The Continuous Plankton Recorder Survey – Monitoring plankton in the Nordic Sea (CPR Survey)

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1. Introduction

The marine ecosystems of the Arctic and its associated regional seas have been undergoing a rapid transformation over the last few decades which includes loss of sea ice cover and ocean warming. The Arctic sea regions in particular are experiencing the strongest warming on the planet (twice as fast as the planetary average) and the loss of sea ice in recent decades has been unprecedented (Smetacek and Nicol 2005). This persistent warming in the Arctic, caused predominantly by the ice-albedo feedback, has pushed the region into 'uncharted territory' (Caesar *et al.* 2018). Many regional seas that were once considered as being inhabited exclusively by Arctic flora and fauna have become more influenced by more southerly species as these species move northward as the Arctic warms (Polyakov *et al.* 2017). These changes are having huge consequences on the biodiversity and populations of plankton, fish, marine mammals and seabirds of these northern seas.

Plankton are highly sensitive to these rapid environmental changes and are excellent indicators of the state of the environment by acting as biological 'sentinels'. As plankton are at the base of the food-web, by monitoring changes in the plankton we can also understand changes to other animals and trophic levels such as fish and seabirds (Edwards *et al.* 2013). The Continuous Plankton Recorder (CPR) Survey has been operating in the North Sea and North Atlantic since 1931 and is one of the most geographically extensive and oldest continuous marine biological surveys in the world (Edwards *et al.* 2010). It has now been operating for over 10 years in Nordic waters beginning in November 2008. Within this region of the Nordic Seas, the CPR survey adds to and complements other monitoring methods by providing a broader spatial and temporal perspective. For example, most other surveys are coastal or are only sporadically sampled (e.g. once per year) through time. The CPR survey also adds value by providing multi-decadal data at the Atlantic basin scale that can help disentangle and interpret changes observed in the Nordic Seas and help predict changes over the next coming decades. For example, regions that currently support Arctic ecosystems will instead support sub-Arctic systems within the next 10 to 20 years (if not sooner). The biological signals of change we see further south in Atlantic sub-polar systems now can be used to detect the early warning signs of change in the Arctic.

The CPR survey has been operating on a monthly basis using ships of opportunity from northern Norway to Svalbard since 2008 (refer Edwards et al. 2019 for a detailed CPR methodology). Generally, the route operates every month from Tromso in northern Norway to Longyearbyen in Svalbard when conditions are favourable (Figure 1). Sometimes there can be reduced sampling during the winter period. The northern Norwegian routes were initially established due to the rapid changes to plankton and climate and the movement of plankton northwards observed over the last 50 years in the sub-polar Atlantic. These rapid changes in plankton were originally observed in the North East Atlantic, where the majority of CPR routes operate, with plankton northerly movement measured at a rapid ~ 23 km per year in this region (Beaugrand et al.2009) . To continue these observations of rapid biological movement and biodiversity changes it was considered crucial to establish more northerly CPR routes covering the Nordic Seas to continue to document these changes as well as to monitor for possible trans-Arctic migrations.

