Global Marine Ecological Status Report

The ecological status of the marine pelagic environment based on observations from the global Continuous Plankton Recorder Surveys

Global Alliance of Continuous Plankton Recorder Surveys (GACS)

2010/2011

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  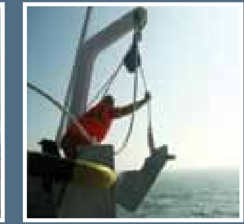

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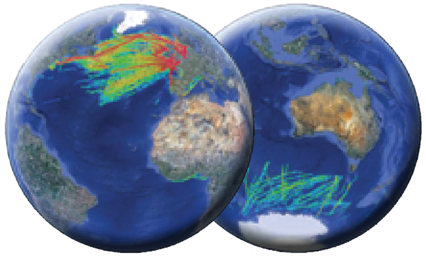


CPR samples in the Northern and Southern hemispheres. Courtesy of Google Earth.

The establishment of a global network of CPR surveys has long been a vision of the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) and finally got underway in 2011. Going Global was also a vision shared by the heads of other regional surveys around the globe, who enthusiastically agreed to form the Global Alliance of CPR Surveys (GACS). It seemed appropriate then, during the celebrations in Plymouth, UK. in September 2011 that marked the 80th Anniversary of the start of the North Sea CPR tows, the heads of the nine regional CPR surveys should meet to discuss the formation of GACS. Joining the group were a number of representatives from the Global Ocean Observing System (GOOS) programme of the Intergovermental Oceanographic Commission (IOC) of UNESCO, the Partnership for the Observation of the Global Oceans (POGO) and the North Pacific Marine Science Organisation known as PICES. They provided invaluable advice to help set up GACS and also witnessed the signing of the Memorandum of Understanding by the founding GACS partners.

The general goal of GACS is to understand changes in plankton biodiversity at ocean basin scales through a global alliance of CPR surveys. By "understand" we mean characterise, analyse and interpret. GACS has a number of specific aims which include:

- **development of a global CPR database**
- **production of a regular Global Marine Status Report (this document)**
- **ensuring common standards and methodologies are maintained**
- **providing an interface for plankton biodiversity with other global ocean observation programmes**
- **to set up and maintain a website for publicity and data access**
- **to facilitate new surveys and develop capacity building procedures**
- **to facilitate secondments of CPR scientists between GACS institutions**

Participants at the first GACS meeting held at SAHFOS in Plymouth 2011

GACS brings together the expertise of approximately 50 plankton specialists, scientists, technicians and administrators from 12 laboratories around the world, towing a common and consistent sampling tool, the CPR, from about 50 vessels. Working together, pooling our data and resources, was considered essential in order to understand the effects of environmental changes on plankton biodiversity at a global level. Numerous local and regional monitoring and observational programmes have been established in the past, but to date we have lacked a holistic perspective on plankton biodiversity in response to global events such as global warming and ocean acidification. GACS will provide that perspective using CPR data, a well recognised and standardised methodology. It will also allow us to assess changes and events at a local or regional level in a world-wide context. At the heart of GACS is the development of the global database of CPR data that will allow us to make such assessments of local, regional and global changes. Subsequently, an important product of GACS will be the production of a regular Ecological Status Report for global plankton biodiversity.

CPR surveys are now well established in the North Sea, North Atlantic, North Pacific and Southern Ocean. New surveys are underway in Australian, New Zealand, Japanese and South African waters with a Brazilian survey under development. These surveys provide coverage of much of the world's oceans. However, there are still vast areas of the mid-Atlantic, Pacific and Indian Oceans where there are no sustained plankton monitoring. One of the long-term challenges will be filling these gaps.

A Board of Governance has been established, comprising the regional heads of CPR Surveys:

Dr Graham Hosie, SCAR Southern Ocean CPR Survey (Chair)
Dr Sonia Batten, North Pacific CPR (Vice-Chair)
Dr Sanae Chiba, Japan JAMSTEC CPR
Prof. Martin Edwards, (P.I.) SAHFOS
Prof. Mitsuo Fukuchi, Japan NIPR CPR
Dr Julie Hall, New Zealand CPR
Assoc. Prof. Anthony Richardson, Australian CPR (AusCPR)
Dr Chris Melrose, Narrangansett USA CPR
Prof. Nick Owens (Director) SAHFOS
Prof. Erik Muxagata, Brazil
Dr Hans Verheye, South Africa CPR
Prof. Peter Burkill, ex officio

Working groups are being developed and will address the formation of the global CPR database, and maintaining standards and methodologies. Supporting all this are also a number of SAHFOS staff involved with secretariat support, database development, collaboration, training and publicity.

In order to keep scientists, governments and the public informed of GACS activities the GACS website has been established at www.globalcpr.org, which provides information about GACS, the member surveys and news of events. Regular newsletters will be produced and the first newsletter has already been distributed. It is exciting times ahead for GACS and for studying and monitoring plankton biodiversity at a global scale.

Global marine ecological status report

At the base of the marine foodweb, the free floating plant life of the sea (phytoplankton) provide food for the animal plankton (zooplankton) which in turn provide food for many other marine organisms. The carrying capacity of marine ecosystems in terms of the size of fish resources and recruitment to individual stocks as well as the abundance of marine wildlife (e.g. seabirds and marine mammals) is highly dependent on variations in the abundance, timing and composition of the plankton.

These organisms also play a crucial role in climate change through the export of the important greenhouse gas CO_2 to the deep ocean by carbon sequestration in what is known as the 'biological pump'. Without this process concentrations of CO_2 would be much higher in the atmosphere and the climate of the world would be much warmer. Apart from playing a fundamental role in the earth's climate system and in marine foodwebs, plankton are also highly sensitive indicators of environmental change and provide essential information on the 'ecological health' of our seas.

The following report provides indicators for the status of the global marine environment and provides information for important marine management issues such as climate warming impacts, biodiversity, pollution and fisheries.

Global research highlights

Marine pathogens and vibrio

As sea surface temperatures increase, predictions favour an increase in the number and range of pathogenic micro-organisms. Such changes are difficult to determine over short time periods that cannot separate short-term variations from climate change trends. In a unique long-term time study,Vezzulli et al. (2011) investigated the spread of the pathogenic bacteria, *Vibrio*, the causative agent of cholera in the North Sea over 54 years, between 1961-2005, and revealed that *Vibrio* bacteria is increasing in this region. The increase was related to rising temperatures in the North Sea.

Vezzulli, L., Brettar, I., Pezzati, E., Reid, P.C., Colwell, R.R., Höfle, M.G. and Pruzzo, C., 2011. Long-term effects of ocean warming on the prokaryotic community: evidence from the vibrios. The ISME Journal: Multidisciplinary Journal of Microbial Ecology, 6: 21-30.

Fish larvae atlas of the NE Atlantic

Retrospective analysis of fish larvae recorded by the CPR survey has produced new spatial and temporal records of 70 species of fish larvae over the last 60 years.

Edwards, M., Helaouet, P., Halliday. N., Beaugrand, G., Fox, C., Johns, D.G., Licandro, P., Lynam, C., Pitois, S., Stevens, D., Coombs, S & Fonseca, L. 2011. Fish Larvae Atlas of the NE Atlantic. Results from the Continuous Plankton Recorder survey 1948-2005. Sir Alister Hardy Foundation for Ocean Science. 22p. Plymouth, U.K. ISBN No: 978-0-9566301-2-7

Climate change and phytoplankton abundance

Hinder, S.L., Hays,G., Edwards, M., Emily C. Roberts, E.C., Walne, A.W. & Gravenor, M.B. 2012. Changes in marine dinoflagellate and diatom abundance under climate change. Nature Climate Change, DOI: 10.1038/NCLIMATE1388.

CPR detects the red-tide dinoflagellate *Noctiluca scintillans* in the Southern Ocean for the first time

Mcleod, D.J., Hallegraeff, G.M., Hosie, G.W. & Richardson, A.J. 2012.Climate-driven range expansion of the red-tide dinoflagellate Noctiluca scintillans into the Southern Ocean. J. Plankton Res : fbr112v1-fbr112.

Northward movement of NE Pacific copepods and climate variability

Batten, S.D. and Walne, A.W., 2011. Variability in northwards extension of warm water copepods in the NE Pacific. Journal of Plankton Research, 33: 1643– 1653.

Major policy document on marine ecosystem research

Reid, P.C., Gorick, G. & Edwards, M. 2011. Climate change and European Marine Ecosystem Research. 53p. Sir Alister Hardy Foundation for Ocean Science, Plymouth, UK.

Restructuring of marine foodwebs caused by overfishing

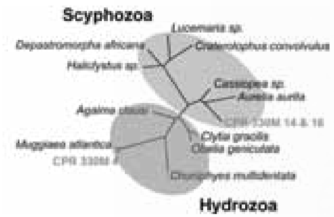
Overfishing of large-bodied benthic fishes and their subsequent population collapses on the Scotian Shelf of Canada's east coast, and elsewhere resulted in the restructuring of entire food webs now dominated by planktivorous, forage fish species and macroinvertebrates.

Frank, K.T., Petrie, B., Fisher, J.A.D. and Leggett, W.C., 2011. Transient dynamics of an altered large marine ecosystem. Nature, 477: 86-89.

BIOLOGICAL MEASUREMENTS 1931-

Genetic analysis

Mega and macro plankton



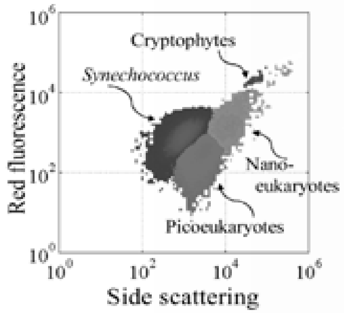
Light microscopy

Meso and micro-plankton

Upto 500 species routinely recorded making the CPR database one of the richest ecological datasets in the world

Flow cytometry

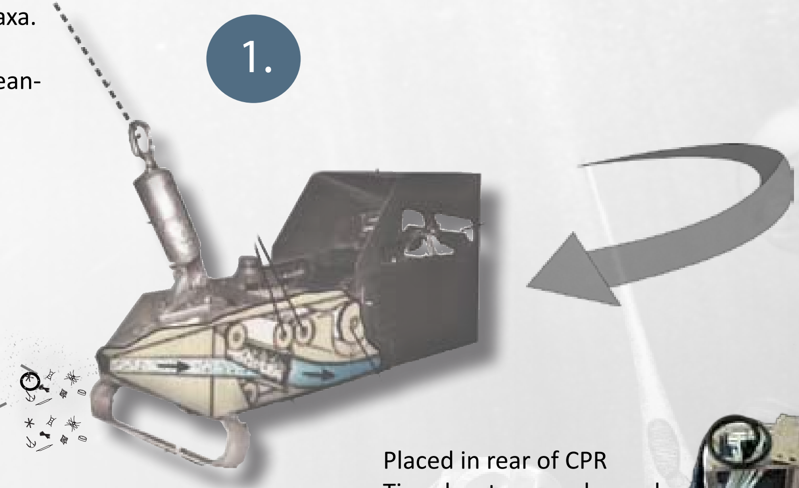
Nano and pico-plankton
(example)



(1) Continuous Plankton Recorder (CPR)

Longest sustained marine biological time-series in the world (1931-). Routine analysis of ~500 plankton taxa.

Multi-decadal sample and molecular archive at ocean-basin scale (1950-).



3.

(2) Water and Microplankton Sampler (WaMS)

Aimed at smaller size-fraction nano and pico plankton community.

