

The Plankton Ecology of the SEA 8 area.

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1. Introduction

The purpose of this report is to consider the ecology of the plankton community in the Strategic Environment Assessment (SEA) area 8, primarily as determined by the Continuous Plankton Recorder (CPR) survey. SEA 8 extends from 48°North, 10°West (the shelf edge), northeast to 52°North (the Celtic Sea), and east to 51°North approx 1.5°East (the end of the English Channel), Figure 1a. Information for this report has been obtained from both current and historical research to give an understanding of the SEA 8 area and any changes that have occurred to the plankton ecology over time.

SEA 8 is a relatively shallow area, with only the south-western tip deeper than 100m. The area is strongly influenced by tidal action in the Channel area and wind-driven currents in the Celtic Sea (Pybus, 2007). The Celtic Sea area stratifies in the summer, and thermal fronts (namely the Ushant front) develop at the western end of the English Channel (Connor et al., 2006, Pingree and Griffiths 1978).

Data for this report are primarily from the CPR survey, which provides a unique long-term dataset of plankton abundance in the North Atlantic and North Sea, using 'ships of opportunity' to tow the CPR on regular routes, sampling at a depth of approximately 10m (methodology described in full in Warner and Hays 1994). Each sample represents 18km of tow and approximately 3m³ of filtered seawater (John et al. 2002). The survey records over 400 taxa of plankton composed of phytoplankton (plants) and zooplankton (animals) entities, many of which are recorded to species level. It is the only biological survey that can monitor long term changes over broad areas, such as the North Atlantic. The survey began in the North Sea in 1931, with computerised records from 1948 (for this report data were extracted from 1960). Data collected from the survey allows long term changes, as well as seasonal cycles, in the plankton community to be identified. In addition to the examination of specific planktonic entities, Phytoplankton Colour Index (PCI), an estimation of chlorophyll *a* values (Hays and Lindley 1994), can be seen to represent changes in primary production.

Figure 1b. shows the samples used for this report, in the SEA 8 area, from 1958 to 2005 there were over 9000 samples in the study area. The aim of this report is to address the following parts of the plankton community:

- Phytoplankton and zooplankton community composition and long term changes
- Physical processes affecting the plankton
- Regional variation in plankton ecology
- Phytoplankton blooms, harmful algal events and toxin producing algae
- Abundance of Calanoid copepods, Meroplankton, Picoplankton and Megaplankton
- Planktonic sensitivity to contaminants & pollution
- Resting stages in sediments & ballast waters
- The influence of climatic forcing upon planktonic communities

1.1 Biological background

The plankton can be broadly divided into two major components; the plant (phyto-) plankton and the animal (zoo-) plankton. Phytoplankton are of great importance as the primary producers in the oceans and thus provide the principal source of primary nutrition for organisms such as zooplankton. As primary producers the phytoplankton require light to perform photosynthesis. However, due to an exponential reduction in light intensity with depth in seawater, phytoplankton abundance is greatest in the upper waters, a region referred to as the photic zone.

Phytoplankton can be further divided with three orders of algae predominating; the diatoms, the dinoflagellates and the smaller flagellates (such as the coccolithophorids). Diatoms are autotrophic (produce energy from photosynthesis) and generally range in size from 15 to 400µm. They are

characterised by their siliceous cell or frustule, which is composed of two overlapping valves that fit together much like a pill-box or petri-dish.

Dinoflagellates are generally heterotrophic, so rely on preformed organic matter, though some are also capable of photosynthesis. The dinoflagellates can be further sub-divided into naked (not generally recorded in the CPR survey) and armoured forms. Both forms are capable of locomotion by means of two whip-like appendages called the flagella.

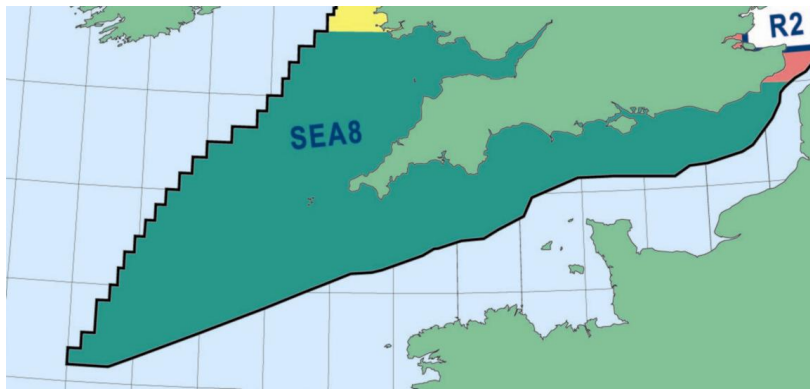
Smaller flagellates make up part of the nanoplankton (organisms 2-20 μ m in diameter) and picoplankton (organisms 0.2-2 μ m in diameter), along with bacteria, fungi and a number of the smallest diatoms and dinoflagellates. Although they are small in size they are thought to make a considerable contribution to primary production, and act as an important food source for many larvae. These components of the community are not recorded by the CPR due to their small size.

Zooplankton, the animal constituent of the plankton, can be divided into holoplankton and meroplankton. Holoplankton consists of permanent members of the plankton where all developmental stages are retained in the plankton (for example copepods). The meroplankton are temporary members of the plankton where only some developmental stages are within the plankton, such as the eggs or larvae of an organism (such as crab larvae).

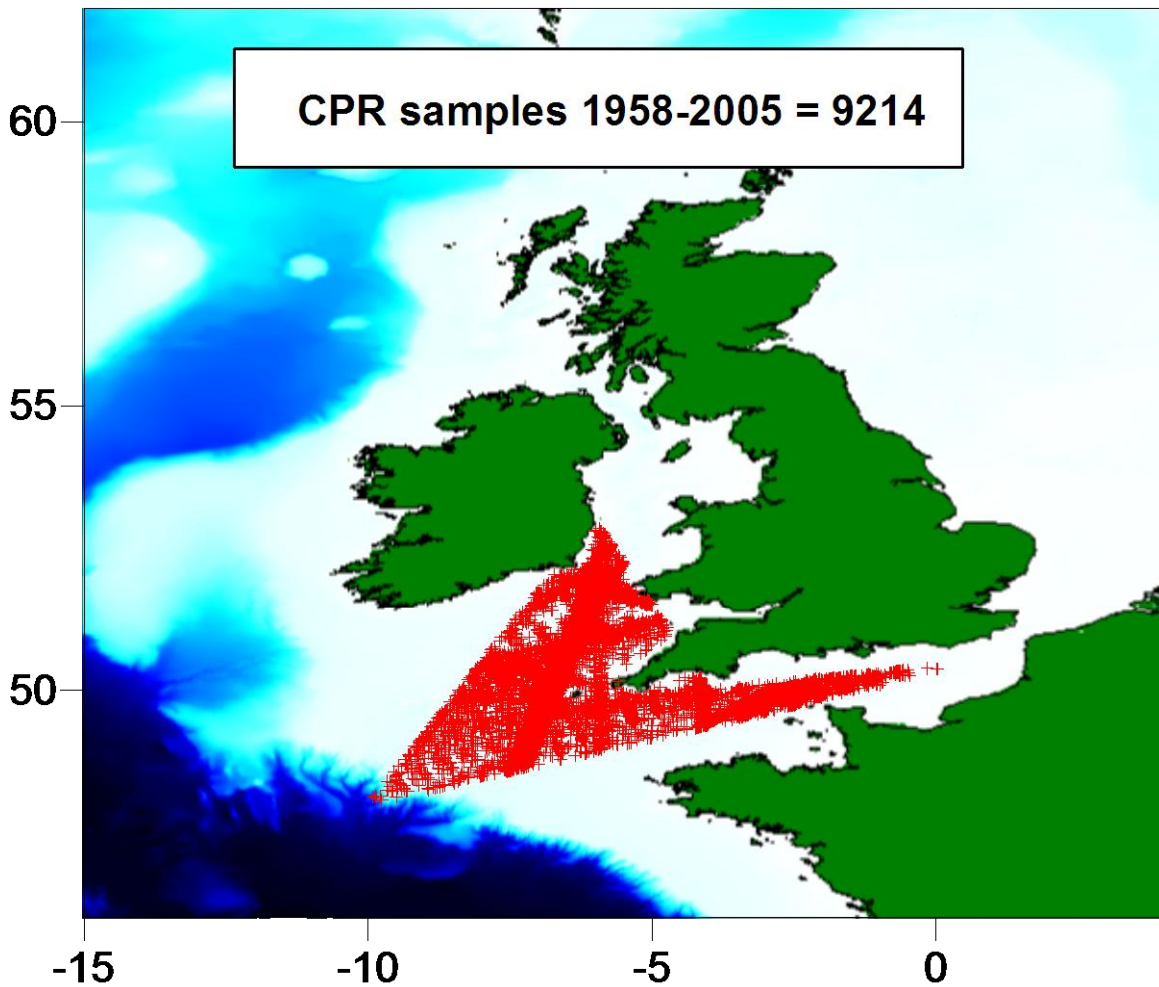
By far the most abundant element of the zooplankton are the copepods, which are small holoplanktonic crustaceans ranging in size from 0.5mm to 6.0mm. These are generally herbivores feeding on phytoplankton and are themselves the main food source for a great many organisms higher in the food chain such as larval and juvenile fish. The copepods can be divided into the calanoids, cyclopoids and harpacticoids by body shape, of which the calanoids are by far the most abundant.

Other crustaceans also form an important constituent of the zooplankton, the majority of which are the larval forms of large benthic crustaceans such as crabs, and are therefore in the meroplankton. Other such meroplanktonic animals include polychaete larvae and echinoderm larvae, as adult forms are also benthic. However, it is not only organisms that lead to a benthic lifestyle in the meroplankton, as fish eggs and larvae are also included (referred to as the ichthyoplankton), due to the fact that they are only part of the plankton during their pelagic egg and larval stages.

The gelatinous zooplankton, can also be important in the zooplankton and include, larvaceans, salps, doliolods, ctenophores and coelenterates. These organisms are generally carnivorous, feeding upon other zooplankton such as copepods and fish larvae. Their importance is due to the fact that ctenophores and medusoid stages of cnidarians (coelenterates) can exhibit rapid growth to form large swarms which can lead to a significant predatory effect on copepods and fish larvae (Bunn et al., 2000). These organisms are likely poorly recorded in the CPR survey, due to the soft nature of their bodies becoming easily damaged on contact with the CPR silk. In the case of coelenterates, they are simply recorded as being present or absent on a sample, i.e. there is no abundance data.



a)



b)

Figure 1a) SEA 8 area, b) CPR samples within the SEA 8 area.

1.2 Physical processes affecting the plankton

The SEA 8 area is generally shallow, deepening to over 100m at the far south-western edge, near the shelf break. The shelf edge area, where deep sea and coastal ocean meet, has complex physical processes resulting from the combination of stratification and steep bathymetry (Rees et al. 1999), and is generally poorly understood. When waters off the shelf-break meet with the tidally mixed waters on the shelf a seasonal front can develop that can produce local upwelling events providing additional nutrients to surface waters thus enhancing local primary production in such areas. Similarly, when water masses with differing surface temperatures meet, fronts can develop

again stimulating planktonic production. The area has two seasonally occurring frontal systems, the Celtic Sea Front (across St. George's Channel, approx. 52°North, 6°West), and the Ushant Front at the mouth of the English Channel, from The Lizard to Brittany. These frontal systems develop in late spring at the meeting of mixed and stratified areas, breaking down with the onset of winter cooling and increased wind-induced mixing (OSPAR Commission, 2000).

The SEA 8 area covers many oceanographic provinces, with coastal waters receiving a moderate input of freshwater from land. The coastal region is also subject to strong seasonal forcing, by surface heating and cooling and by strong westerly winds, which prevail for much of the year. Offshore waters in the region can become stratified during the summer months with warm buoyant waters overlying denser cold waters, creating a thermocline. This acts as a physical barrier to the phytoplankton, and the autotrophic members of the community (the diatoms) rapidly utilize the available inorganic nutrients and decline in abundance. Many dinoflagellate species are heterotrophic, and can therefore increase in abundance during the late summer months when the diatoms have declined. As the year progresses, autumnal gales mix up the water column, breaking down the thermocline and re-circulating nutrients to the surface waters, often causing a secondary diatom bloom. As light levels later in the year decline, the phytoplankton community reduces, often forming resting stages. These are suspended in the water column, or deposited on the bottom, and when light levels increase in the spring, they are activated, and can rapidly flourish as the nutrient content of the surface waters is high after the winter mixing. This appearance of phytoplankton is known as the 'spring bloom'.

1.3 Nutrient salts

In order for a phytoplankton population to be successful, certain micro-nutrients are required in high enough concentrations to support population growth. In the marine environment, nitrogen is generally considered to be the limiting micro-nutrient although phosphorus and silicon are also required in varying quantities by certain phytoplanktonic groups. Whilst it is acknowledged that there is a lack of data and understanding concerning biogeochemical and physical processes in the area, there have been studies on winter nutrient concentrations, which fuel the spring bloom production and therefore effectively set the limits to annual production (Hydes et al. 2004), influencing higher trophic levels. In fact, the spring bloom in the Celtic Sea part of the area is estimated to account for almost half of the annual primary production (Joint et al. 1999)

2. Phytoplankton

2.1 Table 1 shows phytoplankton taxa that have occurred on more than 1% of samples in the SEA 8 area, with the most frequently recorded, *Thalassiosira* spp. (a diatom, most abundant in spring), occurring on almost one fifth of the samples. Most of the 'top 10' are diatom taxa, with two dinoflagellate *Ceratium* species.

Phytoplankton Taxa	% occurrence on CPR samples
<i>Thalassiosira</i> spp.	19.44
<i>Rhizosolenia alata alata</i>	14.84
<i>Ceratium fusus</i>	14.27
<i>Thalassionema nitzschoides</i>	13.57
<i>Phaeoceros</i> spp.	13.48
<i>Hyalochaete</i> spp.	11.00
<i>Ceratium tripos</i>	10.49
<i>Rhizosolenia imbricata shrubsolei</i>	7.81
<i>Rhizosolenia hebetata semispina</i>	6.63
<i>Nitzschia seriata</i>	6.46
Protoperidinium	6.22
<i>Rhizosolenia styliformis</i>	6.18
<i>Pseudonitzschia delicatissima</i>	5.96
<i>Paralia sulcata</i>	4.65
<i>Ceratium furca</i>	4.14
<i>Ceratium lineatum</i>	4.12
<i>Scrippsiella</i> spp	3.84
<i>Odontella sinensis</i>	3.27
<i>Prorocentrum</i> spp.	3.25
<i>Ceratium horridum</i>	3.14
<i>Ceratium macroceros</i>	2.90
Coccolithaceae	2.88
<i>Rhizosolenia stolterfothii</i>	2.64
<i>Dinophysis</i> spp	2.62
<i>Rhizosolenia alata inermis</i>	2.56
<i>Noctiluca scintillans</i>	2.17
<i>Exuviella</i> spp.	2.15
<i>Lauderia borealis</i>	2.03
<i>Coscinodiscus</i> spp.	1.96
<i>Ditylum brightwellii</i>	1.82
<i>Dactyliosolen mediterraneus</i>	1.79
<i>Navicula</i> spp.	1.79
<i>Cylindrotheca closterium</i>	1.78
<i>Rhizosolenia delicatula</i>	1.13
<i>Asterionella glacialis</i>	1.03
<i>Oscillatoria</i> spp.	1.03

2.2 Phytoplankton Colour Index

In the CPR survey, as well as individual phytoplankton taxa being recorded, a visual assessment of 'greenness' is made, this is known as Phytoplankton Colour Index (PCI). It is an estimation of chlorophyll a values (Hays and Lindley 1994), can be seen to represent changes in primary production. Recent research has also noted that PCI matches well with SeaWiFs data (Raitsois et al., 2005)

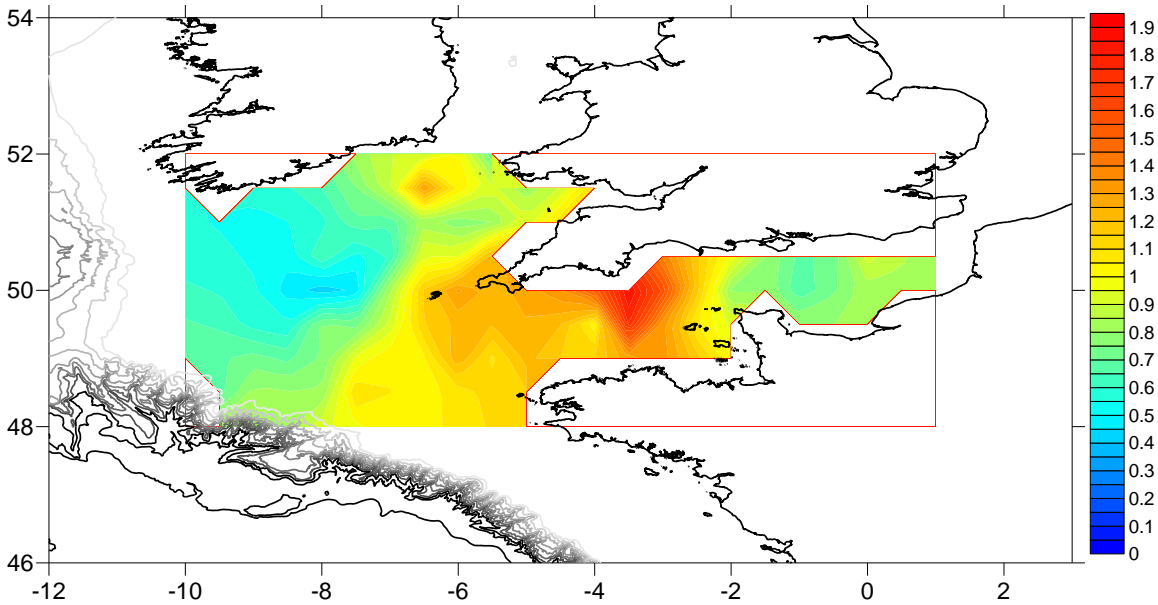


Figure 2 Contour map of PCI, showing regional variations in the SEA 8 area

The Phytoplankton Colour Index is a logarithmic scale, with values of 0, 1, 2 and 6.5. Figure 2 shows the spatial variability of PCI within the SEA 8 area, and highest values are around 3° West, spreading westwards to 8° West, the Ushant front area. There appears to be a distinct transitional area between productive and less productive waters, running approximately southwestwards from Cornwall, with the least productive area in the Celtic Sea (an area of seasonal stratification, Connor et al., 2006). There are also low values to the eastern end of the English Channel.