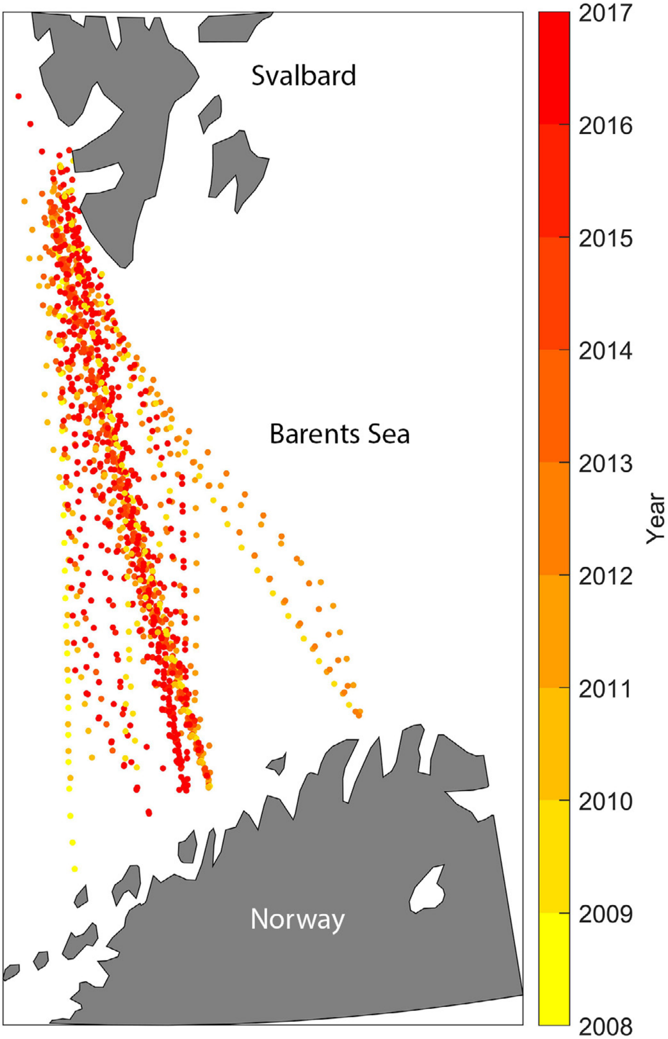

Figure 1: Distribution of CPR samples in the Barents Sea region between northern Norway and Svalbard.

2. The state of plankton

The Barents Sea ecosystem supports some of the world's largest stocks of commercially exploited fish species such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) as well as being the home to some of the largest concentrations of seabirds in the world coupled with a diverse assemblage of marine mammals (Dalpadado et al. 2014). These rich ecosystems are sustained by very high biomasses of phytoplankton and zooplankton found in this region leading to these lucrative marine bio-resources and abundant higher trophic levels.

Generally, the plankton sampled in the Barents Sea consists of a cold-boreal/Arctic to an Atlantic assemblage with the occasional temperate species recorded particularly in the warmer waters of the North Atlantic current to the west and south of Svalbard (Aarflot *et al.* 2018) . Warmer Atlantic water is found to the south and west of Svalbard (known as the Norwegian Current), particularly near the coast of northern Norway, and can also be found to branch as far north as the western coast of Svalbard (as the West Spitsbergen Current). Colder and fresher Arctic waters can be found flowing southward to the east of Svalbard and along the southern coast of Svalbard as far west as Bear Island (approximately halfway between Spitsbergen and Norway's North Cape) (Loeng et al. 1997). As the Barents Sea sits at the doorstep to the Arctic Ocean a number of boreal-Arctic species are also found such as diatom *Ephemera planamembranacea*, the dinoflagellate *Ceratium arcticum* and the copepod *Calanus hyperboreus* (data based on the CPR time-series for this region).

The most commonly recorded phytoplankton in this region are the diatom groups *Chaetoceros* spp., *Thalassiosira* spp., *Rhizosolenia* spp. and *Pseudo-nitzschia* spp which dominate the spring bloom biomass. The dinoflagellate genus *Ceratium* is also very common particularly during the more stratified summer months. Coccolithophore blooms are also a common phenomenon in this region. Calanoid copepods typically dominate the zooplankton assemblage, particularly the boreal species *Calanus finmarchicus*. Euphausiids and hyperiids also contribute to high zooplankton biomasses. Collectively the copepod species *C. finmarchicus* and *C. glacialis* and the krill (*Thysanoessa inermis and T. raschii*) are considered the primary herbivores of this region and as such are the key food sources for higher trophic level predators in the Barents Sea ecosystem (Dalpadado *et al.* 2014).