Flow cytometry (2010-)
Molecular probes and barcoding (2010-)
Harmful Algal Bloom microarrays (2010-)

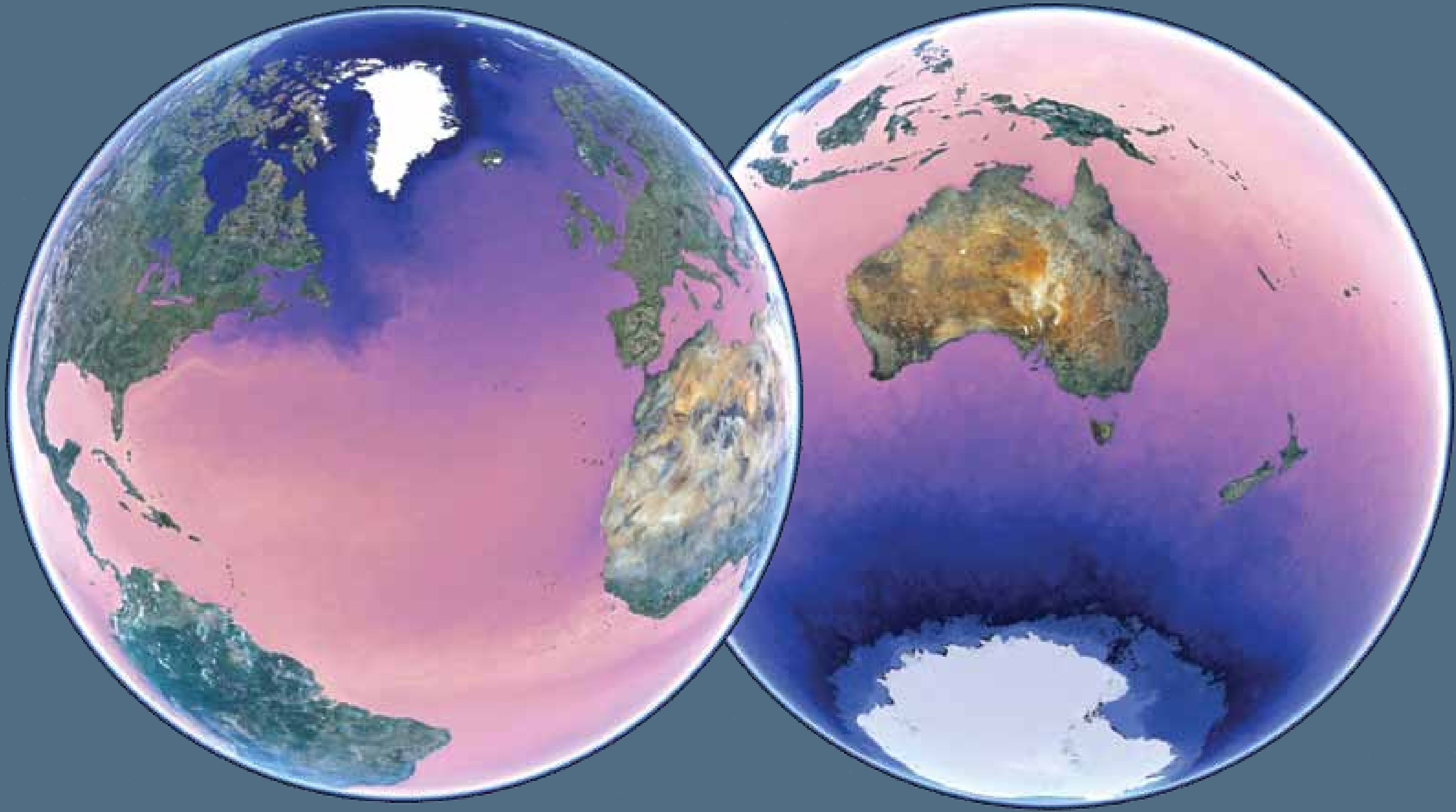
PHYSICAL MEASUREMENTS 1991-

Instruments placed in rear of CPR or onboard vessel

Placed in rear of CPR
Timed water samples and other measurements along CPR route

(3) Physical measurements

Sea surface temperature, salinity, depth and chlorophyll (1991-)
pCO_2 (2002-)
Microplastics (2004-)
Other measurements: Dissolved Inorganic Carbon, Alkalinity, Oxygen content, nutrients.



Global sea surface temperatures

Global environmental change

Arctic and Antarctic ice

Global environmental change

Global Sea Surface Temperatures

Over the last few decades the North Atlantic temperature has continued to show a strong increase similar to the pattern found in Northern Hemisphere temperatures. The temperature increase is currently mainly associated with increasing CO_2 input into the atmosphere from anthropogenic sources. The last few years, however, have seen a slight decline in temperature compared to the early and mid 2000s. Apart from external climate warming there are a number of natural oscillations. In the Atlantic the most important oscillations are the Atlantic Multidecadal Index (AMO) and the North Atlantic Oscillation (NAO). The NAO is responsible, particularly during the winter months, for much of the variability of weather in the North Atlantic region, affecting wind speed and prevailing direction, changes in SST and moisture distribution and the intensity, number and track of storms.

During the last couple of years the NAO has been uncharacteristically 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 NE Atlantic. While Northern Europe was experiencing cold weather areas in Greenland, the Canadian Arctic and the Labrador Sea hit record temperatures in 2010 resulting in extended melt periods. Overall, natural climate variability in the North Atlantic can account for approximately half ofthe temperature change experienced in the North Atlantic over the last 50 years. All these climate indices have been implicated in the changing ecology of the North Atlantic over the last 50 years including rapid biogeographical and phenological shifts in the plankton as well as whole ecosystem shifts.

The SCAR Antarctic Climate Change and the Environment (ACCE) Report identified the Antarctic/Southern Ocean region as particularly vulnerable to the impacts of climate change; warming oceans, changing circulation, diminishing sea-ice habitat and ocean acidification. The Southern Ocean has already experienced substantial warming (Aoki et al., 2003; ; Gille 2002). This warming has not been uniform. Some areas such as the western Antarctic Peninsula (WAP) have recorded significant increase in water temperature caused by Circumpolar Deep Water being pushed up onto the shelf (Dinniman et al. 2012). This has led to a decline in sea-ice, a regime shift in the phytoplankton, a change from a krill-centric to copepod dominated food web and changes in abundance and distribution of Adelie and Gentoo penguins (Dinniman et al. 2012; Hofmann et al., 2008; Montes-Hugo et al. 2009).

Sea surfce temperature in the oceanic north east Pacific is strongly influenced by the Pacific Decadal Oscillation, being cool (warm) in negative (positive) PDO phases. The western oceanic North Pacific generally shows an opposite SST pattern to the east. ENSO events (El Nino Southern Oscillation) can also be apparent in the northeast Pacific, such as the warm conditions following the strong El Nino of 1998. Since about the mid 1980s the oscillations between warm and cool PDO phases have occurred with increased frequency, now switching phase roughly every 4 to 5 years. The most recent negative PDO period began in 2007, resulting in cooler than average conditions in the east, and positive anomalies in the west. In fact the Gulf of Alaska was cooler in 2008 than at any time since the early 1970s and is still cool.

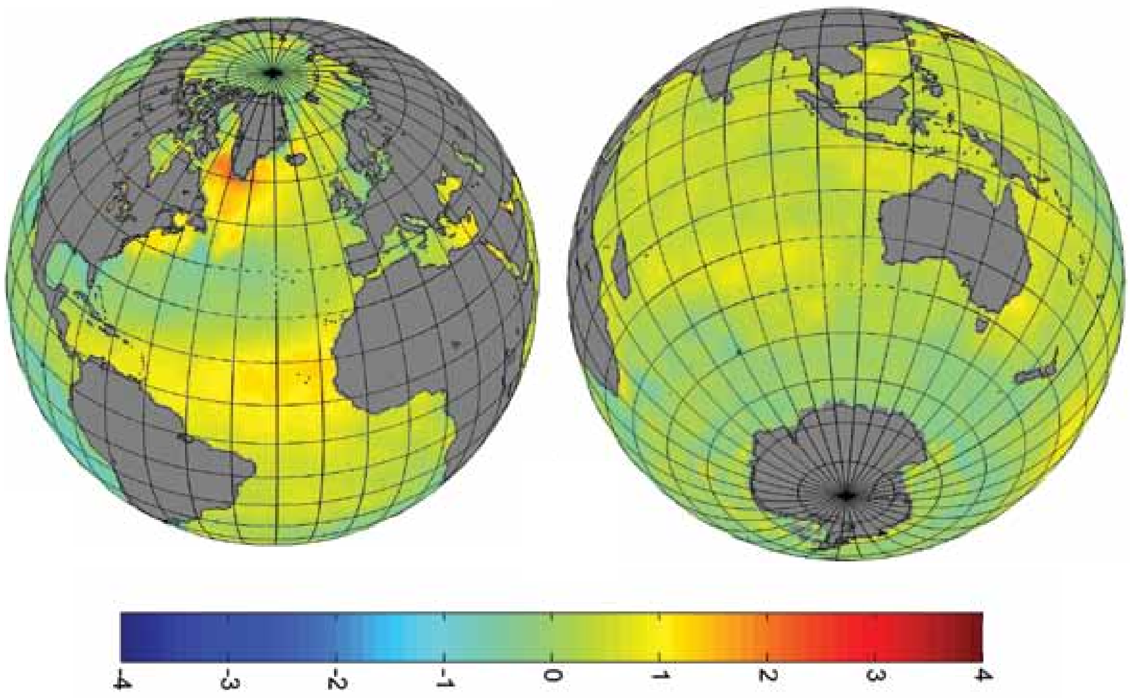


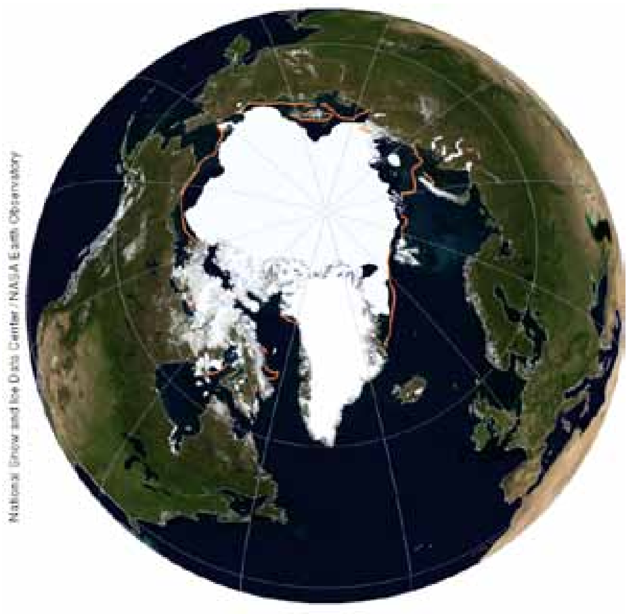
Fig. 1. Global Sea Surface Temperature anomalies for 2010 minus the long-term average 1960-2010. Sea surface temperature data were obtained from the Met Office Hadley Centre (http://www.metoffice.gov.uk/).

Arctic and Antarctic ice

The thickness and areal coverage of summer ice in the Arctic have been decreasing at an increasingly rapid rate over the last two decades, to reach the lowest recorded extent in September 2007 (in respect to1978-2010). In the spring following the unusually large ice free period in 1998 large numbers of the 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. 2010 saw the third lowest recorded sea ice extent since 1979.

In the southern hemisphere the frontal zones of the Antarctic Circumpolar Current (ACC) are moving south. The Bellingshausen Sea in the Pacific sector has recorded the fastest ice retreat, whereas other regions have in particular the Ross Sea has recorded an increase in sea ice extent in the short term. In the long term, the ACCE Report predicts an overall loss of sea-ice of 33% during the 21st Century. Substantial sea ice loss has already occurred during the 1960's (de la Mare 1997, 2009). Atkinson et al. (2004) have reported a substantial decline in the abundance and distribution of Antarctic krill *Euphausia superba*, a major keystone in the Antarctic food web and sea-ice habitat. This decline is likely to be due to the decrease in sea-ice extent. At the same time salps have increased their abundance in the region north of the sea-ice / krill habitat. Further sea-ice loss, warming and southward movements of the fronts is expected to see a contraction of plankton southward. There is a limit to southward movement due to the presence of the continent. For example, the coastal ice krill *Euphausia crystallorophias*, which prefers sub-zero water will have nowhere to retreat.

(a)



(b)

