

The background of the slide features a close-up, artistic photograph of a nautilus shell, showing its intricate spiral and metallic sheen. To the right, a portion of a nautilus head is visible, with its eye stalks and sensory tentacles. The overall color palette is dominated by deep blues and greys, with highlights reflecting off the shell's surface.

Atlas of Calcifying Plankton

Results from the North Atlantic Continuous
Plankton Recorder survey 1960-2007

Sir Alister Hardy Foundation for Ocean Science
Monitoring the health of the oceans since 1931





Front cover image: *Limacina helicina*, S. Comeau

Title page image: *Clione limacina*, R. Hopcroft; NASA

Back cover image: *Limacina helicina*, R. Hopcroft

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Results from the North Atlantic Continuous Plankton Recorder survey

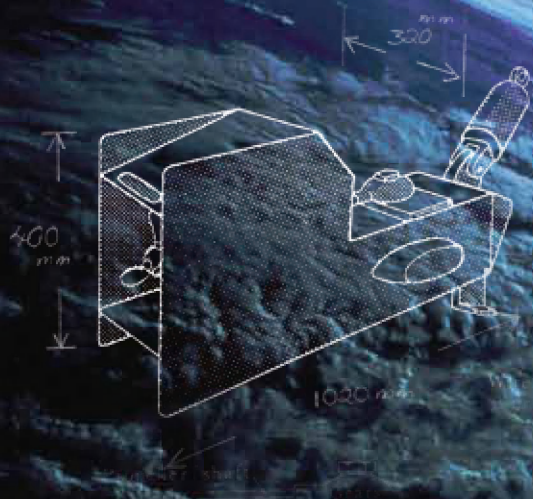
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Preface

Ocean acidification is a fact. The chemistry is straightforward and the declining trend in pH can be observed from time-series data. However, the biological, ecological and biogeochemical impacts of ocean acidification are more uncertain. Some processes, organisms and ecosystems have been shown to respond to lower pH levels in laboratory and mesocosm experiments but field evidence is very rare. Yet, ocean pH has already declined by 0.1 unit (equivalent to an increase of ocean acidity of 30%) since 1800, mostly in the past 50 years. Observational evidence of an impact of ocean acidification would reinforce conclusions drawn from short-term perturbation experiments.

The European Project on Ocean Acidification (EPOCA) gathers scientists from 29 partner institutions and 10 countries. It has the goal to investigate ocean acidification and its impact on marine organisms and ecosystems. One of its work packages aims to study whether ocean acidification could affect the distribution of planktonic organisms in the North Atlantic.

The database collected using the Continuous Plankton Recorder (CPR) operated by SAHFOS covers a long time span (surveys are on-going since 1946) and the whole North Atlantic, including the North Sea. It is therefore a unique tool to investigate changes in the planktonic community composition. Key publications have documented, for example, changes in zooplankton and chlorophyll abundance over the past decades.

However, the data on calcareous plankton archived in the CPR database have not yet been exploited. The publication of the “Atlas of Calcifying Plankton” by SAHFOS and EPOCA begins to fill this gap and is therefore most timely. I am convinced that the scientific community will use this short preliminary description of the data available to investigate the drivers of the changes (or lack of thereof) reported in the Atlas.

Jean-Pierre Gattuso
EPOCA Scientific Coordinator



Introduction

Plankton are crucially important to life on earth. Not only are they one of the most significant resources of biodiversity on our planet, they provide key roles in climate regulation and oxygen production, and form the base of the marine food-web which supports fish, seabirds and marine mammals. Plankton are affected by a complex mix of processes operating over multiple spatial and temporal scales. One of the decadal scale processes is ocean acidification. Ocean acidification is a direct consequence of increased human emissions of CO_2 . Since 1750, the concentration of CO_2 in the atmosphere has risen by 100 ppm to ~390 ppm. A significant proportion of atmospheric CO_2 has been taken up by the ocean, causing the average surface ocean pH to decrease from 8.2 to 8.1, rendering the oceans more acidic than they have been for 20 million years (Orr et al., 2005; Royal Society, 2005). This trend will continue and modelling of future scenarios suggests surface ocean pH may drop to ~7.7 by the end of the 21st century (Caldeira and Wickett, 2005).

How does ocean acidification impact marine plankton? At present the answer is unclear, which is why the EU EPOCA project is so important. However one group of plankton – those with calcified structures – are likely to be the most susceptible to change in pH. Calcifying plankton include taxa that create shells, skeletons or other structures from CaCO_3 . This group is taxonomically diverse and includes phytoplankton such as coccolithophores, zooplankton such as pteropods and the larval stages of benthic bivalve molluscs and echinoderms. Our understanding of their long term spatial distributions is described in this atlas.

Research on the impact of ocean acidification on plankton is still rudimentary with results from different studies appearing incongruous; for instance coccolithophores have been found to show reduced calcification in response to increased atmospheric CO_2 , with thinning of their calcite plates (Riebesell et al., 2000). Yet other work has shown contradictory results, with increased coccolithophore calcification

with decreasing pH (Iglesias-Rodriguez et al., 2008). These studies clearly indicate significantly more research into the effects of ocean acidification on plankton is needed.

Among the zooplankton, pteropods may be one of the first calcifying taxa to be affected by ocean acidification. Pteropods are found throughout surface ocean waters and are particularly abundant in polar regions where they represent an important component of the food web (Bathmann et al., 1991; Pane et al., 2004). Because CO_2 is particularly soluble in cold waters, surface waters in the high-latitudes will become undersaturated faster than other regions with respect to aragonite, which is used in pteropod shell formation (Orr et al., 2005). One of the few studies to date showed that when live pteropods were exposed to undersaturated seawater, their aragonite shells showed notable dissolution (Fabry et al., 2008). Models indicate that Southern Ocean surface waters will begin to undersaturate with respect to aragonite by 2050 (Orr et al., 2005). By 2100, this undersaturation will extend across the Southern Ocean and into the subarctic Pacific Ocean. This suggests that conditions detrimental to high-latitude ecosystems could develop within decades and not centuries as suggested previously.

These results indicate a clear urgency to develop a better understanding of the ecology of calcareous taxa, their abundance and distribution.

