1990) regional mean a) temperature and b) salinity in the Scottish Coastal Zone compared to Stonehaven during 1997 and 1998. Blue shaded area shows the ±1 SD around the longterm regional mean.
Figure 22. Long-term (1960-1990) regional mean nutrient concentrations in the Scottish Coastal Zone compared to Stonehaven during 1997 and 1998. a) nitrate, b) phosphate, c) ammonia, d) silicate. Blue shaded area shows the ±1 SD around the long-term regional mean.
Figure 23. Long-term (1960-1990) regional mean chlorophyll concentrations in the Scottish Coastal Zone compared to Stonehaven during 1997 and 1998. Blue shaded area shows the ±1 SD around the long-term regional mean.
Acknowledgments

Mr Ian Watson, assistant harbour master at Stonehaven, acted as coxwain on the launch Shuna during all of the sampling occasions in 1997 and 1998. The programme forms part of Service Level Agreement AE11n between the Fisheries Research Services and The Scottish Office.

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For up to date information on sampling results see URL:
http://www.marlab.ac.uk/Monitoring/Stonehaven/Stoneframe.html

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