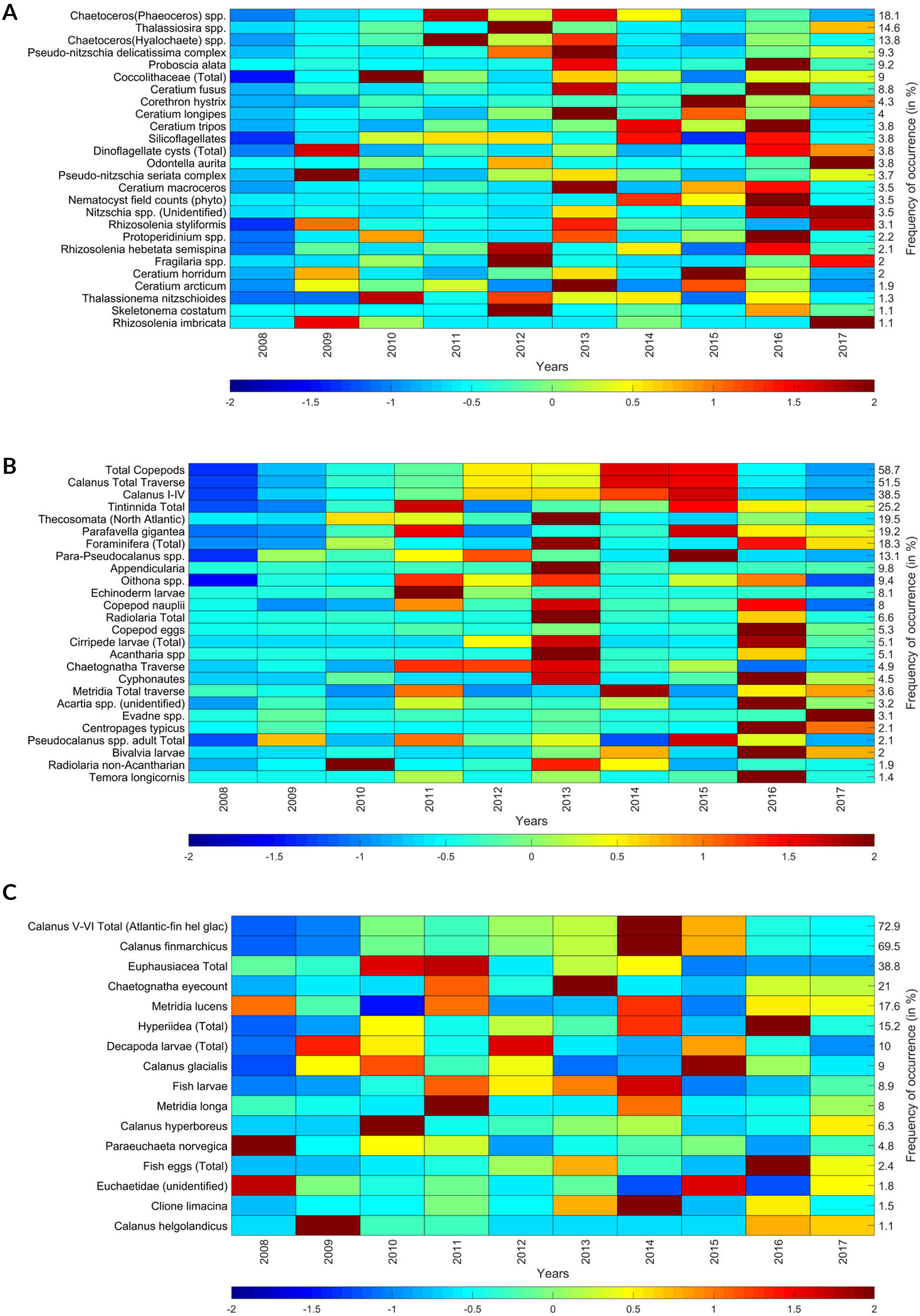
A
Chaetoceros(Phaeoceros) spp.
Thalassiosira spp.
Chaetoceros(Hyalochaete) spp.
Pseudo-nitzschia delicatissima complex
Proboscia alata
Coccolithaceae (Total)
Ceratium fusus
Corethron hystrix
Ceratium longipes
Ceratium tripos
Silicoflagellates
Dinoflagellate cysts (Total)
Odontella aurita
Pseudo-nitzschia seriata complex
Ceratium macroceros
Nematocyst field counts (phyto)
Nitzschia spp. (Unidentified)
Rhizosolenia styliformis
Protoperidinium spp.
Rhizosolenia hebetata semispina
Fragilaria spp.
Ceratium horridum
Ceratium arcticum
Thalassionema nitzschioides
Skeletonema costatum
Rhizosolenia imbricata
18.1
14.6
13.8
9.3
9.2
9
8.8
4.3
4
3.8
3.8
3.8
3.8
3.7
3.5
3.5
3.5
3.1
2.2
2.1
2
2
1.9
1.3
1.1
1.1
Frequency of occurrence (in %)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Years
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
B
Total Copepods
Calanus Total Traverse
Calanus I-IV
Tintinnida Total
Thecosomata (North Atlantic)
Parafavella gigantea
Foraminifera (Total)
Para-Pseudocalanus spp.
Appendicularia
Oithona spp.
Echinoderm larvae