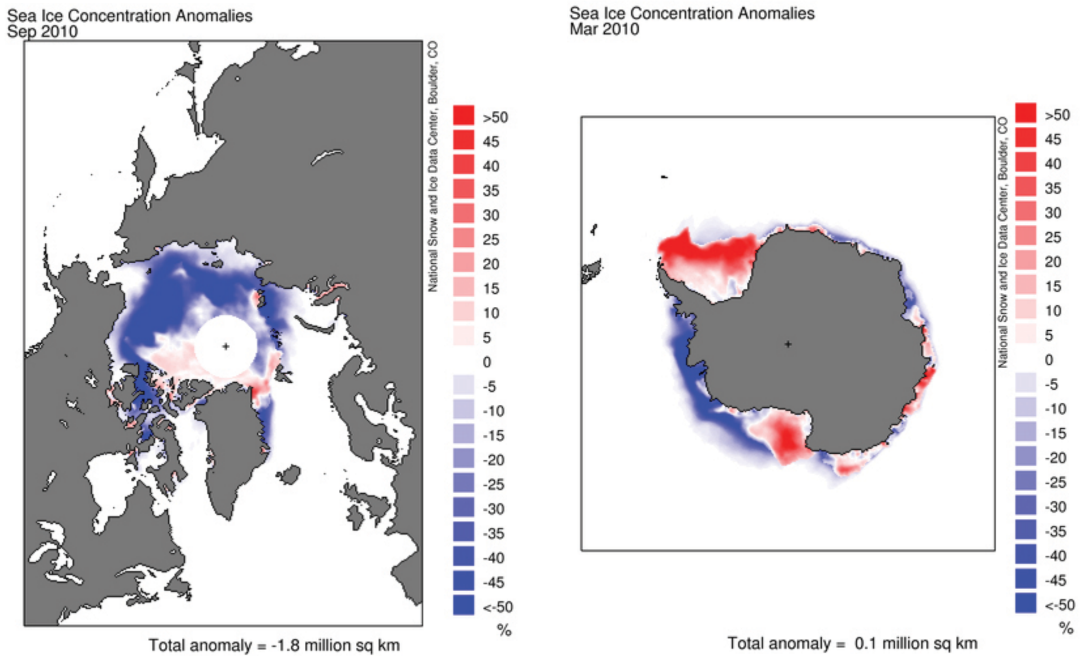
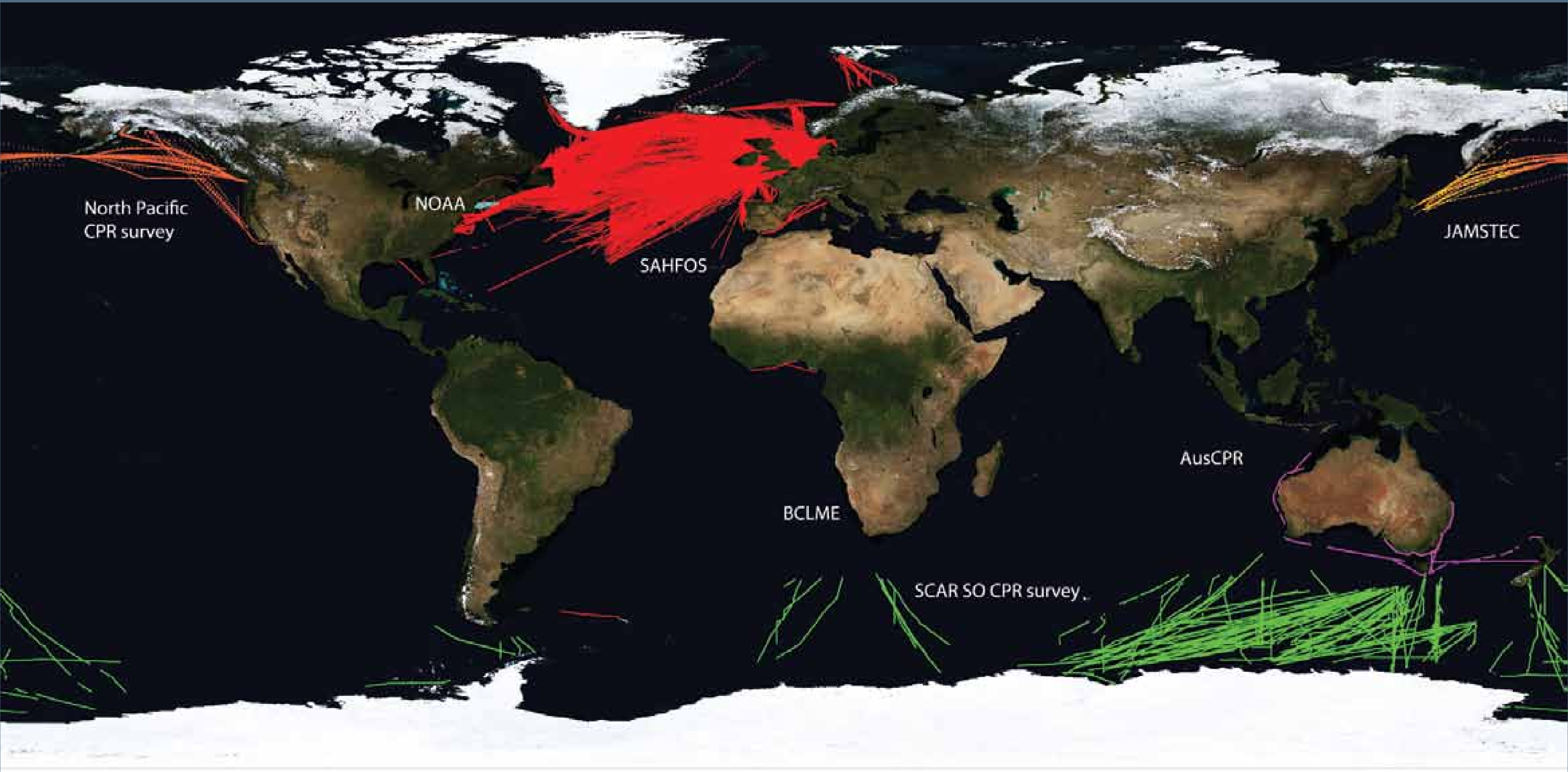


Fig. 2 (a) Sea Ice extent for summer 2010. Orange line is the median from 1979-2000. Source: National Snow and Ice Data Center. (b) Sea ice concentration anomalies for the Northern (September) and Southern Hemispheres (March). 2010 anomalies for the Northern Hemisphere were -1.8 million km^2 below the long-term mean and +0.1 million km^2 for the Southern Hemisphere. Source: National Snow and Ice Data Center.



Global CPR observations

Global CPR observations

The Southern Ocean

Graham Hosie
Australian Antarctic Division

Climate and Oceanography

The Southern Ocean is characterised by the Antarctic Circumpolar Current (ACC), the world's largest current, which flows uninterrupted around Antarctica linking the Atlantic, Indian and Pacific Oceans. The Drake Passage is the only chokepoint in the flow of the ACC, where the passage and the bathymetry of the Scotia Ridge restricts the flow and enhances mixing and vertical circulation. The ACC comprises a number of distinct fronts. The Sub-Antarctic Front (SAF) is the northern edge of the ACC. Moving southward are the Polar Front (PF), Southern ACC Front (SACCF) which lies close to the northern sea-ice limit, and the Southern Boundary (SB) of the ACC. South of the SB is the westward flowing Coastal Current and Antarctic Slope Front. Each front is distinguished by distinct changes in oceanographic characteristics in relation, temperature, salinity, density, and oxygen concentration, each producing distinctive zones, each characterised by discrete plankton assemblages (Hunt and Hosie, 2005). The ACC fronts often have a number of sub-branches. There is a southward latitudinal decline in temperature from about +8°C at the SAF to sub-zero temperatures in high latitudes. The vertical water column is equally stratified through wind mixing, horizontal circulation and the annual formation and melting of the sea-ice.

Since the 1930s there has been a systematic and substantial warming of the Southern Ocean with much of this concentrated in the ACC (Aoki et al. 2003,). Surface temperatures have increased by almost a degree, more than a tenth of a degree per decade, but significant increases are recorded at all depths (Aoki et al. 2003, Gille 2002). This warming can be attributed to the southward movement of the ACC. Increased heat flux and subduction of warmed surface waters are other potential causes of warming waters, and may be due to human influence. The warming of the Southern Ocean is not uniform. Ducklow et al. (2007) described the western Antarctic Peninsula as "experiencing the most rapid warming of any marine ecosystem on the planet". At the same time as the warming and southward shift of the ACC, there has been freshening of the upper surface waters of the Southern Ocean. Freshening of the upper waters will lead to increased stratification and potentially a reduction in the input of nutrients into the euphotic zone.

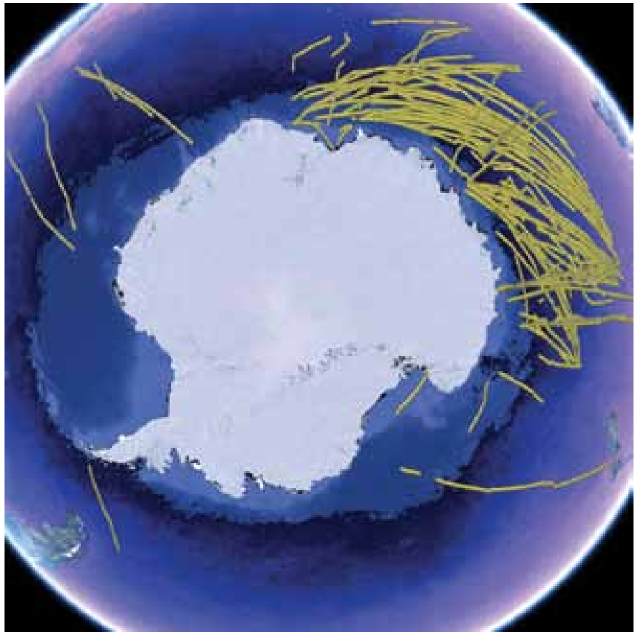


Fig. 3. Continuous Plankton Recorder samples in the Southern Ocean. Courtesy of Google Earth.

Sea-Ice

The annual growth and retreat of Antarctic sea-ice is one of the major drivers influencing the distribution, abundance and survival of the biota of the region. At its maximum extent in September sea-ice covers 19 to 20 million km^2 before retreating to about 3 to 4 million km^2 in February. The major concern is that global warming will affect the extent and volume of sea-ice, which in turn will affect the sea-ice organisms such as Antarctic krill. There has been an approximate 25% loss of sea-ice between the 1950s and 1970s (de la Mare, 2009). Since the late 1970s there has been a slight but statistically significant increase in sea-ice overall of about 0.9% per decade, higher in the Ross Sea of 4.2% but there has been a substantial decline in sea-ice in the neighbouring Amundsen and Bellingshausen Seas area of 5.7% per decade. In the long term, it is predicted that there will be an overall decline of winter sea-ice extent and volume of 24 to 34 % by the end of the 21st Century. Further sea-ice loss, warming and southward movements of the fronts is expected to see a contraction of plankton southward. There is a limit to southward movement due to the presence of the continent. For example, the coastal ice kill *Euphausia crystallorophias*, which prefers sub-zero water will have nowhere to retreat.

The Royal Society Report on Ocean Acidification (2005) has predicted that increased absorption of CO_2 will lead to an under-saturation of aragonite by the end of this century which would result in plankton such as thecosome pteropod snails unable to produce a shell. This could occur as early as 2050 (Orr et al. 2005). Pteropods are very abundant in the Southern Ocean, they are important in the diet of other zooplankton and myctophid fish, and play an important role in the Southern Ocean carbon pump removing carbon from the upper waters to the deep. We can only speculate the consequences on the food web and carbon pump of the loss of plankton with calcium carbonate shells.

Ecological Status

The Antarctic region can be split into three major regions. These are the Atlantic sector of the Southern Ocean which includes the Antarctic Peninsula, Weddell Sea, Scotia Arc and the southern Atlantic. To the east is the Indian Ocean (eastern Antarctic) sector extends from south of Africa to south of Tasmania. The third region is the Pacific sector from south of New Zealand to the Antarctic Peninsula incorporating the Ross, Amundsen and Bellingshausen Seas. These sector correspond with FAO statistical areas 48, 58 and 88, respectively. Each region will be treated separately.

Atlantic sector

The south-west Atlantic is one of most productive sectors of the ACC largely due to pronounced bathymetric variability. Over much of the region spatial and temporal variability of phytoplankton production is only beginning to be understood (Whitehouse et al. 2012). Predictable phytoplankton blooms are only found in a small sector of the south-west sector such as the fringing island shelves and southern areas seeded by iron from sources such as the Southern Scotia ridge. Elsewhere ephemeral blooms occur stimulated by iron supplied from diverse sources such as ice-melt, deep upwelling and periodic dust deposits (Smith et al. 2007). Satellite imagery around the WAP has demonstrated a decline of around 12% in summertime surface Chl *a* over the last 30 years particularly north of 63°S although substantial increases have occurred further south (Montes-Hugo et al 2009).

Macro and mesozooplankton distributions within the Atlantic sector have been reasonably well studied and species and community distributions link closely to temperature and physical features such as fronts and seasonal ice-cover (Whitehouse, 2012), as well as large-scale atmospheric forcing . Although CPR research in this sector is too recent to say anything regarding long-term change the use of data from Discovery Investigations, samples taken ~80 years ago prior to a rise in ocean temperatures of ~≥1°C , has hypothesised how macroplankton distributions may have changed subsequently (Mackey et al 2012). Model results showed that species generally showed a southward movement in response to a 1°C rise in temperature, with some warmer water species such as *Themisto gaudichaudii* and *Euphausia triacantha* showing extensions of their historical range of up to 12° latitude south. Conversely, cold water species showed contractions of their ranges demonstrating how vulnerable these species might be to further rises. Attempts to investigate changes in mesozooplankton populations have, to date, been largely inconclusive. Vuorinen et al. (1997) compared the spatial and temporal variation of copepods in the Weddell Sea based on samples taken in 1929–1939 and 1989–1993. Their comparison while finding no change in overall abundance between periods, did detect recent increases in the abundance of the copepod *Calanus propinquus* juveniles and adults. However, other changes were only marginally significant and they concluded that overall there were no uniform and consistent changes that could be sensibly linked to environmental change.

Discovery data obtained by Hardy and Gunther (1935) in 1926/7 from around South Georgia have also been compared with

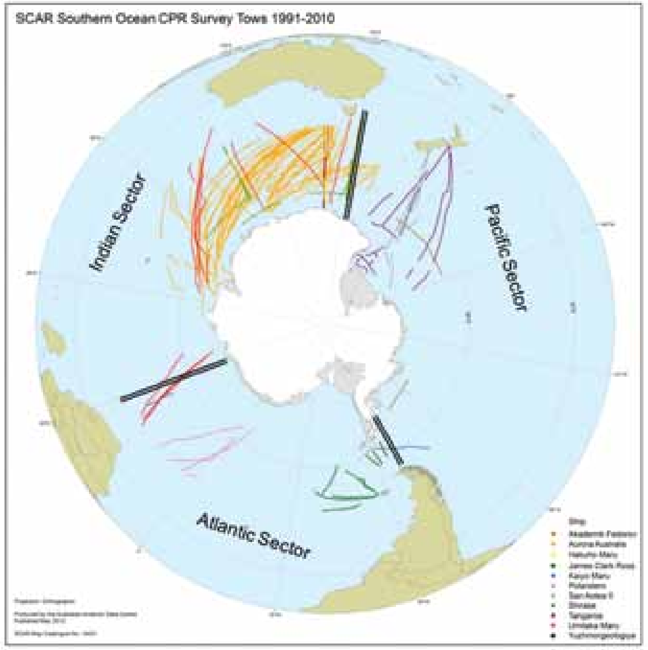


Fig. 4. Continuous Plankton Recorder samples in the Southern Ocean highlighting the three sectors used in the report

samples obtained post 1995. Again no significant differences in distribution or community structure were apparent , although more subtle changes were not ruled out. Changes in the distribution of plankton resulting from atmospheric forcing have been clearly demonstrated. At the WAP ENSO variability invoked frontal movement of the Southern ACC Front resulting in fluctuations between salp-dominated coastal zooplankton assemblages and copepod-dominated oceanic zooplankton assemblages. Takahashi et al. (2010b) reported the opportunity to replicate one of Sir Alister Hardy's early CPR transects across Drake Passage and to compare species composition between 1927 and 2000. The two sets of tows recorded markedly different species composition with Hardy's tow recording high abundances of larger copepods and chaetognaths, whereas the tow in 2000 recorded a dominance of smaller copepods, notably *Oithona similis,* plus other species. Natural spatial and seasonal variation cannot be discounted between the 1927 and 2000 tows, but it does highlight the need for the establishment of routine CPR tows in the region.

