A1a.1   Plankton

A1a.1.1   UK context

This section describes the plankton community of UK waters, and how this has changed over the past few decades. The plankton community may be broadly divided into a plant component (phytoplankton) and an animal component (zooplankton). The ecology of the plankton community is strongly influenced by environmental and, potentially, anthropogenic factors. Consequently the plankton acts as an important link between the biological and physical components of the ecosystem. Members of the plankton are key producers and primary consumers in marine ecosystems and so population changes will have impacts on organisms at higher trophic levels, with environmental and economic consequences. Plankton across the north Atlantic has been monitored for over 80 years by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), using the Continuous Plankton Recorder (CPR). Remote sensing by satellites such as the Coastal Zone Colour Scanner (CZCS - 1978-1986) and Sea-viewing Wide Field-of-View Sensor (SeaWiFS – 1997-2010) is also used to examine phytoplankton biomass, which may be measured on the Phytoplankton Colour Index (PCI). From these data, changes in abundance and long-term trends can be distinguished.

The majority of the plankton is found within the top 20m of the water column, known as the photic zone, into which light can penetrate, allowing photosynthesis to take place. The phytoplankton accounts for <1% of the total photosynthetic biomass on Earth, but is responsible for almost 50% of primary production (Field *et al.* 1998). The phytoplankton commuity is dominated by dinoflagellates and diatoms. Diatoms are encased in a silicon shell, or test, and are predominantly autotrophic. Dinoflagellates have a pair of flagella and can produce energy both autotrophically and heterotrophically. In the north-east Atlantic, diatoms comprise a greater proportion of the phytoplankton community than dinoflagellates from November to May – see Figure A1a.1.1 (McQuatters-Gollop *et al.* 2007). The phytoplankton also includes smaller flagellates, sometimes known as the pico- or nanoplankton, which are difficult to study because of their size and consequently are under-researched. Nanoplankton can be a significant component of the phytoplankton community, with abundances of *Phaeocystis pouchetti* peaking in early spring and abundances of the coccolithophore *Emiliana huxleyi* peaking in late summer and autumn (Boney 1986).

The zooplankton communities are dominated in terms of biomass and productivity by copepods, particularly *Calanus* species such as *C. finmarchicus* and *C. helgolandicus*. There is a strong geographical divide between these two species, with *C. finmarchicus* more abundant in colder, more northern waters and *C. helgolandicus* dominating warmer waters in more southerly regions, though their ranges show considerable overlap. Calanoid copepods are large crustaceans which range in size between 0.5-6mm and are an important prey item for many species at higher trophic levels. Other important taxa include *Acartia* spp., *Temora longicornis* and *Oithona* spp. The larger zooplankton, known as megaplankton, includes euphausiids (krill), thaliacea (salps and doliolids), siphonophores and medusae (jellyfish). The gelatinous taxa are poorly sampled as their bodies disintegrate on contact with the CPR although they are known to be more abundant in late summer and autumn (Witt *et al.* 2007, Pikesley *et al.* 2014).

Figure A1a.1.1: Mean monthly spatial patterns of (a) diatoms, (b) dinoflagellates and (c) their relative community abundances (as percentage diatoms) in NE Atlantic between 1958-2003.
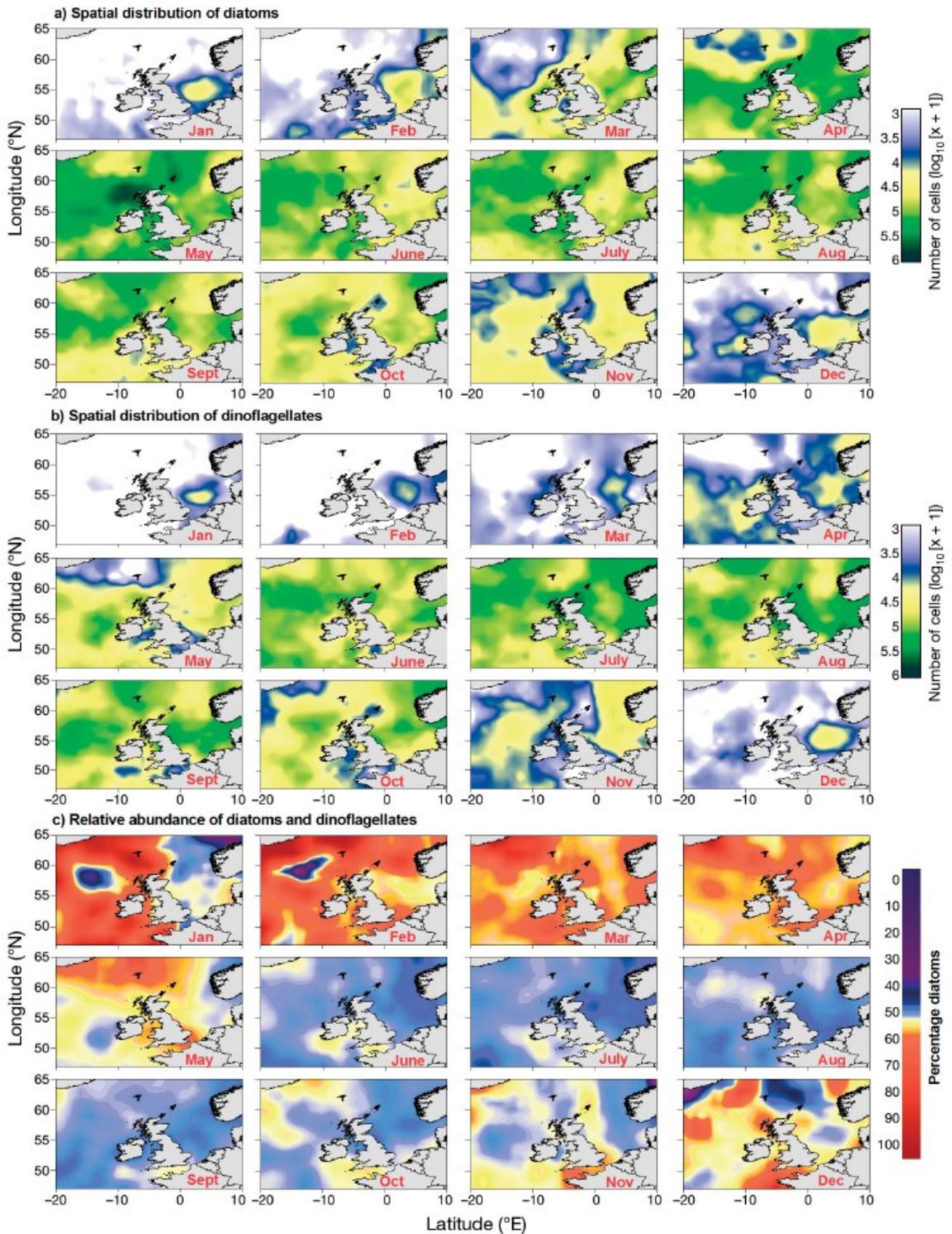
Source: McQuatters-Gollop *et al.* (2007)

Krill is very abundant throughout the North Sea and is a primary food source for fish, seabirds and whales. Siphonophores (colonial hydrozoa) can reach large densities under favourable conditions. Cosmopolitan species of jellyfish such as *Cyanea lamarckii*, *C. capillata* and *Aurelia aurita*, are abundant around all UK coasts (Hay *et al.* 1990, Pikesley *et al.* 2014), while other species, such as the barrel jellyfish, *Rhizostoma octopus*, are geographically limited. Pikesley *et al.* (2014), using public sightings data, demonstrated that the highest frequency of reported jellyfish observations was in the south-west of the UK during the summer months. Jellyfish typically have short life-spans and high growth rates. Consequently they are able to respond to favourable conditions very rapidly (Lynam *et al.* 2004). The interannual variability of jellyfish populations has been reported previously in Lynam *et al.* (2004, 2005, 2011). Physical discontinuities, such as differences in water column stratification can act as barriers between species, leading to apparent segregation between species, as demonstrated in the Irish Sea by Doyle *et al.* (2007).