Copepod nauplii
Radiolaria Total
Copepod eggs
Cirripede larvae (Total)
Acantharia spp
Chaetognatha Traverse
Cyphonautes
Metridia Total traverse
Acartia spp. (unidentified)
Evadne spp.
Centropages typicus
Pseudocalanus spp. adult Total
Bivalvia larvae
Radiolaria non-Acantharian
Temora longicornis
58.7
51.5
38.5
25.2
19.5
19.2
18.3
13.1
9.8
9.4
8.1
8
6.6
5.3
5.1
5.1
4.9
4.5
3.6
3.2
3.1
2.1
2.1
2
1.9
1.4
Frequency of occurrence (in %)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Years
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
C
Calanus V-VI Total (Atlantic-fin hel glac)
Calanus finmarchicus
Euphausiacea Total
Chaetognatha eyecount
Metridia lucens
Hyperiidea (Total)
Decapoda larvae (Total)
Calanus glacialis
Fish larvae
Metridia longa
Calanus hyperboreus
Paraeuchaeta norvegica
Fish eggs (Total)
Euchaetidae (unidentified)
Clione limacina
Calanus helgolandicus
72.9
69.5
38.8
21
17.6
15.2
10
9
8.9
8
6.3
4.8
2.4
1.8
1.5
1.1
Frequency of occurrence (in %)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Years
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