Antarctic krill *Euphausia superba* and salps are major grazers in the Southern Ocean. The south-west Atlantic contains ~70% of the total krill stock (Atkinson et al 2008) but density has declined since the 1970's (Atkinson et al. 2004). Sea-ice extent and Chl *a* are shown to be key correlates and it has been suggested that decreased ice extent will result in reduced recruitment. Salps generally occupy the lower productivity regions of the Southern Ocean and are more tolerant of warmer waters than krill and have increased in the southern part of their range as krill have decreased.

Indian Ocean sector

The SCAR Southern Ocean CPR Survey has conducted extensive sampling in this region, notably south and west of Australia since January 1991 (Hosie et al. 2003; McLeod et al. 2010). Approximately, 36,000 samples at 5 nautical mile resolution have been collected to date. In addition, the Japanese Antarctic Research Expeditions (JARE) have conducted annual summer-time routine Norpac net sampling on route to and from the Japanese station Syowa since 1972. This builds on the extensive RMT net sampling surveys conducted during three decades since 1981. Zooplankton biomass (wet weight) from JARE Norpac sampling 1972/73 to 1995/96 in the Indian sector showed some cyclic variation in abundance with 4-6 year periodicity, which may be related to physical processes such as sea-ice extent or the Antarctic Circumpolar Wave (Takahashi et al., 1998).

In the region off east Antarctica (90 to 160°E), meso-scale variations in zooplankton communities have been observed due to changes in ocean circulation patterns from 1987/88 to 1995/96 seasons (Chiba et al., 2001). The extensive spatial and temporal coverage of the SO-CPR Survey has detected the close relationship of zooplankton assemblages with the different frontal zones in the Indian sector (Hunt & Hosie, 2005). There is also evidence that these frontal zones have moved south. We expect that zooplankton distribution ranges will move south with the fronts. A sudden large increase in the abundance of foraminiferans has been reported in the Indian sector collected in samples from January 2005 (Takahashi et al., 2010a) and February to March in 2002 . Takahashi et al. (2010a) suggested that the elevated average Chl *a* concentration provided favourable conditions for foraminiferans. Foraminiferans are a large group of protists; they produce a shell made of calcium carbonate. Because calcium carbonate is susceptible to dissolution in acidic conditions, foraminiferans may be strongly affected by a changing climate and ocean acidification. Moy et al. (2009) compared the shell weights of the modern foraminiferan *Globigerina bulloides* collected from sediment traps in the Southern Ocean with the weights of foraminiferan shells preserved in the underlying

Holocene-aged sediments. They found that the modern shell weights are 30–35% lower than those from the sediments, consistent with reduced calcification induced by ocean acidification. They noted that "it was unclear whether reduced calcification will affect the survival of this and other species, but a decline in the abundance of foraminifera caused by acidification could affect both marine ecosystems and the oceanic uptake of atmospheric carbon dioxide."

Recently the red-tide forming, heterotrophic dinoflagellate *Noctiluca scintillans* was observed in the sub-Antarctic Zone of Southern Ocean up to 240 km south of Tasmania in December 2010 (McLeod et al., 2012a). This is the most southerly, oceanic record of *Noctiluca* globally and can be linked to the intensification of the East Australian Current (EAC), a situation apparently caused by altered circulation patterns associated with global warming. The prediction is the EAC is likely to continue to strengthen and transport more warm water and eddies further south. Thus may result in viable populations of *Noctiluca* become established in the Southern Ocean in the future with unknown effects for the food web.

The coccolithophorid *Emiliania huxleyi* is now very abundant, up to 100 cells ml-1 between 2002 and 2006, in the sea-ice zone in the eastern Antarctic region of 140°E whereas it was absent or extremely rare south of 60°S prior to 1995 (Cubillos et al., 2007). Similar extensions south have been observed along 45°E and may be a function of general warming in the region.

Pacific sector

The region comprising the Ross, Amundsen and Bellingshausen Seas has been the least studied of the Antarctic region. Most of the focus of plankton research has focused on the Ross Sea, whereas there has been no routine surveys of plankton in the Amundsen or Bellingshausen Sea. Net sampling studies have been conducted, some recording extremely high abundances of pteropods, of up to 1397 individuals m-3 or 63% of total zooplankton numbers (Pane et al., 2004). *Limacina helicina antarctica* was most likely the main contributor to these numbers and is a species likely to be affected by ocean acidification. Routine CPR tows are now conducted by New Zealand in support of the SO-CPR Survey since 2006. Results to date show a high degree of spatial and seasonal variation in abundance. This is reflected in predictive biogeographic models using Boosted Regression Tree modelling (Pinkerton et al., 2010), which has predicted high numbers of the cyclopoid copepod *Oithona similis* in the mid-ocean, Permanent Open Ocean and Polar Frontal zones, and very low abundances in the southern Amundsen and Bellingshausen Seas. These low abundances have since been confirmed by CPR tows by Russia in 2008. The predictive models have also identified a number of persistent hot spots of high abundance in the eastern Antarctic and south-east of New Zealand (Pinkerton et al., 2010).

The Northeast Pacific: the temperate shelf region and the oceanic subarctic gyre

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Climate and Oceanography

The North Pacific CPR survey consists of two transects, both originating in the Strait of Juan de Fuca that forms the border between Washington State, USA and British Columbia, Canada. The north-south CPR transect crosses the eastern NE Pacific terminating in Cook Inlet, Alaska (6 times per year, monthly between about March and September). This transect began sampling in 2004 but from 2000 to 2003 a similar transect between Prince William Sound, Alaska and California was sampled. The east-west transect follows a great circle route across the Alaska Gyre, Aleutian Island chain, southern Bering Sea and western Pacific gyre to the coast of Japan (3 times per year, about April, June and September). Sampling began here in 2000.

The status of two eco-regions are described here; the oceanic subarctic gyre (equivalent to the eastern portion of Longhurst's biogeochemical province PSAE) and the temperate shelf and slope to the east, (equivalent to the northernmost part of Longhurst province CCAL). Note that the ALSK coastal province is also sampled by the CPR transects but at 3 widely separated points and with less temporal resolution than the two regions described here. Future reports may include this region. More detailed information on the status of regions of the North Pacific from a wide range of data sources can be found in McKinnel and Dagg (2010).

Unlike much of the global ocean the NE Pacific has been experiencing colder than average SST since 2008, primarily due to La Niña conditions which have predominated into spring 2012. For this report data from the most recent cool phase (2008 to 2011) have been compared to the 2000-2007 data which comprised

Fig. 5. Continuous Plankton Recorder samples in the Northeast Pacific. Courtesy of Google Earth.

some cool and some very warm years. Four summary indices are considered, mesozooplankton biomass (estimated by summing the product of taxon specific dry weight and taxon abundance), mean Copepod Community Size (as described in Richardson et al., 2006), Phytoplankton Colour Index (see e.g. Batten et al., 2003 for a definition) and the proportion of the total diatom and dinoflagellate cell counts that were diatoms.

Ecological Status

Oceanic region

The NE Pacific gyre region is a high nitrate low chlorophyll (HNLC) region, and as such it has little seasonal variation in chlorophyll levels and is dominated by small cells (Harrison et al., 1999). The annual mean PCI bears this out with March having the lowest values, rising slightly into spring and summer and then higher into autumn. The monthly mean ranges only from 0.5 to 1.04. The mean monthly PCI values for the most recent 2008-2010 cool period were lower than the 2000-2007 monthly means.

The large phytoplankton cells that are identified from CPR

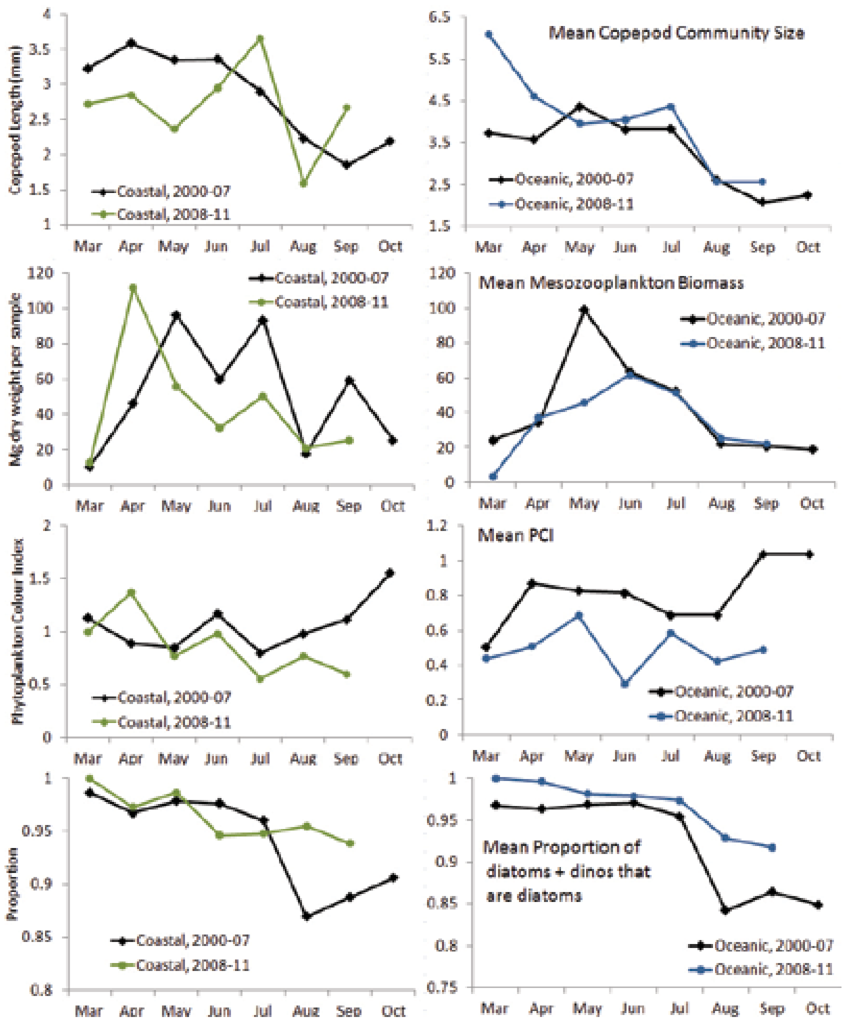

Fig. 6. Mean monthly values of each index for the coastal region (left) and the oceanic region (right). Black lines include data from 2000 to 2007 while coloured lines comprise data from 2008 to 2011.

samples are not likely to be representative of the phytoplankton community here, however, of those cells counted diatoms typically comprise 96-98 % in spring and summer, falling to 85-88% in autumn when dinoflagellates become more abundant. During the 2008-2011 period, diatoms comprised a greater proportion (92-100% in all months) suggesting a decline in dinoflagellates during the cool period.

The oceanic mesozooplankton is dominated in the spring by large calanoid copepods that typically undergo an ontogenetic migration to depth in summer. Copepod community size shows a shift from a mean of 3.8-4.2 between March and July to 2.2-25 during August-October. Biomass reaches a peak in late spring/early summer. In the recent 2008-2011 cool period the biomass peak was delayed by about a month into summer. The copepod community had a larger mean size in March in early spring of the years 2008-2011, possibly caused by an absence of smaller taxa. The method used to determine copepod community size ignores the separate copepodite stages which have been used elsewhere to show a change in phenology associated with cold and warm conditions in the NE Pacific and which would have been more abundant in March than the larger copepodite stages. Batten and Mackas (2009) showed that there has been a narrower cohort of the dominant *Neocalanus plumchrus* copepods in recent years. While copepod community composition is not discussed in this report it should be noted that warm water species were absent, or in low numbers, during the cool period and not found as far north (Batten and Walne, 2011).

Coastal region

Although termed the coastal region, because the shelf is relatively narrow and the CPRs are not deployed until clear of coastal traffic, the majority of the CPR samples are over deeper waters on the slope. However, they are outside of the main gyre, in areas where mesoscale eddies and upwelling may affect productivity. PCI is higher in each month than in the oceanic region, although there is no real evidence of a spring bloom with levels consistent through the year at 0.7-1.6. During the recent 2008-2011 period spring values were higher than autumn values, in contrast to the 2000-2007 period, driven mainly by high values in April 2009 although 2011 also had higher spring values than late summer. Otherwise, values for this period were similar to those for 2000-2007. The contribution of diatoms shows a similar pattern to the oceanic area, being high through spring and summer and lower in the autumn when dinoflagellates occur in higher numbers. The recent 2008-2011 period had similar numbers, with evidence that dinoflagellates were also lower in numbers in the autumn. The copepod community has a mean size smaller than the oceanic region through spring and summer, ranging from 1.8 to 3.4. The subarctic species are still present, producing a larger mean size in the spring, but smaller shelf species are also numerous reducing the overall mean size until the autumn when the oceanic and coastal communities have almost identical size. The biomass peak is typically earlier than in the oceanic region, and the cool 2008-2011 period did not show a delay in the peak timing as the oceanic region did, if anything it was earlier. However, the mean copepod community size was noticeably smaller in the 2008-2011 period, likely caused by unusually high numbers of *Pseudocalanus* in 2009 and 2010.