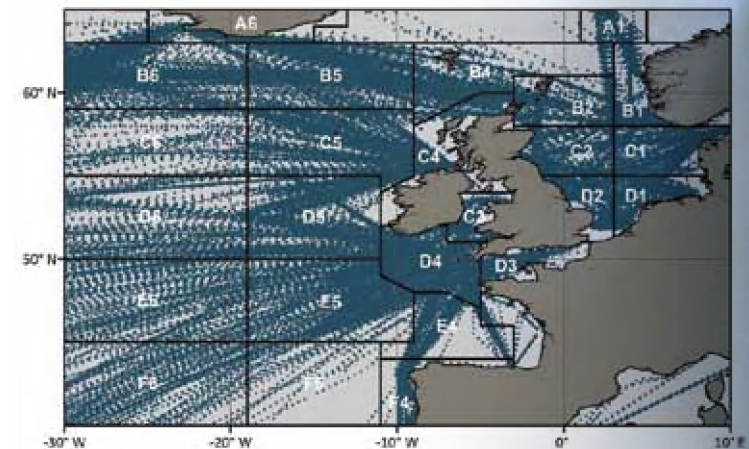
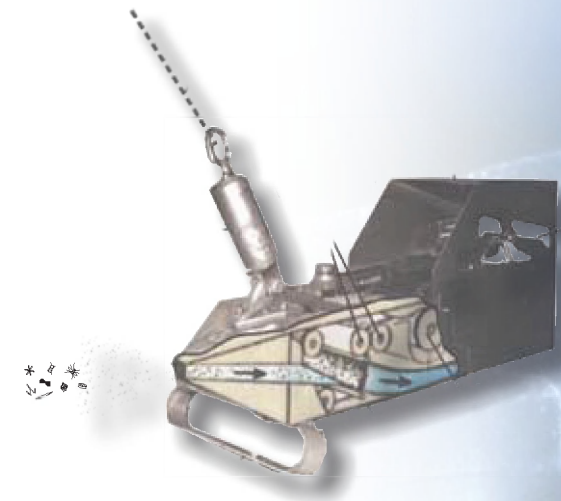


CPR methodology

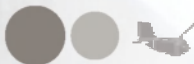
The Continuous Plankton Recorder (CPR) survey has been operating in the North Atlantic and North Sea since 1931 and measures the abundance of approximately 450 phytoplankton and zooplankton taxa (Warner and Hays, 1994). The CPR is a high-speed plankton recorder that is towed behind 'ships of opportunity' through the surface layer of the ocean (~10 m depth). Water passes through the recorder, and plankton are filtered by a slow moving silk (mesh size 270 μm). A second layer of silk covers the first and both are reeled into a tank containing 4% formaldehyde. Upon returning to the laboratory, the silk is unwound and cut into sections corresponding to 10 nautical miles and approximately 3 m³ of filtered sea water. The colour of each section of CPR silk is then evaluated and categorized according to four levels of 'greenness' (green, pale green, very pale green and no colour) using a standard colour chart; these numbers are given a numerical value as a measure of the 'Phytoplankton Colour Index'. This is a semiquantitative measure of phytoplankton biomass; the silk gets its green colour from the chloroplasts of the filtered phytoplankton. Phytoplankton cells are then identified and recorded as either present or absent across 20 microscopic fields spanning each section of silk; CPR phytoplankton abundance is therefore a semiquantitative estimate (i.e. the species is recorded once per field independent of the number of cells in a field). However, the proportion of cells captured by the silk reflects the major changes in abundance, distribution, and community composition of the phytoplankton (Robinson, 1970), and is consistent and comparable over time. Zooplankton analysis then carried out in two stages with small (<2 mm) zooplankton identified and counted on-silk and larger

(>2 mm) zooplankton enumerated off-silk. The collection and analysis of CPR samples have been carried out using a consistent methodological approach since 1958, making the CPR survey the longest continuous dataset of its kind in the world (Edwards and Richardson, 2004).

To map calcifying taxa distributions, CPR data were partitioned by both year and calendar month to ensure each map was decadal representative. The inverse squared distance method of interpolation was used to plot the taxa distributions on a 250 km grid throughout the time-series. The technique is described in Beaugrand et al. (2000). Distribution maps for *Clione limacina*, *Limacina* spp., echinoderm larvae and bivalve larvae show quantitative abundance; however, due to changes in CPR sampling methodology, the maps of coccolithophores and foraminifera illustrate percent frequency of occurrence in CPR samples.



Top: A cross-section of the CPR, its internal mechanism and CPR body. Bottom: Map illustrating CPR sample coverage in the North Atlantic between 1958 – 2008. The CPR standard areas, used for time-series extraction in this atlas, are shown.



Coccolithophores

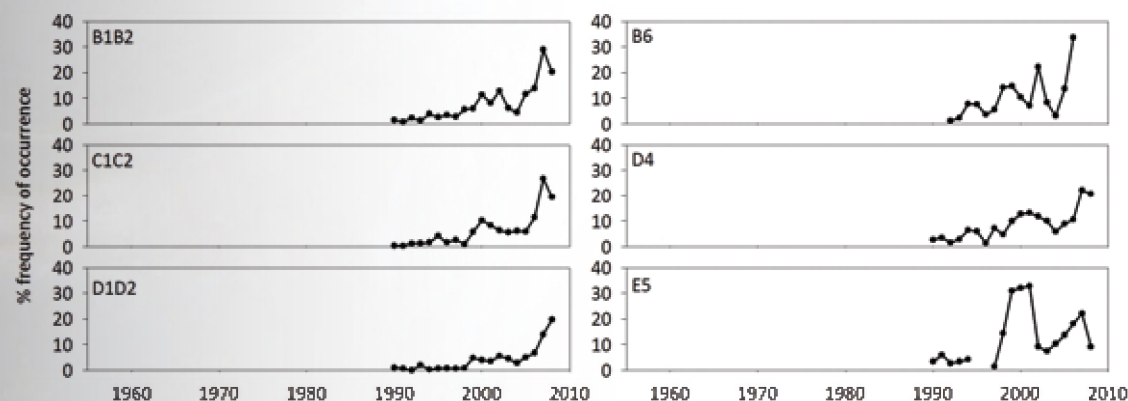
Coccolithophores, a calcareous phytoplankton group which secretes CaCO_3 plates, called coccoliths, are important contributors to the global production and vertical flux of CaCO_3 in the oceans (the inorganic carbon pump; Tyrrell and Young, 2009). They also affect the albedo of the oceans, both because they are important dimethyl sulphide (DMS) producers and also because of light-scattering by their coccoliths (Tyrrell et al., 1999). Their blooms can be so extensive that they are visible from space (top image).

Potential ocean acidification impacts:

Some laboratory and field experiments have indicated that coccolith formation may be compromised due to increasing ocean acidification (Riebesell et al., 2000; Zondervan et al., 2001). However, one recent study found increased calcification in the coccolithophore species *Emiliania huxleyi* (bottom image) with decreasing pH (Iglesias-Rodriguez et al., 2008), and another study found varying results even between different strains of this one species (Langer et al., 2009). These contradictory results indicate that further research is needed into the effects of ocean acidification on coccolithophores.

What we've seen with CPR data:

Coccolithophores have experienced an increased frequency of occurrence in most regions of the North Atlantic since the mid 1990s.



Above: Time-series of frequency of occurrence of coccolithophores on CPR samples for selected CPR standard areas.