Figure 2: The average annual abundance of the most common plankton taxa recorded since 2008, (A) phytoplankton; (B) small zooplankton (C) large zooplankton. Standardised abundance, 0=mean. Aggregated data for the whole Svalbard transect.

Annual trends (2008-2017) in the CPR data for the most common phytoplankton and zooplankton species are shown in Figure 2. Figure 2 also show the most dominant phytoplankton and zooplankton recorded in this region ordered by the percent frequency of occurrence on CPR samples. In 2017 a total of 87 zooplankton and 38 phytoplankton taxonomic entities were routinely recorded for this region on CPR samples representing a fairly diverse plankton community considering the high latitude of these observations. Of particular note for 2017 was the large numbers of *C. hyperboreus* (highest since 2010) and low numbers of *C. finmarchicus* recorded as well as a high number of fish larvae sampled in April. The abundance of the marine cladoceran *Evadne* spp was well above its long-term mean. In the phytoplankton very large blooms of *Pseudo-nitzschia delicatissima* were recorded in July 2017 and the abundances of *Odentella aurita* and *Rhizosolenia imbricata* were well above the long-term mean.

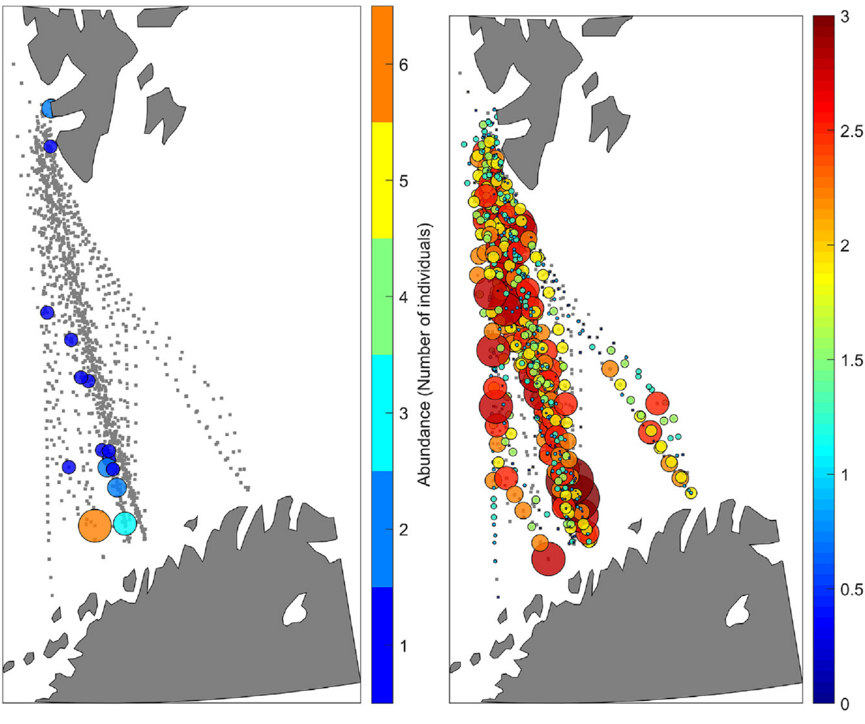

Figure 3: The spatial distribution and abundance of the calanoid species *Calanus helgolandicus (left)* and *Calanus finmarchicus (right)*. Colours represent abundances per sample.