In summary, the impact of the recent cool period is clearly evident in the plankton; a later spring zooplankton peak in oceanic waters. There was a noticeable reduction in the abundance of dinoflagellates across both regions and a decline in PCI values in the oceanic region. However, by April 2012 the La Niña conditions were becoming neutral so future updates may reveal additional changes in lower trophic level phenology and community composition.

The Northwest Pacific: Oyashio region and western North Pacific subarctic gyre

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The Japanese Team is participating in the North Pacific CPR survey by analyzing samples collected in the area west of 170°E on the east-west transect, which has been conducted 3 times per year since 2000 (see the Northeast Pacific Status details of the North Pacific CPR survey). Prior to the analysis, the area was subdivided at the meridional boundary of 155°E according to biogeochemical properties, into Oyashio region (west section) and western North Pacific subarctic gyre (east section).

Ecological Status

Oyashio region

The Oyashio region is known to have a distinctive spring bloom in April – May with rich macronutrient supply by wintertime water mixing and high spring-summer zooplankton abundance. Bloom species are dominated by centric diatoms and large calanoid copepods, including three *Neocalanus spp*. and *Eucalanus bungii*, which perform ontogenetic vertical migration.

Influence of Aleutian Low (AL) dynamics, which is the climatic forcing of the Pacific Decadal Oscillation (PDO), on interannual and interdecadal variations in water temperature is obvious, with cool (warm) anomaly in the years of strong (weak) AL and positive (negative) PDO. That cool-warm cycle determines the lower trophic level phenology. Retrospective analysis based on the Odate Collection data sets showed that abundance peak of *Neocalanus plumchrus* delayed approximately one month during the cold period with positive PDO for the mid 1970s – late 1980s compared to the warm period in the1990s (Chiba et al., 2006). In recent years, satellite observation and CPR survey revealed that the spring bloom occurred later in cool years, 2003-2007, and earlier in warm years, 2000-2002 and 2008, 2009.

Relative abundance of dinoflagellates to diatoms significantly increased in the years of rapid summertime warming, rather than merely being correlated to monthly or seasonal mean temperature, indicating seasonal process in mixed layer stratification might be responsible for formation of seasonal phytoplankton community structure (Chiba et al., 2012).

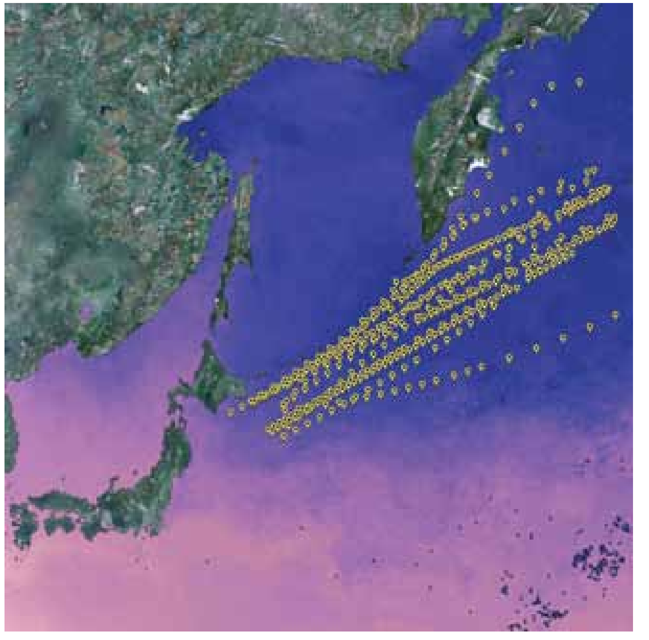

Fig. 7. Continuous Plankton Recorder samples in the Northwest Pacific. Courtesy of Google Earth.

Western North Pacific subarctic gyre

Dominant bloom species in this area are similar to those of Oyashio region, centric diatoms and large calanoid copepods. This area is generally characterized as HNLC region in particular inner part of the gyre. However, as extensive phytoplankton bloom occurs along the coast of Kamchatka peninsula and occasionally expends to offshore region, CPR transects potentially run over areas with large spatial-temporal heterogeneity in terms of environmental and biological properties.

Relationship between the PDO index and water temperature anomaly is seasonally reversed; these are positively correlated from winter to spring, and negatively correlated from spring to summer, indicating colder (warmer) winter tends to be followed by hot (cooler) summer. This unique temperature seasonality is considered to largely influence plankton phenology and community structure in this area.

The Benguela Current Large Marine Ecosystem (BCLME)

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Climate and oceanography

The Benguela Current is the eastern limb of the South Atlantic sub-tropical gyre and includes the Benguela Current Large Marine Ecosystem (BCLME). The BCLME stretches along the coasts of Angola, Namibia and South Africa, from 5°S-12°E off Cabinda in Angola to the Nelson Mandela Metropole (Port Elizabeth) on the south coast of South Africa at 34°S-26°E. Unlike the other three major eastern boundary current systems, the Benguela upwelling system is uniquely bounded and significantly influenced by warm-water regimes of equatorial Atlantic and Indian Ocean origin at its northern and southern ends. The Benguela region is also strongly influenced by the Southern Ocean because of its close proximity. Moreover, the region is situated at the choke point in the "global ocean climate conveyor belt", where warm surface waters from the Indo-Pacific pass around Africa into the Atlantic.

Not surprisingly, this complex ecosystem is characterized by considerable environmental variability on several temporal and spatial scales. Features of its circulation inherent of other upwelling systems include: offshore Ekman-transport at the surface driven by equatorward winds; a poleward undercurrent along the continental shelf-break; and the growth and decay of frontal jets into meanders, eddies and filaments. The South Atlantic high-pressure system and its seasonal shift facilitate the upwelling-favourable, equatorward wind regime, which is dominant during summer in the southern Benguela and perennial in the northern Benguela. Based on this and associated physical and biological characteristics, the BCLME is divided by the Lüderitz Upwelling Cell and Orange River Cone (LUCORC) area (at around 25°S) into the northern (= the Namib ecoregion) and southern (= the Namaqua ecoregion) Benguela upwelling regimes.

Besides being complex and highly variable, the Benguela is a highly productive ecosystem, characterised by phytoplankton-rich coastal waters. Phytoplankton variability is driven by the non-linear relationships between upwelling-favourable winds that lift nutrient-rich water to the surface, solar radiation, stabilization, sinking and the response times of individual species. Species of zooplankton provide a link between primary producers and larger heterotrophs, which tend to prey on them in a size-selective manner. These preferences suggest the importance of zooplankton distributions to the composition and distribution of planktivorous (mainly pelagic) fish resources.

The Benguela upwelling system supports a host of commercially valuable living marine resources including small pelagic, mid-water and demersal fish species, as well as rock lobster. Diets of many top-predators, which include large pelagic fish, seabirds and marine mammals, in turn depend on the availability of these economically important fish stocks, which they favour as prey. Dietary analyses therefore provide useful indicators of the state of these stocks, thereby also tracking shifts in species dominance. The abundances of harvested fish stocks not only depend on the variability of the physical environment and its influence on food availability, but also on fishing. Indeed, human impact, which includes pollution, mining, exploration for and extraction of oil and gas in addition to fisheries, is superimposed onto the inherent natural variability of the ecosystem.

Ecological Status

The following paragraphs provide a summary of recent observations of ecological conditions prevailing primarily off the west coast of South Africa, i.e. the southern Benguela. Data were obtained from a variety of sources including web-based sources, satellite sensors, coastal and moored instruments, and research and routine monitoring cruises. In September 2011, the first CPR survey was launched between Luanda, Angola and Durban, South Africa and samples from this inaugural and subsequent tows in the Benguela Current are currently being analysed at SAHFOS in Plymouth, UK and the local CPR Centre in Cape Town. A good correlation exists between warm (El Niño) and cold (La Niña) events in the equatorial Pacific and, respectively, positive and negative sea level atmospheric pressure anomalies along the South African west coast. The relationship persisted through the past 2010/2011 austral summer when Pacific La Niña conditions were associated with below-average atmospheric pressures along the west coast. At Hondeklip Bay, in particular, the pressure was very low - in fact the lowest in the available data series since 1981.

The St Helena Island climate index (HIX), of which the winter (July-September) value is thought to be indicative of upwelling in the northern Benguela Current region, had been positive since the winter of 2006 – indicating above-average upwelling. The index level has, however, been declining since 2006 and became slightly negative during winter of 2011. During the 2010/2011 summer both the southerly and easterly wind components measured at Cape Point increased to levels which, in January 2011, were respectively about twice and three times stronger than the previous maxima seen in this 1960 to 2011 series. Above- average southerly and easterly winds are in agreement with what was expected from the La Niña conditions, which prevailed in the tropical Pacific during the summer.

Examination of the January 1850 to December 2010 Cape Town precipitation series in conjunction with sea surface temperature (SST) anomalies and wind in the Southern Ocean indicates intensification and a poleward shift of the west wind belt which, according to modelling, should result in more Agulhas Current water leaking into the South-East Atlantic, increasing the incidence of positive SST anomalies and thus, possibly, enhancing the risk of abnormal precipitation events.

The 2002-2011 time-series of MODIS satellite-derived SSTs indicate that along the entire west coast shelf north of Cape Point, SSTs were far above average during the 2009/2010 summer (except for January 2010). The positive anomaly persisted in the 2010/2011 summer but much less severely so. In both summers the anomaly weakened from north to south. These conditions agree well with weak southerly winds and upwelling indices observed in scatterometer data. During the 2010 and 2011 winters west coast SSTs were cooler than normal and this also agrees well with wind and upwelling indices. On the western Agulhas Bank SSTs were above average during the 2009/2010 summer and 1-1.5°C below average in 2010/2011. The cool 2010/2011 conditions are in agreement with very strong easterly and southerly winds recorded at Cape Point. The 1856-2010 Kaplan 5°x5° global SST anomaly data set was used to compute the annual SST anomalies for the 30-35°S, 15-20°E block along the South African west coast. The resulting series showed that SSTs in the South East Atlantic have been increasing from around the 1970s at a mean rate of about 0.06°C per decade.

Time series of Ekman upwelling indices computed from 1999 - 2011 satellite scatterometer wind data for Hondeklip Bay, Cape Columbine, and Cape Point indicate the following inter-annual trends and features: (1) The winter indices at all three sites demonstrate positive trends (i.e. towards increasing levels of upwelling) from 2007 to 2011. This is in agreement with observed decreasing trends in winter northerly and westerly winds over this period; (2) In 2011 upwelling was perennial at all three sites. This is a common occurrence at Hondeklip Bay and Cape Columbine but

Fig. 8. Continuous Plankton Recorder samples in the South Atlantic. Courtesy of Google Earth.

this was the first time it was also observed at Cape Point and was expected from the strong southerly and easterly winds observed at this location during the 2010/2011 summer and 2011 winter; (3) During the past two summers upwelling at Hondeklip Bay and Cape Columbine was at the lowest level yet seen in the series; (4) At Cape Point upwelling was more or less at the average level during the 2009/2010 summer but at a series maximum in the 2010/2011 summer. Coastal nutrient concentrations on the St. Helena Bay Monitoring line (SHBML, 2000-present) were generally high from the beginning of the series in 2004 to 2006/2007 and this was followed by about two years of strikingly low concentrations (up to 2009). Thereafter concentrations increased again to reach high concentrations during the 2010/2011 summer. These high nutrient concentrations are contrary to what is expected from the above average sea surface temperatures and low levels of upwelling recorded at Cape Columbine and vicinity during the 2010/2011 summer.

In the SHBML time-series of dissolved oxygen concentration at the bottom, the years 2006-2008 stand out as a period when low oxygen concentrations extended unusually far offshore. This was a period of anomalously low surface temperatures, relatively high

levels of upwelling and high chlorophyll concentrations in the St. Helena Bay area. At the GWB002 monitoring station bottom oxygen concentrations were very low in late winter/spring of 2011 and this coincided with above-average southerly winds and upwelling during the 2011 winter.

The 2002-2011 time-series of surface ocean colour obtained from MODIS satellite images indicate below-average surface chlorophyll concentrations along the west coast during the 2009/2010 summer, except for the Cape Columbine-Cape Point region where it was slightly above average. This is in agreement with observed high SSTs and weak upwelling. By contrast, Chl concentrations were far above average along the entire west coast north of Cape Point during the 2010 winter, which would be expected from an observed declining trend in winter northerly and westerly winds, below-average SSTs and above-average upwelling. Surface Chl concentrations during the 2010/2011 summer were spatially variable along the west coast, ranging from very low in the north to above average in the south. This pattern fits in well with southerly winds and upwelling, which also increased from north to south. Concentrations along the west coast during the 2011 winter were near average and this is contrary to what was expected from the observed increasing trend in winter upwelling.

The SHBML time-series of monthly in situ measured surface chlorophyll concentrations confirms that concentrations in the vicinity of Cape Columbine had been relatively low during the 2009/2010 summer, but shows that in March 2010 moderately high concentrations (5 to10 mg.m-3) extended more than 170 km from the coast - the farthest yet seen in the 2000-2011 series. The time-series further confirms the high nearshore concentrations of the early 2010/2011 summer seen further along the west coast, as well as the low concentrations of the late summer and average concentrations of the 2011 winter.