The meroplankton comprises the larval stages of benthic organisms and fish that spend a short period of their lifecycle in the pelagic stage before settling on the benthos. Important groups within this category include the larvae of starfish and sea urchins (echinoderms), crabs and lobsters (decapods) and some fish.

Certain species of phytoplankton and zooplankton form resting cysts which sink to the bottom sediment where they remain until they are resuspended. This feature allows them to survive unfavourable conditions, when nutrient availability may be low. Dinoflagellates (including toxic species associated with paralytic shellfish poisoning (PSP)) and the copepod genera *Acartia* and *Centropages* commonly form resting cysts. Resting cysts are usually found in silt or mud sediments (Johns & Reid 2001).

The development of plankton indicators to inform MSFD and OSPAR assessments has been the focus of recent research (e.g. Bedford *et al.* 2018, 2019, 2020, McQuatters-Gollop *et al.* 2019). The UK initial assessment of Good Environmental Status with respect to the MSFD (HM Government 2012) concluded that although there was clear evidence of regional-scale change in the composition and abundance of plankton communities linked to rising sea temperatures, plankton as a whole were considered healthy and subject to few direct anthropogenic pressures. Since the initial assessment, new indicators of zooplankton and phytoplankton community structure and biomass have been developed and utilised by the OSPAR Intermediate Assessment[1] [2]. The more detailed assessment in 2018 (Defra 2019) largely confirmed the initial assessment findings, but work is underway to improve our understanding of the extent that natural variability, climate change, ocean acidification and cascading effects from anthropogenic activities such as fishing may be contributing to change. Therefore, whilst the updated assessment indicated that it was likely that GES would be achieved by 2020, not knowing the effect of human activities meant that this was uncertain (Defra 2019).

A1a.1.1.1   Plankton blooms

Typically in the temperate seas a phytoplankton bloom occurs every spring, generally followed by a smaller peak in the autumn. Productivity will be determined by a combination of seasonal changes in light penetration and a cycle of nutrient introduction into the water column through

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[1] https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/habitats/changes-phytoplankton-and-zooplankton-communities/
[2] https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/habitats/plankton-biomass/

mixing and turbulence caused by winds in the autumn and winter, followed by nutrient depletion as phytoplankton blooms.

Figure A1a.1.2: Satellite image of plankton blooms around the UK in June 2020

Note: Clear skies and unseasonable heat was experienced in northwestern Europe in spring and early summer 2020, providing conditions to promote large and persistent blooms of phytoplankton in the waters around the UK and Ireland. The milky, light-coloured waters are probably filled with coccolithophores, while greener waters may be rich with diatoms or suspended sedimenT. Source: NASA Earth Observatory website[3]

The progress of the spring bloom, primarily comprising diatoms, is predominantly dependent upon episodic turbulence following short periods of stratification, which allows the re-suspension of phytoplankton and the mixing of nutrients into the photic zone. The spring bloom of diatoms typically begins in shallow regions, such as the southern North Sea, where there is greater light penetration, and mixing leads to a greater quantity of re-suspended material from the seabed (McQuatters-Gollop *et al.* 2007). In spring, as the day length increases and the water column becomes more stratified, there is a bloom of diatoms (Williams & Lindley 1980). As little mixing of the water occurs, silicates, which are essential for diatom

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[3] https://eoimages.gsfc.nasa.gov/images/imagerecords/146000/146897/englishchannel_tmo_2020176_lrg.jpg

growth, become depleted and other groups such as flagellates, followed later by dinoflagellates, bloom. In most regions, the diatom population peaks between April and July, while dinoflagellates peak in the late summer, when the water tends to be more stratified – see Figure A1a.1.1. This is typical of waters in the north-east Atlantic, as increased levels of stratification in the summer promote the growth of dinoflagellates, while opportunistic diatoms flourish in a more turbulent, nutrient-rich water column (Margalef 1973, cited in Leterme *et al.* 2006).

Consequently, phytoplankton biomasses may be relatively low in estuarine environments, where there is high turbidity, for example in the Severn Estuary (Underwood 2010). The factors that affect the onset of the bloom are complicated and difficult to resolve, with variables such as air-sea flux (Taylor & Ferrari 2011) and sub-surface eddies (Mahadevan *et al.* 2012) proposed as key drivers and predictors of the bloom. In addition to this, different environmental variables will take on greater significance in different locations – for example, in deeper oceanic waters stratification in the water column is a key driver of the spring bloom, while in coastal waters, the amount of incidental light is a more important factor (Wiltshire *et al.* 2008).

Under certain conditions (e.g. rapid reproduction, reduced grazing pressures, favourable environmental factors), blooms can occur at other times of the year. Many of these blooms involve nuisance or noxious species and are described as Harmful Algal Blooms (HABs). Examples include those connected with Paralytic Shellfish Poisoning (PSP), such as the dinoflagellate *Alexandrium tamarense*. Other groups known to cause HABs include *Dinophysis* spp. and *Prorocentrum* spp. (both associated with shellfish toxins), *Tripos furca*, and *Noctiluca* spp. (both associated with nuisance blooms) (Edwards *et al.* 2006).

A1a.1.2   Features of Regional Sea 1

The northern North Sea was, until recently, a cold-boreal province. However, after the late 1980s regime shift, the northern North Sea is now considered a temperate province. Plankton in the northern North Sea generally comprise Atlantic and offshore species as these waters are stratified during summer months. The inflowing warm, nutrient rich waters from the north Atlantic are thought to be a factor promoting earlier stratification (Drinkwater *et al.* 2003), conditions suited for successful competitors such as dinoflagellates (Margalef 1973, cited in Leterme *et al.* 2006); dinoflagellates typically comprise a greater proportion of the phytoplankton community than diatoms from June to October, when waters will be most stratified - see Figure A1a.1.1 (McQuatters-Gollop *et al.* 2007). Data from the Marine Scotland Scottish Coastal Observatory monitoring site at Stonehaven indicated a decrease in the abundance of the summer dinoflagellate *Tripos* since 2000, which has begun to recover (Bresnan *et al.* 2016) in line with patterns observed in the open northern North Sea (Edwards *et al.* 2020). The spring bloom in this region is stronger, relative to the autumn bloom, than elsewhere (Longhurst 1998). HABs observed in the region include the diatom *Pseudo-nitzschia*, a cause of amnesic shellfish poisoning, and the dinoflagellate *Alexandrium tamarense*.

Zooplankton species richness is higher in the northern North Sea than in the southern North Sea and the community displays greater seasonal variability (Lindley & Batten 2002). The zooplankton community is dominated by calanoid copepods, although other groups such as *Paracalanus* and *Pseudocalanus* are also abundant. There is also a high biomass of *Calanus* larval stages present in the region. Euphausiids, *Acartia*, and decapod larvae are all important components of the zooplankton assemblage. Jellyfish are typically less abundant in northern and eastern coasts of the UK, although species commonly sighted include *Aurelia aurita*, *Cyanea capillata* and *Cyanea lamarckii* (Pikesley *et al.* 2014).