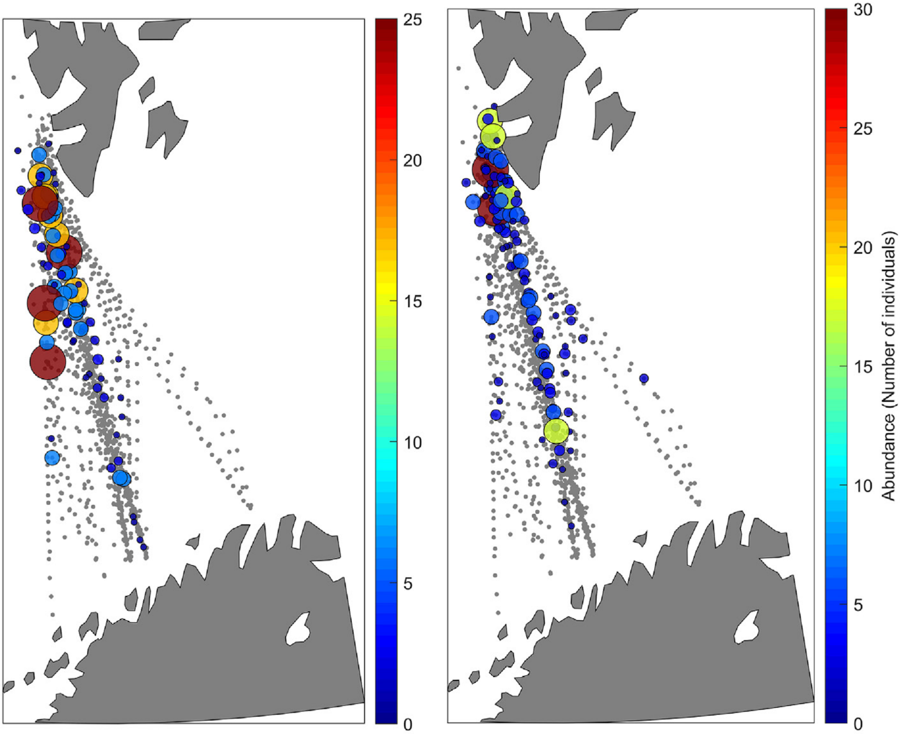

Figure 4: The spatial distribution and abundance of the calanoid species *Calanus hyberboreus (left)* and *Calanus glacialis (right)*. Colours represent abundances per sample.

The spatial distribution of the most common zooplankton *C. finmarchicus* and its relatives are show in Figure 3 and 4. We have focused on *C. finmarchicus* and its congeneric relatives *C. helgolandicus*, *C. glacialis* and *C. hyperboreus* as they are the numerically dominant zooplankton found in this region and they also occupy distinctive thermal preferendums and niches. As such, these species can act as useful indicators and 'sentinel' species to environmental changes and in particular highlight the consequences of climate warming in this region. Thermal niches mentioned in the text have been calculated from gridded CPR North Atlantic data. By far the most numerically dominant species *C. finmarchicus* shows the most cosmopolitan thermal envelope for this region ranging between 0-11 °C with an optimum of around 5-6 °C. The more southerly distributed and warmer-water species *C. helgolandicus* has a thermal preferendum ranging between 9-18 °C with a thermal optimum of 11 °C. To put the two species into context from the Svalbard region into the wider North Atlantic region we have shown the biogeographical distributions of the two species for the whole North East Atlantic and Norwegian Sea (Figure 5). In the North Sea *C. finmarchicus* is at its southern edge and *C. helgolandicus* is close to its optimum (Helaouët, Beaugrand and

Edwards, 2013). For the more cold water species *C. glacialis* the thermal range was between 0-7 °C with a thermal optimum of ~4 °C. The larger and lipid rich species *C. hyperboreus* shows a strong affinity towards more polar waters with a thermal range between 0-7 °C and a thermal optimum of between 0-2 °C in these waters.

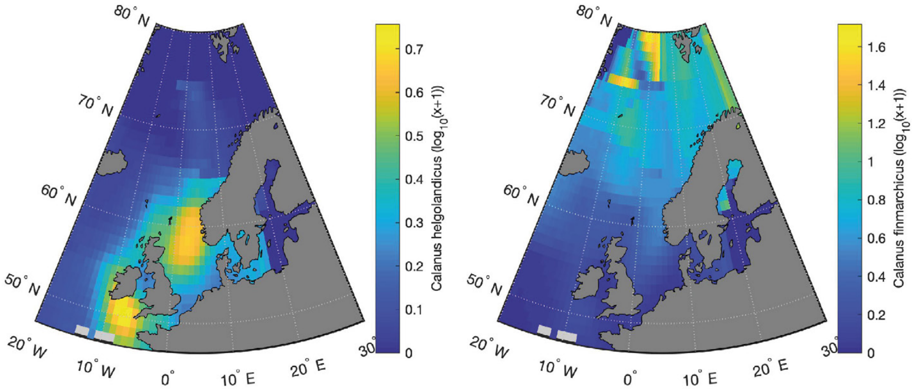

Figure 5: The mean spatial abundance of *C. helgolandicus* and *C. finmarchicus* in the North East Atlantic and Nordic Seas. Data based on CPR sampling and interpolated using objective mapping procedures.