A time-series of autumn abundances of copepod species collected in St Helena Bay since 1951 shows an initial gradually increasing trend in copepod abundance that however reversed in the mid-1990s and steadily declined to the mid-2000s, reversing and increasing again from thereon. This pattern, although observed in all dominant species albeit to varying extents, is largely driven by the abundances of the small calanoid and cyclopoid species. Whereas the copepod community of the 1950s and 1960s was generally dominated by larger species, indicative of cooler ocean conditions, smaller species predominated during the 1990s and 2000s, indicative of ocean warming.

Bi-annual sampling of zooplankton on the western Agulhas Bank (WAB) and central Agulhas Bank (CAB) has taken place each year during spring (October-November) from 1988 onward. Mean biomass on the WAB has declined by 36% from the first half of the time-series (1988-1999) to the second half (2000-2010). Biomass was relatively high over the periods 1988-1990, 1996-1999 and 2002-2004, but was relatively low from 1991-1993, 2000-2001, and 2005-2010. It was particularly low in 2005 and 2007, but has increased gradually since then. Both the biomass and proportion of *Calanus agulhensis*, the dominant large copepod on the Agulhas Bank, declined over the time-series. Most other copepod species also declined over the time-series, but to a far lesser extent than *C. agulhensis*. On the CAB there was a more marked decline - with less interannual variability - of total copepod biomass as well as that of *Calanus agulhensis* than on the WAB. Mean copepod biomass on the CAB, averaged over the time-series, is almost identical to that of the WAB, but has declined by 59% from the first half of the time-series (1988-1999) to the second half (2000-2010), while mean biomass of *C. agulhensis* has declined by as much as 68%. Moreover, there has been, between 1988 and 2008/2009, a shift from a large-species-dominated copepod community to an increasingly smaller copepod-dominated community on the Agulhas Bank. This is suggestive of progressive warming in the region and may reflect the slow but steady warming trend for the Agulhas Current Large Marine Ecosystem reported in the literature.

Fig. 9. Continuous Plankton Recorder samples in the Northwest Atlantic. Courtesy of Google Earth.

Monitoring transport of spawning products (eggs and early larvae) of pelagic fish from their spawning grounds on the WAB to the west coast nursery area was initiated in August 1995 and has since been performed more or less monthly up to the present along the SARP (Sardine and Anchovy Recruitment Programme) Monitoring Line. The SARP line extends southwestwards from the Cape Peninsula through the equatorward flowing shelf-edge jet current along the west coast of South Africa. The results indicate relatively low annual abundances of anchovy eggs and larvae from the 1995/1996 to 1999/2000 seasons and generally higher abundances from 2001/2002 onwards. The abundance of anchovy eggs along the SARP line from 1995 to 2010 was found to be significantly negatively correlated with the biomass of *Calanus agulhensis* on the WAB during late spring/early summer, the peak spawning period of anchovy. This observation supports the hypothesis that low copepod biomass on the WAB and CAB during spring/summer is a consequence of predation by a large anchovy biomass during the time of their peak spawning, presumably accompanied by a high abundance of eggs. The low abundance of sardine eggs and larvae since 2001 corresponds to an eastward shift in the distribution of adult sardine along the South Coast. Sardine larvae spawned east of Cape Agulhas are likely to be too

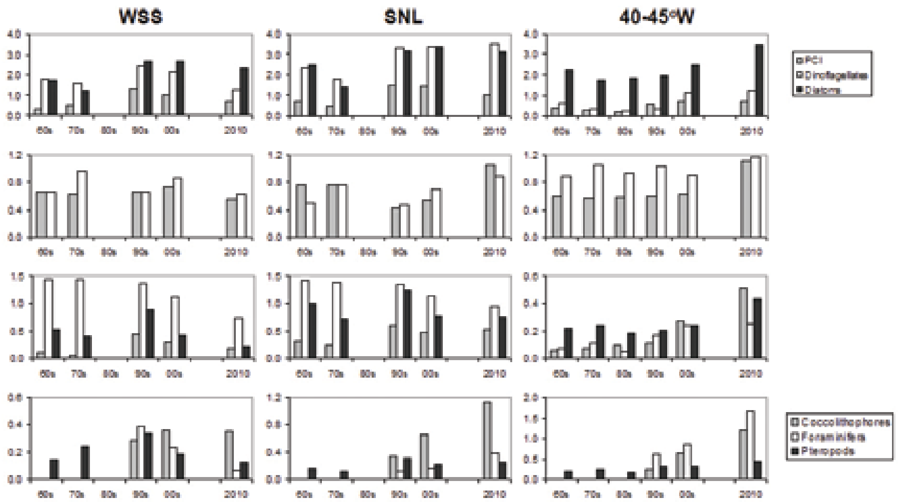

Fig. 10. Annual average abundances by decade of selected phytoplankton and zooplankton taxa on the Western Scotian Shelf (WSS) and the South Newfoundland Shelf (SNL) and in the region of the sub-polar gyre between 40 and 45 degrees west (40-45oW) for the decades since the 1960s and for 2010.

large, by the time they reach the SARP line, for capture with the mini-Bongo net used for sampling on the line.

The diet of Cape gannets has been monitored at a number of locations along the West Coast on a monthly basis since 1978. On average, anchovy contributed 20-40% of the diet over the period 1978–2010. The contribution of sardine to the diet increased in the 1980s, as South Africa's sardine abundance increased. Sardine remained important in the diet until the early 2000s. Up until 2003, the combined contribution of anchovy and sardine to the diet averaged 50-75%, but fell dramatically in 2004 with a minimum of 13% in 2005. During 2009 and 2010 the sardine contribution increased to the highest level since 2003 but the anchovy contribution dropped. Interestingly, the contribution of horse mackerel to the gannet diet increased during 2010 to the highest level in the data series.

Canadian Atlantic Zone Monitoring Programme: Scotian Shelf, Newfoundland Shelf and Labrador Basin ecoregions.

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Climate and oceanography

Continuous Plankton Recorders (CPRs) have been towed along routes between Iceland and Newfoundland (the Z route) and between Newfoundland and the NE coast of the United States (the E route) since the early 1960s. In 2010 the North Atlantic Oscillation (NAO) index dropped to its lowest level since 1969. When this index of atmospheric conditions is low, air and water temperatures in the Labrador Sea region are relatively warm and winter-time convective vertical mixing is relatively shallow.

Ecological status

For the shelf regions, the phytoplankton colour index (PCI) and diatom abundance remained at the high levels of the 1990s and 2000s in 2010, while dinoflagellate abundance returned to the low levels of the 1960s and 1970s on the western Scotian Shelf, but remained at the high levels of the 1990s and 2000s on the eastern Scotian Shelf and the South Newfoundland Shelf. The regions in the Labrador Basin ecoregion showed similar patterns of change for all three phytoplankton indices, with gradual increases after low values the 1980s, which were sustained in 2010. The abundance of young *Calanus* (*Calanus* I-IV) and the late stage of *Calanus finmarchicus* (*C. finmarchicus* V-VI) has remained relatively stable over the decades on the Scotian Shelf and in the Labrador Basin (40-45°W). Three taxa, Coccolithophores, Foraminifera and Pteropods, are used to monitor potential effects of increasing acidification in the NW Atlantic. The abundances of Coccolithophores have increased in all regions, while abundances of foraminifera have either decreased (Scotian Shelf), or increased (Labrador Basin). Pteropods, which have been counted for all decades, had their highest levels in the 90s in shelf regions, while in the sub-polar gyre levels have slightly increased over the decades.

The Australian Continuous Plankton Recorder Survey (AusCPR)

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Ecological Status

The AusCPR survey runs tows in Australian waters, across to New Zealand and in the Southern Ocean (in conjunction with SO-CPR). Since 2009, we have towed >35,000 nautical miles, counted a total of 3,379 samples for 637 zooplankton taxa and 224 phytoplankton taxa. This is a relatively new survey and we are just starting to analyse the data collected. Australia is unique globally in being bounded by two poleward-flowing warm-water currents. We sample the east, west and south coasts of Australia, with our best sampled region on the east coast. This is the East Australia Current, a warm, southward current. Generally waters around Australia are warm and so many of the copepods are small. Our mean copepod size across all samples is 1.15 mm. Despite the small copepod size, there is still the a strong diel vertical migration signal, with the abundance doubling in the middle of the night. Seasonally off the east coast, diatoms peak in Aug/Sep, dinoflagellates Dec-Mar, and copepods in Apr/May and Nov/Dec. Interannually, there were significantly more diatoms, dinoflagellates, and copepods in 2010 than in 2009 or 2011. Regionally, the ratio of diatom to diatoms+dinoflagellates declines on the east coast from north to south, from 85-92% in the north to 60% in the south. This is because of the steep decline in diatoms and dinoflagellates remain reasonably consistent.

The AusCPR survey has already highlighted the benefit of long-term observations to providing context for ephemeral events. During the 3 days following 22 Sept 2009, after a severe 10-year drought, a massive dust plume originating in Central Australia swept eastward and covered an area 25 times the size of England. Some 16 Tg of dust was stripped from central Australia with 75,000 t/h estimated to have crossed the New South Wales coast. In the wake of this dust event, we discovered massive concentrations of 4-5 µm diameter black spinose fungal spores in coastal samples collected between Brisbane and Sydney from 16-20 Oct 2009 (up to 150,000 spores per m3). The formalin-preserved plankton recorder silks, appeared black as if they were covered in oil. Using molecular sequencing of 3 different genes, we unambiguously identified this fungus as *Aspergillus sydowii* (99-100% sequence match). We also succeeded in establishing viable sporulating cultures, even from formalin preserved material and from samples kept at -20°C for several months. This fungus was never seen before Oct 2009 and has not been since. Interestingly, there has not been a similar event reported by the North Atlantic CPR survey over the past 70 yrs, the Southern Ocean survey over the past 20 yrs or the North Pacific survey over the past decade. *A. sydowii* is believed to essentially be a terrestrial fungus, but salt-tolerant and well capable of growing in the sea. We speculate that *A. sydowii* spores originated from terrestrial Lake Eyre habitats, were deposited in the form of nutrient-rich floating dust slicks in Australian coastal waters, which allowed rapid fungal growth and sporulation. In laboratory simulations sporulation only occurred at the air-water interface. Aerosol fungal impacts have been well-documented in terms of human health, agriculture, ice nucleation, cloud formation and atmospheric chemistry, but broader impacts on marine ecosystems remain largely uncharted.

Fig. 11. Continuous Plankton Recorder samples in Australian waters. Courtesy of Google Earth.

Basin-scale and ecoregional assessment of the North Atlantic

Ecoregional assessment of the North Atlantic

Sampling by the Continuous Plankton Recorder

The Continuous Plankton Recorder survey is a long-term sub-surface marine plankton monitoring programme consisting of a network of CPR transects towed monthly across the major geographical regions of the North Atlantic. It has been operating in the North Sea since 1931 with some standard routes existing with a virtually unbroken monthly coverage back to 1946. After each tow, CPR samples are returned to the laboratory for routine analysis including the estimation of phytoplankton biomass (Phytoplankton Colour Index), and the identification of over 500 different phytoplankton and zooplankton taxa (Warner and Hays 1994). Direct comparisons between the phytoplankton colour index and other chlorophyll a estimates including SeaWiFS satellite estimates indicate strong positive correlations (Batten, et al 2003; Raitsos,et al. 2005) . The CPR instrument is towed at the surface behind volunteer-operated vessels (ships of opportunity), sampling plankton onto a moving 270 µm band of net silk as the vessel and CPR unit traverse the North Atlantic and/or North Sea. Within the CPR instrument, the net silk and its captured plankton are preserved in formalin until they are returned to SAHFOS. During the processing, the net silk is divided into sections representing 10 nautical miles of towing, and each section is analysed for plankton composition and abundance. Using this analysis method, 500 plankton taxa have been routinely identified and counted by the CPR survey since 1958.

Due to the mesh size of CPR silks, many phytoplankton species are only semi-quantitatively sampled owing to the small size of the organisms. There is thus a bias towards recording larger armoured flagellates and chain-forming diatoms and that smaller species abundance estimates from cell counts will probably be underestimated in relation to other water sampling methods. However, the proportion of the population that is retained by the CPR silk reflects the major changes in abundance, distribution and specific composition (i.e. the percentage retention is roughly constant within each species even with very small-celled species) (Edwards, et al 2006). The CPR now has a water sampler housed onboard certain CPRs to provide additional data and sample the whole size-spectrum of plankton using molecular techniques from bacteria and viruses to flagellates and other taxa not normally identified using standard CPR analysis. For the purpose of this assessment, the North Atlantic Basin has been geographically subdivided into different ecoregions. The 40 geographical regions shown in the figures are known as the CPR standard areas. Included in this assessment are some trends in the microzooplankton community and trends in marine pathogens from molecular analysis of the CPR sample archive. The figures 13-15 showing regional trends in standard areas were generated using standard statistical methods for calculating annual means.