A1a.1.3 Features of Regional Sea 2

The southern North Sea is characterised by shallow, well-mixed waters, which undergo large seasonal temperature variations (JNCC 2004). The region is largely enclosed by land and, as a result, the environment here is dynamic with considerable tidal mixing and nutrient-rich run-offs from the land (eutrophication). Under these conditions, there is relatively little stratification throughout the year and constant replenishment of nutrients, so opportunistic organisms such as diatoms are particularly successful (Margalef 1973, cited in Leterme *et al.* 2006); diatoms comprise a greater proportion of the phytoplankton community than dinoflagellates from November to May, when mixing is at its greatest - see Figure A1.1.1 (McQuatters-Gollop *et al.* 2007). The phytoplankton community is dominated by the dinoflagellate genus *Tripos*, along with higher numbers of the diatom, *Chaetoceros* (subgenera *Hyalochaete* and *Phaeoceros*) than are typically found in the northern North Sea. Phytoplankton biomass is greater than in the northern North Sea, and has been increasing since the 1988 ecological shift (Edwards *et al.* 2020). HABs caused by *Noctiluca* spp. are often observed in the region.

The zooplankton community comprises *C. helgolandicus* and *C. finmarchicus* as well as *Paracalanus* spp., *Pseudocalanus* spp., *Acartia* spp., *Temora* spp. and cladocerans such as *Evadne* spp. Commonly seen jellyfish in the region include *A. aurita* and *Chrysaora hysoscella* (Pikesley *et al.* 2014). There has been a marked decrease in copepod abundance in the southern North Sea in recent years (Edwards *et al.* 2013a), possibly linked to the North Atlantic Oscillation (NAO) index, which has a significant impact in the southern North Sea, where the interface between the atmosphere and the sea is most pronounced (Harris *et al.* 2013).

A1a.1.4 Features of Regional Sea 3

Waters in the eastern English Channel are mixed and shallow, with strong tidal streams (JNCC 2004) and the plankton community is quite distinct from that seen further west. The PCI reveals lower plankton biomasses in this region than in surrounding waters, with the diatoms *Thalassiosira*, *Rhizosolenia* and *Chaetoceros* (subgenera *Hyalochaete* and *Phaeoceros*) and the dinoflagellate species *Tripos fusus* and *T. muelleri* among the most abundant (Johns 2008). Diatoms are dominant for most of the year, with dinoflagellate dominance limited to just January and AugusT. Diatom abundance is greatest in April and May, while dinoflagellates are most abundant in July and August – see Figure A1.1.1. HABs are not common in this region, due in part to the lower overall phytoplankton biomasses.

Key taxa in the zooplankton community include *Acartia*, *Centropages typicus* and *Temora longicornis* along with decapod and cirripede larvae and chaetognaths. The eastern English Channel is notable for the near absence of euphausiids, cladocerans and echinoderm larvae and the very low biomass of *C. helgolandicus* and *C. finmarchicus* (Johns 2008). Commonly seen jellyfish in the area include *C. hysoscella* (Pikesley *et al.* 2014).

A1a.1.5 Features of Regional Sea 4 & 5

The waters of the western English Channel and Celtic Sea are seasonally stratified, although with greater mixing in shallower parts. There is a heavy terrestrial influence, but also an important oceanic influence from the Atlantic (JNCC 2004). The phytoplankton community in this region comprises *Thalassiosira* spp. (the most frequently recorded phytoplankton taxa), *Rhizosolenia* spp., *Chaetoceros* spp. and *Tripos* spp. and the PCI is higher than in the eastern Channel (Johns 2008). Diatoms dominate the plankton community from September to May and are most abundant from April to July, with dinoflagellate abundances peaking between June and July – see Figure A1.1.1. In 2012, HABs of the dinoflagellates *Dinophysis* and *Prorocentrum*, both of which can cause Diarrhetic Shellfish Poisoning (DSP), and *Pseudo-nitzschia*, a diatom associated with Amnesic Shellfish Poisoning (ASP) were recorded.

Small copepods such as *Acartia* spp., *Oithona* spp., *C. typicus*, *Paracalanus* spp. and *Pseudocalanus* spp. are abundant in the region, along with euphausiids, cladocerans and meroplankton such as echinoderm larvae. Amongst the calanoid copepods, *C. helgolandicus* is considerably more numerous than *C. finmarchicus* (Johns 2008). The most commonly seen jellyfish in the area include *A. aurita*, *C. hysoscella* and *C. lamarckii*, as well as the hydrozoans *P. physalis* (the Portuguese man-o-war) and *Velella* (Pikesley *et al.* 2014).

A1a.1.6   Features of Regional Sea 6

The Irish Sea is strongly influenced by both coastal processes and influxes of water from the continental shelf current and the Celtic Sea. Stratification in the water column is restricted to deeper areas (JNCC 2004). The phytoplankton community within the Irish Sea is typically dominated by diatom species from December to May – see Figure A1a.1.1. Important diatom components of spring blooms in coastal regions include *Chaetoceros* spp., *Thalassiosira* spp., *Leptocylindrus danicus* and *Leptocylindrus minimus* (Kennington & Rowlands 2006). During the summer months, dinoflagellates dominate the community, with important genera including *Tripos*, *Gymnodinium* and *Scripsiella*, as well as the bloom forming *Noctiluca scintillans*. Other HAB-forming species in the region include *Pseudo-nitzschia*, *Prorocentrum* and *Phaeocystis*.

The zooplankton community is dominated by copepods which comprise almost 70% of all zooplankton. Of these, the smaller copepods are the most important in the Irish Sea, with species such as *Pseudocalanus elongatus*, *Temora longicornis* and *Acartia clausi* among the most numerous (Kennington & Rowlands 2006). Larger calanoids are also important components of the community, with the warmer water *C. helgolandicus* more abundant than *C. finmarchicus*. Abundant jellyfish species in the area include *A. aurita*, *C. hysoscella*, *C. lamarckii* and *R. octopus* (Pikesley *et al.* 2014).

A1a.1.7   Features of Regional Sea 7

The Minch is characterised by sheltered, warm waters mainly comprising North Atlantic Water as part of the continental shelf current and heavily influenced by freshwater run-offs from sea lochs and the Clyde Estuary (JNCC 2004). High riverine inflow is typically associated with higher phytoplankton biomasses and extended seasons of growth due to nutrient inputs. However, due in part to the local geology and to the low level of anthropogenic impact in the north-west of Scotland, nutrient levels can be relatively low in and around these lochs (Kennington & Johns 2007). Tidal stirring and wind mixing tend to keep shallow regions mixed, with the exception of short periods of fine weather in the summer when thermal stratification may become established, or periods of high freshwater loading which will stimulate haline stratification (Kennington & Johns 2007). As a result, most of the region remains well-mixed, frontal or only weakly stratified through much of the year, although deep sea loch basins are likely to remain stratified. The phytoplankton community within the Minch is typically dominated by diatom species in the first half of the year, and in adjacent sea lochs *Skeletonema costatum* can account for up to 90% of the biomass during the spring bloom (Wood *et al.* 1973). Other important diatom components of spring blooms in these coastal regions include *Rhizosolena* spp., *Chaetoceros* spp. and *Thalassiosira* spp. (Simpson *et al.* 1979). During the summer months, dinoflagellates dominate the community, with important genera including *Tripos*, *Protoperidinium*, *Gymnodinium* and *Scripsiella*.

The dinoflagellate *Alexandrium tamarense*, known to cause PSP, has been reported in a number of the west coast lochs (Tett & Edwards 2002). In 1998, *Chaetoceros wighami* was responsible for the deaths of £500,000 worth of farmed salmon in the region (Treasurer *et al.* 2003) and *Phaeocystis pouchetti* has been recorded in waters to the west of Scotland (Tett & Edwards 2002).

The zooplankton communities of the region are dominated in terms of biomass and productivity by large calanoid copepods. *C. helgolandicus* is present in greater numbers in the shallow, shelf waters of this region than in offshore waters at the same latitude and the population peaks in June (Kennington & Johns 2007). The *C. finmarchicus* population peaks in May and is much more evenly distributed between coastal and offshore areas to the west of Scotland (Kennington & Johns 2007). Other important copepods include *Acartia* spp., *Oithona* spp. and *Metridia lucens*. Abundant jellyfish in the area include *A. aurita*, *C. capillata* and *R. octopus* (Pikesley *et al.* 2014).