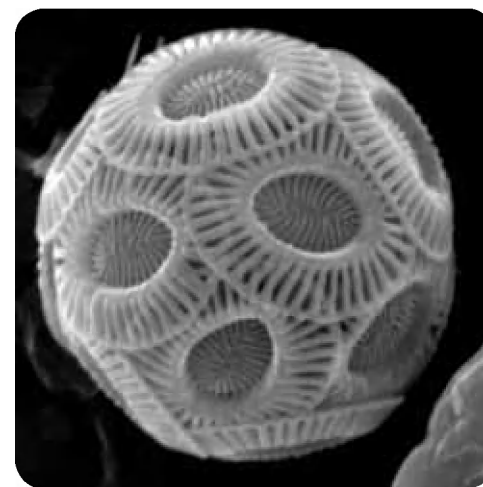
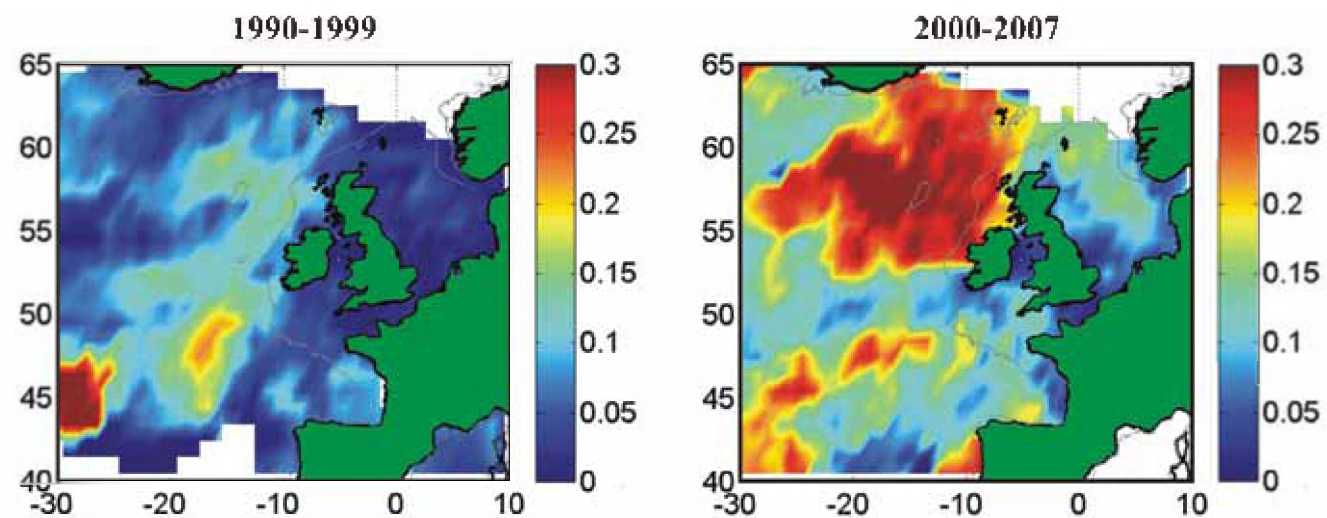


Image credits: (top) a coccolithophore bloom, NASA; (bottom) coccolithophore, taken from a CPR sample, G. Hallegraeff.



Above: Distribution maps of coccolithophores on CPR samples (measured as percent frequency of occurrence). Although coccolithophores have been recorded by the CPR since its inception, the enumeration methodology changed in the early 1990s. Therefore only post-1990 maps are presented here.



Foraminifera

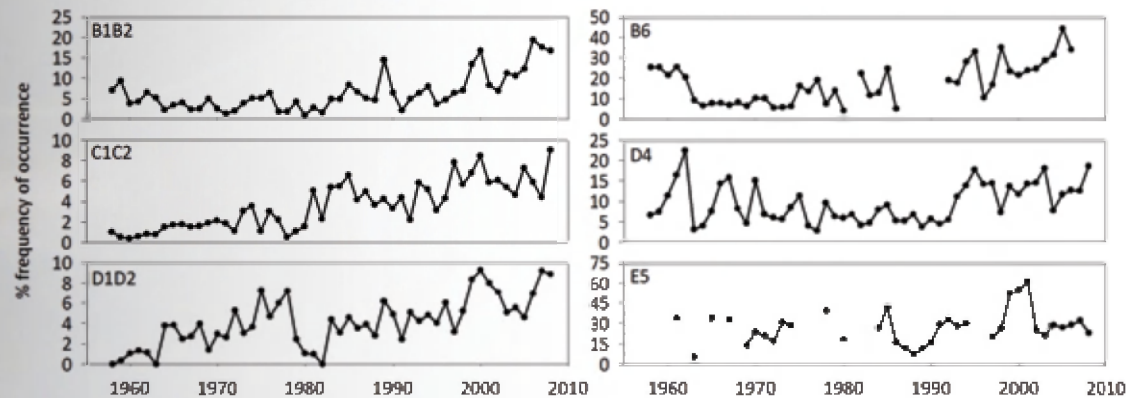
Foraminifera are a large group of protists which use CaCO_3 to produce elaborate shells, or tests. These tests are present in the fossil record as far back as the Cambrian period, and many marine sediments consist primarily of foraminiferal tests, which form sedimentary rocks such as limestone. Together with coccolithophores, they are responsible for more than ca. 90% of the pelagic carbonate production or roughly 50% of the global carbonate production (including benthos and coral reefs).

Potential ocean acidification impacts:

It is thought that foraminiferan calcification rates will decrease with increasing ocean acidification; however experimental evidence currently exists for only 2 of the ~50 planktonic species (Fabry et al., 2008). Laboratory experiments have shown that shell mass decreased in foraminifera grown in an acidic environment (Bijma et al., 1999) but shell formation and foraminifera growth also depend on water temperature and food supply. Warming sea surface temperature could lead to increased foraminiferal growth rates (Bijma et al., 2002; Fabry et al., 2008).