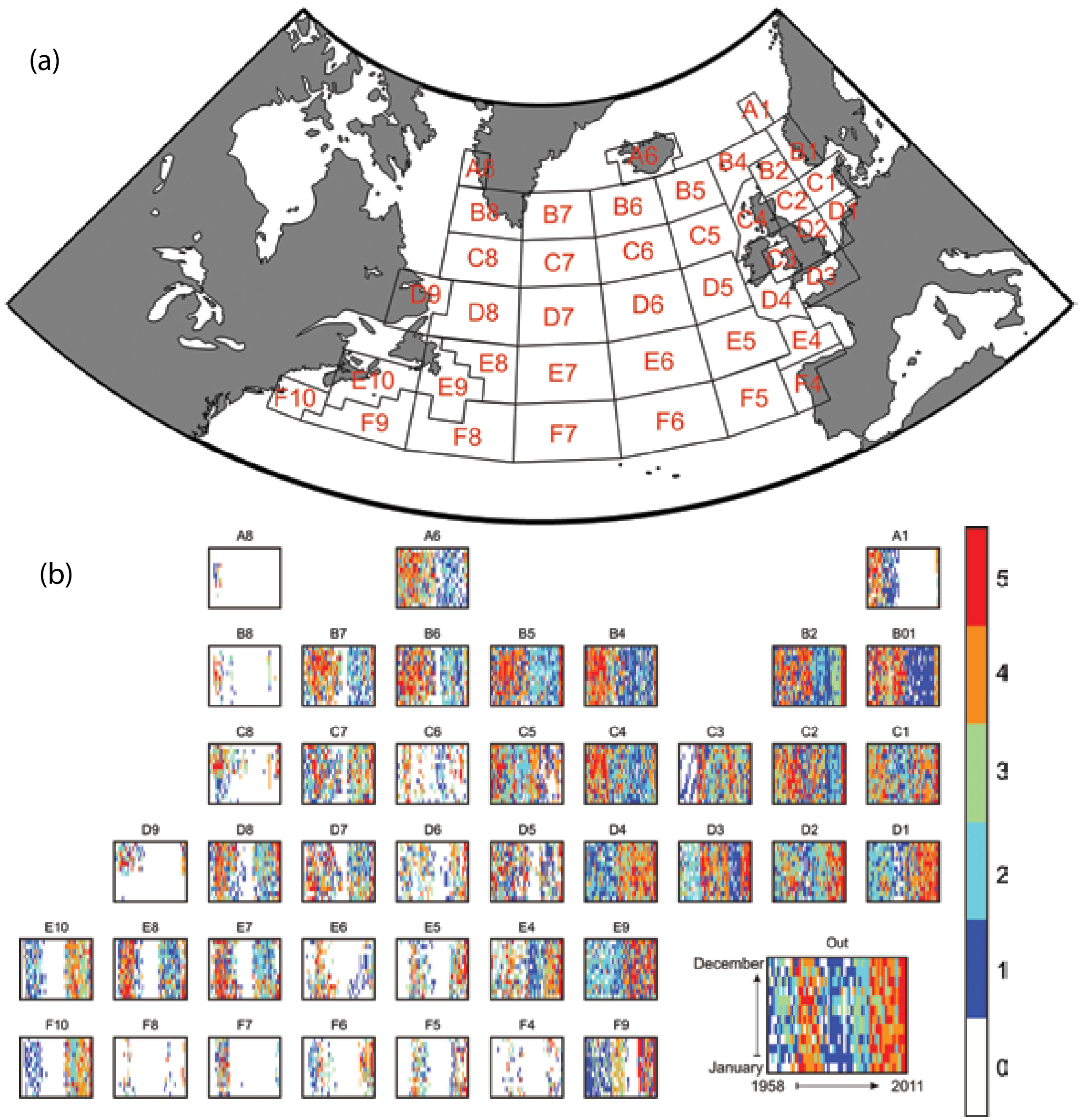


Fig. 12. (a) Continuous Plankton Recorder survey standard areas used in the analysis of regional patterns of plankton for the North Atlantic. (b) Monthly and annual sampling effort for the standard areas from 1958-2011.

Basin scale trends in plankton and natural variability

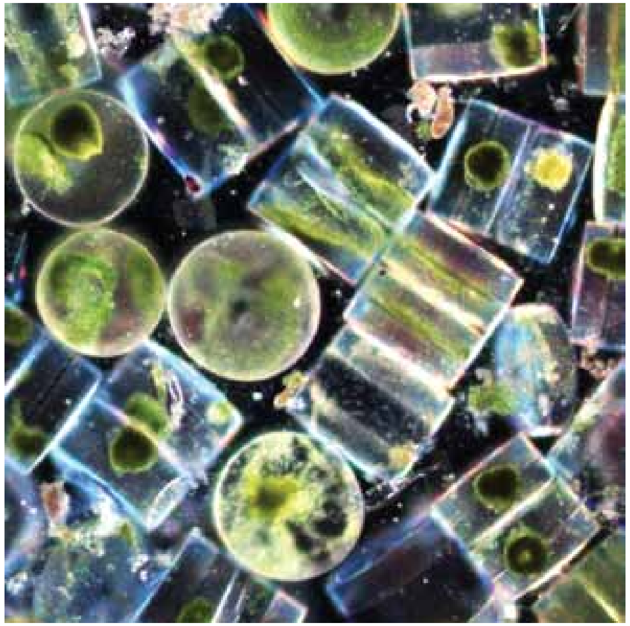
To summarise the long-term trends in phytoplankton in the North Atlantic Basin we used indices of plankton that included the CPR Phytoplankton Colour Index (PCI) and the sum of the abundance of all counted diatoms and all counted dinoflagellates and total copepod numbers and mean copepod size. Using bulk indices like this are less sensitive to environmental change and will quite often mask the subtleties that individual species will give you; however, it is thought that these bulk indices represent the general functional response of plankton to the changing environment. In the North Atlantic, at the ocean basin scale and over multidecadal periods, changes in plankton species and communities have been associated with Northern Hemisphere Temperature (NHT) trends, the Atlantic Multidecadal Oscillation (AMO), the East Atlantic Pattern (EAP) and variations in the North Atlantic Oscillation (NAO) index. These have included changes in species distributions and abundance, the occurrence of sub-tropical species in temperate waters, changes in overall plankton biomass and seasonal length, changes in the ecosystem functioning and productivity of the North Atlantic (Beaugrand, et al 2003; Edwards, et al 2001; Edwards, et al, 2002; Reid & Edwards, 2001; Edwards & Richardson, 2004).

While contemporary observations over a 10 year period of satellite-in situ blended ocean chlorophyll records indicate that global ocean net primary production has declined over the last decade particularly in the oligotrophic gyres of the world's oceans (Behenfeld, et al 2006). Over the whole temperate NE Atlantic there has been an increase in phytoplankton biomass with increasing temperatures but a decrease in phytoplankton biomass in warmer regions to the south (Richardson & Schoeman, 2004), as shown in Figs 13 and 14, respectively. Presumably this is a trade-off between increased phytoplankton metabolic rates caused by temperature in cooler regions but a decrease in nutrient supply in warmer regions.

The amount of nutrients available in surface waters directly dictates phytoplankton growth and is the key determinant of the plankton size, community and foodweb structure. In terms of nutrient availability, warming of the surface layers increases water column stability, enhancing stratification and requiring more energy to mix deep, nutrient-rich waters into surface layers. Particularly warm winters will also limit the degree of deep convective mixing and thereby limit nutrient replenishment necessary for the following spring phytoplankton bloom.
It must be noted, however, that climate variability has a spatially heterogeneous impact on plankton in the North Atlantic and not all regional areas are correlated to the same climatic index. For example, trends in the AMO are particularly prevalent in the oceanic regions and in the sub-polar gyre of the North Atlantic and the NAO has a higher impact in the southern North Sea where the atmosphere-ocean interface is most pronounced. This is also apparent with respect to the Northern Hemisphere Temperature where the response is also spatially heterogeneous with areas of the North East Atlantic and shelf areas of the North West Atlantic warming faster than the North Atlantic average and some areas like the sub-polar gyre actually cooling. Similarly, regime shifts or abrupt ecosystem shifts do not always occur in the same region or at the same time. The major regime shift that occurred in plankton in the late 1980s was particularly prevalent in the North Sea and was not seen in oceanic regions of the North Atlantic. However, a similar regime shift occurred in the plankton colour 10 years later in the Icelandic Basin and in oceanic regions west of the British Isles. The different timing and differing regional responses to regime shifts have been associated with the movement of the 10ºC thermal boundary as it moves north in the North Atlantic (Beaugrand, et al. 2008).

In examining the long-term trends in the plankton indices the general pattern is an increase in PCI for most regions in the North Atlantic with differing timings for the main step-wise increase being later in oceanic regions compared to the North Sea. For the dinoflagellates there has been a general increase in abundance in the North West Atlantic and a decline in the North East Atlantic over a multi-decadal period (see Fig. 14). In particular, some regions of the North Sea have experienced a sharp decline over the last decade. This decline has been mainly caused by the dramatically reduced abundance of the *Ceratium* genus in the North Sea. However, *Ceratium* abundance has recovered in the North Sea over the last two years. For the diatoms there is not really a predominant trend for the North Atlantic Basin (Fig. 14) as a whole but some regions show a strong cyclic behaviour over the multidecadal period. The time signal resembles an oscillation of about 50-60 years and a minimum around 1980 reflecting changes in the AMO signal. Trends in copepod abundances have been more stable in oceanic regions but have shown a decrease in abundance particularly in the southern North Sea.

In summary, while climate warming is a major driver for the overall biomass of phytoplankton, diatoms are less influenced by temperature and show a strong correlation with the AMO signal and wind intensity in many regions. The increase in diatoms associated with the positive phase of the AMO and the decline in dinoflagellate abundance over the last 10 years in the NE Atlantic can be reflected in the diatom/dinoflagellates ratio favouring



diatoms.

Indirectly the progressive freshening of the Labrador Sea region, attributed to climate warming and the increase in freshwater input to the ocean from melting ice, has resulted in the increasing abundance, blooms and shifts in seasonal cycles of dinoflagellates due to the increased stability of the water-column (Johns, et al. 2001). Similarly, increases in coccolithophore blooms in the Barents Sea and HABs in the North Sea are associated with negative salinity anomalies and warmer temperatures leading to increased stratification (Edwards, et al, 2006; Smyth, et al, 2004). It seems likely that an important environmental impact caused by climate change is an increase in the presence of haline stratification in regions susceptible to fresh-water inputs resulting in an increase in bloom formation.

Sea Surface Temperature

Phytoplankton Colour Index

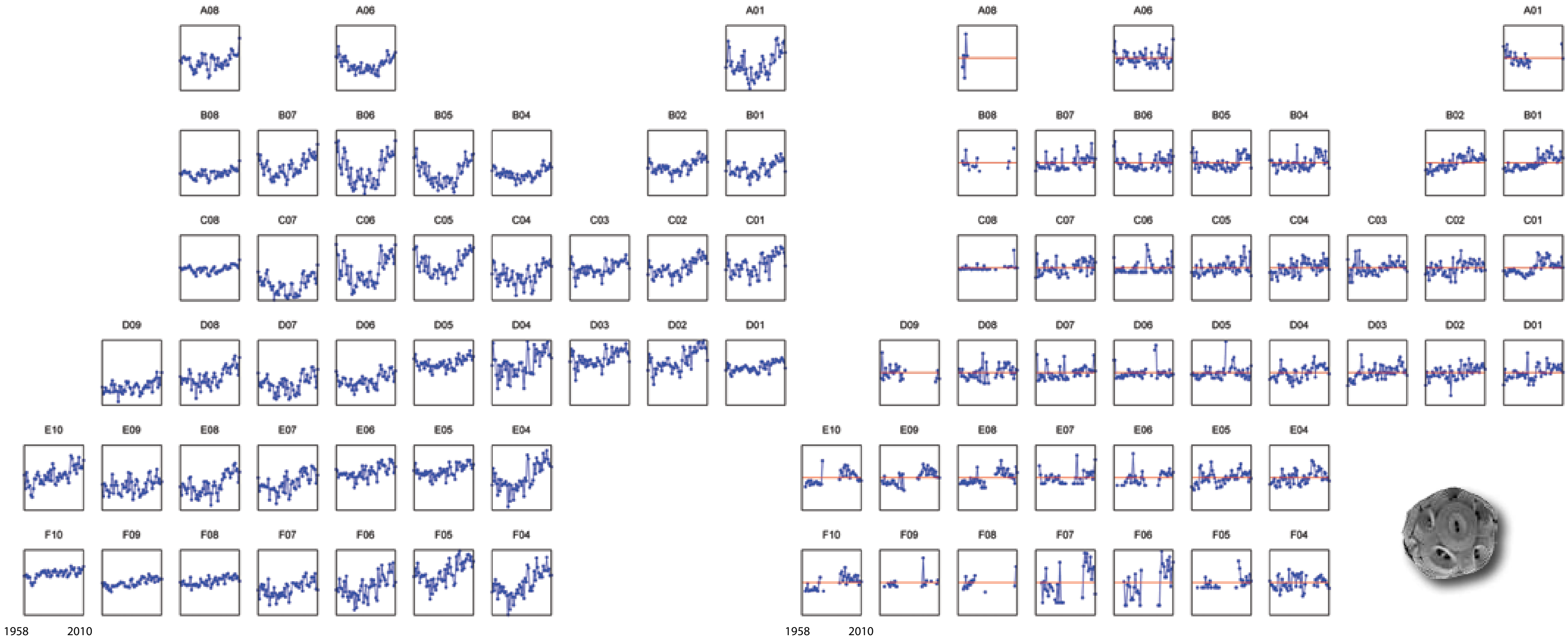
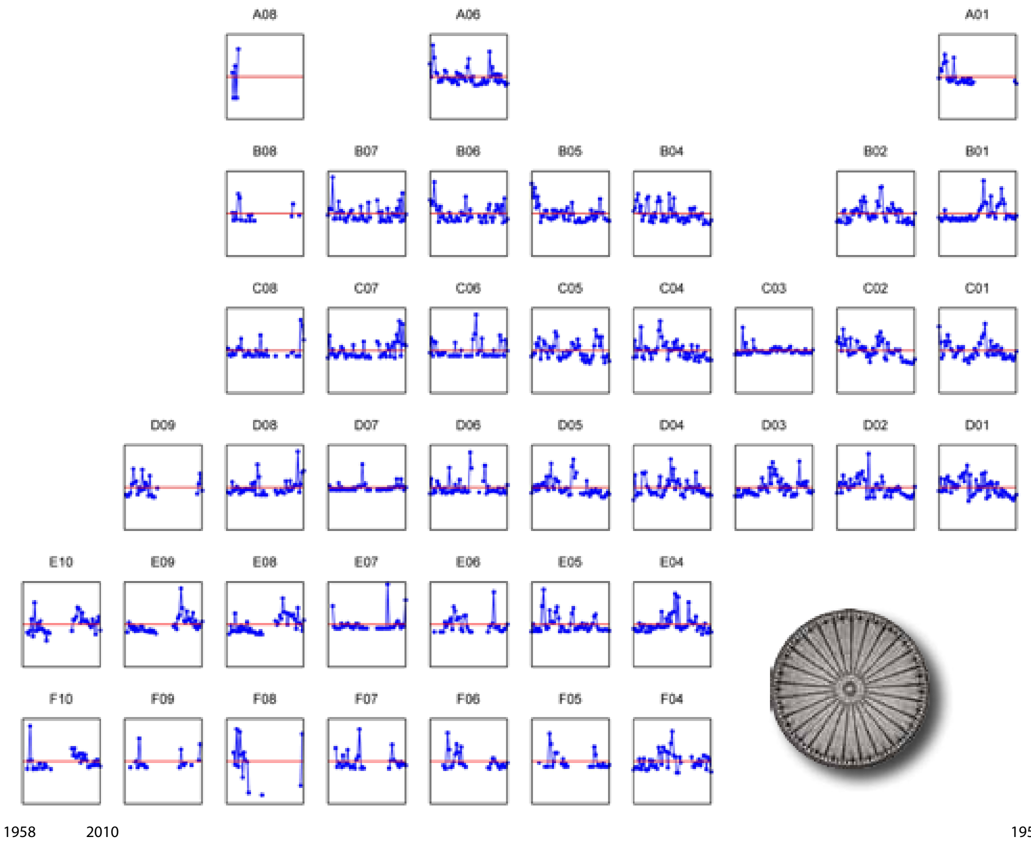