A1a.1.8 Features of Regional Sea 8

This region is influenced by the warm waters of the continental shelf current and the currents entering the North Sea from the north-east Atlantic and the Norwegian Sea (JNCC 2004). The phytoplankton community in these waters is dominated by the dinoflagellate genus *Tripos* (mainly *T. fusus*, *T. furca* and *T. muelleri*), with diatoms such as *Thalassiosira* spp. and *Chaetoceros* spp. also abundant to the west of Scotland, diatoms such as *Rhizosolenia* spp. and *Fragillariopsis* spp. and coccolithophores increase in abundance towards the shelf edge, while dinoflagellates such as *Protoperidinium*, *Gymnodinium* and *Scripsiella* also abundant in late summer. HABs caused by *Pseudo-nitzschia* occurred in the region in 2012.

The zooplankton communities of the Scottish continental shelf region are dominated in terms of biomass and productivity by calanoid copepods, particularly *Calanus* spp. (*finmarchicus* and *helgolandicus*), *Paracalanus* spp. and *Pseudocalanus* spp. Meroplanktonic echinoderm larvae and decapod larvae are also abundant. Other important taxa in the region include *Acartia* spp., *Evadne* spp., *Oithona* spp. and *Metridia lucens*. Commonly observed jellyfish species include *A. aurita* and *C. capillata* (Pikesley *et al.* 2014).

A1a.1.9 Features of Regional Sea 9

Regional Sea 9 is a deep, oceanic region, following the contours of the Faroe-Shetland Channel. The region is characterised by cold water inflowing from the Arctic and Norwegian Sea at depths below 600m (JNCC 2004). The Faroe Shetland Channel typically has lower phytoplankton biomass and a shorter productive season than waters more influenced by coastal processes (Johns & Wootton 2003). The phytoplankton community in the region is dominated by the dinoflagellate genus *Tripos* (mainly *T. fusus*, *T. furca* and *T. muelleri*), with diatoms such as *Thalassiosira* spp. and *Chaetoceros* spp. also abundant.

The zooplankton communities of the Faroe-Shetland Channel are dominated in terms of biomass and productivity by oceanic calanoid copepods, particularly *Calanus* spp. (*C. finmarchicus* and *C. helgolandicus*), *Pseudocalanus elongatus*, *Metridia lucens* and *Acartia clausii*. The Faroe-Shetland Channel is a particularly important site for *Calanus finmarchicus* as the species over-winters in dense aggregations in cold waters below the warm North Atlantic Current (Heath 1999). Spawning females migrate to surface waters in early spring and are transported to the North Sea by the Norwegian Trench Atlantic Inflow (Madden *et al.* 1999). It is thought that the channel contains the majority of this over-wintering population (Gallego *et al.* 1999). Cyclopoid copepods, such as *Oithona* spp., are also important in the region. Doliolids and salps are oceanic organisms and are far more common in these waters than in the North Sea. Particularly high abundances of doliolids were recorded in 1989 and 1997 and are indicative of increased oceanic inflow (Edwards *et al.* 1999). Surveys using ROVs near the seabed of the Faroe-Shetland Channel revealed concentrations of krill *Meganyctiphanes norvegica*, particularly between 400 and 600m water depth; krill appeared to favour the transitional zone between warmer shallower waters and colder deep waters, with none observed deeper than 900m (Hirai & Jones 2012). The oceanic water travelling through the

channel introduces warm/temperate oceanic plankton such as the copepods *Euchaeta hebes*, *Rhincalanus nasatus* and *Eucalanus elongatus*, and the doliolids *Doliolum nationalis* and *Dolioletta gegenbauri* (Edwards *et al.* 1999). Commonly observed jellyfish species in coastal waters of the region include *A. aurita* and *C. capillata* (Pikesley *et al.* 2014).

Due to the depth of this region and the vertical distribution of water masses within it, the composition of the plankton community will vary within the water column. Pipe & Coombs (1980) identified five characteristic groups of zooplankton along the northern face of the Wyville Thomson Ridge. Surface waters down to depths of about 160m are dominated by three species, with the most abundant being *Acartia clausii*. The North Atlantic Oceanic Water community is dominated by *Pseudocalanus elongatus* and *Munida* larvae and is restricted to the upper 420m where temperatures are between 8-8.7°C. A third group of plankton is found throughout the water column and is dominated by *C. finmarchicus*, *M. lucens* and *Scolecithricella minor*. *Metridia longa*, *Calanus hyperboreus*, *Pleuromamma robusta* and *T. longicaudata* dominate the intermediate depths, between 430-510m. Finally, the Norwegian Sea Deep Water plankton community is found at peak abundance between 530-580m depth and is characterised by eight copepods and two chaetognaths, with *Spinocalanus abyssalis* and *Oncaea conifera* the most abundant species.

A1a.1.10 Features of Regional Sea 10 & 11

These deep-water regions are completely oceanic in nature with an absence of terrestrial input and little seasonal variation in primary productivity (JNCC 2004). In these offshore regions, diatoms dominate the phytoplankton assemblage in early spring, with larger taxa such as *Rhizosolenia*, *Fragillariopsis*, *Thalassionema*, *Thalassiosira* and *Nitzschia* dominating. As silicate levels decline, smaller coccolithophores such as *Emiliana huxleyi*, *Coccolithus pelagicus* and *Cyclococcolithus leptoporus* increase in abundance (Okada & McIntyre 1979). A period of dinoflagellate dominance in the phytoplankton community in January and February, as well as in late summer and autumn, is a feature of these offshore regions not seen in other UK waters – see Figure A1a.1.1.

The most frequently recorded zooplankton taxa in the offshore waters of these regions are the euphausiids, with small copepods also abundant. In these cold, oceanic waters, *C. finmarchicus* is more abundant than *C. helgolandicus* (Kennington & Johns 2007). Gelatinous organisms are also particularly abundant in these regions, with an initial increase in biomass in early summer spreading across the continental shelf by the autumn (Witt *et al.* 2007).

A1a.1.11 Evolution of the baseline

A1a.1.11.1 Climate

Interactions between the climate and plankton communities are complex and not fully understood and there is considerable debate over the relative importance of various driving forces on the changes that have been observed in the plankton community over recent decades (Goberville *et al.* 2013, Harris *et al.* 2015, Barton *et al.* 2016). A key influence of the north Atlantic weather patterns is the North Atlantic Oscillation (NAO). It is described using an index, typically the pressure differential between the Iceland Low and Azores High (Dickson *et al.* 1996). When the NAO is in its negative phase, westerly winds tend to be weaker, and the climate over the North Sea region colder and drier. When in a positive phase, westerly winds tend to be stronger and the climate warmer and wetter. It has been suggested that the state of the NAO is driven in part by sea surface temperature (SST) in the north Atlantic (Rodwell *et al.* 1999). The NAO is also linked to eutrophication, as increased rainfall will increase nutrient inputs. Consequently, the NAO seems to have a greater impact in the southern North Sea, where the shallow waters, surrounded by land mean the interface between the atmosphere

and the sea is most pronounced (Harris *et al.* 2013). The North Sea is heavily influenced by inflows of water from the North Atlantic. The volume and source of these inflows can have an effect on plankton communities in the North Sea and the effect of exceptional inflows can be significant. In the late 1970s, a pulse of cold, low salinity water entered the North Sea, coinciding with a negative phase of the NAO. This event, known as the Great Salinity Anomaly, was possibly associated with particularly cold winters in the southern North Sea and an observed delay in the onset, and decrease in the primary production, of the spring bloom (Edwards *et al.* 2002). Conversely, in the late 1980s, warm, more saline oceanic water entered the North Sea (Edwards *et al.* 2002).