Long term PCI values are rising in the SEA 8 area (Fig. 3A), in keeping with most of the rest of UK waters (Edwards et al., 2006a and b). The exact reason for this is unknown, but rising sea surface temperatures are likely to be an important factor. Eutrophication, the excessive nutrient loading of a water body, has been suggested as a possible cause, but research by Edwards et al. suggests that regional climate change is a more important factor on the scales that the CPR survey operates at.

Figure 3B shows long term seasonal data plotted as a contour plot, clearly showing an increase in PCI not only on a long term scale, but also throughout the year. In the early part of the time series, there is a distinct spring bloom (mostly diatoms), and an occasional autumnal bloom as well (dinoflagellates). But as the time series has progressed, there is a clear move to higher PCI values throughout the year, though there does not appear to have been a significant phenological shift in the phytoplankton (as opposed to some zooplankton groups, notably the meroplankton, Edwards and Richardson, 2004).

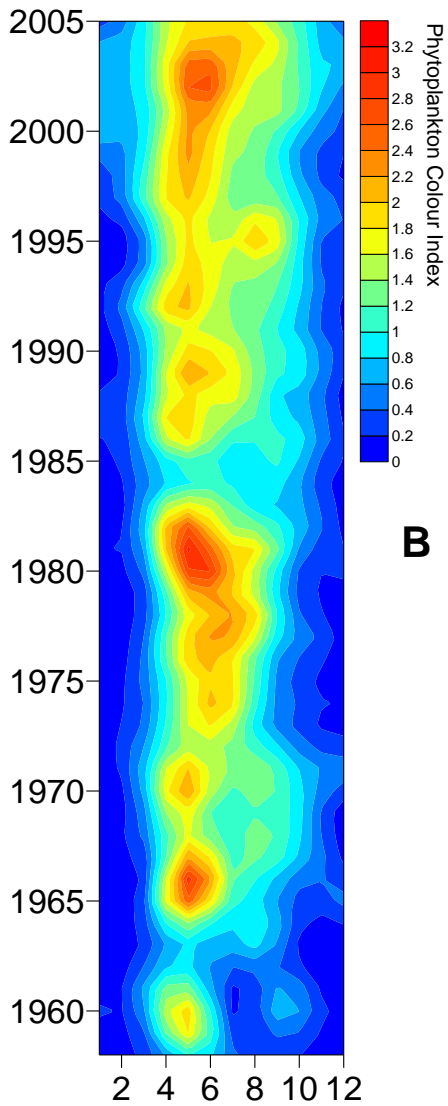
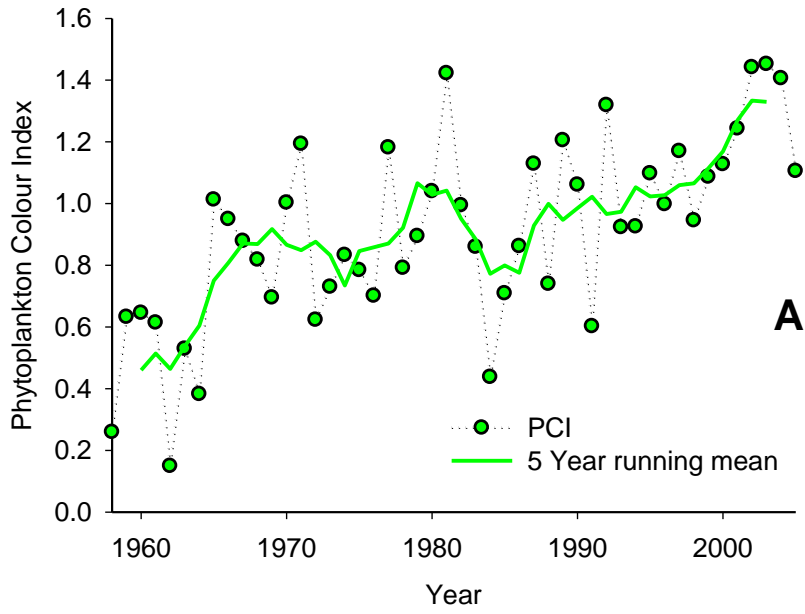


Figure 3 Phytoplankton Colour Index A) long term data and B) contour plot

2.3 Phytoplankton blooms, harmful algal events and toxin producing algae

In the plankton community a 'bloom' of phytoplankton occurs every spring, often followed by a smaller peak in the autumn. Phytoplankton (diatom) blooms are normally initiated by the establishment of a thermal stratification in spring, as a result of increased light and temperature. Dinoflagellate communities are associated with post spring bloom conditions, when surface waters are limited by the amount of phosphorus and nitrogen left after the initial diatom bloom (Williams and Lindley 1980). 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, advantageous diatom species increase rapidly in abundance, hence the term '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. Silicate (essential for diatom growth, being incorporated into their 'test') eventually becomes limited and other groups, such as flagellates, bloom, followed later by the dinoflagellates. 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. This secondary bloom is limited in size by the amount of phosphorus and nitrogen left after the initial diatom bloom (Edwards and John 1996).. 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. This describes a typical annual cycle, that is the phytoplankton bloom can be thought of as a natural annual event.

In addition to this, there are exceptional phytoplankton blooms (transient, un-sustained growth, often monospecific) and Harmful Algal Blooms (HAB's). The issue of HAB's is highly topical, with an attempt to separate anthropogenically forced increases, through eutrophication, from more widespread 'natural' changes, such as global warming (Edwards et al. 2006a). Due to the spatially and temporally extensive nature of the CPR survey the data can be used as a general reference point to deviations from ecological 'normal' conditions and therefore in the assessment of the overall health of an ecosystem. By using CPR data it has been concluded that the affects of eutrophication on European regional seas cannot be assessed without taking into account the wider Atlantic influences on phytoplankton populations, helping to distinguish between eutrophication and climate signals (Edwards and Reid 2001). For example, some of the most exceptional phytoplankton blooms recorded by the CPR survey have been associated with ocean climate anomalies and oceanic incursions into the North Sea (Edwards et al. 2002).

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

Table 2. Potentially harmful / detrimental phytoplankton taxa recorded by the CPR survey.

Work presented in the Annual Status report (Edwards et al. 2006b) shows that blooms of certain taxa occur in the SEA 8 area, notably *Noctiluca* spp., and *Pseudo-nitzschia* spp. (see Table 2, taxa that have been identified as harmful as recorded in the CPR survey). In fact, 6 of the harmful / detrimental taxa occur on over 1% of samples, the most commonly occurring being *Chaetoceros* (which includes *Phaeoceros* spp. and *Hyalochaeta* spp.), which is found on over 11% of samples. These species are not in themselves thought to be toxic, but by means of their large bloom-forming abilities can cause anoxic conditions, leading to localised die-offs of higher trophic levels, and clog the gills of fish in the case of *Chaetoceros* (due to their spines). The most recent data, from the Annual Status report (Edwards et al. in prep, Fig. 4), shows that in 2005 there were few blooms in the SEA 8 area.

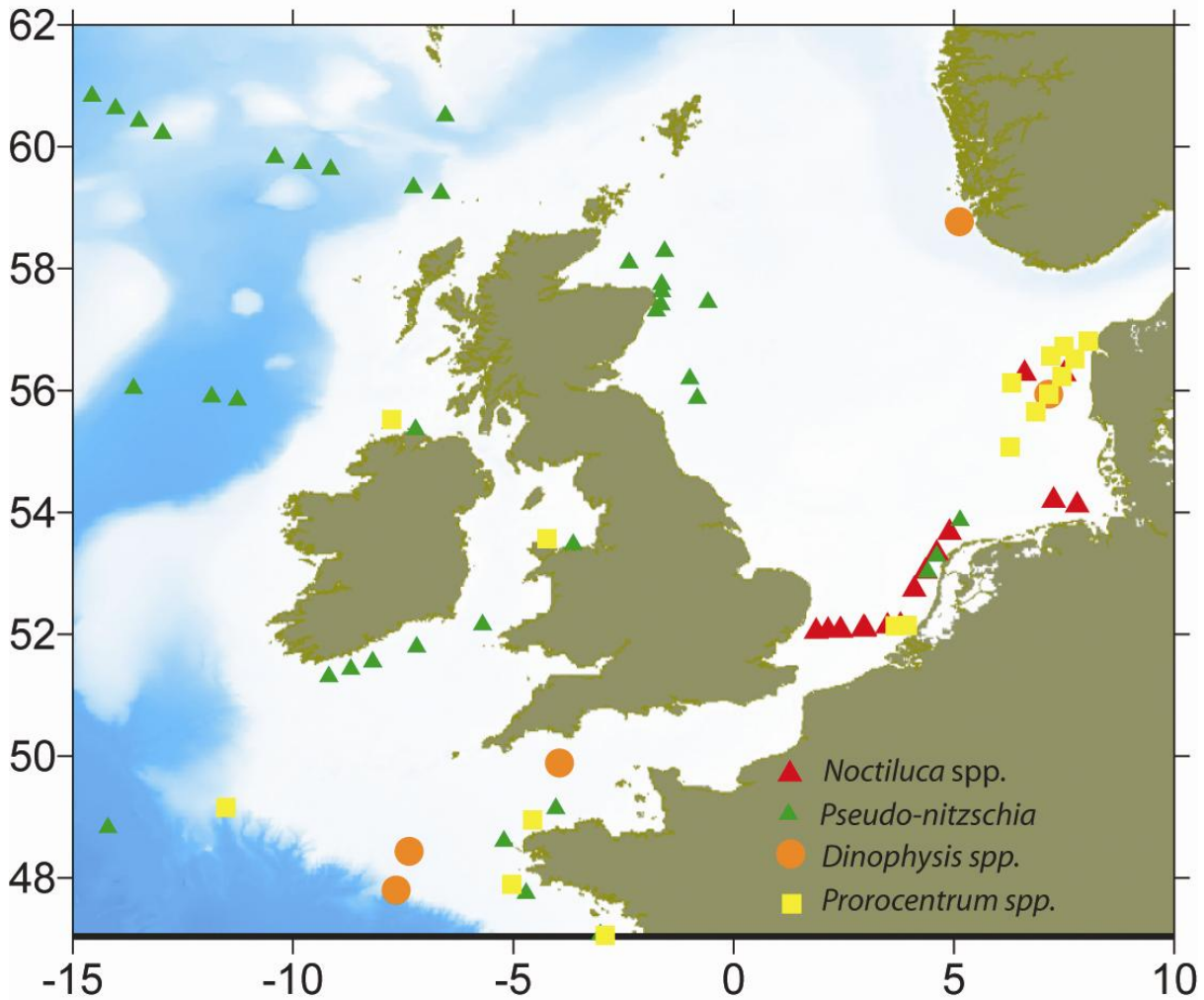


Figure 4. Map of blooms around the UK in 2005 (from Edwards et al. In prep)

3 Zooplankton

3.1 Zooplankton represent the animal part of the plankton community, some of which feed on the phytoplankton, whilst others are carnivorous and feed on other zooplankton. The community consists of both permanent (holoplankton, eg copepods) and temporary (meroplankton, eg decapoda larvae) members of the plankton. Many zooplankton groups are an important food source for higher trophic levels, particularly larval fish. The zooplankton community of SEA 8 (Table 3 shows all taxa occurring on over 1% of samples) is diverse, and this section shows the results of some of the more abundant / important groups within the community.

Zooplankton taxa	% occurrence on CPR samples
<i>Calanus helgolandicus</i>	71.15
<i>Para-pseudocalanus</i> spp.	54.67
Decapoda larvae	44.38
Euphausiids	34.79
Chaetognatha	31.86
<i>Acartia</i> spp.	31.02
<i>Centropages typicus</i>	23.31
<i>Oithona</i> spp.	20.22
Echinoderm larvae	19.59
<i>Pseudocalanus elongatus</i> adult	18.74
<i>Metridia lucens</i>	18.72
Larvacea	16.38
Fish larvae	15.21
<i>Limacina retroversa</i>	14.42
<i>Temora longicornis</i>	13.63
Gammaridae	12.51
<i>Calanus finmarchicus</i>	10.07
Hyperiidea	9.34
<i>Evadne</i> spp.	9.28
Podon spp.	9.08
<i>Corycaeus</i> spp.	7.85
<i>Candacia armata</i>	7.00
<i>Euchaeta hebes</i>	5.72
<i>Clausocalanus</i> spp.	5.70
Lamellibranchia larvae	3.99
Cirripede larvae	3.36
Cyphonautes larvae	3.18
<i>Tomopteris</i> spp.	2.59
<i>Centropages hamatus</i>	2.52
Mysidacea	2.08
Polychaeta larvae	1.51
<i>Oncaea</i> spp.	1.40
Doliolidae	1.28
<i>Eucalanus crassus</i>	1.10

Table 3. The zooplankton community of SEA 8, taxa occurring on over 1% of samples

The temperate water calanoid copepod *Calanus helgolandicus* is the most frequently recorded in the SEA8 area, occurring on over 71% of samples. This species is an important food source for larval fish, along with its colder water cousin *C. finmarchicus*. The long term trends, seasonality and spatial variation of these are discussed below. Other zooplankton that are examined in this method are five other calanoid copepod taxa, *Acartia* spp., *Centropages typicus*, *Temora longicornis*, *Para-pseudocalanus* spp. and *Oithona* spp. (all important food for higher organisms), Decapoda larvae (the young of crabs and lobsters, therefore including commercially important species), Amphipoda (hyperiids and gammarids), Euphausiids (often considered megaplankton), Total Cladocera (*Podon* spp., *Evadne* spp. and *Penilia avirostris*), Mollusca (predominately *Limacina retroversa*), Echinodermata larvae (the young of sea urchins etc., provides an insight into the plankton link with the benthos), Larvacea (including *Oikopleura* spp. and *Fritillaria* spp.), Chaetognatha (arrow worms), Polychaeta larvae (mainly *Tomopteris* spp.), Cirripede larvae (the young of barnacles) and an index of gelatinous organisms known as Coelenterate tissue (recorded as presence / absence due to their destruction on hitting the CPR, represent the presence of jelly fish).

3.2 Abundance of calanoid copepods

Calanoid copepods constitute a major food resource for many commercial fish species, such as cod and herring. 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 SEA 8 area, the dominant species are *Calanus finmarchicus* and *Calanus helgolandicus*, 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 (hence the time series used for investigation starts in 1958). In the SEA 8 area, *Calanus helgolandicus* is the more dominant of the two species, having the more southerly distribution of the two, being recorded on over 71% of samples. *Calanus finmarchicus* is much less common, but it is still examined as it is such an important source of food, and has declined drastically around the UK in recent years (Edwards et al., 2006b).

It can be seen from Table 3 that there are a number of other dominant calanoid taxa, *Acartia* spp., *Centropages typicus*, *Temora longicornis*, *Para-pseudocalanus* (includes both *Paracalanus* and *Pseudocalanus* spp.) and *Oithona* spp. The majority of these are only identified to genus due to time constraints within the CPR survey.

3.2.1 *Calanus finmarchicus* Figure 5.

Long term abundance for this species is low and variable, with a greater abundance in the 1980s to early 1990s, with very low values after 2000. The species increases in abundance in April, with a peak in April, and then rapidly drops off, with a very small secondary peak in the last three months of the year. Spatially, the species is most abundant in the northwest part of the area, south of Ireland in the Celtic Sea, but again numbers are very low.

3.2.2 *Calanus helgolandicus* Figure 6

Long term abundance for *C. helgolandicus* shows a gradual increase, particularly after 1990, with considerably higher values than the colder species of *C. finmarchicus*. Seasonally, there are distinct peaks in both June and October, with low values in December to March. Spatially the species is more prevalent to the west of the area, and is almost absent from the English Channel region, and most abundant south of Ireland in the Celtic Sea.

3.2.3 *Acartia* spp. Figure 7

From the long term graph, it would appear that this taxa has declined, particularly from 1990, with peaks in abundance pre-1970. The seasonal cycle shows a build up from April to a peak in June, with a gradual drop in numbers until the end of the year, with lowest abundance from December until March. Spatially the group is most common south of the Lizard, near the position of the seasonal Ushant Front.