What we've seen with CPR data:

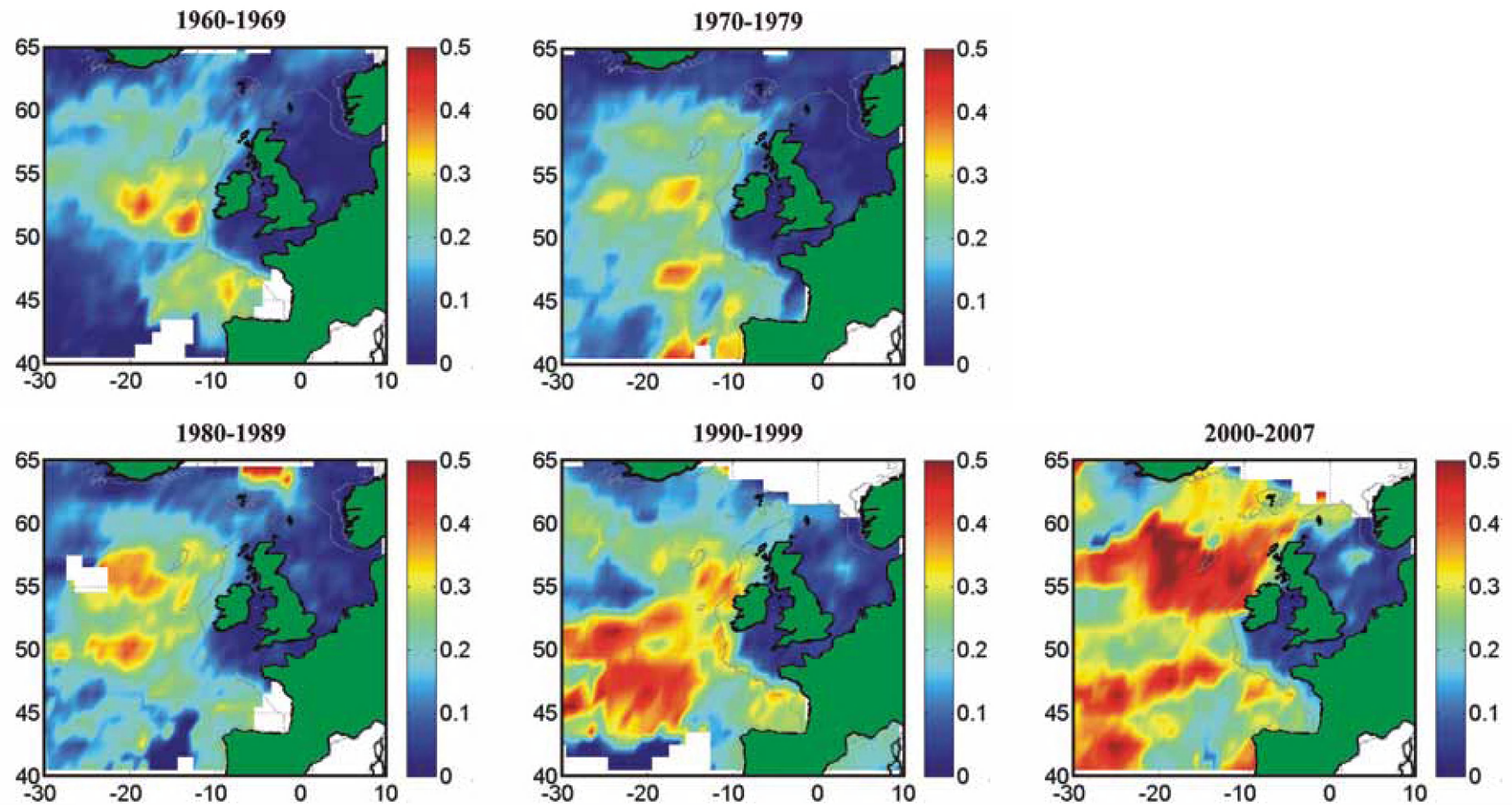
Change in the frequency of occurrence of foraminifera is regionally variable. In the North Sea there has been an increased frequency of foraminifera since the 1980s, while ocean regions have experienced periods of increase and decrease during the CPR's time-series.



Above: Time-series of frequency of occurrence of foraminifera on CPR samples for selected CPR standard areas.



Image credits: foraminifera, J. Bijma.



Above: Distribution maps of foraminifera on CPR samples (measured as frequency of occurrence).



Clione limacina

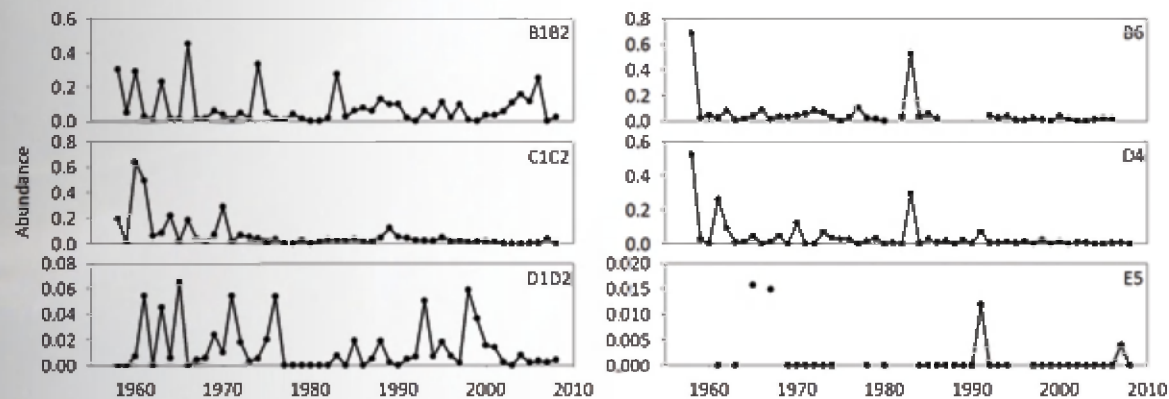
Clione limacina is a type of pteropod gymnosomata, or swimming sea snail (images, right). Though unshelled as an adult, *C. limacina* larvae form delicate shells. This species has evolved wing-like flapping appendages which have earned it the common name of 'sea angel'. *C. limacina* reaches lengths of up to 5 cm, and inhabits cold and temperate waters where it preys on *Limacina retroversa*, another species of pteropod.

Potential ocean acidification impacts:

Pteropods are most abundant in high latitudes, regions which may be particularly sensitive to ocean acidification due to their low calcium carbonate saturation state. The shells of pteropods are constructed from aragonite, a form of CaCO_3 that is particularly soluble, making them especially vulnerable to ocean acidification. Changes in pteropod abundance could have repercussions on marine food webs and may also affect the biological pump, particularly in polar regions.

What we've seen with CPR data:

No clear trend in abundance of *Clione limacina* is observable across the North Atlantic; however some regional changes have occurred. In standard areas C1C2 and D4 abundance of *C. limacina* appears to have declined since the 1960s.