Phytoplankton biomass as measured on the PCI has increased since the late 1980s across the north-east Atlantic (Edwards *et al.* 2014). This trend is not fully explained by dinoflagellate and diatom abundances (dinoflagellate abundance has declined in the North Sea and NE Atlantic between 1950 and 2009 (Hinder *et al.* 2012)), suggesting that the overall increase in phytoplankton biomass may be due to taxonomic groups which are too small to be sampled by the CPR (Leterme *et al.* 2006). During the 1990s an increase in winter months of over 90% of the long-term mean was recorded (Johns & Wootton 2003). This has been linked to increases in nutrient inputs from European rivers (Richardson 1997), although evidence suggests that the effect of eutrophication on phytoplankton biomass is restricted to coastal regions (Edwards *et al.* 2002). The increase in phytoplankton biomass has been linked with an increase in SST and wind strength (Beaugrand 2003), and it has been suggested that dominant trends in the southern North Sea are climatically forced rather than linked with nutrient inputs (Edwards *et al.* 2002, Harris *et al.* 2013). A study of data collected from 1960 to 2009 (Hinder *et al.* 2012), revealed a change in the ratio of dinoflagellate species to diatom species within the phytoplankton community of the north-east Atlantic. As dinoflagellates have declined, diatom abundances have remained relatively stable (Figure A1a.1.3, see also Chivers *et al.* 2020). A shift in the community composition such as this is likely to have an effect on grazing zooplankton communities, as well as on the occurrence of HABs. The decline in dinoflagellate abundance has been particularly marked since 2002. In addition to this, a number of dinoflagellates were recorded reaching their peak abundance up to two months earlier during the 1990s than the long-term mean (Johns & Wootton 2003). This could have important ramifications for marine ecosystems, as dinoflagellates are less palatable than diatoms for copepods and fish larvae (McQuatters-Gollop *et al.* 2007), and many species are noxious to other organisms. A general shift to the north-east of North Atlantic phytoplankton communities has been observed by Barton *et al.* (2016), studying CPR data gathered between 1951-2000. The shift was driven by changes in various environmental conditions, including nutrient availability, light level and ocean circulation rather than being simply temperature driven. This indicates the complexity of the effects of physical interactions with the phytoplankton community which will, in turn, affect changes at higher trophic levels.

Figure A1a.1.3: Ratio of dinoflagellate and diatom abundance in the north-east Atlantic, 1960-2009
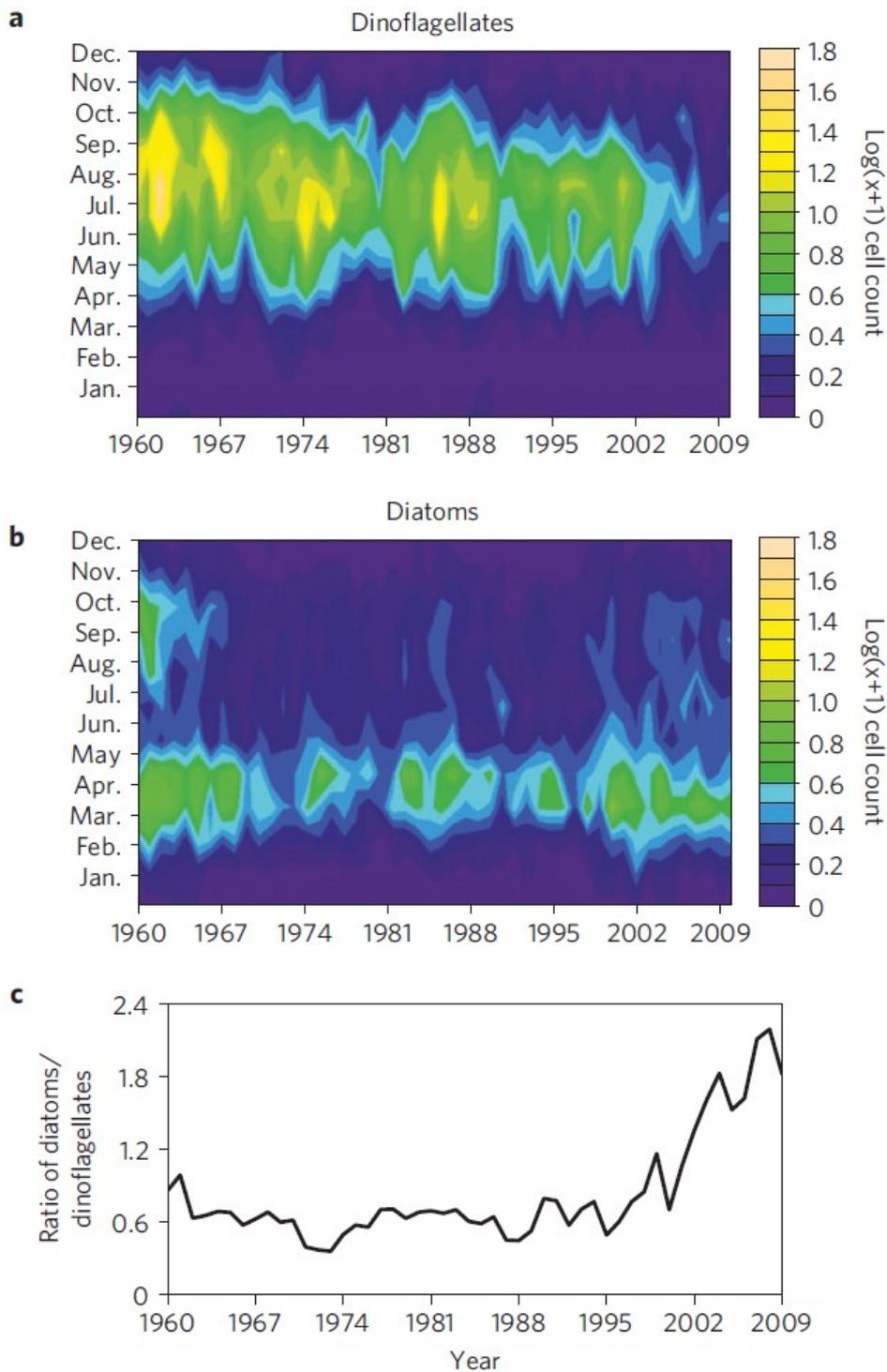
Source: Hinder *et al.* (2012)

The zooplankton community is driven to a large extent by the peak of food availability represented by the phytoplankton bloom. Settling of ungrazed phytoplankton on the seabed, resulting from increased phytoplankton biomass and extended growing seasons (Reid *et al.* 2003) may cause an increase in meroplankton from the larvae of benthic organisms, a trend that has been observed within the North Sea (Lindley & Batten 2002), with Bedford *et al.* (2020) also noting a significant increasing trend in meroplankton lifeforms in the Greater North Sea. The southern North Sea has shown a particular increase in abundance of decapod larvae since the 1950s (Edwards *et al.* 1999). Of increasing importance in European waters are jellyfish populations, with a number of blooms of *Rhizostoma* jellyfish recorded in the Irish

Sea (Lilley *et al.* 2009). The size and occurrence of these blooms is unpredictable, with considerable inter-annual variability. There was a particularly high abundance in 2003, a year which saw high summer temperatures across Europe. For example, Carmarthen Bay had 478 times more *Rhizostoma* jellyfish than in 2005 (Lilley *et al.* 2009).