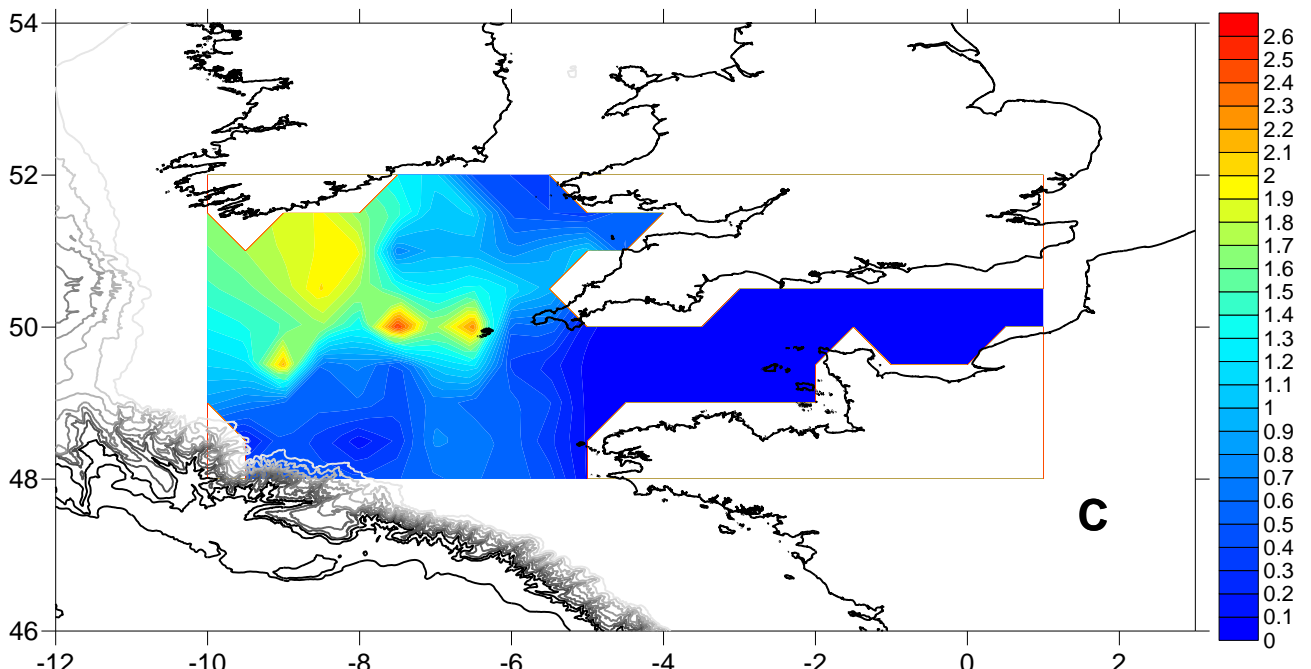
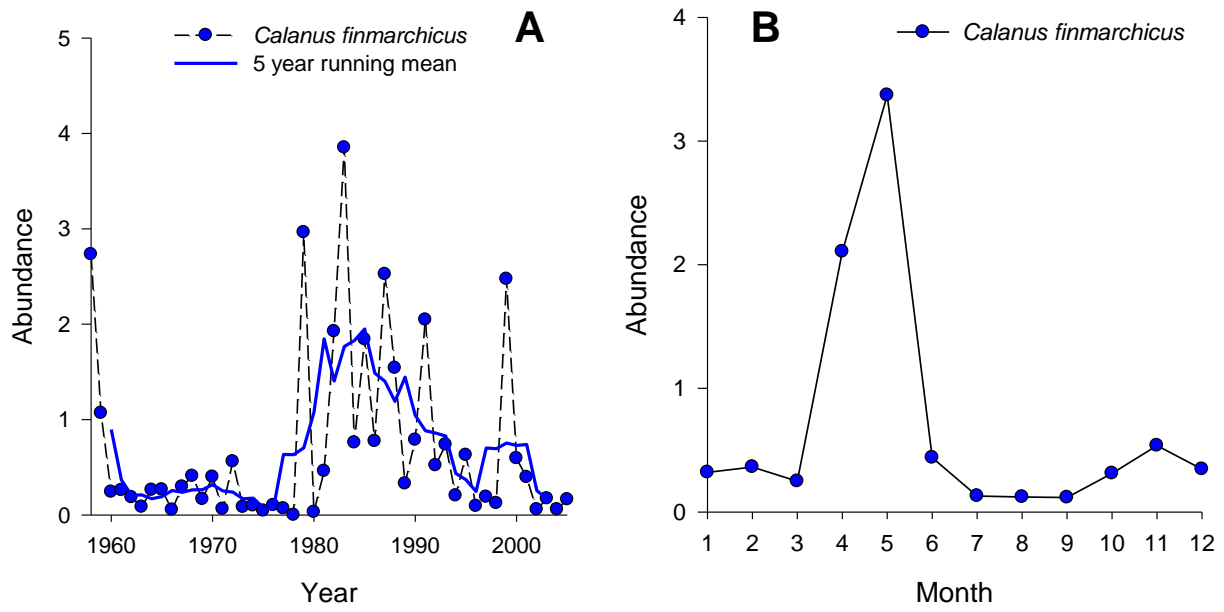


Figure 5.A) *Calanus finmarchicus* long term abundance B) seasonal cycle C) average spatial distribution

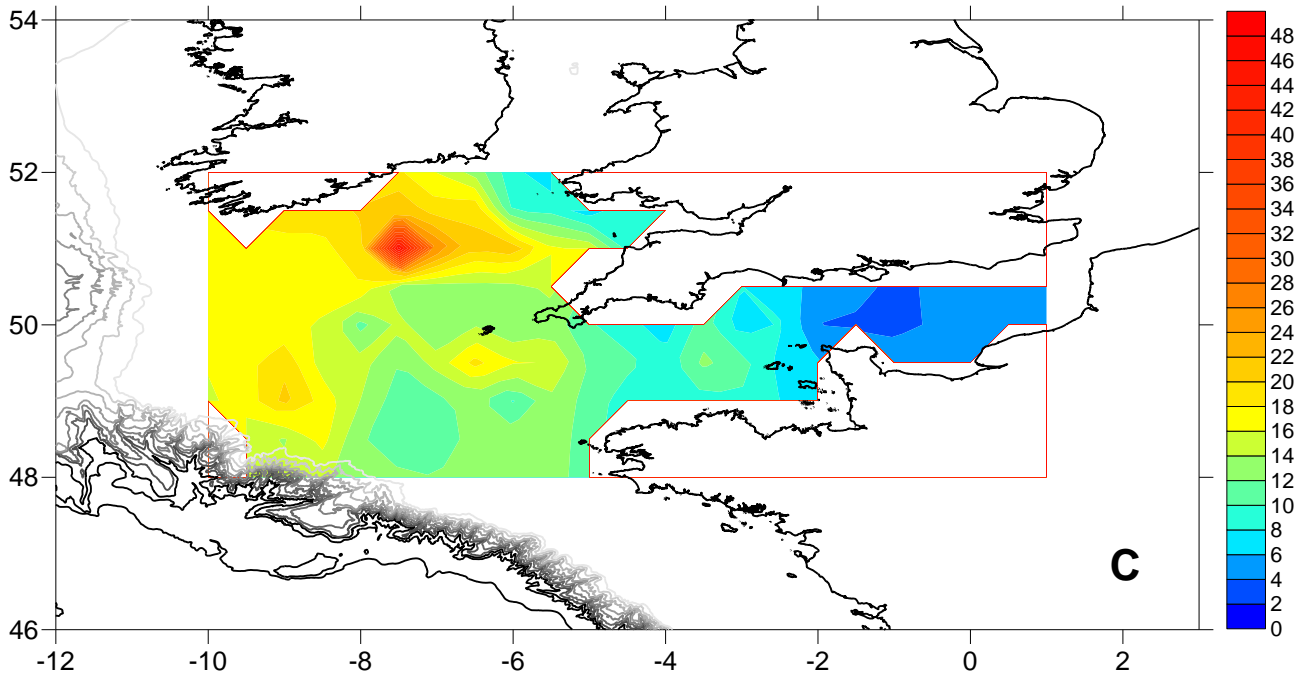
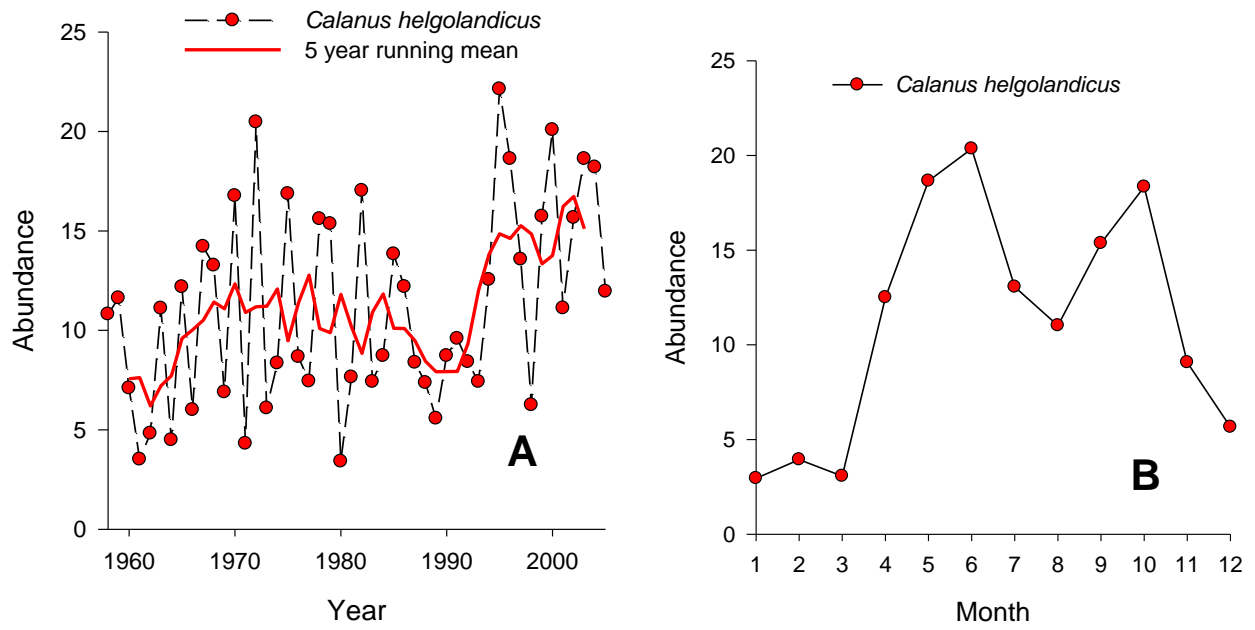


Fig 6 A) *C. helgolandicus* long term abundance B) seasonal cycle C) average spatial distribution

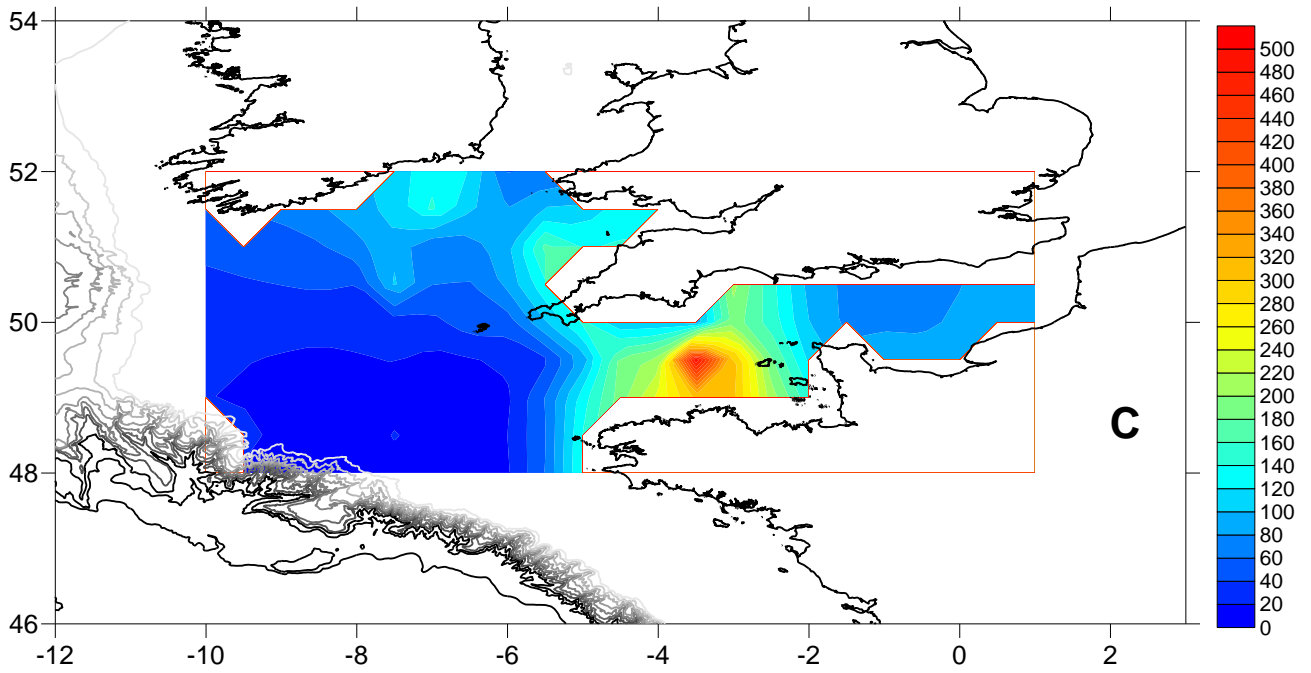
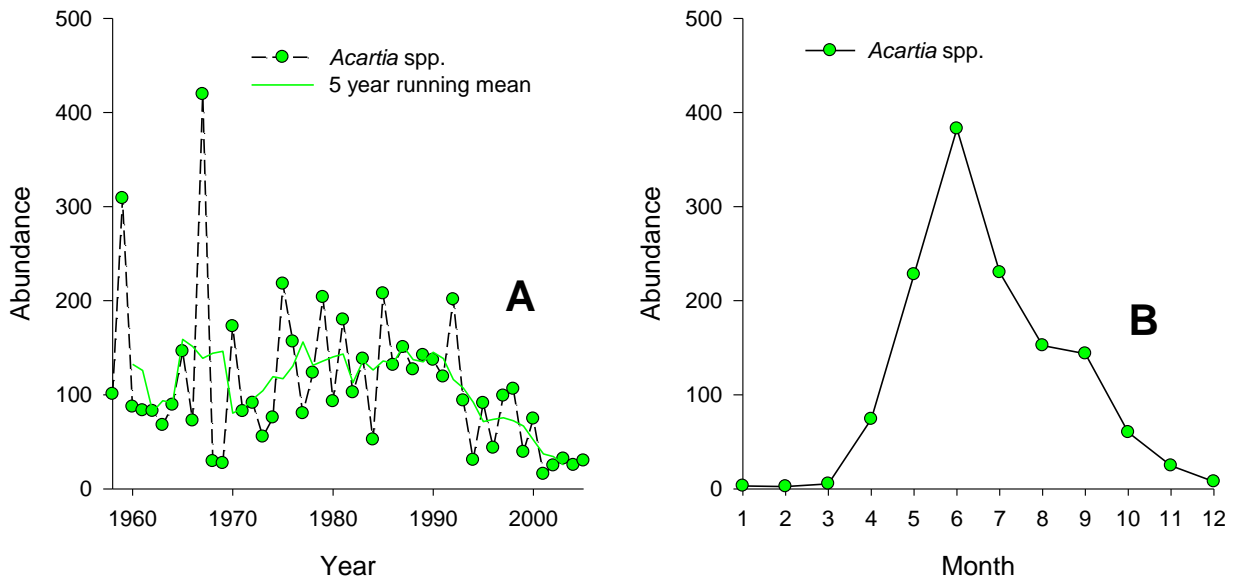


Fig 7 A) *Acartia* spp. long term abundance B) seasonal cycle C) average spatial distribution

3.2.4 *Centropages typicus*. Figure 8

Long term abundance has declined from the highest values in the 1960s, to a period of very low abundance in the 1970s, with a subsequent gradual increase. Seasonally the species is most abundant in the late summer to autumn period (July to September), with lowest values in December to March. Spatially the species is almost exclusively found to the west of the Ushant front area, with highest values at the mouth of the English Channel.

3.2.5 *Temora longicornis*. Figure 9

Abundance values have remained relatively low throughout the study period, with occasional high values (early 1960s and mid 1980s, and to a lesser extent around 2000). The species increases in abundance in April through to October, with highest values in June and August, lowest values from December to March. In contrast to *Centropages typicus*, the species is most abundant to the east of the Ushant front area, almost absent to the west of the Lizard, except with an area of high abundance northwestwards off Cornwall.

3.2.6 *Para-pseudocalanus* spp. Figure 10

This is one of the most abundant groups in the study, and its long term values have fallen from the late 1950s / early 1960s to an all time low in the mid 1970s, with a subsequent increase from then until the mid 1990s, and then a slight drop from the late 1990s until present. There is a seasonal peak in May, and a secondary peak in the autumn months (September and October), with lowest values December to March. Spatially, the group is most common to the west of the area, particularly south of Ireland in the Celtic Sea region, with low values in the eastern English Channel and the far southwest of the area.

3.2.7 *Oithona* spp. Figure 11

This genus has a variable long term graph, with a period of low abundance in the early 1970s, a peak in the mid 1980s / early 1990s, and then a drop in abundance to the present day. Seasonally the genus has a single peak in May / June, with lowest values from November through to February. The group is most abundant south of Ireland, with very low values on the eastern side of the study area.

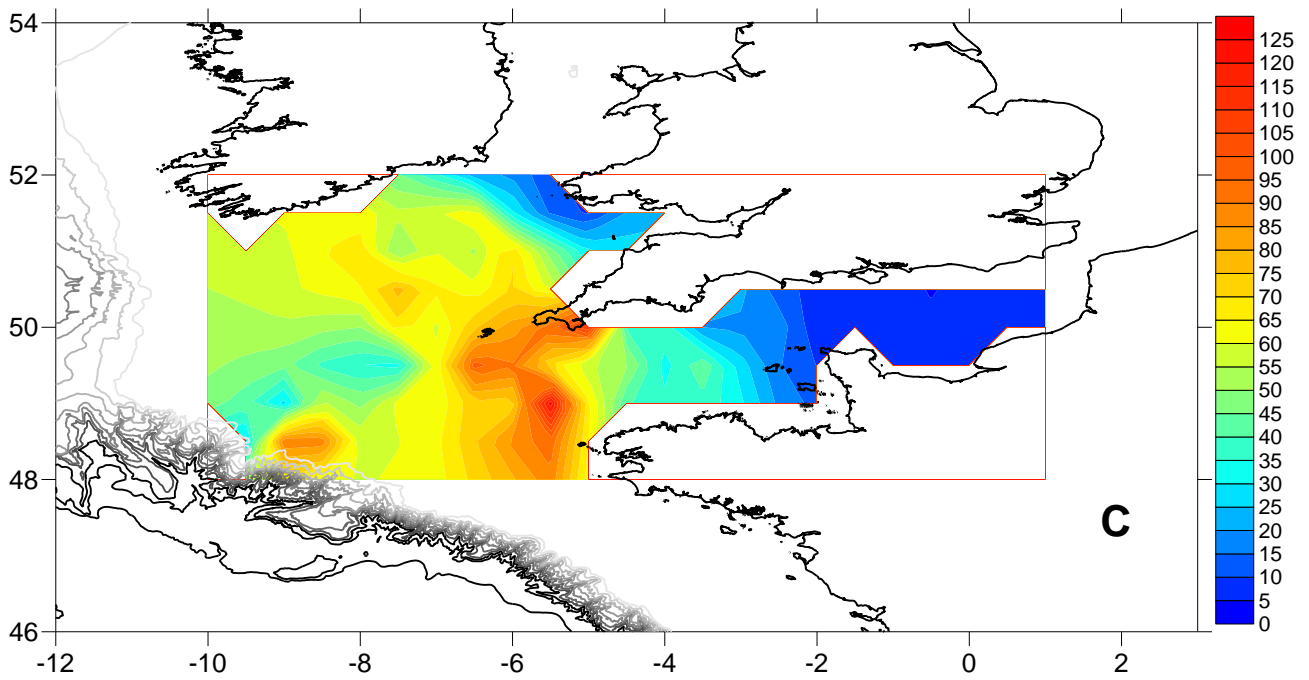
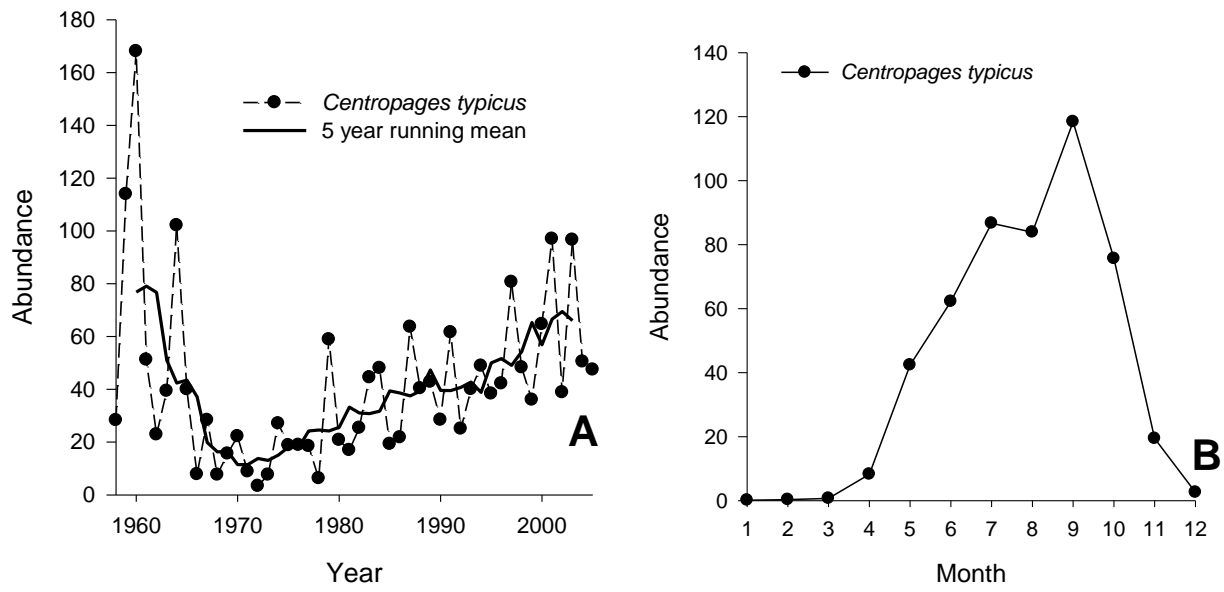