C. finmarchicus is most abundant off the northern coast of Norway with the more colder distributed species *C. glacialis* and *C. hyperboreus* found most abundant off the south-west coast of Svalbard and Storfjord Channel following the penetration of the colder Arctic Current from the east. Interestingly the warm-temperate species *C. helgolandicus* is also recorded on this route with highest abundances recorded off northern Norway. Rather surprisingly, the species has also been recorded off the west coast of Svalbard itself, presumably being carried northward there by the warmer West Spitsbergen Current. The northernmost record of this southerly distributed species *C. helgolandicus* (from CPR records) is currently 77.902 °N recorded off the west coast of Svalbard. There is increasing evidence that temperate species are becoming more commonly recorded in the Barents Sea over the last few years. This is in line with the observed and rapid increase in temperatures recorded in the Barents Sea over the last decade (Lind et al. 2018). Seasonally the *C. finmarchicus* season extends from March to October, whereas the warmer-water species *C. helgolandicus* is generally only present in the autumn months in this region. The seasonal presence in the surface waters of *C. hyperboreus* is generally restricted to the late spring/ early summer in this region.

2.1 Trans-Arctic invasive species

Apart from shifting species boundaries (e.g. *Calanus helgolandicus*) that are moving progressively poleward and, in some cases, expanding, the rapid climate change observed the Arctic may have even larger consequences for the establishment of invasive species and the biodiversity of these northern seas (Reid et al. 2007). The thickness and areal coverage of summer ice in the Arctic have been melting at an increasingly rapid rate since records began (Lind et al. 2018). In the spring following the unusually large ice free period in 1998 large numbers of a Pacific diatom *Neodenticula seminae* were found in samples taken by the CPR survey in the Labrador Sea in the North Atlantic. *N. seminae* is an abundant member of the phytoplankton in the subpolar North Pacific and has a well-defined palaeo history based on deep sea cores.

According to the palaeo evidence and modern surface sampling in the North Atlantic since 1948 this was the first record of this species in the North Atlantic for at least 800,000 years. The reappearance of *N. seminae* in the North Atlantic, and its subsequent spread southwards and eastwards to other areas in the North Atlantic, after such a long gap, could be an indicator of the scale and speed of changes that are taking place in the Arctic and North Atlantic oceans as a consequence of climate warming (Reid *et al.* 2007).

The species has been recently found in the Barents Sea north of Iceland and west of Svalbard and also on the ST route in the spring of 2016 at 77.387 N and 13.557 E which is currently its most easterly record. Independent of the CPR survey, the presence of *N. seminae* has recently been recorded from sediment samples along the west Spitsbergen slope (Miettinen, Koç and Husum, 2013). It is possible we could witness more trans-Arctic exchanges in the near future if the ongoing warming trend and reduction of sea ice continues in the Arctic.

The diatom species may itself could be the first evidence of a trans-Arctic migration in modern times and be a harbinger of a potential inundation of new organisms into the North Atlantic. The future consequences of such a change to the biodiversity, productivity and health of Arctic systems caused by these trans-Arctic migrations as well as the encroachment and establishment of more southerly distributed species are at present unknown but are being closely monitored by the CPR survey. Figure 6 shows the distribution of *N. seminae* in the Northern Hemisphere from CPR records in the North Pacific and records from the North Atlantic from 1998 and also the first record from the Svalbard region.