Figure A1a.1.4 : Decadal abundance maps for the cold-water copepod *Calanus finmarchicus* and the temperate copepod *Calanus helgolandicus* from 1960–2015
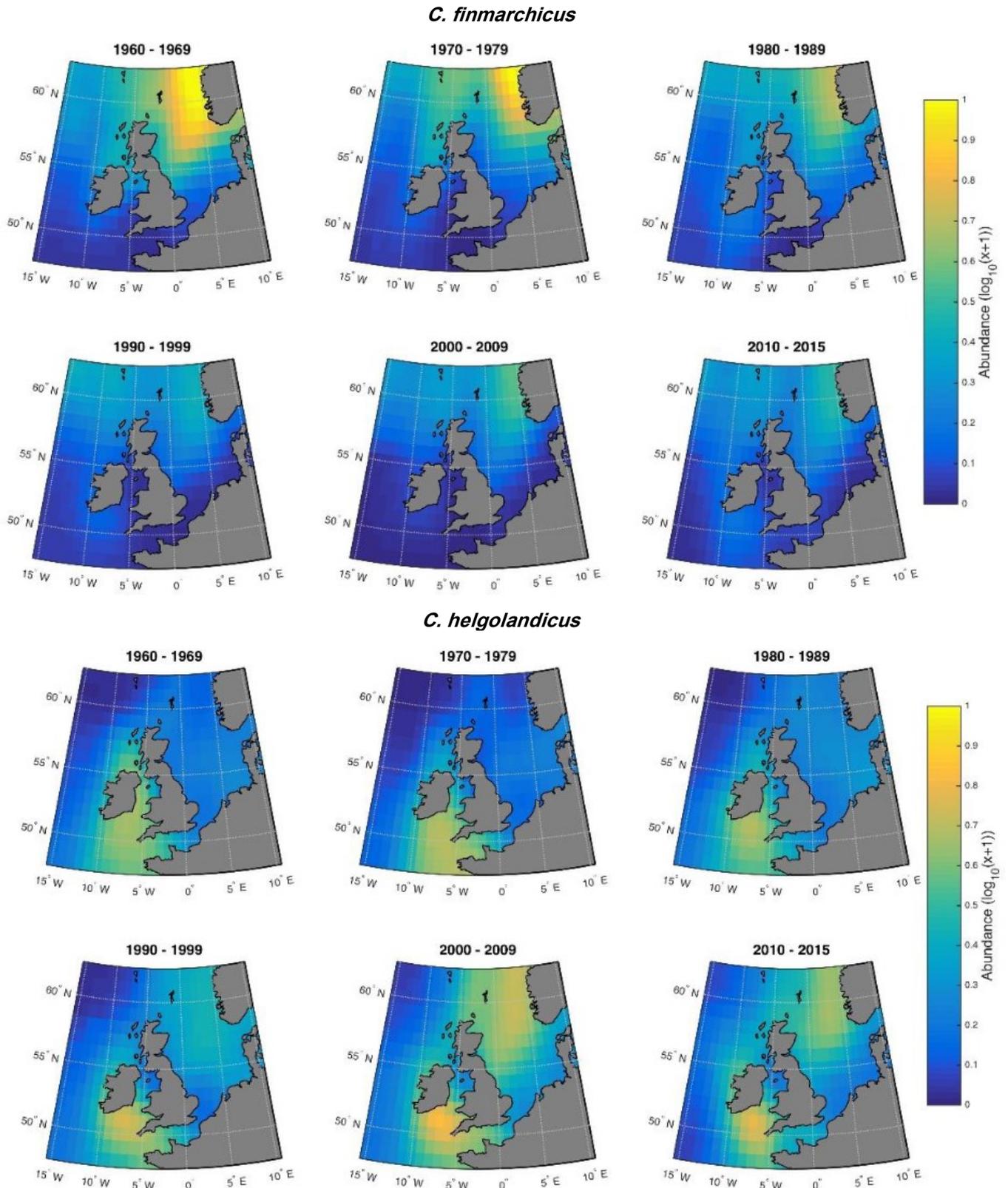
Source: Edwards *et al.* (2020)

The 1980s warm anomaly is thought to have been an important factor in one of the most studied examples of regime shift in the plankton community. Typically, abundances of *C. helgolandicus* are greatest at temperatures between 13-17°C (Bonnet *et al.* 2005), and are positively correlated with the temperature of the previous year (Planque & Fromentin 1996). Consequently, increasing SST may have resulted in a northwards spread in the population of the shelf dwelling *C. helgolandicus* with a corresponding decline in the oceanic, cold-water *C. finmarchicus* (Beaugrand 2003). Over a decadal period *C. helgolandicus* has moved northwards from its particular stronghold in the Celtic Sea to replace *C. finmarchicus* in most of the ecoregional areas of the British Isles (Figure A1a.1.4). This is a clear sign of warming waters around the British Isles (Edwards *et al.* 2020).

Examination of CPR data up until 2016 revealed the percentage ratio between *C. helgolandicus* and *C. finmarchicus* in 2009 to 2011 was for the first time in twenty years dominated by *C. finmarchicus* in spring (Figure A1a.1.5). This was a reflection of the particularly cold winter experienced in Northern Europe caused by a very low winter NAO index during that period. Uncharacteristically, during this period the NAO has been in a very low negative phase contributing to the very cold winters experienced in Northern Europe during 2009/2010 and 2010/2011 reflected in below average SST in the North-east Atlantic. Similarly, this has had an effect on the timing of seasonal cycles in the North Sea for many species. The last couple of years have seen a later seasonal peak of plankton compared to the long-term trend, which was a trend towards earlier seasonal cycles (Edwards *et al.* 2020).
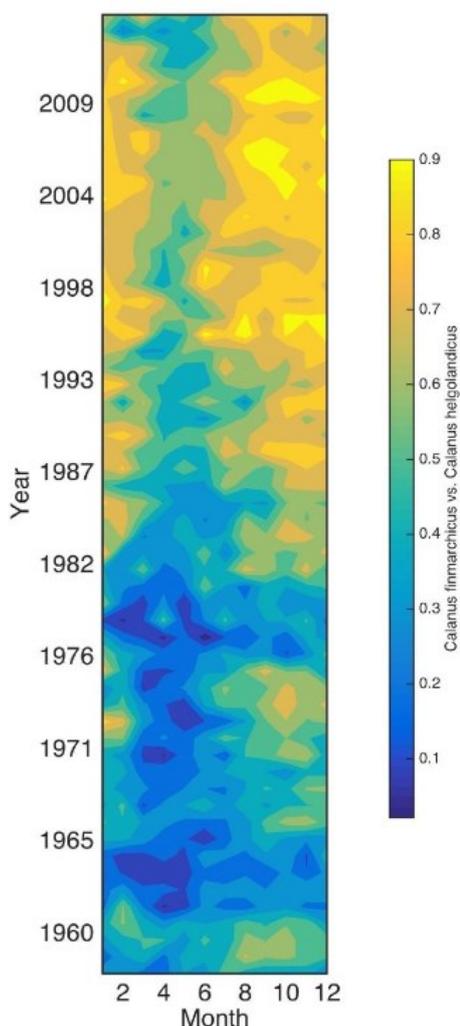
Figure A1a.1.5: Long-term monthly plots (1960-2016) of the ratio between *C. finmarchicus* (cold water/blue colour) and *C. helgolandicus* (warm-water/yellow colour) in the North Sea

Note: An increase in the warmer C. helgolandicus can be seen over the last 60 years particularly after the 1980s. Source: Edwards *et al.* (2020)

Evidence suggests that the increase of warmer water species at the expense of colder water species in the north-east Atlantic, as illustrated by the general trend in *C. finmarchicus* and *C. helgolandicus*, has accelerated over the last 5 years (Edwards *et al.* 2014). Since the 1960s, total *Calanus* spp. biomass in the North Sea has declined by approximately 70%. Warm water inflows have also been linked to increases in euphausiid abundances around coastal regions, with consequences for animals that feed on them (Reid *et al.* 2001). Different regional responses are associated with the movement of the 10°C thermal boundary as it moved northwards (Edwards *et al.* 2013a). Throughout the eastern north Atlantic and European shelf seas, strong biogeographical shifts in all copepod assemblages have occurred, with a northward extension of more than 10° latitude of warm-water species associated with a decrease in the number of colder-water species (Beaugrand *et al.* 2002, Harris *et al.* 2015).