Fig 8 A) *Centropages typicus* long term abundance B) seasonal cycle C) average spatial distribution

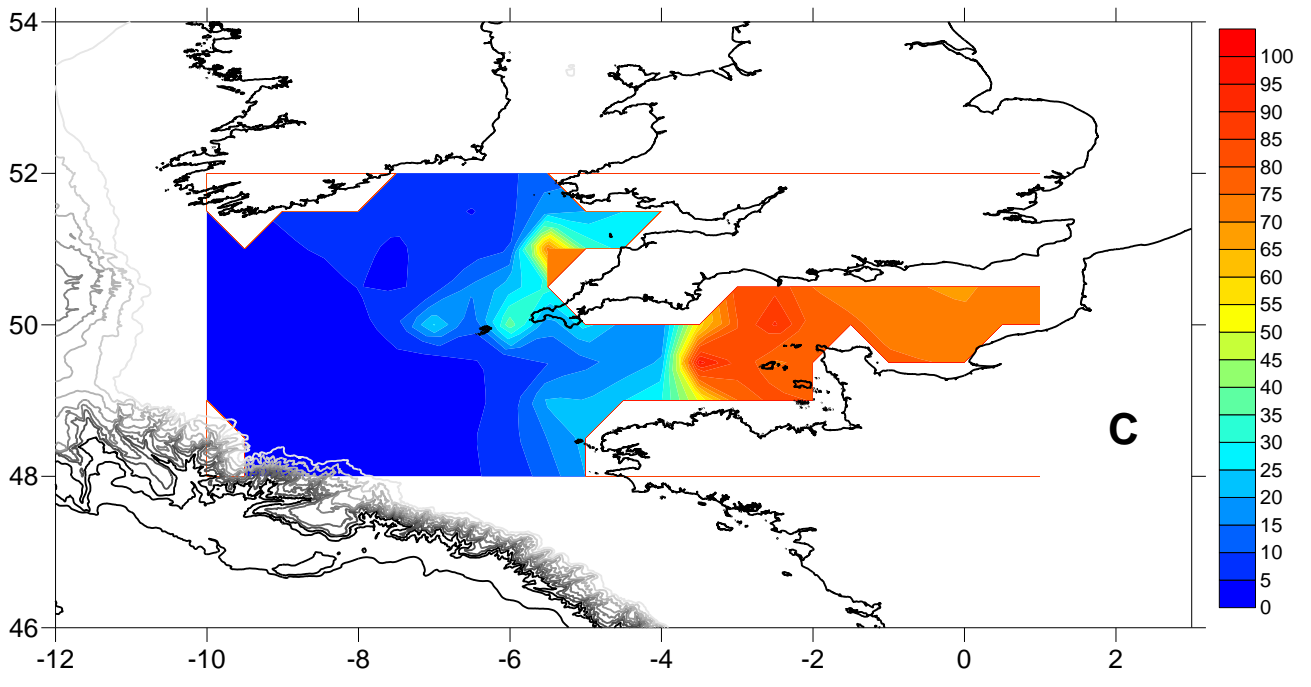
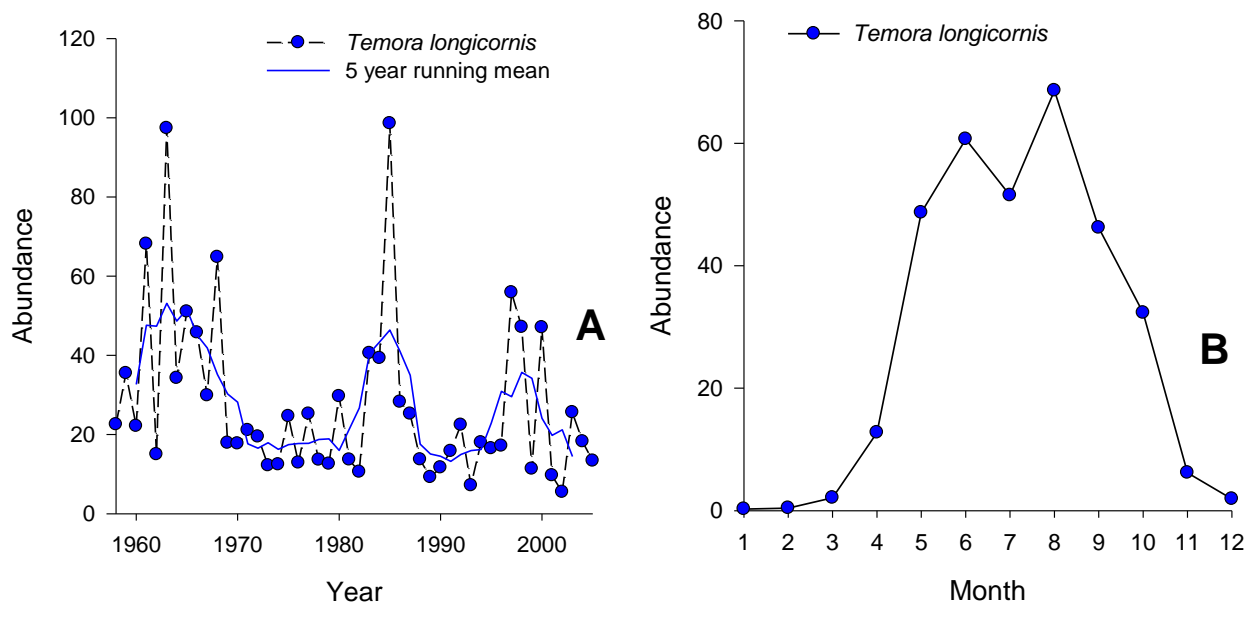


Fig 9 A) *Temora longicornis* long term abundance B) seasonal cycle C) average spatial distribution

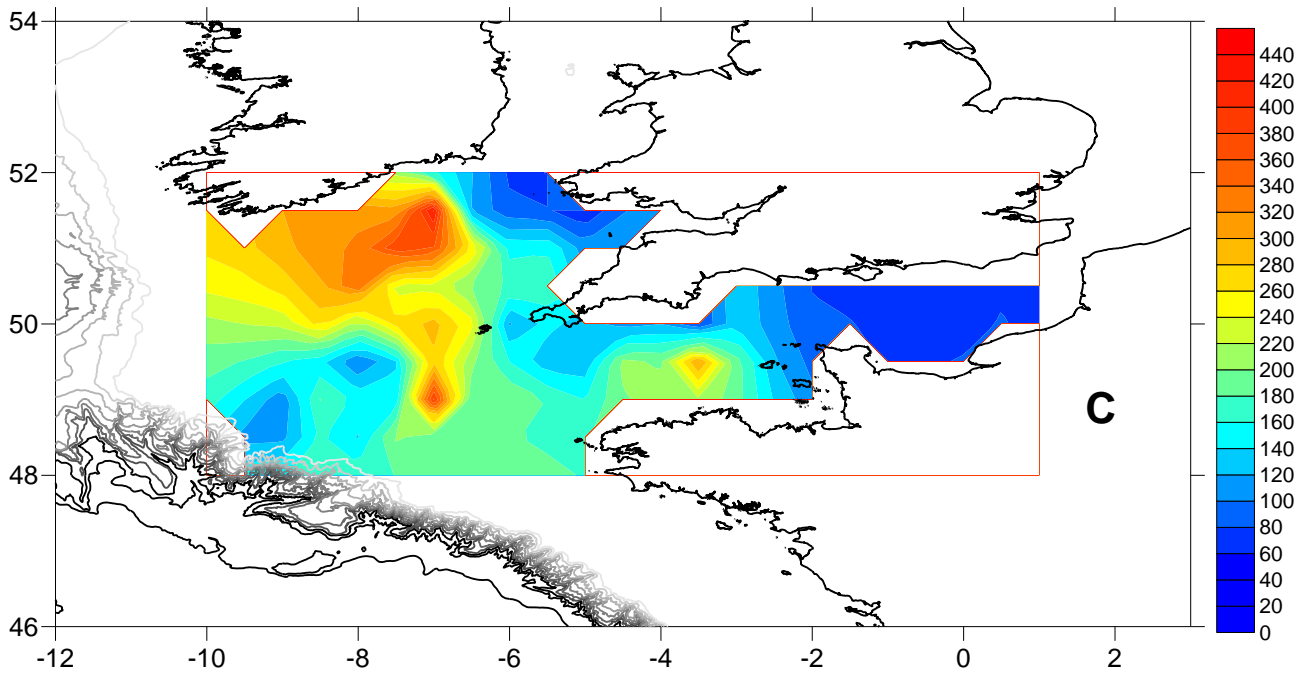
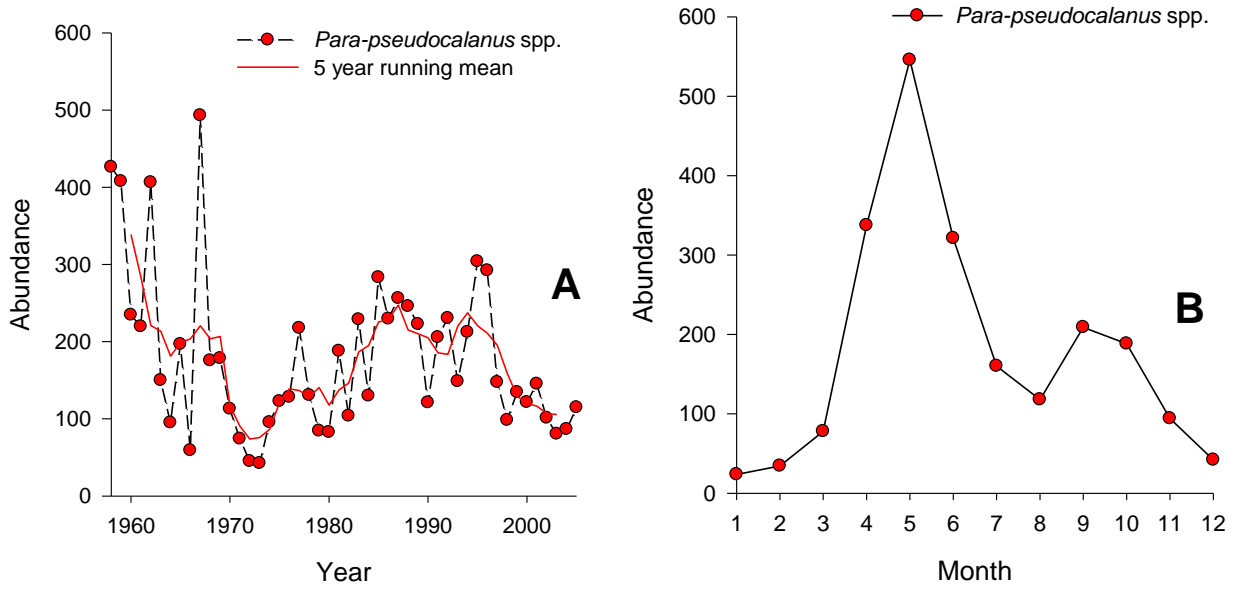


Fig 10 A) *Para-pseudocalanus* spp. long term abundance B) seasonal cycle C) average spatial distribution

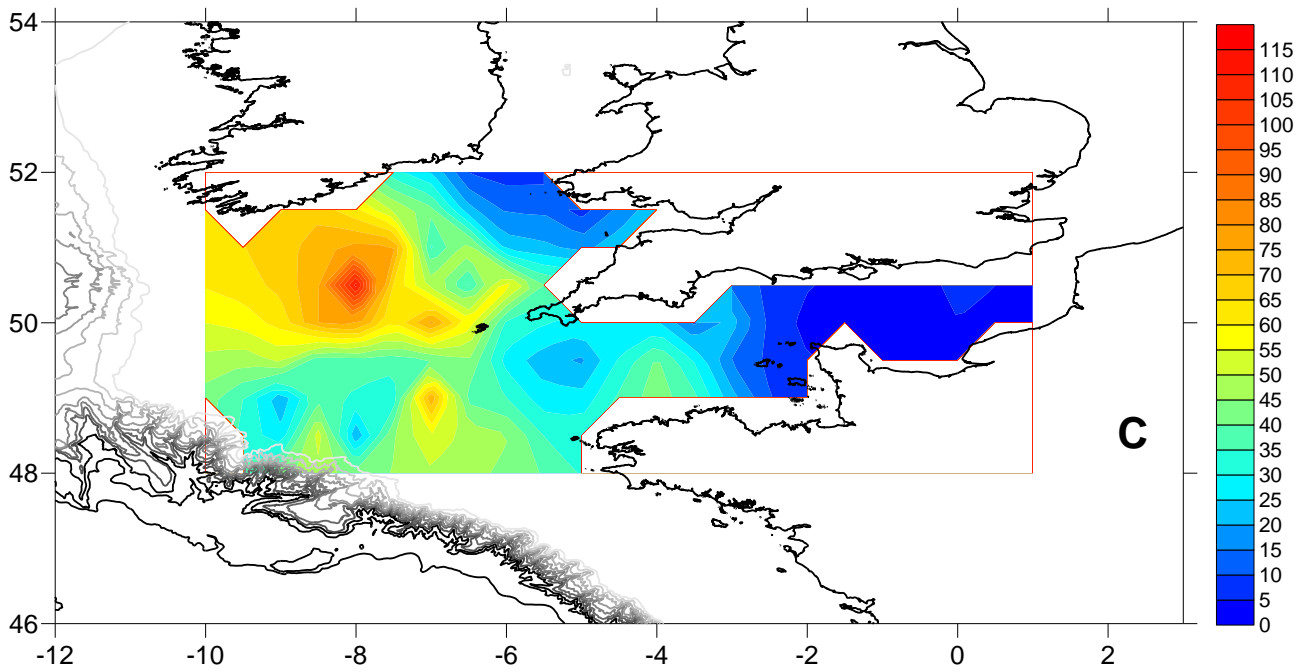
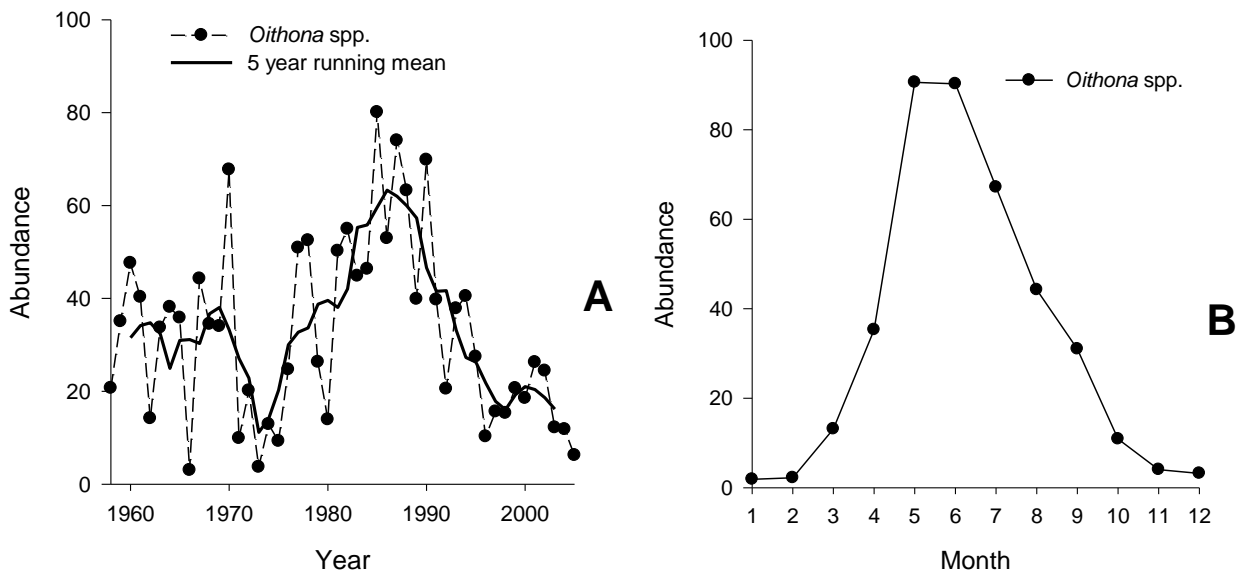


Fig 11 A) *Oithona* spp. long term abundance B) seasonal cycle C) average spatial distribution

3.2.8 Decapoda larvae. Figure 12

Decapoda larvae have fallen in abundance from high values in the 1960s / 1970s, to subsequently lower numbers, but with a slight increase post mid-1990s (and a high value in 2000). Seasonally the group is abundant from March through to October, with very low numbers November through to January. As this is a group, the peaks through the middle of the year could represent several species. Spatially the group is mostly confined to the eastern part of the area, with highest values to the south and east of the Isle of Wight. The group is almost totally absent west of approx. 3° West, except for small numbers off Lands End and south of Milford Haven.

3.2.9 Amphipoda. Figure 13

This group is found in low numbers in the SEA8 area, with a relatively stable long term trend, except for higher values in the 1960s and a slight increase post 1990. The seasonal cycle peaks in July and August, with a slow drop in numbers through to January, with lowest numbers in the early spring. Spatially the group is quite scarce, with largest numbers occurring south of the Isles of Scilly, and very low numbers elsewhere.