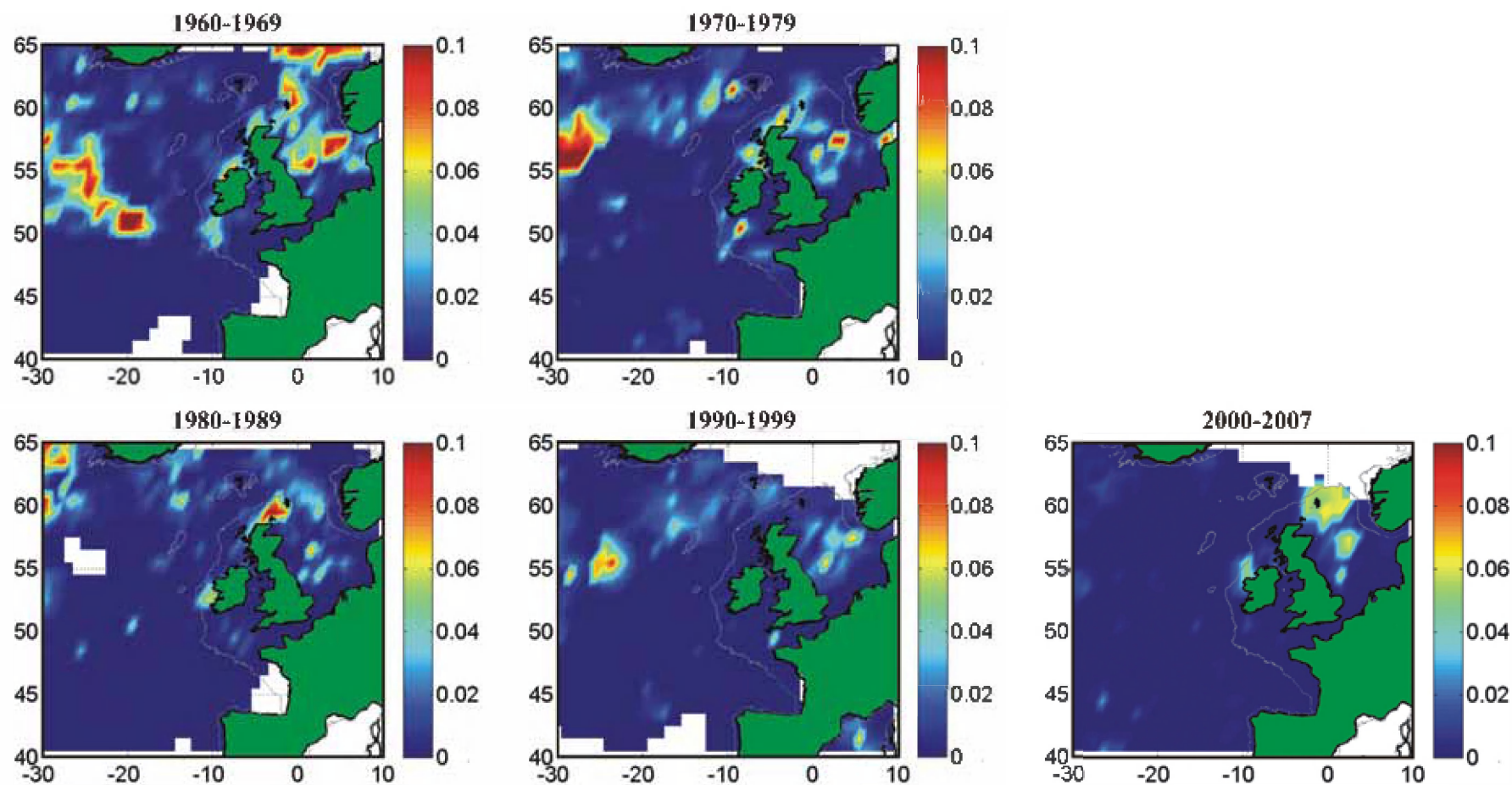


Above: Time-series of *Clione limacina* abundance on CPR samples for selected CPR standard areas.



Image credits: (top) *Clione limacina*, R. Hopcroft; (bottom) *Clione limacina*, M. Wakeling.





Above: Distribution maps of *Clione limacina* abundance on CPR samples.



Limacina spp.

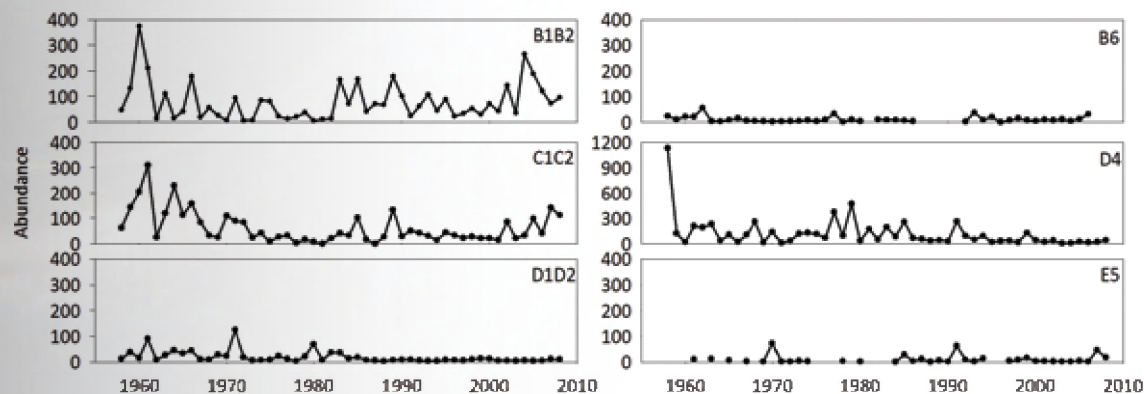
Like *Clione limacina*, *Limacina* spp. are 'winged' pteropods, and are sometimes known as 'sea butterflies'. *Limacina* spp., however, are from the order thecosomata, and retain their delicate shell throughout their life cycles. One species common to the CPR survey, *Limacina retroversa*, is an important phytoplankton grazer as well as the primary food source for *Clione limacina* and many fishes (Hunt et al., 2008). Changes in its abundance may impact food webs, particularly at high latitudes.

Potential ocean acidification impacts:

Experiments have shown that pteropod shells may form more slowly in water conditions expected by the end of the century (Comeau et al., 2009). Additionally, lower pH in seawater may cause their shells to be damaged by pitting, peeling and even dissolution (Orr et al., 2005). However, most research on acidification effects and pteropods has been carried out on only one of 34 species and species-specific responses to changes in pH are likely (Fabry et al., 2008).