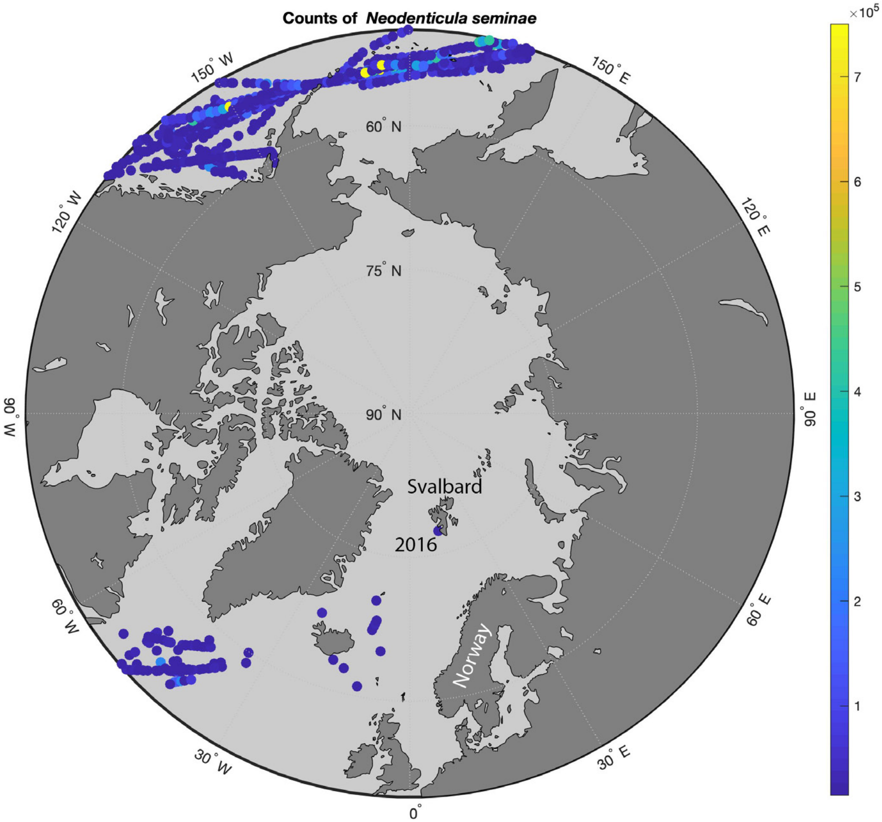

Figure 6. The distribution of the Pacific diatom species *N. seminae* in the Northern Hemisphere from CPR records in the North Pacific and records from the North Atlantic from 1998. The species was recorded off Svalbard in 2016, its most easterly observation in the North Atlantic.

3. Unanswered questions

Many unanswered questions concern the impact of climate change on plankton including the potential acidification of the marine environment and the consequences of these changes to higher trophic levels. Some key emerging issues are listed below.

- Establishing mechanistic links between climate warming, plankton and fisheries (and other higher trophic levels such as seabirds) to form a predictive capacity.
- Identifying species and habitats particularly vulnerable or resilient to climate change impacts and separating the impacts of climate from other anthropogenic pressures such as nutrients/overfishing.
- Understanding the risks to species and habitats and the potential opportunities for new species colonisations as well as potential new pathogens and Harmful Algal Bloom species.
- Understanding the risks caused by warming temperatures and acidification on native marine organisms.
- Understanding the rate of genetic adaptation to climate change impacts.

4. Recommendations for the future

It is envisioned that in the near future the CPR survey will form part of a more integrated observation system within this region and enhance its monitoring with an additional suite of biogeochemical and molecular sensors. It will also endeavour to explore where possible synergies between other oceanographic monitoring and the biological monitoring conducted by the CPR survey. For example, the CPR survey works closely with Norwegian scientists to coordinate its sampling on board of this ship of opportunity and shares data with the Norwegian ferrybox system to obtain further and complimentary information such as pCO_2. Although this region has limited commercial shipping activities, if the CPR monitoring was to be expanded in this region, additional CPR routes could be towed using other ships of opportunity in this region such as tourist vessels.

5. Data availability

All data are freely available on request by contacting the Continuous Plankton Recorder Survey at the Marine Biological Association (MBA), United Kingdom. Data requests (Dan Lear: dble@mba.ac.uk).

Dataset	Parameters	Period	Location or area	Dataset landing page	Comment
CPR Survey: Svalbard plankton data	>100 plankton taxa	Monthly data since 2008-11-01	CPR tow route from Tromso in northern Norway to Longyearbyen in Svalbard	http://doi.dassh.ac.uk/data/1629	Data requests (Dan Lear: dble@mba.ac.uk).

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