3.2.10 Euphausiids. Figure 14

Long term values are highly variable throughout the time series, with occasional large peaks (mid 1970s and late 1990s). 2005, the last year of currently available data, was the lowest annual mean since 1966. Seasonally there is an initial peak in May, followed by a slight decrease, building to the years main peak in October. Lowest values are January through to March. Spatially Euphausiids are confined to the western side of the study area, being virtually absent from the English Channel and most abundant immediately south of Ireland. There appears to be a clear divide around 5° West, with the taxa present to the west of this and absent to the east.

3.2.11 Cladocera. Figure 15

Despite the long term time series being quite variable, there does appear to have been an increase post 1980, and a slight decline after 2000. The group are most abundant through the late spring, summer time (May to August), with a peak in June and low values from October through to March. Spatially Cladocera are most common around the Ushant front area, very little in the eastern English Channel or to the west of Lands End. There is a small area of higher abundance just south of Ireland and to the southwest of the Isles of Scilly.

3.2.12 Mollusca. Figure 16

Long term values are relatively consistent, with anomalous large peaks in the late 1960s and late 1970s. There appears to have been a very slight decline post-1980. Seasonal peak is in July and September (with a drop in August), with lowest values in the year between December and March. Spatially the group is almost exclusively confined to an area south of Ireland, 7 to 8° West, and virtually absent elsewhere.

3.2.13 Echinodermata larvae. Figure 17

Long term trends show an increase in this group, particularly post mid 1980s, but with some variability subsequently. Highest values have all occurred since the late 1980s / early 1990s. There is an increase seasonally from April through to June, with the main peak in July / August. Numbers are at their lowest from November through to March. Spatially the group is widespread although in very low numbers in the eastern English Channel. Peak numbers appear to be northwest of Cornwall and running in a southwestern direction from there.

3.2.14 Larvacea. Figure 18

This group appears to have increase in abundance, particularly after the late 1980s, with 2005 seeing some of the highest values throughout the time series. Seasonally the group reaches a single peak in May, and tails off gradually, with lowest values from November through to February. Spatially the group is predominately found west of the Lizard, with two main areas of occurrence north of St.Ives and to the southwest of the Isles of Scilly, and virtually absent from the eastern English Channel.

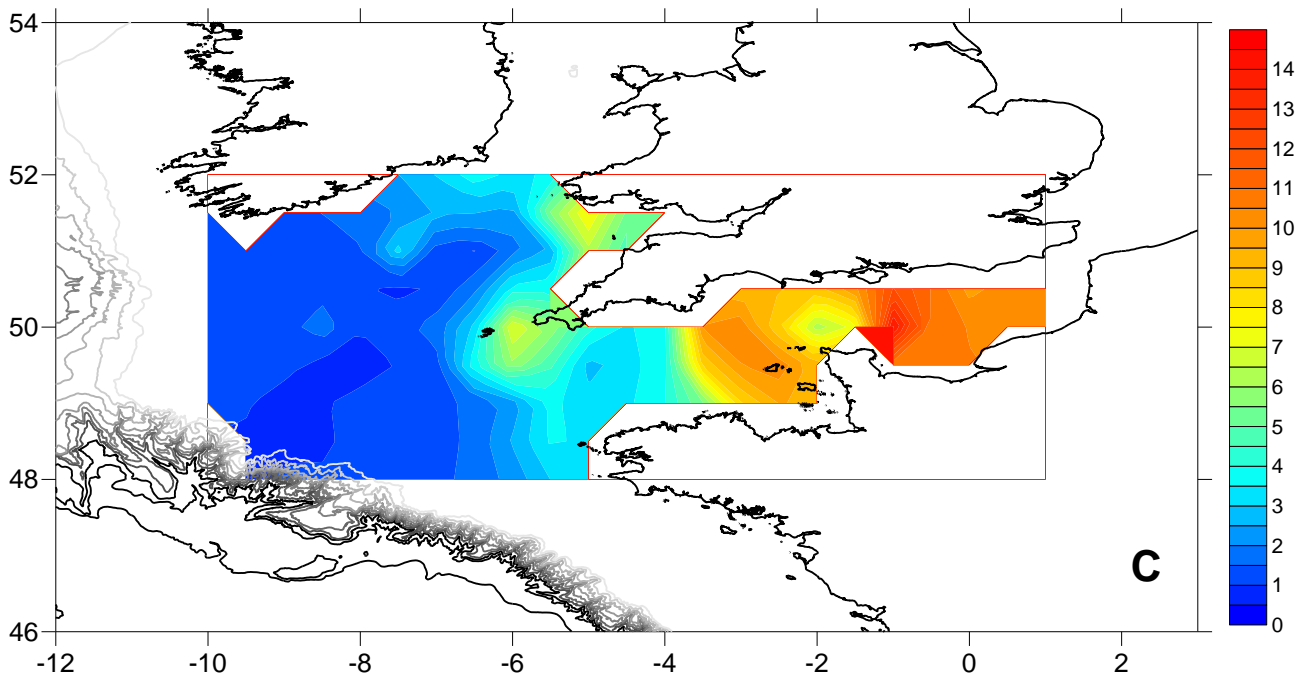
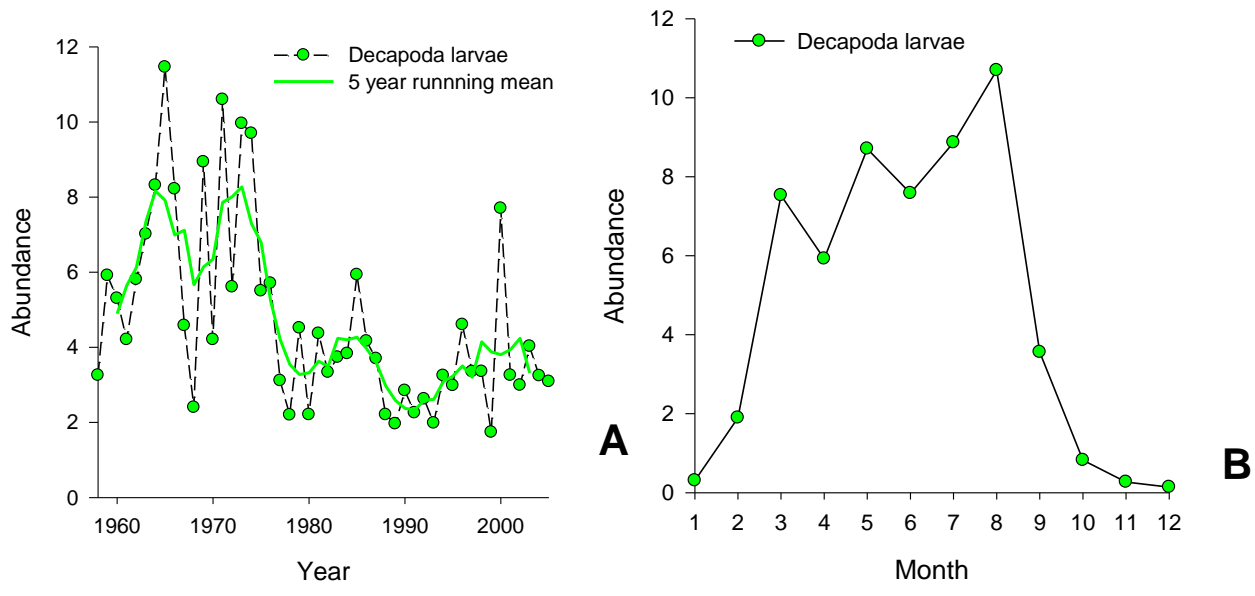


Fig 12 A) Decapoda larvae long term abundance B) seasonal cycle C) average spatial distribution

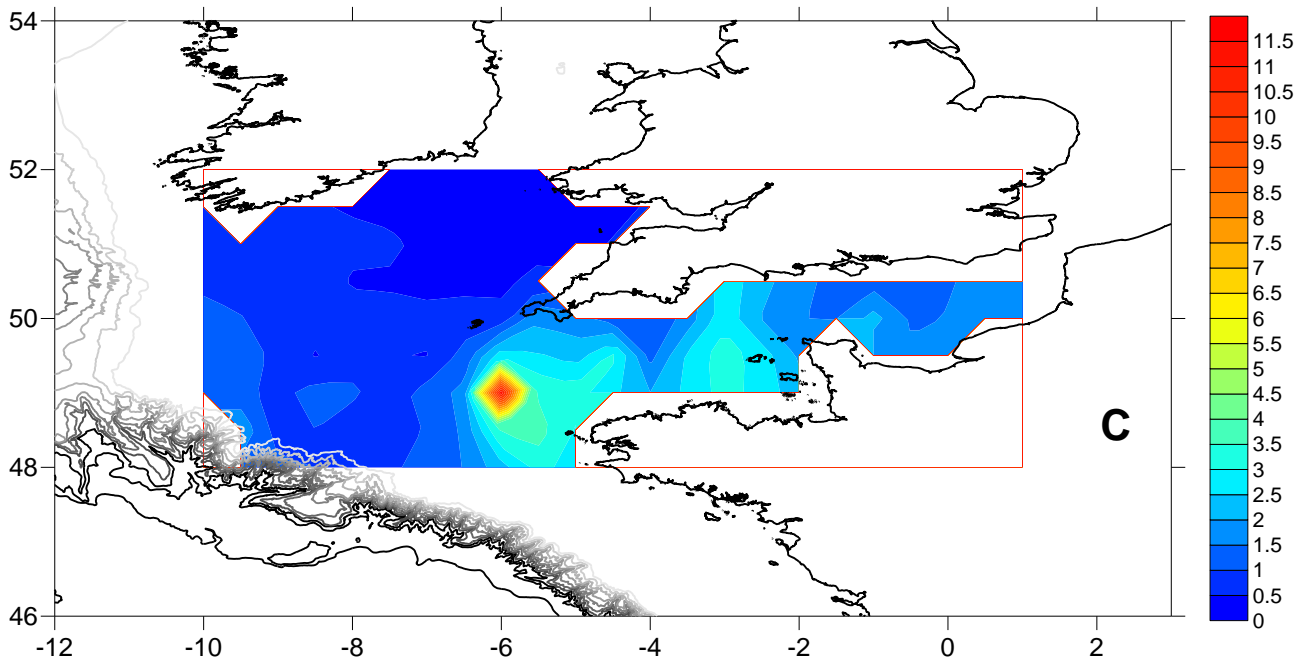
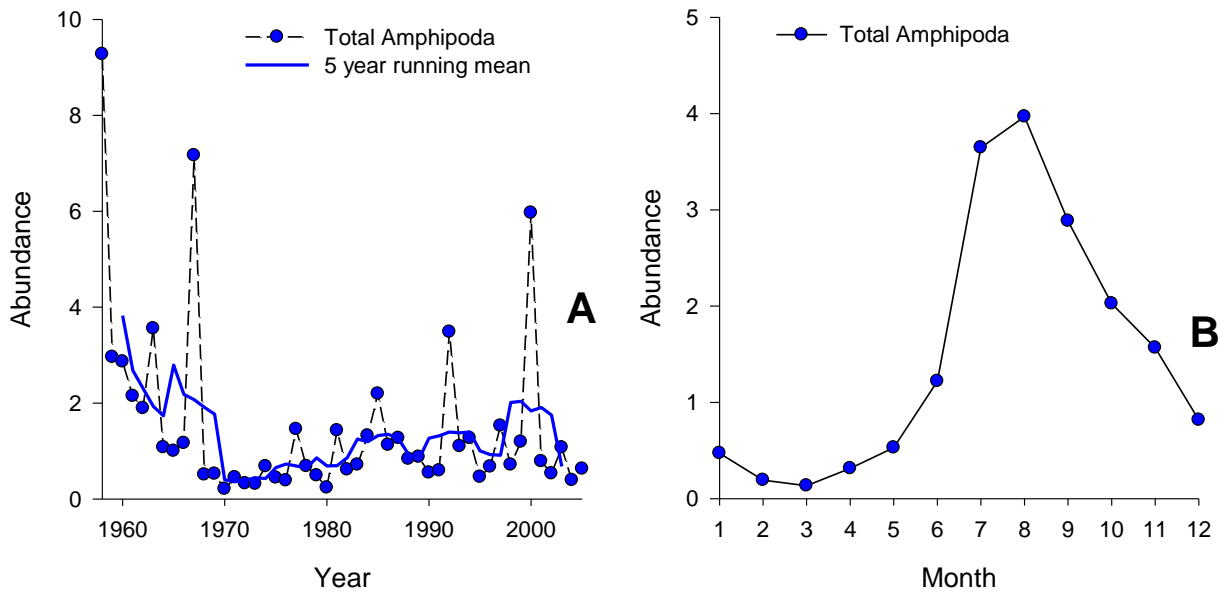


Fig 13 A) Total Amphipoda long term abundance B) seasonal cycle C) average spatial distribution

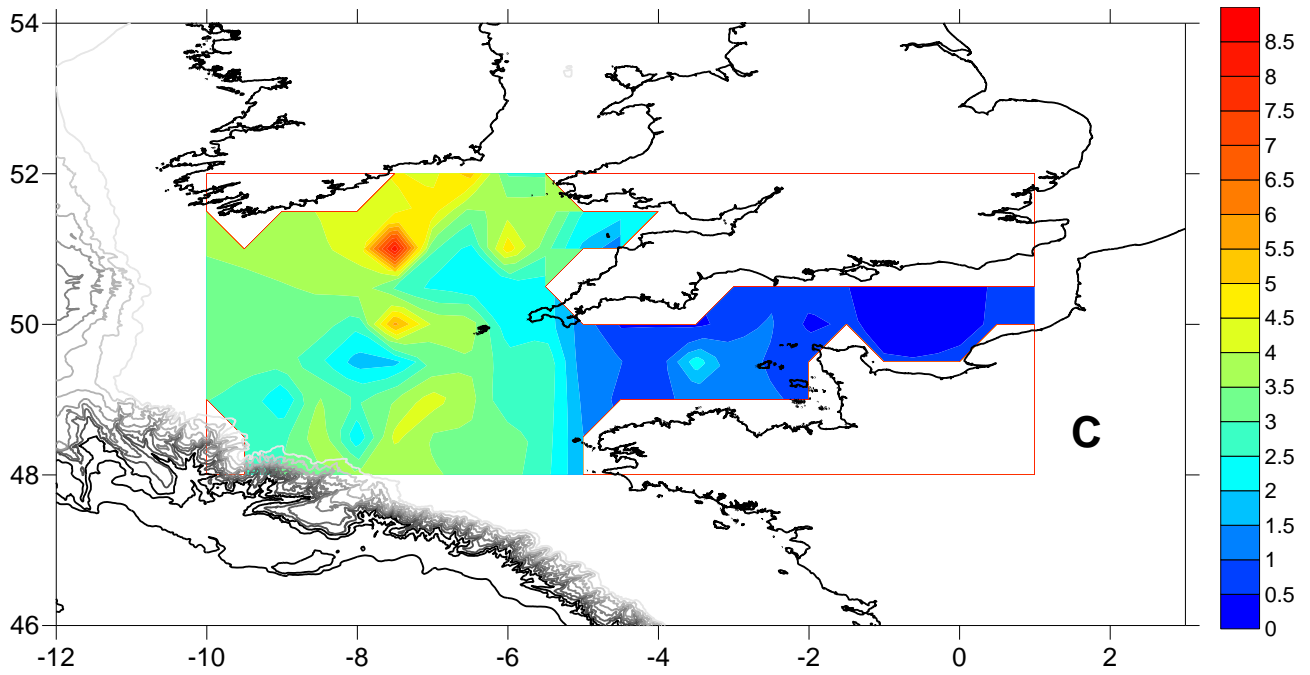
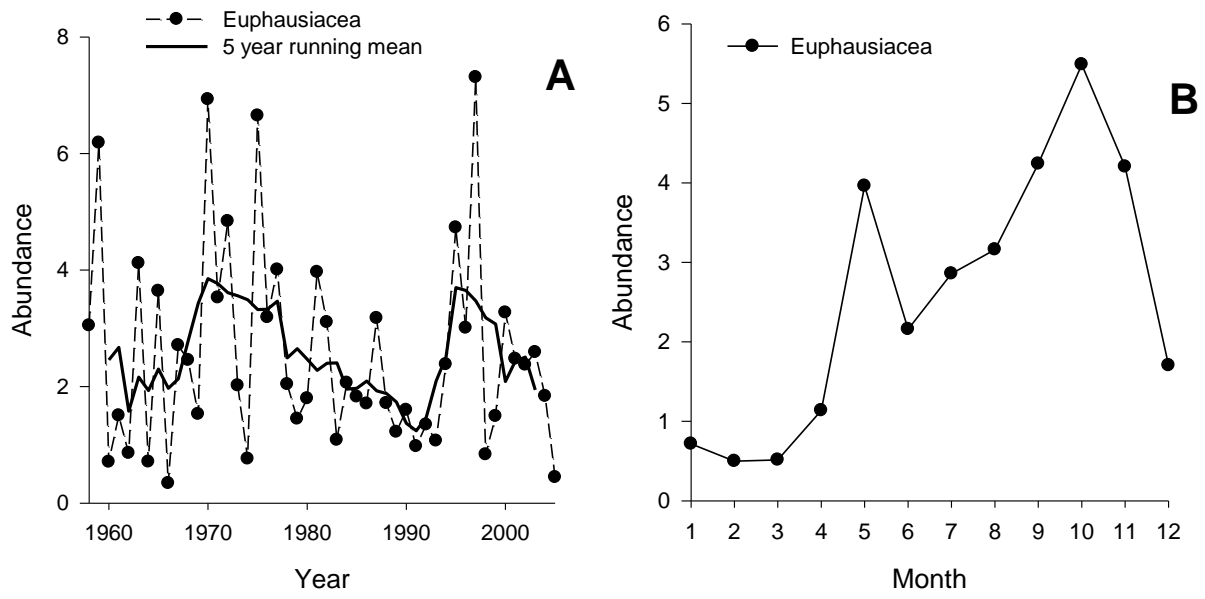


Fig 14 A) Euphausiid long term abundance B) seasonal cycle C) average spatial distribution