What we've seen with CPR data:

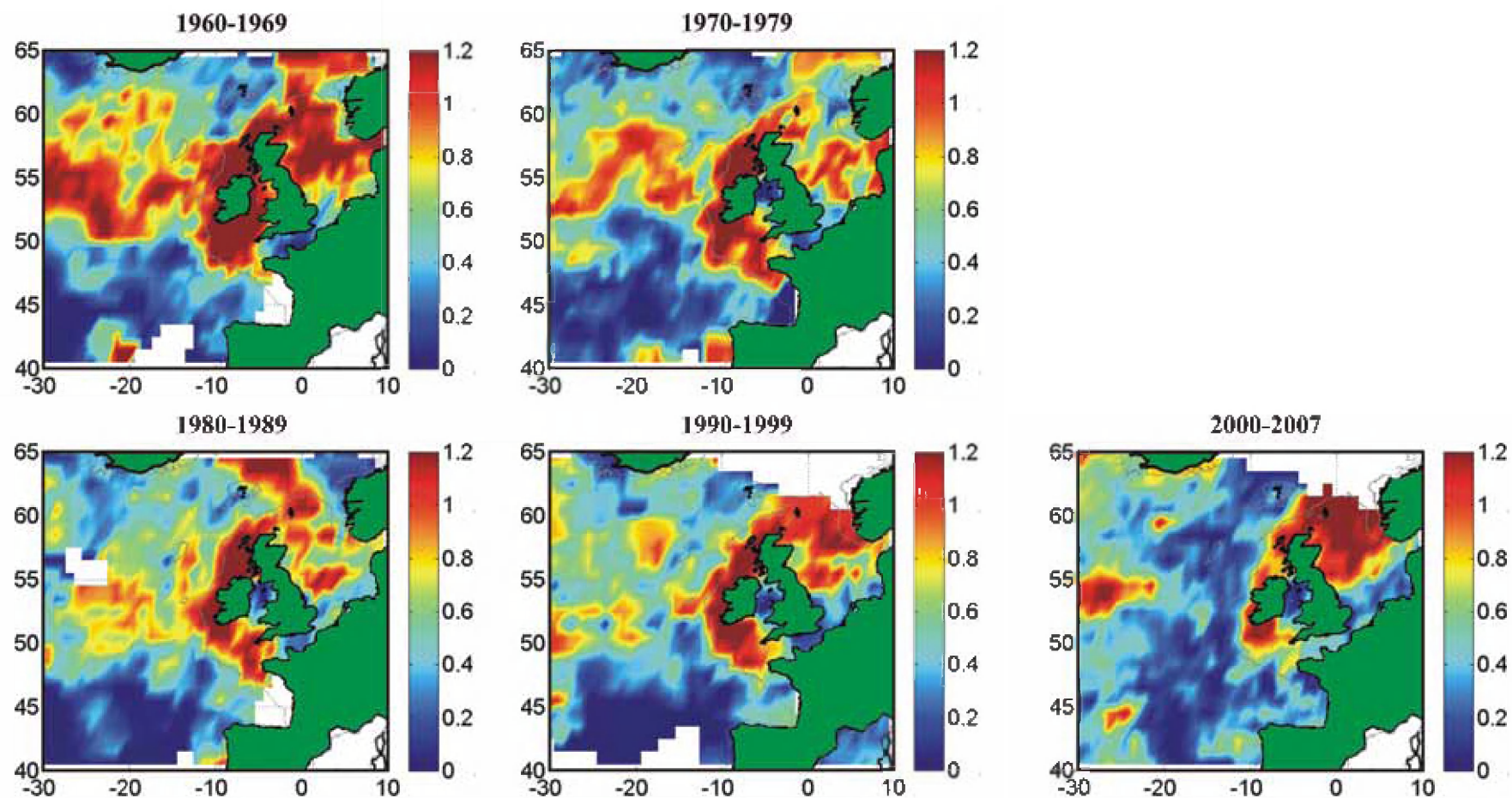
No clear trend in abundance of *Limacina* spp. is observable in the North Atlantic.



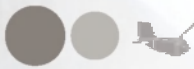
Above: Time-series of *Limacina* spp. abundance on CPR samples for selected CPR standard areas.



Image credits: *Limacina helicina*; R. Hopcroft.



Above: Distribution maps of *Limacina* spp. abundance on CPR samples.



Echinoderm larvae

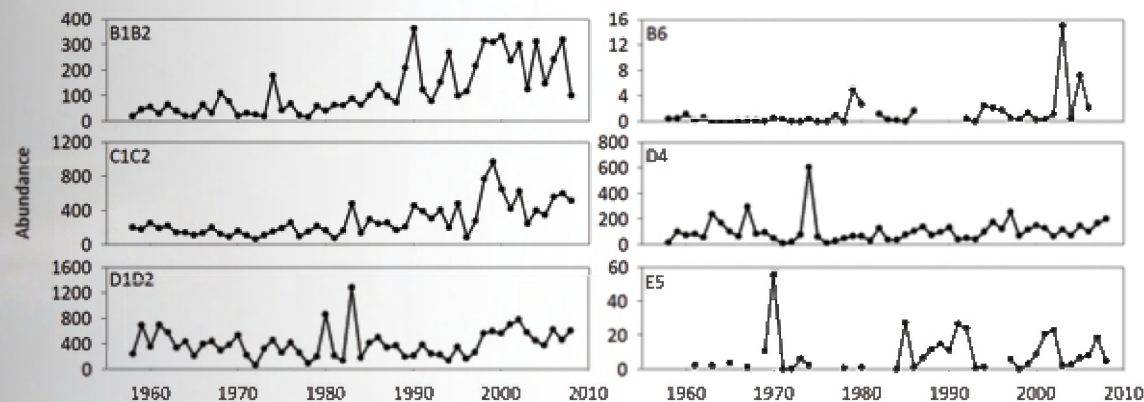
Echinoderms include organisms such as starfish and sea urchins which spend their early life stages in the plankton before settling on the sea floor. Echinoderms use a particularly soluble form of CaCO_3 to form their skeletons, which may make them especially sensitive to ocean acidification.

Potential ocean acidification impacts:

Experimental work has indicated that some sea urchins experience shell dissolution, acidification of the blood, reduced fertilization rates, reduced development speed, and reduced larval size when exposed to low pH conditions (Fabry et al., 2008). However, another study has shown that brittle stars may increase their calcification rates at higher CO_2 levels, but only at the expense of reduced muscle mass and physiological fitness (Wood et al., 2008).

What we've seen with CPR data:

There has been a large increase in echinoderm larvae in the North Sea, while abundance is temporally variable in oceanic regions of the North Atlantic.



Above: Time-series of echinoderm larvae abundance on CPR samples for selected CPR standard areas.