As plankton communities are so closely linked to the physical environment, they can be good indicators of changes in the climate. Long-term trends in phytoplankton communities are not consistent across the North Sea, highlighting the danger of using global influences such as oceanic

inflows to explain inter-annual variability and trends, when processes at a smaller, more localised scale are clearly important (Leterme *et al.* 2008). Nevertheless, nearly half of the increase in north-east Atlantic temperatures can be related to global temperature rises (Beaugrand *et al.* 2009). Temperature was identified as the primary driver of zooplankton abundance and spatial re-organisation across the north-east Atlantic over recent decades (Harris *et al.* 2015). The biodiversity of calanoid copepods has moved northwards at a rate of 23km/year in response to rising SST, a far greater rate of movement than in terrestrial ecosystems. However, Chivers *et al.* (2017) noted significant variation in the range changes exhibited by plankon taxa to increasing SST, pointing to a major spatial reorganisation of plankton communities, rather than existing communities simply moving northwards collectively as ocean temperatures warm. There have also been changes recorded in the timing of phytoplankton and zooplankton production in response to climate, with some species present 4-6 weeks earlier than 20 years ago, an effect that will impact on fish and other organisms at higher trophic levels (OSPAR 2010, Edwards *et al.* 2010). Trophic amplification of this nature may provide a mechanism to drive ecosystems towards new regimes (Kirby & Beaugrand 2009), and in the North Sea, this new regime appears to favour jellyfish in the plankton and decapods and detritivores (such as echinoderms) in the benthos (Kirby *et al.* 2007). The transition since the late 1960s of the siphonophore *Muggiaea atlantica* from a transient visitor to the western English Channel to a resident species has been linked to community composition changes that have occurred in the region during the study period (Blackett *et al.* 2014).

Marine micro-organisms are also affected by climate. The tintinnids, ciliated protozoans usually described as microzooplankton, are grazers of nanophytoplankton and remove between 10-27% of phytoplankton production from coastal waters (Edwards *et al.* 2013b). There has been a marked increase in abundance of tintinnid species in UK waters since 2003, with some genera expanding their seasonal occurrence from the usual spring and summer months into winter (Hinder *et al.* 2011). An increase in the abundance of *Vibrio* bacteria, the cause of cholera, in the North Sea from 1961-2005 was reported by Vezzulli *et al.* (2011) following a long-term study. This increase was linked to SST, with the copepods acting as a vector as the bacteria attach to the chitin surfaces of their carapaces.

It is therefore apparent that hydro-climatic events are important factors in the marine ecosystem. Organisms will respond differently and at different rates to climatic events (Beaugrand 2004), and it has been suggested that this may lead to the decoupling of biological relationships and changes at the level of the ecosystem (Edwards & Richardson 2004). Predictions of future change are difficult to make as detailed understanding of the effects of climate is limited. A recent report by the Marine Climate Change Impacts Partnership (MCCIP) (Edwards *et al.* 2020) suggested with medium confidence, that changes in geographical distributions of centres of plankton production occurring over the next 0-5 years could affect biogeochemical cycling, oxygen production, carbon sequestration and fish, mammal and seabird populations within the next 20-50 years.

A1a.1.11.2   Ocean acidification

Rising carbon dioxide concentrations in the sea (see Appendix 3d Water Environment for details) are expected to reduce levels of calcification by marine organisms, by lowering the calcium carbonate saturation state of seawater. However, the Continuous Plankton Recorder (CPR) has recorded a steady increase in abundance of calcareous taxa, such as foraminifera, coccolithophores and echinoderm larvae over the past 50 years. Beaugrand *et al.* (2013) suggest that this increase is primarily in response to increased temperatures in the north Atlantic from 1960-2009 (most of the calcareous taxa saw a marked increase around the mid-

1990s, coinciding with a significant increase in global temperature) and that increasing sea temperature may be over-riding the current effects of acidification.

Despite this, there is evidence from the Southern Ocean that the shell weights of modern foraminifera are less than those recorded in older sediments, a possible effect of ocean acidification (Edwards *et al.* 2010). Beare *et al.* (2013) also observed that coccolithophore and foraminiferan populations are coping better under increasingly acidic conditions than pteropods or bivalves in the central North Sea. This may be in part due to a combination of stress factors (e.g. pH decrease, temperature rise, eutrophication) having a greater adverse impact on some taxa than on others, as well as differences in the mineral composition and physical shape of shells between taxa. In addition, the increased levels of CO_2 in the water may boost photosynthesis in coccolithophores, resulting in a counterbalancing population increase. Laboratory evidence collected by Iglesias-Rodriguez *et al.* (2008) suggests that coccolithophore *Emiliania huxleyii* calcification and primary production has increased with CO_2 partial pressures. Meanwhile, field evidence shows there has been a 40% increase in average coccolithophore mass over the last 220 years, evidence of a rapid and impressive response from coccolithophores to ocean acidification.

Although there is currently little evidence suggesting that populations of calcareous taxa are currently declining as a direct result of ocean acidification, it is uncertain what effect continued acidification will have on plankton communities in UK waters over the course of the 21st Century, although MCCIP suggests with moderate confidence that it will become a problem within the next 20-100 years (Edwards *et al.* 2020).

A1a.1.11.3 Eutrophication and Harmful Algal Blooms

Eutrophication is considered to be a major threat to coastal ecosystems worldwide, although the exact relationship between eutrophication and HABs is unclear (Gowen *et al.* 2012). In general, HABs are naturally occurring events although some exceptional blooms have been associated with eutrophication in coastal waters (Edwards *et al.* 2016). The southern North Sea, which is heavily impacted by coastal processes, is most affected. Research in Helgoland Roads in the German Bight showed that nutrient levels, water temperature, underwater light and wind strength have all changed substantially over the past 30 years, with the effect of making the region less of a coastally dominated system. Despite this, the timing of the phytoplankton bloom was found to have stayed very stable over this period (Wiltshire *et al.* 2008). Nevertheless, the community composition of the bloom was found to have changed, with large diatoms (such as *Coscinodiscus wailesii*) increasing in relative abundance. Larger diatoms are relatively inedible to grazing copepods and so this may be a factor influencing changes in the copepod community observed in the region (Wiltshire *et al.* 2008).

Analysis of long-term spatial variability in CPR data indicates that in the south and east North Sea, there have been increases in abundances of the HAB causing genera *Dinophysis* spp. and *Prorocentrum* spp. in recent decades, while large blooms of *Pseudo-nitzschia* spp. have become more common in the North Sea over the past decade and were particularly numerous in 2012 (Edwards *et al.* 2014). One of the most studied HABs is of the foam alga *Phaeocystis* spp. (Defra 2005), blooms of which are often tightly coupled with those of diatoms (Lancelot *et al.* 1987). *Phaeocystis* spp. can occur either as single cells or in large gelatinous colonies (Stelfox-Widdicombe *et al.* 2004), so blooms can provide a food source for a wide range of organisms and can have a rapid impact throughout the food chain. HABs may be related to water surface temperatures in spring, as early seasonal stratification may favour phytoplankton growth in the water column (Joint *et al.* 1997). Along the west coast of Norway, where there has been a large increase in HABs, a strong significant correlation was evident between the increase in dinoflagellate taxa and environmental variability (including Atlantic inflow, salinity,

SST and wind speed) (Edwards *et al.* 2006). The most recent CPR survey report indicated that the summer of 2015 saw record high abundances and frequency of occurrences of the dinoflagellate *Dinophysis norvegica* (associated with diarrheal shellfish poisoning), in the northern North Sea, particularly close to the Norwegian coast (Edwards *et al.* 2016).