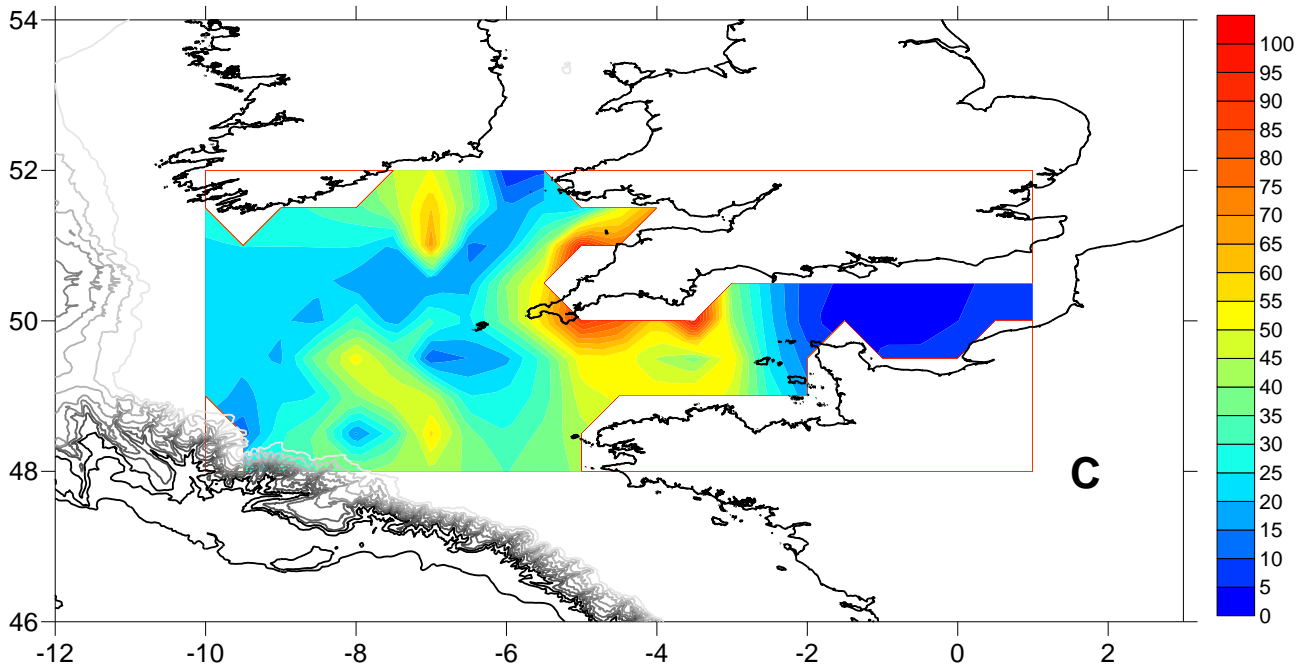
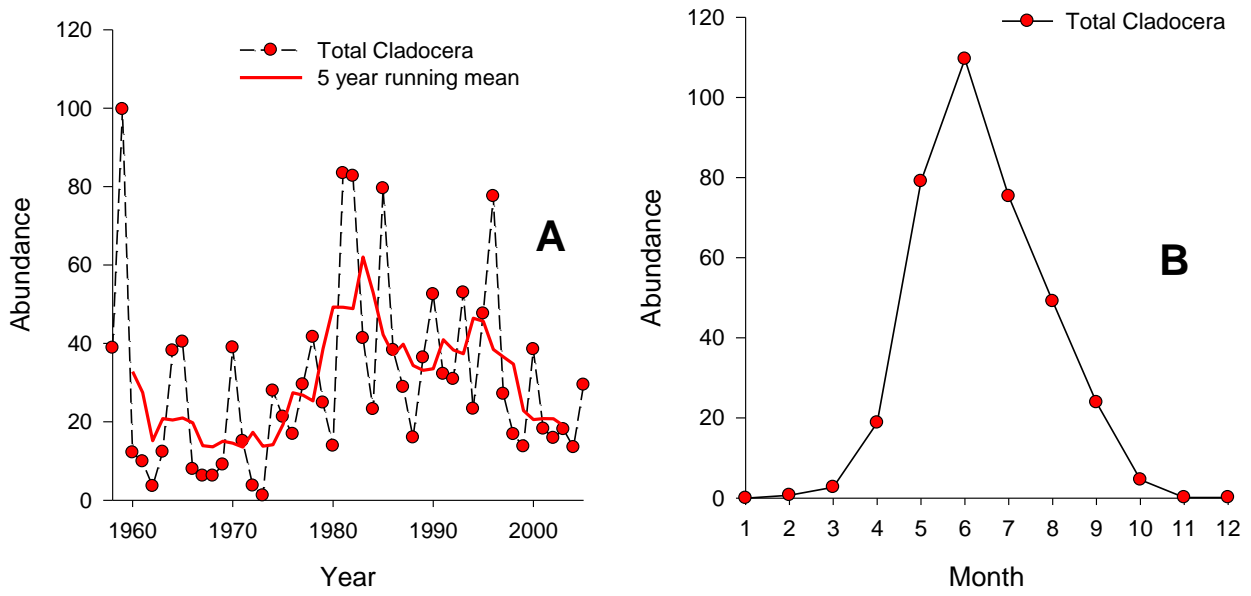


Fig 15 A) Total Cladocera long term abundance B) seasonal cycle C) average spatial distribution

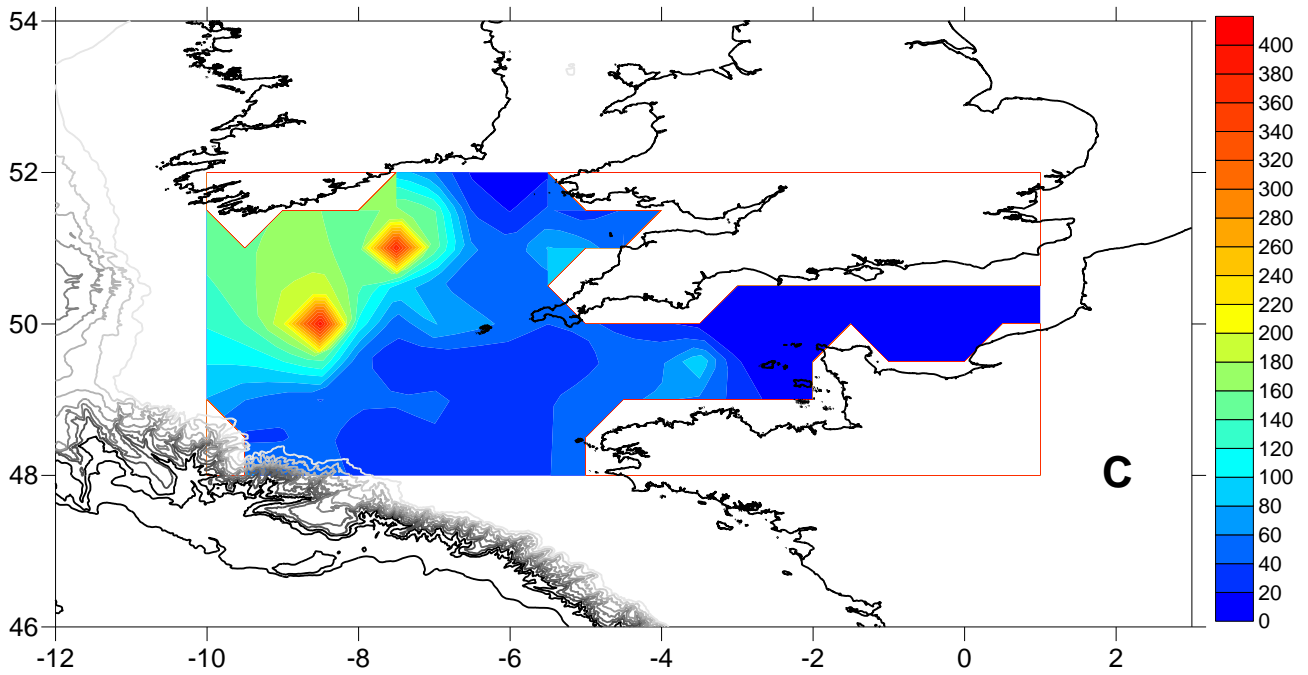
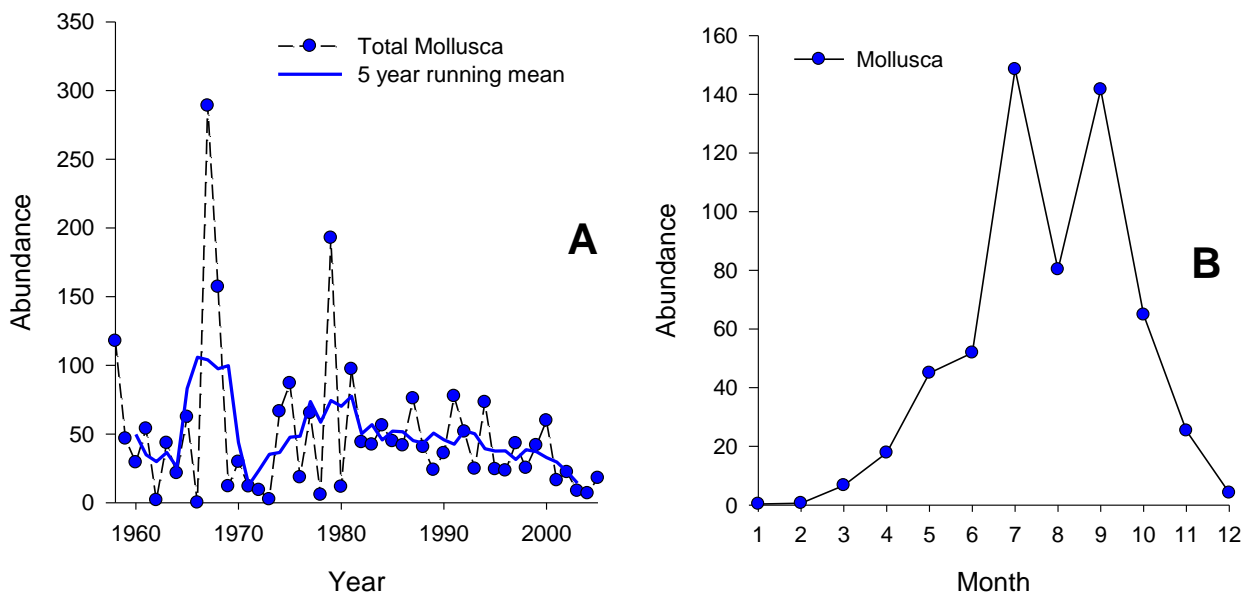


Fig 16 A) Total Mollusca long term abundance B) seasonal cycle C) average spatial distribution

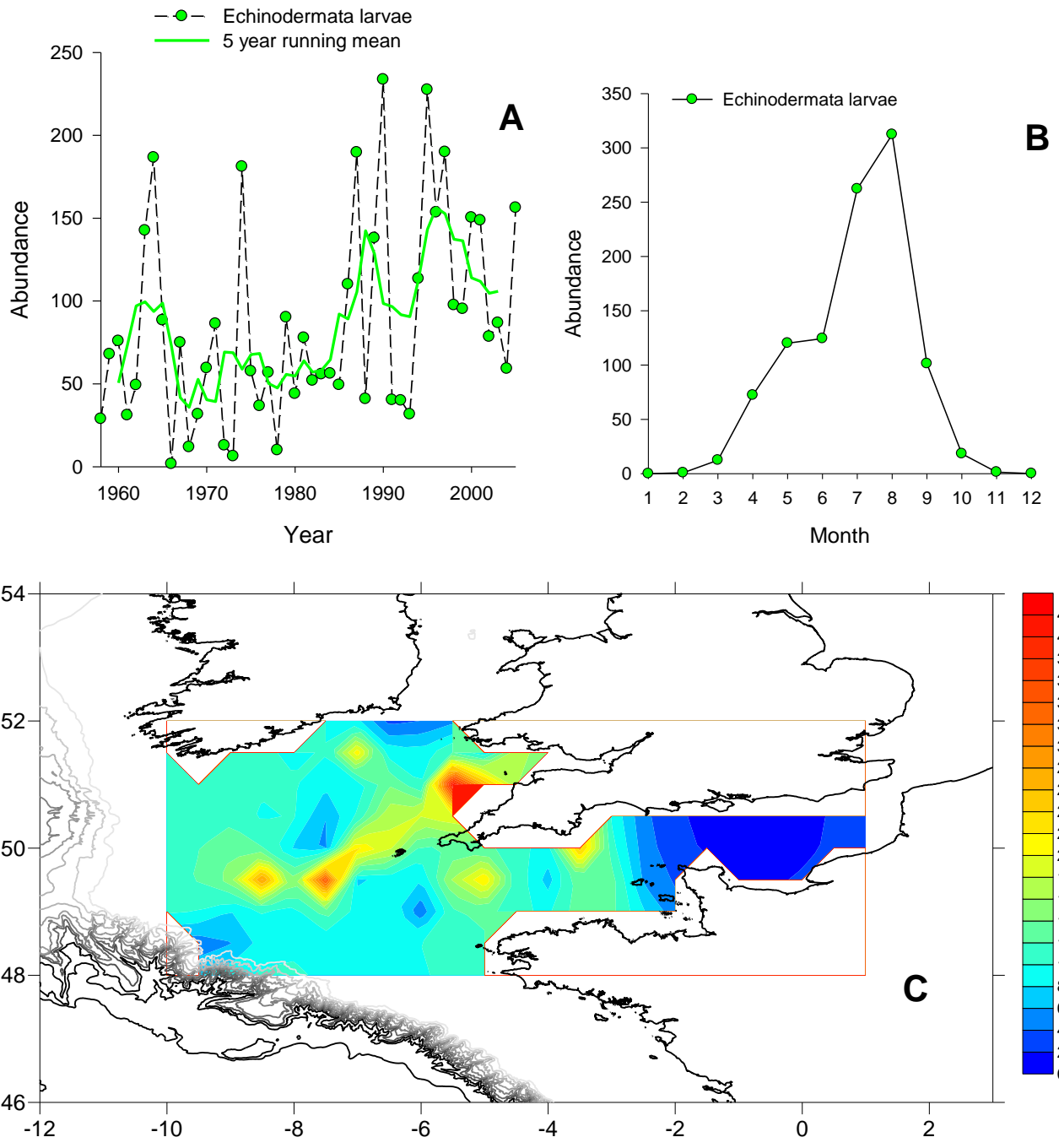


Fig 17 A) Echinodermata larvae long term abundance B) seasonal cycle C) average spatial distribution

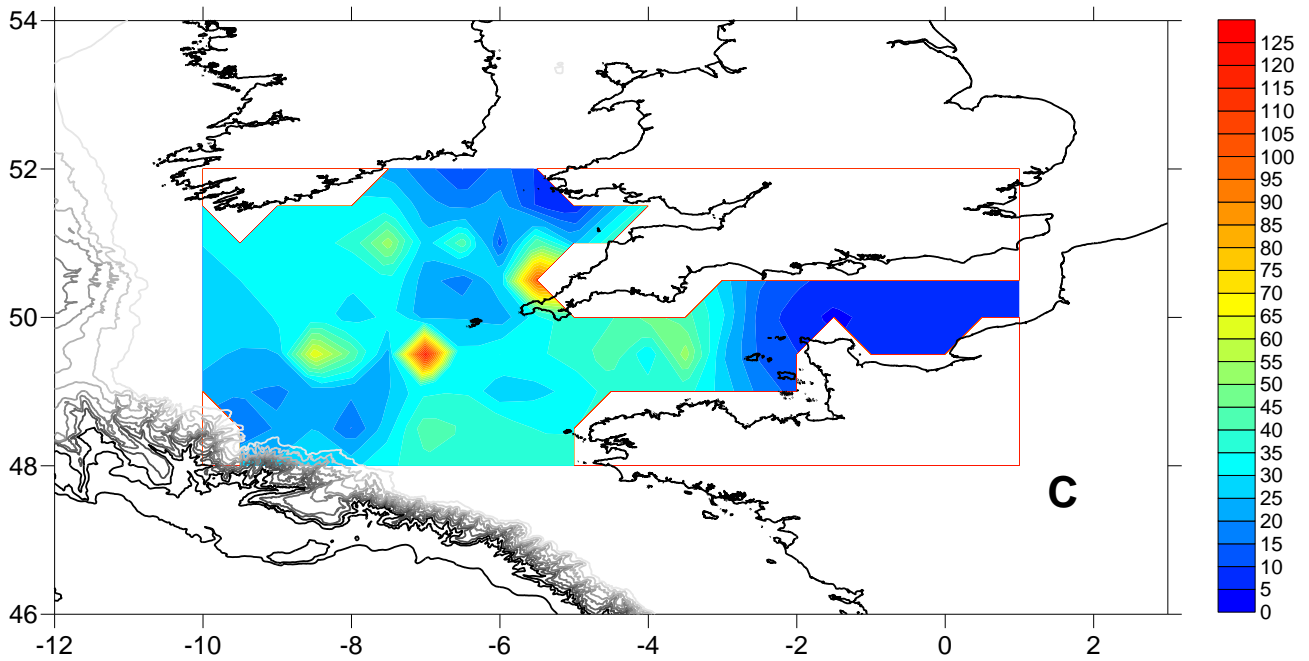
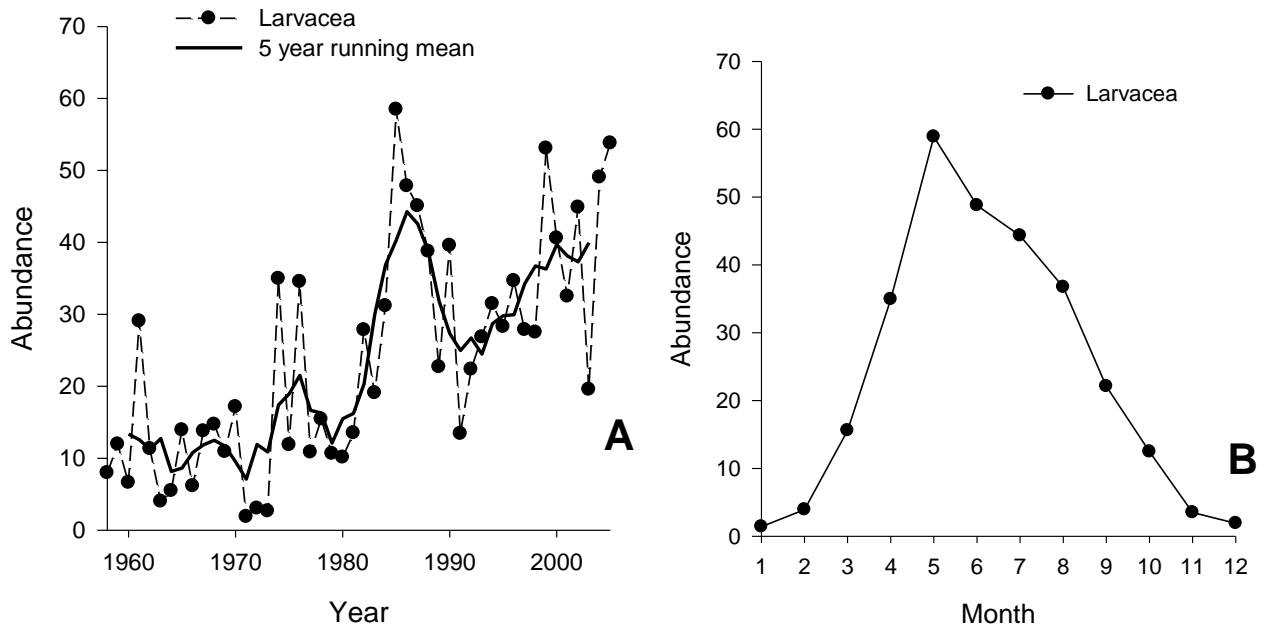


Fig 18 A) Larvacea long term abundance B) seasonal cycle C) average spatial distribution

3.2.15 Chaetognatha. Figure 19

Chaetognatha abundance has remained relatively stable over the study period, with a couple of peaks in the mid 1960s and the mid 1990s. One of the largest peaks in abundance occurred in 2003, latest data from 2005 is nearer the long term norm. The seasonal cycle sees an increase in number from July through to the end of the year, dropping off in February, with lowest values occurring from March until June. Spatially the group is fairly common throughout the SEA 8 area, with highest values found in the middle of the English Channel, around 3° West, the mouth of the Bristol Channel and southwest of the Isles of Scilly. The group is scarce in St. Georges Channel.