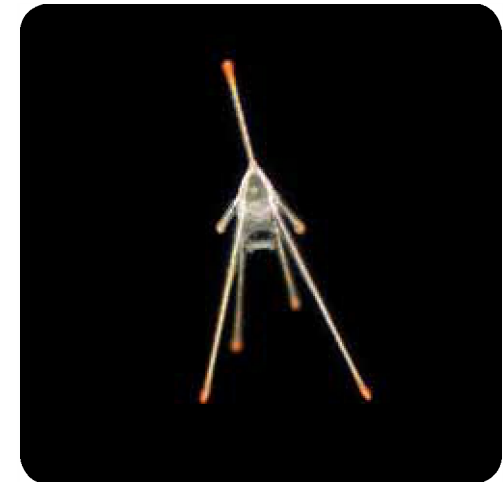
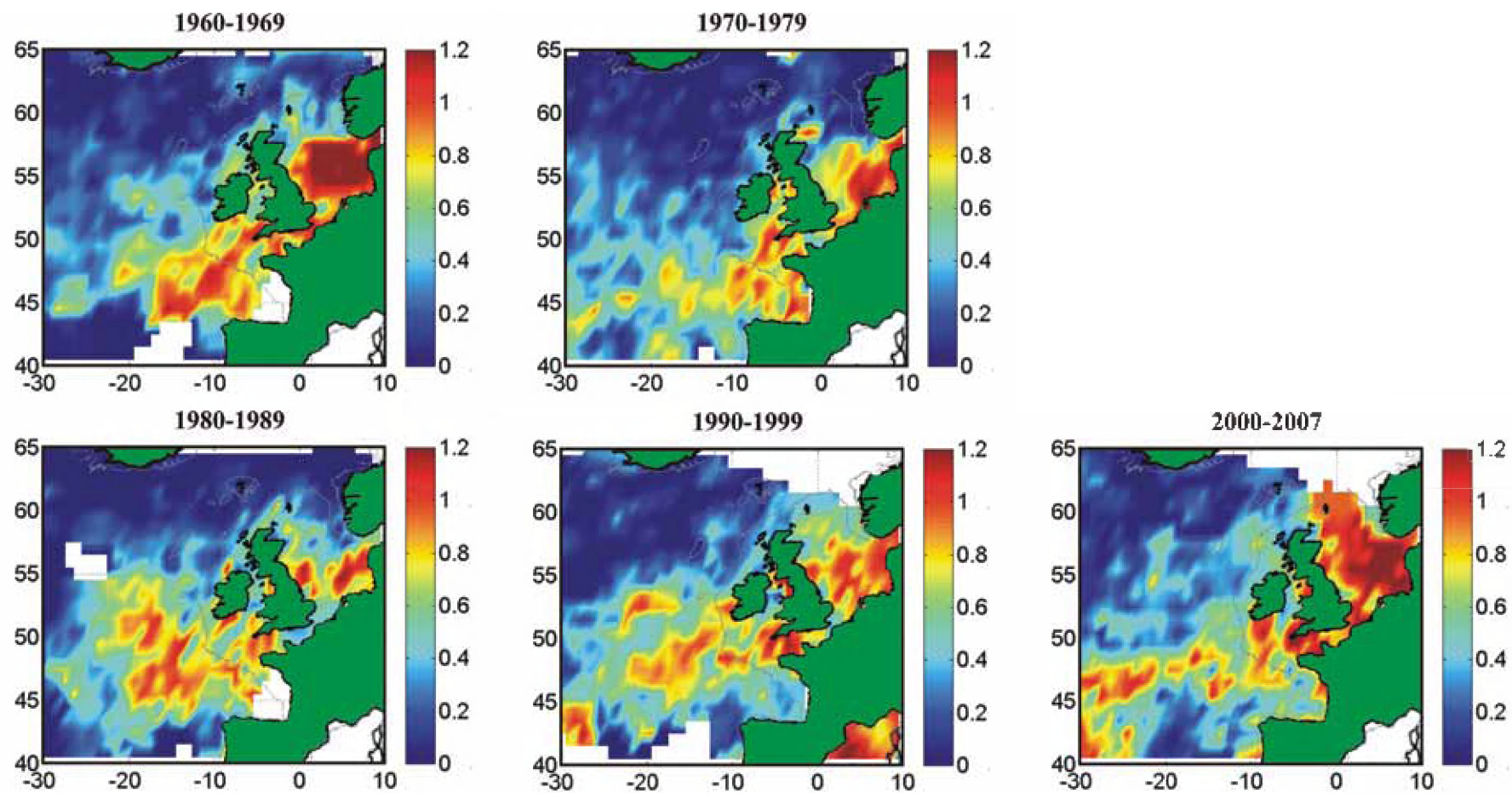


Image credits: (top) echinoderm larva, R. Kirby; (bottom) *Echinus esculentus*, N. Mieszkowska.



Above: Distribution maps of echinoderm larvae abundance on CPR samples.



Bivalve larvae

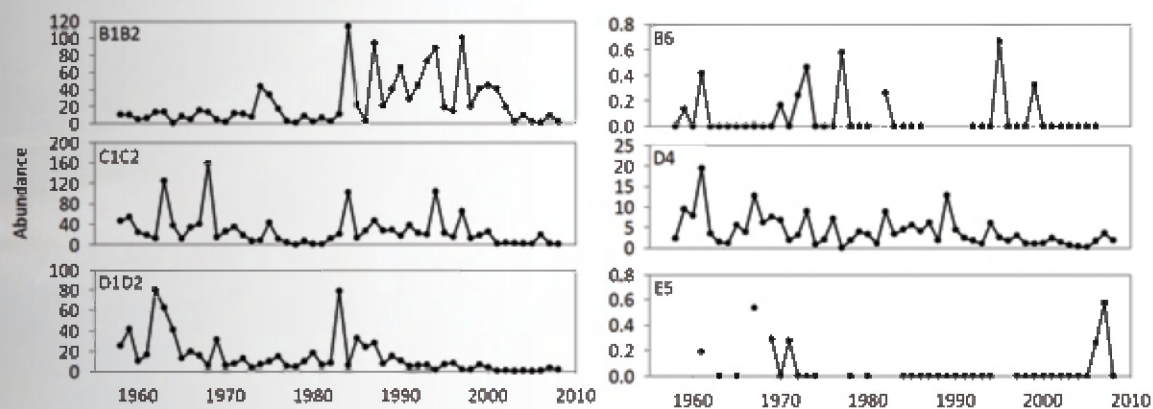
Bivalves are molluscs that include clams, scallops and mussels. Many bivalve species have planktonic larvae which are a food source for zooplankton. In their adult form, mussels, oysters, clams and scallops are consumed by higher organisms such as sea otters, sea birds, and humans. These organisms are also cultivated commercially and a negative response to environmental change may have economic repercussions.

Potential ocean acidification impacts:

Laboratory experiments indicate that, as pH decreases, the growth rate of the hard shells of bivalve molluscs, such as mussels, could decrease. One recent study suggests that by 2100, calcification could be reduced by 25% for mussels and 10% for oysters (Gazeau et al., 2007). In addition to reduced calcification, ocean acidification may affect other functions such as metabolism, immune responses, and growth rate; planktonic stages may be particularly vulnerable to the effects of acidification (Fabry et al., 2008).