Modelling approaches have been used to examine the relationship of selected HAB species with temperature (Edwards *et al.* 2020). Gobler *et al.* (2017a, b) modelled an increase in *Dinophysis* species growing period in the North Sea associated with increases in sea surface temperature. However, the lack of inclusion of additional drivers (e.g. prey availability, predation, or ecological interactions) and phytoplankton loss terms into the model may have over-estimated the resultant HAB populations (Dees *et al.* 2017).

The influence of weather on HAB events has been confirmed in multiple studies (Bresnan *et al.* 2020). A DST intoxication event in 2013 where human illness was recorded after consumption of shellfish harvested from Shetland, was driven by a sudden change in wind direction, transporting a population of *Dinophysis* onshore, resulting in a rapid increase in DSTs in *Mytilus edulis* (Whyte *et al.* 2014). Wind direction and intensity has also been seen as a driving factor behind prolonged DST events in Loch Fyne in Scotland (Morris *et al.* 2010) as well as contributing to changes in phytoplankton community composition over multiple decades recorded by the CPR (Hinder *et al.* 2012).

A1a.1.11.4   Invasive species

There is a growing concern about the risk of invasive species and the importance of protecting native biodiversity. Changes in climate are also likely to result in an incursion of non-indigenous species; rising SST is already leading to northwards incursions of warmer water species such as *C. helgolandicus*. In the northern North Sea, the diversity of zooplankton species has increased, due in part to large numbers of non-native migrants from warmer waters (Lindley & Batten 2002). Reid *et al.* (2009) describe a number of non-native species that have recently been recorded in UK waters, including *Mnemiopsis leidyi* and *Sargassum muticum,* and suggest that non-native plankton species may extend to cover UK waters within 25 years. Edwards *et al.* (2014) indicates that a number of warm water *Tripos* species (*T. arietinus*, *T. lamellicornis* and *T. pentagonus*) were recorded 40-100 miles off the coast of north-west Scotland in 2009, the furthest north these species have ever been recorded. Conversely, the tintinnid species *Parafavella gigantea*, usually an indicator of cold water masses, was recorded off the coast of Brittany in the same year (Edwards *et al.* 2010).

Ballast water in ships has long been recognised as a source for the introduction of non-indigenous and potentially harmful organisms. A number of non-native planktonic organisms have been identified in UK waters, including diatoms such as the Indo-Pacific *Odontella sinensis* (Ostenfeld 1908) and *Coscinodiscus wailesii* (Edwards *et al.* 2001), which is now particularly abundant in waters near to the continent and has spread throughout northern European coastal waters since its first recorded observation at Plymouth in 1977.

A species of copepod, *Pseudodiaptomus marinus*, naturally occuring in east-Asian waters, was first recorded in the southern North Sea in 2011 and has since been observed throughout the region, from the German Bight to the UK coast (Edwards *et al.* 2014). It is highly likely that this species was transported to the southern North Sea by the release of ballast water or other human activities such as aquaculture.

With raised awareness, there are a variety of operational and technical innovations being introduced (e.g. through IMO 2003) to reduce the risk of organism transfer via ballast water.

The threat of invasion will be greater from those species that can form resting stages that may remain inert in ballast water for a considerable time.

A1a.1.12 Environmental issues

A1a.1.12.1 Ecological importance

A number of studies have demonstrated that a change in the plankton community composition can have a significant effect on organisms at higher trophic levels. Fish populations, already under significant pressure from fishing activity, may be affected, potentially with economic and environmental consequences.

Beaugrand *et al.* (2003) suggested that cod recruitment fluctuates with changes in the plankton ecosystem. The Gadoid Outburst between 1963 and 1983 saw high rates of cod recruitment at a time of high abundances of calanoid copepods and krill, important prey items for cod larvae. Since the mid-1980s, however, conditions in the plankton ecosystem have not been so favourable and this has coincided with a decrease in cod recruitment. The increasing abundance of *C. helgolandicus* at the expense of *C. finmarchicus* may also have had an effect on cod recruitment as the population of *C. helgolandicus*, unlike that of *C. finmarchicus*, peaks too late in the year for cod larvae to feed on (Helaouet & Beaugrand 2007), and is less nutritious and lipid rich (Edwards *et al.* 2013b). Relationships between the plankton community and the abundance of salmon (Beaugrand & Reid 2003, Beaugrand & Reid 2012) and horse mackerel (Reid *et al.* 2001) in the North Sea have also been identified.

Sudden increases in plankton abundance may also have deleterious effects on fish populations. In 1968, a bloom of the dinoflagellate *Alexandrium tamarense* caused large scale mortality of sandeels and seabirds off the northeast coast of England (as well as hospitalising 78 people) (Coulson 1968). The zooflagellate *Noctiluca scintillans* is an important predator of copepod eggs and is estimated to be responsible for the clearance of up to 50% of these eggs in the southern North Sea (Daan 1987). High abundances of jellyfish have been shown to have a deleterious effect on herring larvae through competition and predation at spawning grounds (Lynam *et al.* 2005).

A1a.1.12.2 Contamination

Effects of hydrocarbon contamination on plankton have not been studied extensively, although the effects from relatively recent oil spills from tankers e.g. *Torrey Canyon*, *Braer* and *Sea Empress* have been assessed. Studies conducted after the *Sea Empress* spill off the coast of south-west Wales failed to find any significant effects on the plankton (Batten *et al.* 1998), although other studies have shown the presence of oil lowers fecundity and offspring mortality in zooplankton through the hydrocarbon content of food and indirect ecosystem effects (van Beusekom & Diel-Christiansen 1993). There is also a strong suggestion that dispersant treated oil has a more pronounced effect (van Beusekom & Diel-Christiansen 1993). Any long-term genetic changes are difficult to assess.

Oil pollution from exploration/production only forms a small percentage of entry of oil to the marine environment. In less major spills, bacteria can play an important role in removing the oil. Produced water from oil and gas extraction may include dissolved hydrocarbons, organic acids and phenols which are used in biocides, corrosion and scale inhibitors and gas treatment. Plankton may be exposed to these contaminants through passive diffusion, active uptake or through eating contaminated prey. As planktonic organisms spend most of their lives in the water column, they will be particularly exposed to those contaminants that remain in solution (Sheahan *et al.* 2001). Produced water has been shown to affect recruitment in calanoid copepods (Hay *et al.* 1988). The toxicity of produced water will decrease as it

disperses away from the source. Stomgren *et al.* (1995) found that acute toxicity in the diatom *Skeletonema* spp. was only likely in individuals in the immediate vicinity of the source of produced water, while at distances greater than 2km the effects are negligible.

Micro-plastics in the marine environment may result from the break-down of plastic waste over time, or from specifically manufactured micro-beads or fibres typically found in products such as toothpaste or exfoliants. Analyses of micro-plastics recorded from CPR samples indicate that the quantity is increasing over time in the north-east Atlantic, with greater concentrations found at the coasts (Edwards *et al.* 2014). It has been demonstrated that micro-plastics may be ingested by zooplankton, where they can adhere to external appendages and internal organs, impeding feeding (Cole *et al.* 2013). This micro-plastic pollution will be passed to higher trophic levels by predation on affected zooplankton. Desforges *et al.* (2015) demonstrated the presence of micro-plastics in the bodies of 1 in every 34 copepods and 1 in every 17 euphausiids in the north-east Pacific; and estimated that adult salmon in the area could be ingesting up to 90 particles each day, and an apex predator such as a humpback whale, up to 300,000 particles in a day.

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