3.2.16 Polychaeta larvae. Figure 20

This group, composed primarily of *Tomopteris* spp. larvae, is recorded in low numbers, with peaks in abundance in the mid 1980s and mid 1990s, but virtually absent after 1999. The seasonal cycle shows peaks in the summer months through to autumn, with lowest values in the early spring. Spatially the group is scarce, absent from the English Channel and occurring in higher numbers out into the Celtic Sea.

3.2.17 Cirripede larvae. Figure 21

Long term data shows relatively stable, low numbers recorded in the SEA 8 area, but with an anomalously high value in 1989, far above the mean. Many years have zero values. The seasonal cycle follows a peak in April, followed by lower summer values and a slight secondary peak in the autumn. Lowest values occur from October through to February. Spatially the group is almost entirely confined to the east of the Ushant front area, but also occurring near the mouth of the Bristol Channel. The group is virtually absent outside the English Channel, ie in deeper waters.

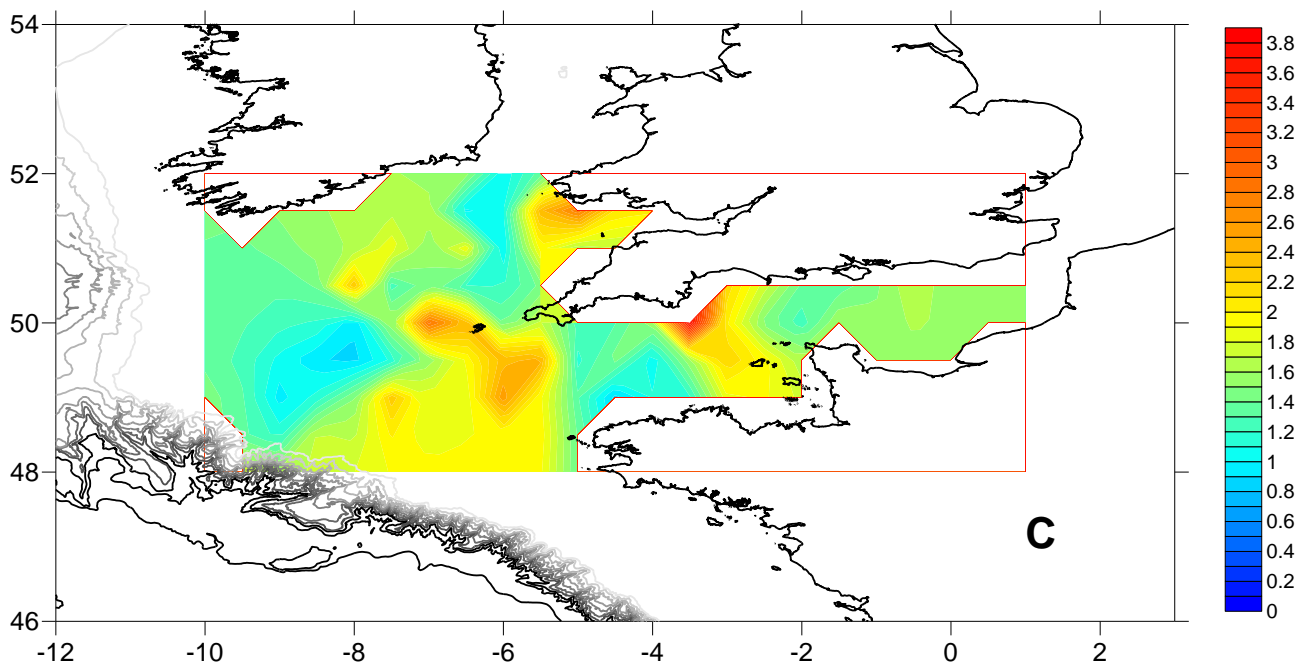
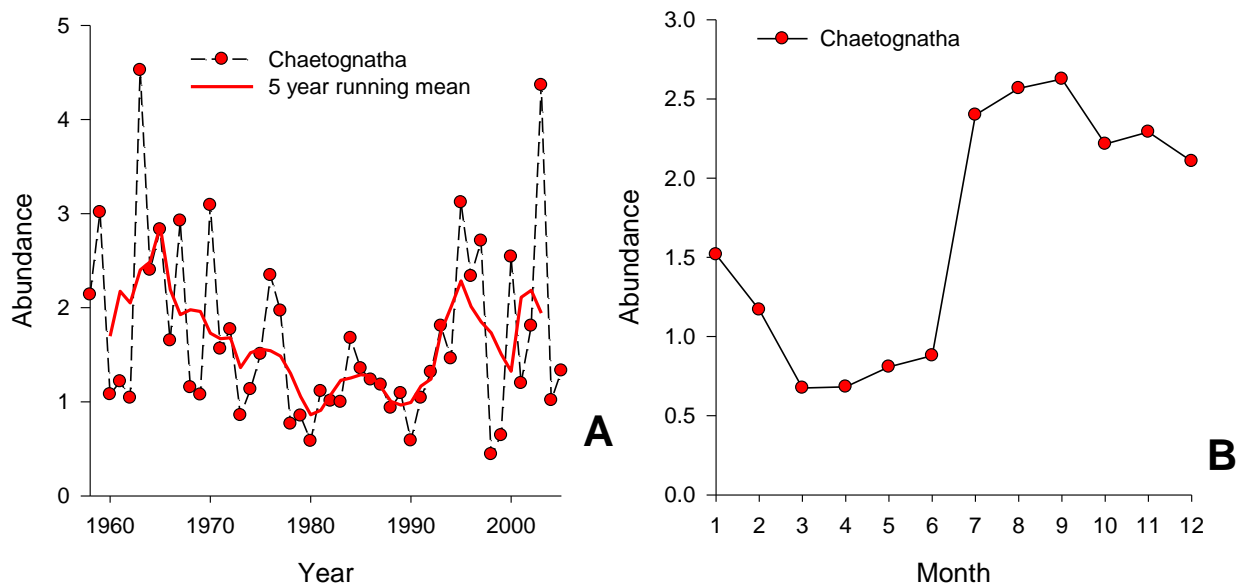


Fig 19 A) Chaetognatha long term abundance B) seasonal cycle C) average spatial distribution

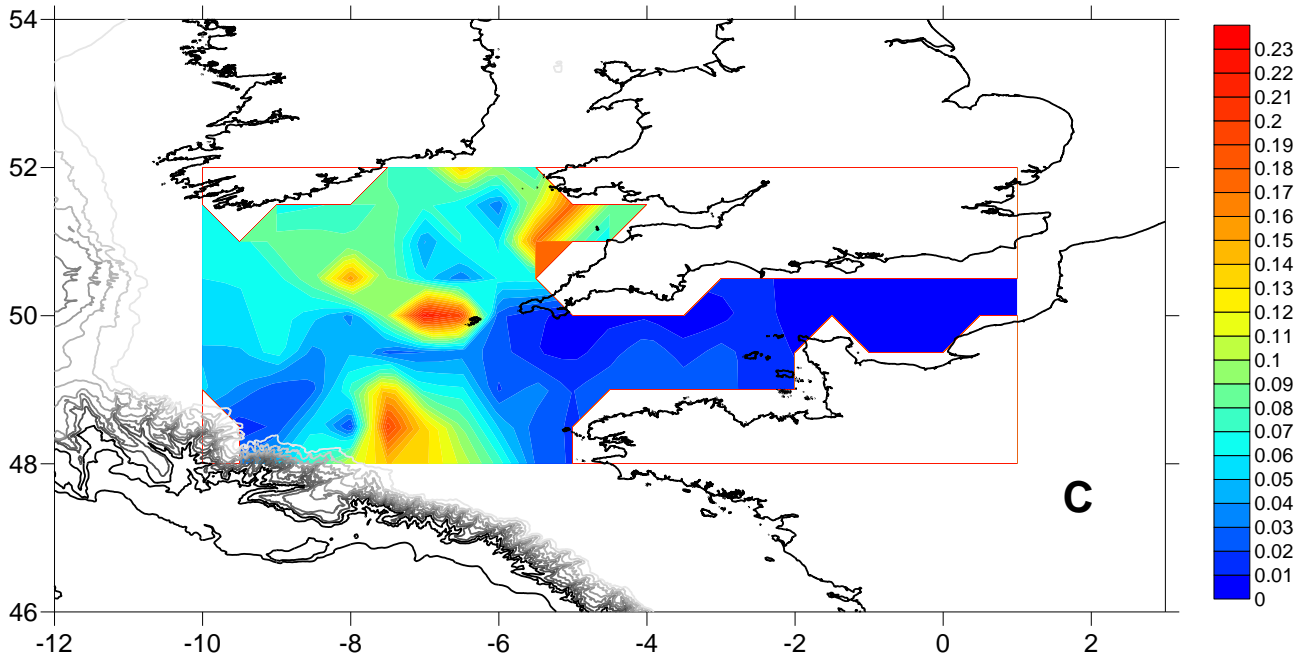
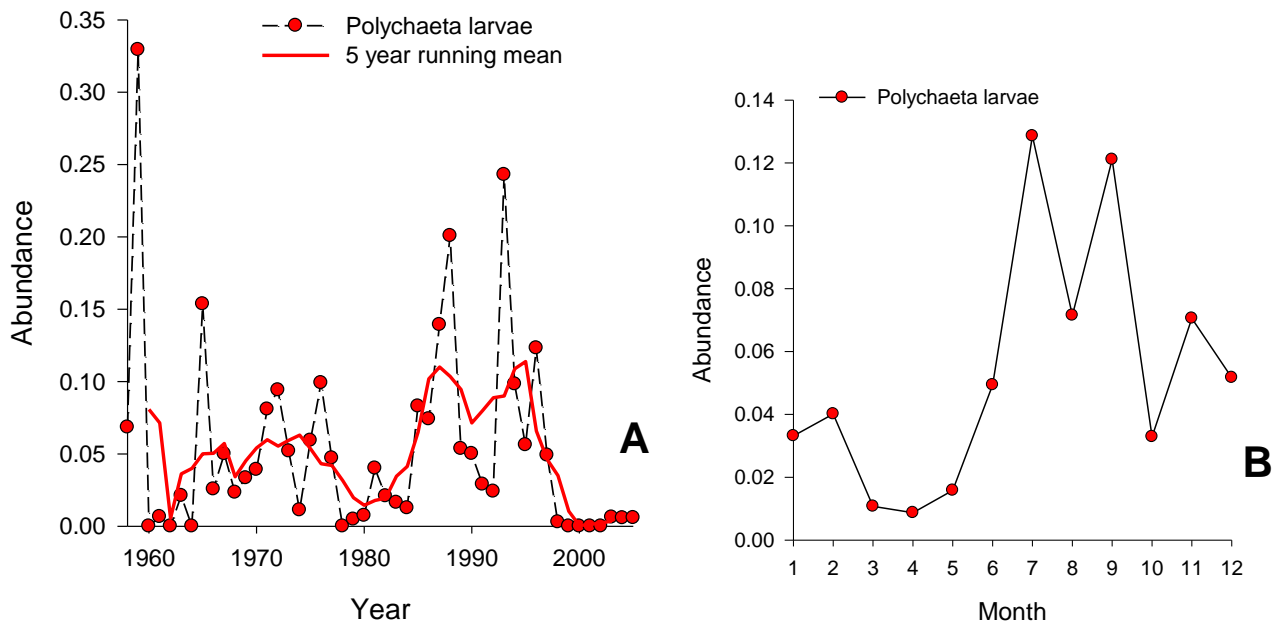


Fig 20 A) Polychaeta long term abundance B) seasonal cycle C) average spatial distribution

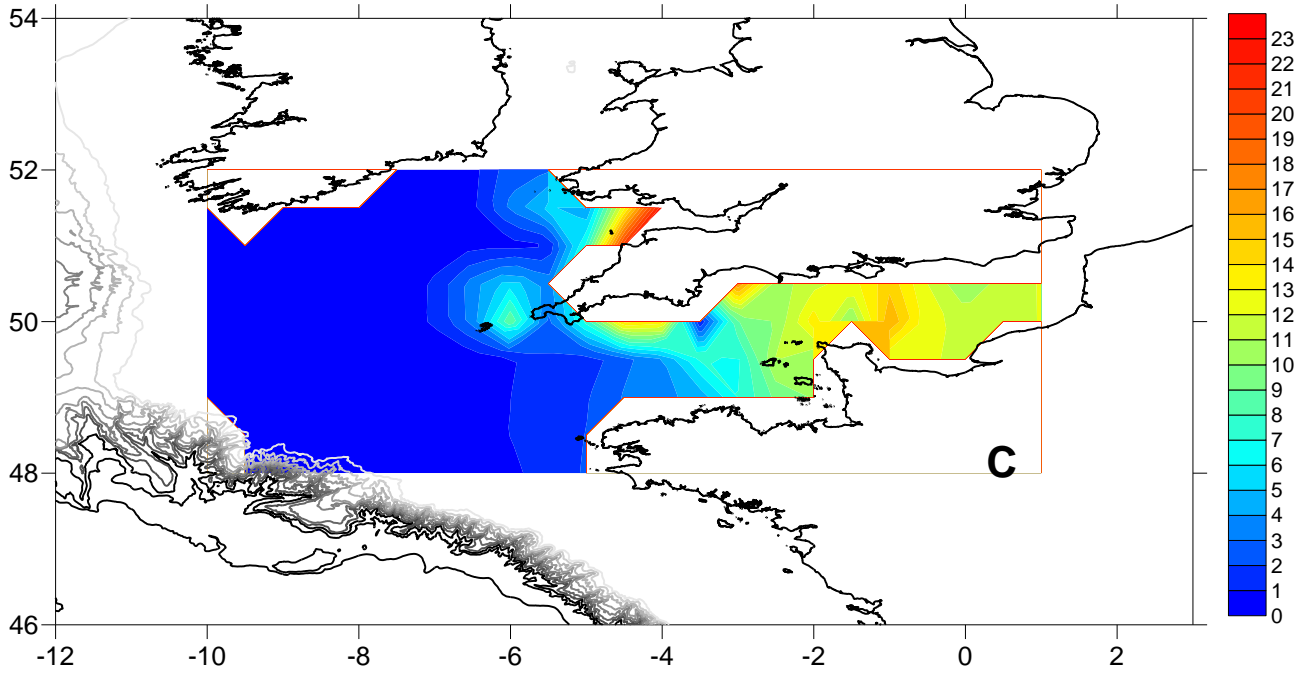
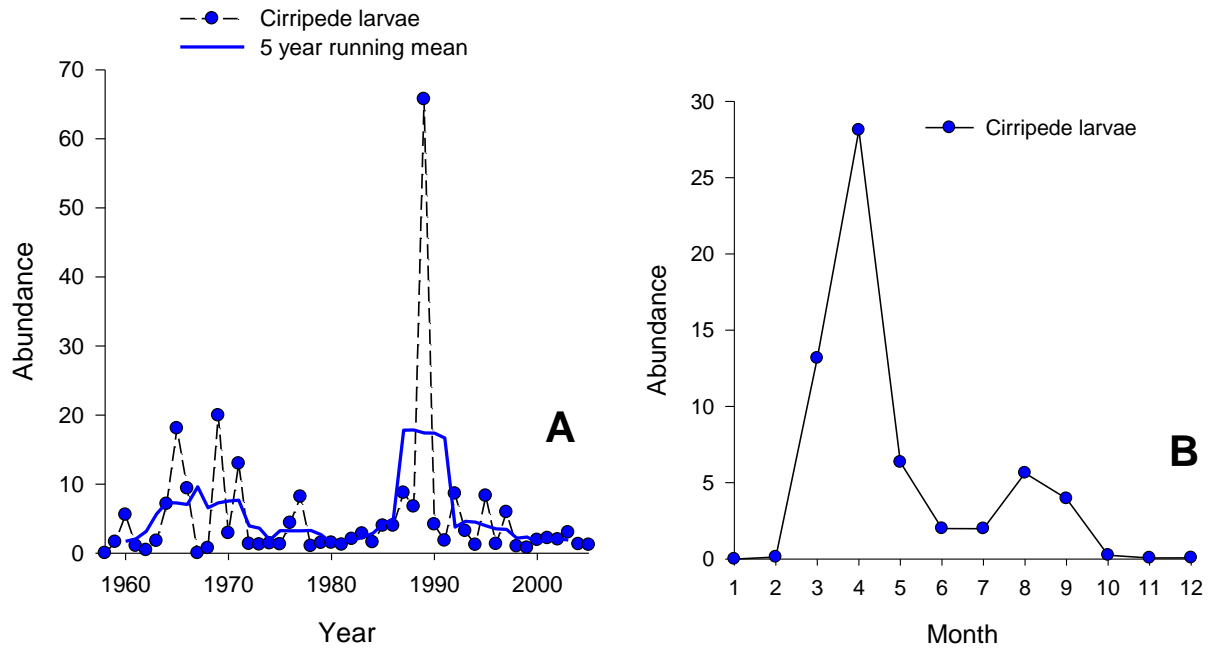


Fig 21 A) Cirripede larvae long term abundance B) seasonal cycle C) average spatial distribution

3.2.18 Gelatinous organisms. Figure 22

Gelatinous organisms, by their nature, have soft bodies that are easily damaged on contact with the CPR. It is not appropriate to record abundance, as matter found on CPR samples could have come from multiple sources. Despite this, Coelenterate tissue (mainly nematocysts) is recorded as present / absent, in this way the percent occurrence of gelatinous organisms can be discussed. The organisms recorded, ie those with nematocysts, are pelagic cnidarian groups, in particular scyphomedusae, hydromedusae and siphonophores. Recent work by Attrill et al. (2007) and Witt et al. (In press) has shown that this is a valuable indicator of changes in jellyfish abundance.