What we've seen with CPR data:

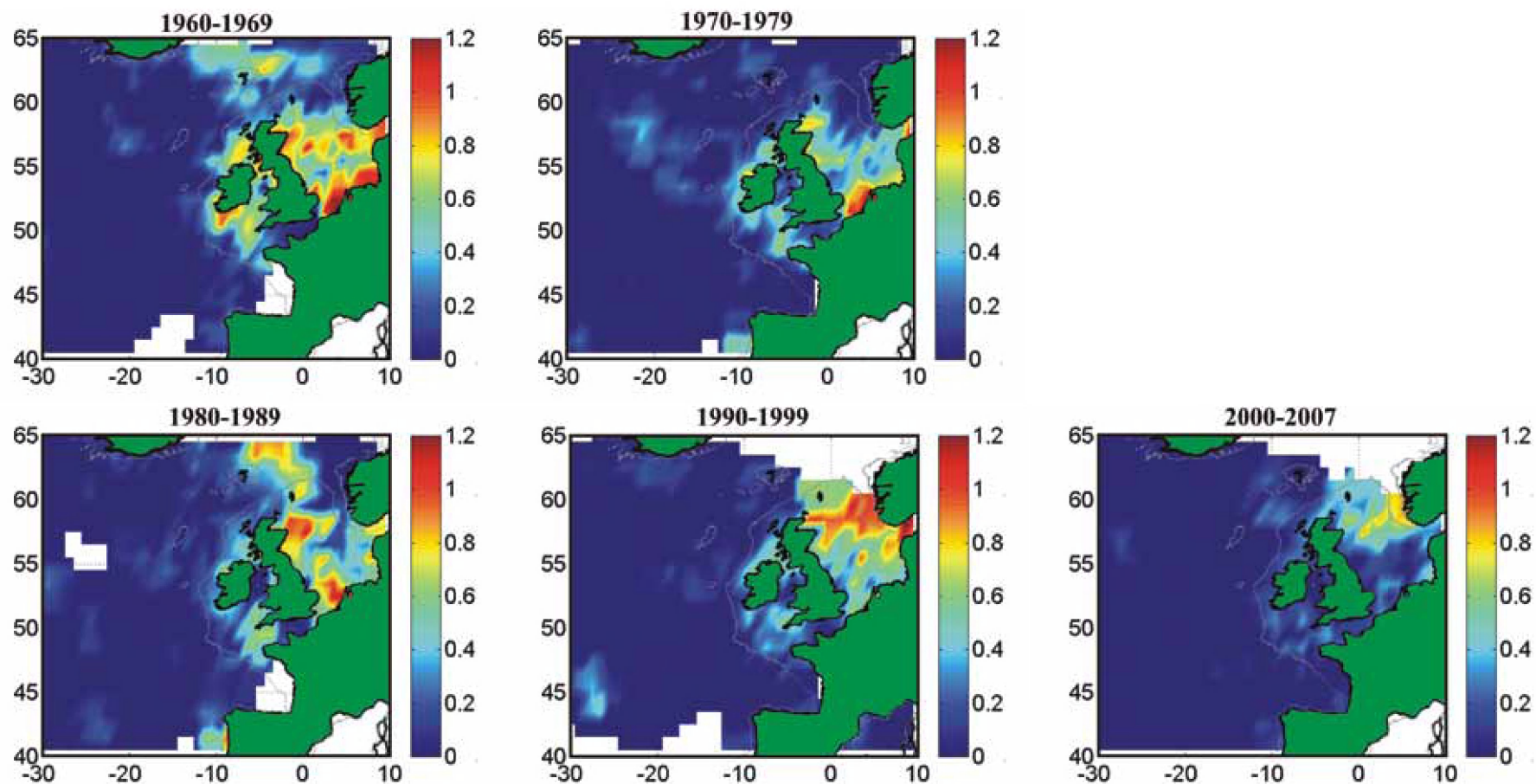
Abundance of bivalve larvae has decreased since the 1990s throughout most of the North Atlantic.



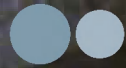
Above: Time-series of bivalve larvae abundance on CPR samples for selected CPR standard areas.



Image credits: (top) bivalve larva, R. Kirby;
(bottom) *Mytilus edulis*, N. Mieszkowska.



Above: Distribution maps of bivalve larvae abundance on CPR samples.



Summary

While we have a high degree of certainty that the oceans will become increasingly acidic, our knowledge of the potential consequences for the plankton is much less certain. Although calcifying plankton are more vulnerable to ocean acidification than non-calcifying taxa, the level of threat remains unknown. Because calcifying plankton play key roles in fundamental life support processes (e.g. coccolithophores are important contributors to primary production) and are commercially important (e.g. bivalve species such as oysters, scallops and mussels) a better understanding is vital. Laboratory and mesocosm experiments provide necessary information about the effects of decreasing pH on plankton biology; however, spatially and temporally extensive observations of changes in abundance and distribution are required in order to provide context at a larger, ecosystem scale. Therefore, there is a requirement to maintain an active program monitoring the abundance and distribution of calcifying and non-calcifying plankton in European waters. Only through the integration of experimental work, the perspective provided by the CPR's basin-scale approach to ecological monitoring, and research conducted through collaborative projects such as EPOCA can we hope to gain an understanding of, and eventually the ability to predict, the impacts of ocean acidification on the plankton.



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3. Leibniz-Institut für Meereswissenschaften IFM-GEOMAR (Germany)
4. Natural Environment Research Council NERC (United Kingdom)
5. Alfred Wegener Institute for Polar and Marine Research AWI (Germany)
6. The Chancellor, Masters and Scholars of the University of Cambridge of the Old Schools UCAM (United Kingdom)
7. Commissariat à l'Energie Atomique CEA (France)
8. Plymouth Marine Laboratory PML (United Kingdom)
9. Scottish Association for Marine Science SAMS (United Kingdom)
10. Max-Planck-Gesellschaft zur Förderung der Wissenschaften E.V MPG (Germany)
11. The Marine Biological Association of the United Kingdom MBA (United Kingdom)
12. Göteborgs Universitet UGOT (Sweden)
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14. Universiteit Utrecht UU (The Netherlands)
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16. Sir Alister Hardy Foundation for Ocean Science SAHFOS (United Kingdom)
17. GKSS-Forschungszentrum Geesthacht GmbH GKSS (Germany)
18. Universität Bern Bern (Switzerland)
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21. Vereniging voor Christelijk Hoger Onderwijs Wetenschappelijk Onderzoek en Patientenzorg VUA (The Netherlands)
22. Eidgenössische Technische Hochschule Zuerich ETH ZURICH (Switzerland)
23. Háfrannsóknastofnunin - Marine Research Institute HAFRO-MRI (Iceland)
24. University of Southampton SOTON-SOES (United Kingdom)
25. University of Plymouth Higher Education Corporation UoP (United Kingdom)
26. Intergovernmental Oceanographic Commission of UNESCO IOC-UNESCO (France)
27. University of Bristol UNIVBRIS (United Kingdom)

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