Long term abundance of Coelenterate tissue shows a peak in the mid 1980s (also recorded around other UK waters by Attrill et al. 2007), and a distinct rise in occurrence after a low in 2000, with the latest data from 2005 showing that almost 1 in 3 samples had Coelenterate tissue on. In contrast, 1972 had no records. Seasonally, values start to rise from lowest levels in April, to a peak in November. This seasonal pattern is likely due to a number of different groups contributing.

Figure 22 C) shows a contour plot combining the information of both figures A and B, to give a better idea of long term changes. The mid to late 1980s peak is clear, as is the large increase post 2000. There are also a number of isolated 'blooms' throughout the time period that would not be apparent from using graphs A and B alone. These bloom situations can occur rapidly when conditions are ideal, sometimes leading to the disruption of the local ecosystem (Mills, 2001), as jellyfish feed on many forms of plankton, from zooplankton to fish larvae and eggs (affecting fish recruitment). Attrill et al. suggest that jellyfish (gelatinous predators) occurrence will increase in UK waters over the next 100 years, potentially impacting the environment.

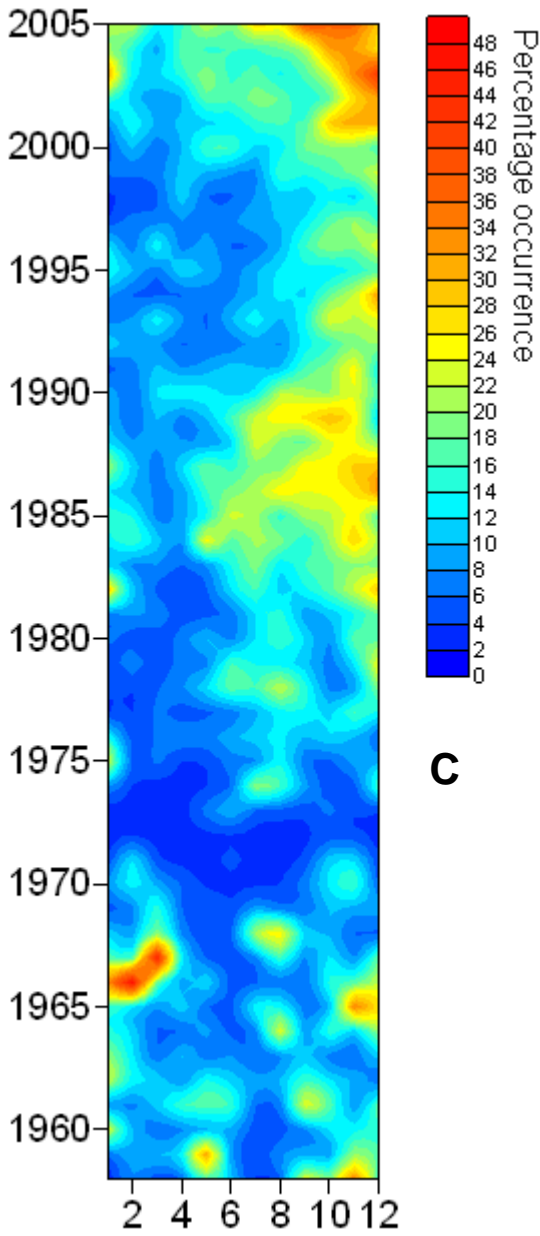
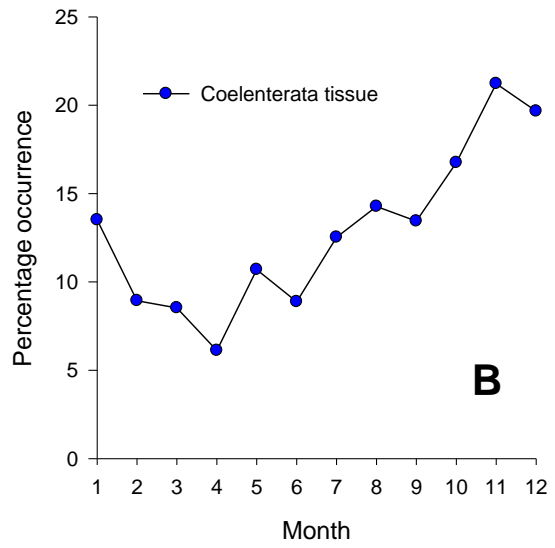
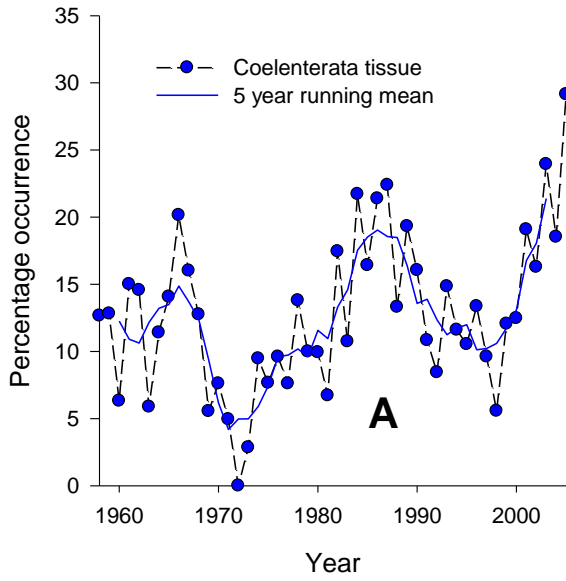


Fig 22 A) Long term percentage occurrence of Coelenterata tissue B) seasonal cycle and C) contour plot of long term seasonality

4 Process affecting the plankton

4.1 Sensitivity to contaminants and pollution

SEA 8 covers one of the busiest shipping areas in the world, the English Channel. Figure 23 shows the number of ships per year passing through the eastern side, and it can reach over 100000. Therefore, the potential to affect the marine ecosystem is high, in fact the area has been called 'most important oil spill hotspot worldwide' (Vieites et al., 2004), data from NOAA suggests though that the Gulf of Mexico, with 267 spills over 34 tons is the highest region (English Channel has 49 spills).

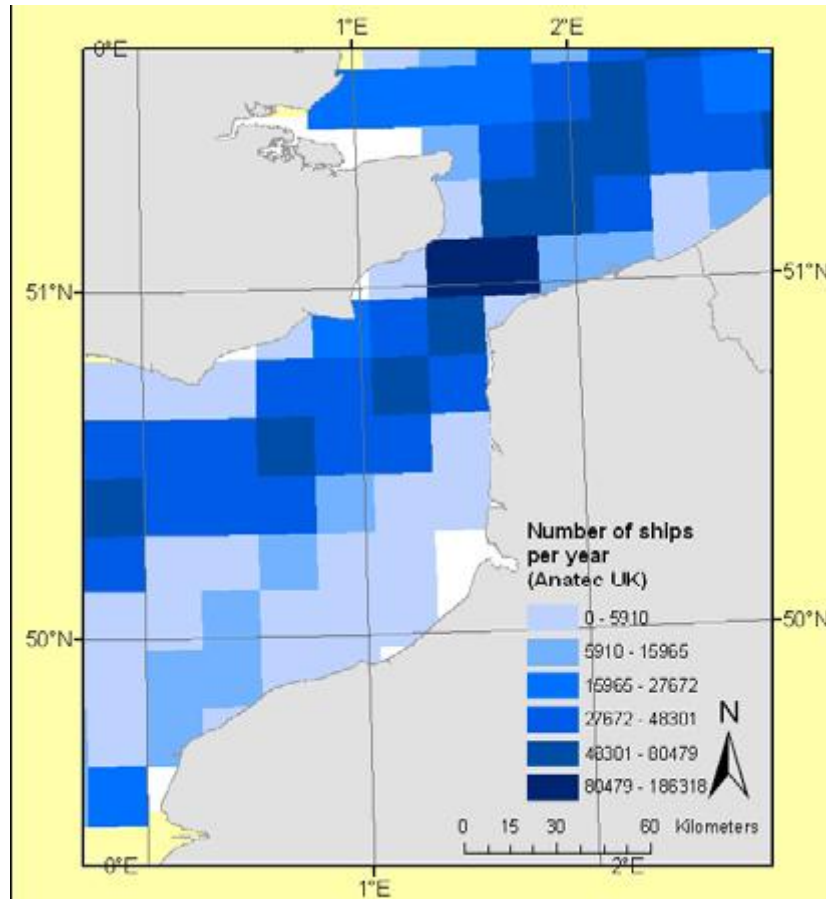


Figure 23. Number of ships per year in the eastern English Channel (source <http://charm.canterbury.ac.uk>)

The plankton community of the SEA 8 area is open to contamination from oil spills, as well as pollutants contained in freshwater run-off, much as any other shelf ecosystem. Some spills have allowed detailed examination of trophic level response to oil contamination, for example on adult, juvenile and larval stages of lobsters (Laurenson and Wishart, 1996). But results on adults are inconclusive, with mortality due to oil exposure low, although behavioural changes took place on a short term in adult and juvenile stages. Planktonic larval stages and eggs were more susceptible, with higher mortalities, and an enhanced level of premature hatching. This effect on eggs was also apparent in Clark's (1997) study of the response of capelin (*Mallotus villosus*) to oil, and the response of sea urchin eggs to Ekofisk crude oil (Falk-Peterson, 1979). Conversely to this finding, the photosynthesis (and hence primary production) of phytoplankton is enhanced by low (<50ng g⁻¹) levels of petroleum hydrocarbons (Gin et al., 2001).

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 (Frithsen et al., 1985, Poggiale and Dauvin 2001). 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 (possibly in a similar way to the aforementioned lobster study), 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. 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.

In addition to easily identifiable inputs of oil into the marine ecosystem (i.e. oil spills), industrial discharges and urban run-off of oil and other chemicals often amount to a greater volume. Pesticides for example can enter via runoff, and have a deleterious effect on phytoplankton communities (Rajendran and Venugopalan, 1983, DeLorenzo et al., 2002), particularly organochloride – based products, although there appears from some of the results to be an accumulation of toxins in the phytoplankton that are not necessarily passed up the trophic levels. Some pesticide chemicals disturb natural organic chemical communication in the plankton community (Hanazato, 1999), upsetting an ecosystem in a subtle way that is difficult to monitor.

As for pollution by shipping itself, the North Sea and English Channel will become a SECA (Sulphur oxide Emission Control Area) in November 2007. Ships sailing in SECAs must either use fuel oil with a maximum sulphur content of 1.5% m/m or fit an approved exhaust gas cleaning system or other technological method to reduce the emission of sulphur oxides to 6.0g SO_x/kWh or less (source www.seaat.org).

4.2 Resting stages in sediment and ballast waters

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. In phytoplankton, 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. The cysts often pass through the guts of deposit feeders before germination, and the ingestion process, far from being detrimental can in fact increase germination success (Kremp et al. 2003). The formation and germination of resting cysts represents a positive gain to a population through seeding, although there is a negative effect of sedimentation (Itakura et al. 1997). Excystment is commonly thought to be triggered by temperature, although light and oxygen levels to a lesser extent maybe involved (Paranjape 1980, Müller 2002).

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 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.

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. Tropical species may also be carried in this way and could pose an invasive threat. 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 a successful establishment of a self-sustaining population of exotic species is expected to increase with greater volumes of ballast water and reduced ship transit times (Rosenthal et al. 1998). Ships have been recognised as a major vector for the introduction of non-indigenous and harmful organisms (with their large volumes of ballast). Recent publications have advocated the use of ultraviolet radiation followed by a period of darkness to prevent photorepair (Sutherland et al. 2001, Wonham et al. 2001). 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).

In the zooplankton most information comes from copepods of which 44 species have been shown to produce two types of eggs, the normal or subitaneous eggs and resting or diapause eggs. The production of these diapause eggs is caused by a change in environmental conditions and is induced by high population densities or a combination of shortening day length and temperature reduction. Once formed these diapause eggs do not develop immediately but sink to the seabed. If buried in the sediment the duration of the resting stage is increased and in some species can remain viable for as long as 40 years. However, in general the resting stages are a seasonal occurrence and hatch-time is measured in months, triggered by a period of cooling. (See review in Mauchline, 1998).

It has been known since the 1890's that planktonic organisms can survive within ships ballast tanks, and a number of biologists used ship seawater systems to collect plankton samples. However, it was Ostenfeld (1908) who first proposed shipboard transportation of an organism as an explanation concerning the occurrence of the Asian diatom *Odontella (Biddulphia) sinensis* into the North Sea in 1903. During transport in ballast tanks organisms have to put up with hostile conditions with a lack of light, varying temperatures, and reduced food availability (Carlton, 1985). However, as some planktonic organisms can produce resting stages, their survival in even the harshest conditions and subsequent hatching is commonplace.

A study in Australia (Hallegraeff and Bolch, 1992) surveyed cargo boat ballast tanks and showed 65% were carrying significant amounts of silt in the bottom of their ballast tanks. All of these sediments contained diatoms and diatom auxospores and 50% contained dinoflagellate resting spores that were not endemic to Australian waters. As well as transport in the sediment, Williams et al. (1988) found 22 zooplankton species and 45 other planktonic taxa in ballast water, in cargo vessels operating between Japan and Australia. Therefore, it can be assumed that sediments and water in ballast tanks are an important vector for the spread and introduction of planktonic species. Introduction of such species can lead to the problem of genetic mixing of different stocks and the introduction of new species to an environment (Carlton, 1985). It is also noted that the transport of these organisms can also occur on a smaller scale in domestic traffic, which can rapidly move nuisance species and increase the distributional ranges of species (Lavoie et al., 1999).

The introduction of a new species can have unfavourable effects and one such introduction reported for European waters is the non-indigenous diatom *Coscinodiscus walesii* originally from the Pacific and Sea of China. It was first reported in the English Channel in January of 1977 and by June/July of 1978 was found in the eastern Irish Sea and now has a sizable population and is regularly recorded from UK waters (Edwards et al., 2001). Although non-toxic, blooms have been reported to produce large quantities of mucilage which attracts sediment particles causing problems to fishermen, such as the clogging and breaking of fishing nets (Boalch & Harbour, 1977).

The introduction of new marine species from ballast waters has increased from the 1960's and is now thought to be responsible for about 20% of all new species introduced to the marine environment in Britain. It is potentially difficult to separate some of these arrivals (for example the

warm water cladocera *Penilia avirostris* (Johns et al. 2005) with northerly movements of the plankton that have been recorded (Beaugrand et al. 2002).

4.3 Climate forcing

The influence of climatic processes upon plankton community dynamics within the SEA 8 region are complex, with areas of seasonal stratification, areas under the influence of open ocean and shelf edge processes, and freshwater inputs. The northern Atlantic Ocean plays a key role in the global circulation of water. It is in this region that the deep water mass characteristics of the global ocean are determined and the interaction between climate and the oceans are at their most dynamic. The climate of the SEA 8 region is dominated by the so-called North Atlantic Oscillation (NAO) which determines the strength and direction of winds blowing over the UK and western Europe. The NAO is governed by the relative differences in Atmospheric pressure between the low pressure region centered around Iceland and the high pressure region located near the Azores. It is the fluctuations in these low-high pressure regions that determine the frequency and severity of storms and the amount of rainfall that falls within the SEA 8 region. Fluctuations in the severity and duration of winter storms have several implications for the plankton community of these waters.

During periods when the winter high atmospheric pressure cells over the Azores are intensified there is a general strengthening of winter southwesterly winds over the North East Atlantic. During such times the maritime regions of western Europe receive increased amounts of precipitation. Increased precipitation falling on land will invariably increase both the amount of dissolved available nutrients and sediment load entering the coastal waters. This can have several implications for the phytoplankton community. Firstly, increased nutrient loading to the system during the winter months can be responsible for elevated phytoplankton growth during the spring and summer. Secondly, increased sedimentary loads to the coastal zone can limit the depth of the photic zone potentially limiting phytoplankton growth via light limitation. In more offshore waters the timing of the spring bloom are linked to the onset of stratification of the waters column. If wind strengths remain high during the early spring then stratification can be delayed due to wind-driven mixing processes, this in turn can delay the spring bloom as the phytoplankton require relatively stable waters and a favourable light climate for bloom development. As phytoplankton are the base of the marine food-web such climatically modified processes can have a knock on effect throughout the food chain.

Changes in SST, through global warming, can have pronounced effects on the planktonic community, such as biogeographical shifts, phenological shifts and successful invasions by 'alien' species. For instance, the calanoid copepod community has shifted 10° northwards over the last few decades (Beaugrand et al. 2002), bringing warmer water species into the SEA 8 area, and displacing the colder water community. On a higher trophic level, at the southwestern edge of the SEA 8 area, during the last couple of years there has been an enormous increase in the number of pipefish (*Entelurus aequoreus*, Kirby et al., 2006). The reason for the increase could be due to a rise in sea surface temperatures (SST), affecting the animals physiology. Male *E. aequoreus* brood the eggs on their abdomen, where they are laid by the females in an incubation area. Whilst the eggs are in position, the males are unable to mate with the females, who are batch spawners. It is thought that *E. aequoreus* responds to a rise in temperature similarly to the related *Sygnathus typhle*, where an increase in sea temperature from 10 to 15°C can reduce egg incubation time by approximately 23 days. This would allow the males to breed more frequently (Kirby et al., 2006). Another possible reason for the increase could be due to changes in the plankton prey of the pipefish. These changes could be in abundance or distribution of prey species, both of which may have altered due to increased SST. For example, there has been a decrease in the abundance of *Calanus* around the UK (Edwards et al., 2006), and the aforementioned northward shift in calanoid copepods (Beaugrand et al., 2002). Incidentally, there have been other reports of increased numbers of pipefish around UK waters (Harris et al., In press).

Phenology is the study of the timing of recurring natural phenomena (e.g. seasonal events). Interannual changes in seasonal /successional timing is considered to be a good indicator of climate change (Edwards et al. 2006). For example, interannual changes in the timing of species

associated with the spring bloom, or the earlier appearance of dinoflagellates, associated with summer stratified conditions, may indicate hydroclimatic changes. The physiological development of meroplankton to temperature is very sensitive, and there has been a major trend towards an earlier seasonal peak. In particular, since 1988, with the exception of 1996 (a negative NAO year), the seasonal development of decapod larvae has occurred much earlier than the long-term average. For example, the seasonal cycle has been up to 4-5 weeks earlier in the 1990s than the long-term mean. This trend towards an earlier seasonal appearance of meroplanktonic larvae during the last decade is highly correlated to SST (Edwards and Richardson, 2004).

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