Fig. 13. Long-term trends in Sea Surface Temperature and Phytoplankton Colour in standard CPR regions of the North Atlantic from 1958-2010.

Diatom abundance



Dinoflagellate abundance

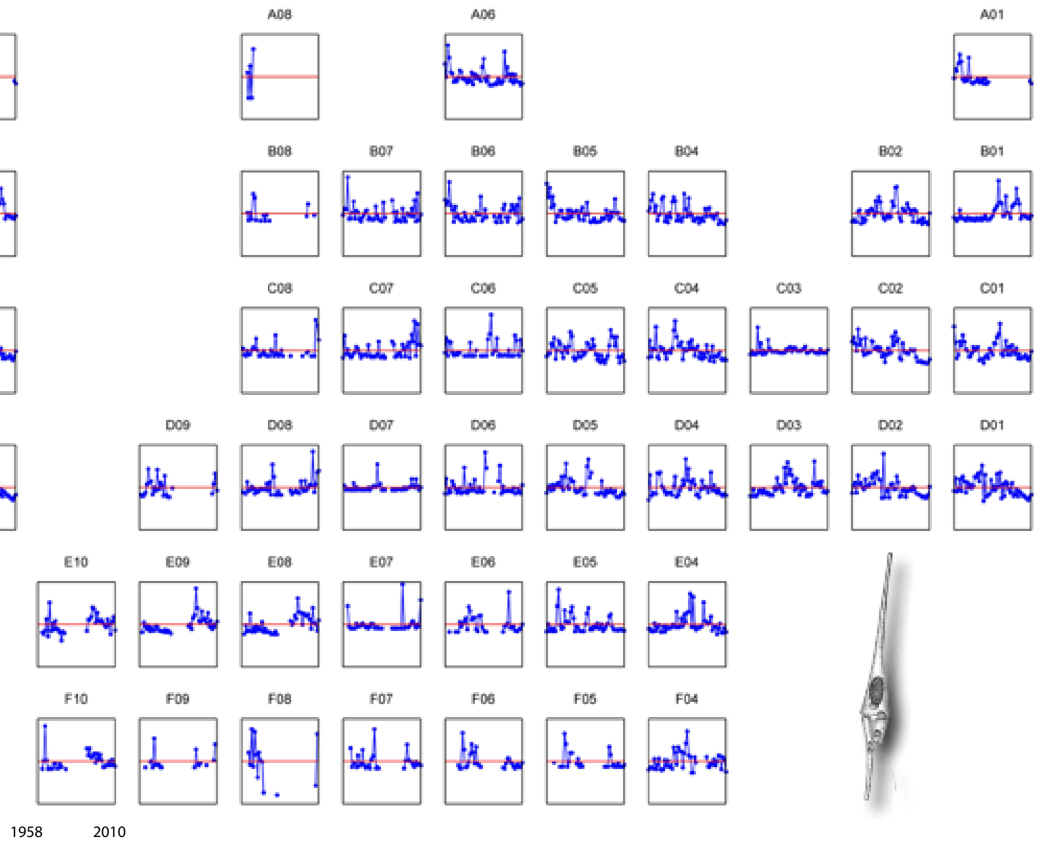


Fig. 14. Long-term trends in diatom and dinoflagellate abundance in standard CPR regions of the North Atlantic from 1958-2010.

Other anthropogenic pressures

Eutrophication:
Globally, eutrophication is considered a major threat to the functioning of near-shore ecosystems, as it has been associated with the occurrence and a perceived increase of harmful algal blooms (HABs). HABs are in most cases a completely natural phenomenon having occurred throughout recorded history and entangling natural bloom events caused by natural hydro-climatic variability, global climate change and eutrophication is difficult. For example, increasing temperature, nutrient input fluctuations in upwelling areas, eutrophication in coastal areas and enhanced surface stratification all have species specific responses. Prediction of the impact of global climate change is therefore fraught with numerous uncertainties. There is some evidence that biogeographical range extensions caused by regional climate change has increased the presence of certain HABs in some regions (Edwards, et al. 2006). Regional climate warming and hydrographic variability in the North Sea has also been associated with an increase in certain (HABs) in some areas of the North Sea particularly along the Norwegian Coastal Current (Edwards, et al. 2006). The abundance of *Prorocentrum* spp and *Noctiluca scintillans* abundance is strongly correlated with increasing SST (Hinder, et al. 2012). The increase in a number of diatom species in the North Sea over the last decade has been associated with increasing wind intensity (Hinder, et al. 2012). Phenological studies have also found strong correlations between the movement of dinoflagellates (up to 1 month earlier) in their seasonal cycle and regional climate warming (Edwards & Richardson, 2004). In summary, at the large ecoregional and provincial scale trends in plankton are associated with hydro-climatic variability. This is not to say, however, that eutrophication is not a problem and may in fact be the primary driver in certain coastal regions and at the more localised scale.

Ocean acidification:
While temperature, light and nutrients are probably the most important physical variables structuring marine ecosystems, the pelagic realm will also have to contend with, apart from global climate warming, the impact of anthropogenic CO_2 directly influencing the pH of the oceans. Evidence collected and modelled to date indicates that rising CO_2 has led to chemical changes in the ocean which has led to the oceans becoming more acidic. Ocean acidification has the potential to affect the process of calcification and therefore certain planktonic organisms (e.g. coccolithophores, foraminifera, pelagic molluscs) may be particularly vulnerable to future CO_2 emissions. Apart from climate warming, potential chemical changes to the oceans and their effect on the biology of the oceans could further reduce the ocean's ability to absorb additional CO2 from the atmosphere, which in turn could affect the rate and scale of climate warming.

Presently in the North Atlantic certain calcareous taxa are actually increasing in terms of abundance, a trend associated with climate shifts in the Northern Hemisphere temperature. However, there is some observed evidence from the Southern Ocean that modern shell weights of foraminifera have decreased compared with much older sediment core records with acidification being implicated (Nature Geoscience (2009) doi:10.1038/ngeo460). It is not yet known how much of an effect acidification will have on the biology of the oceans in the 21st century, whether rapid climate warming will override the acidification problem, and whether or not species can buffer the effects of acidification through adaptation. The CPR survey is providing a critical baseline (both in space and time) and is currently monitoring these vulnerable organisms in case in the future these organisms begin to show negative effects due to acidification.

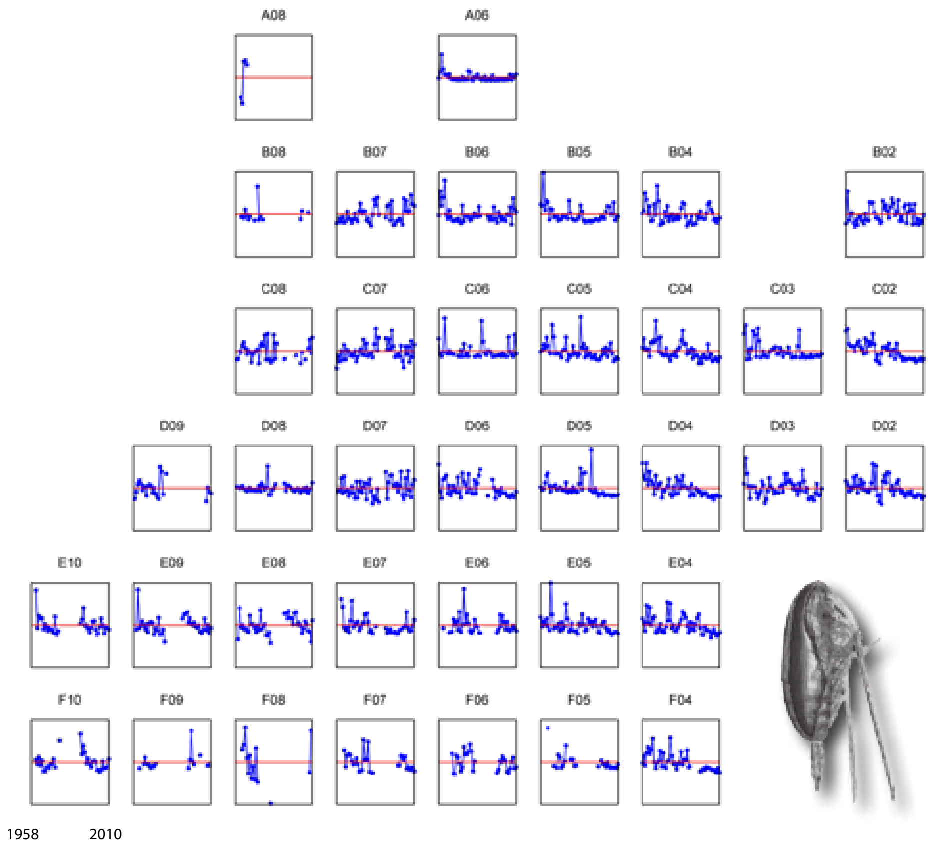
Plankton biodiversity and invasive species

At the ocean basin scale biodiversity of phytoplankton are related to temperature and an increase in warming over the last few decades has been followed by an increase in diversity particularly for dinoflagellates and marine copepods (Beaugrand, et al. 2010). Plankton as a whole show a relationship between temperature and diversity which is linked to the phytoplankton community having a higher diversity but an overall smaller size-fraction and a more complex foodweb structure (i.e microbial-based versus diatom based production) in warmer more stratified environments. Climate warming will therefore increase planktonic diversity throughout the cooler regions of the world's oceans as temperature isotherms shift poleward. Apart from thermal boundaries limits moving progressively poleward and in some cases expanding, the rapid climate change observed in the Arctic may have even larger consequences for the establishment of invasive species and the biodiversity of the North Atlantic. The thickness and areal coverage of summer ice in the Arctic have been melting at an increasingly rapid rate over the last two decades, to reach the lowest ever recorded extent in September 2007. 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 diatom species 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 consequences of such a change to the function, climatic feedbacks and biodiversity of Arctic systems are at present unknown.

The copepod species *Pseudodiaptomus marinus* naturally occurs in east Asiatic waters but has been subsequently spreading more widely in the Indo Pacific region over the last decade. The first record of the species in European waters comes from its discovery in the Adriatic Sea in 2007. In October 2011 the species was recorded on CPR routes operating in the southern North Sea (Jha et al. In prep). The present records extend the known distribution of *P. marinus* across the southern Bight from the Netherlands to the British coast and to the German Bight. It is highly probable the species presence is due to human activity linked to ballast water release or aquaculture. The CPR survey will continue to monitor its

Copepod abundance



Copepod mean size

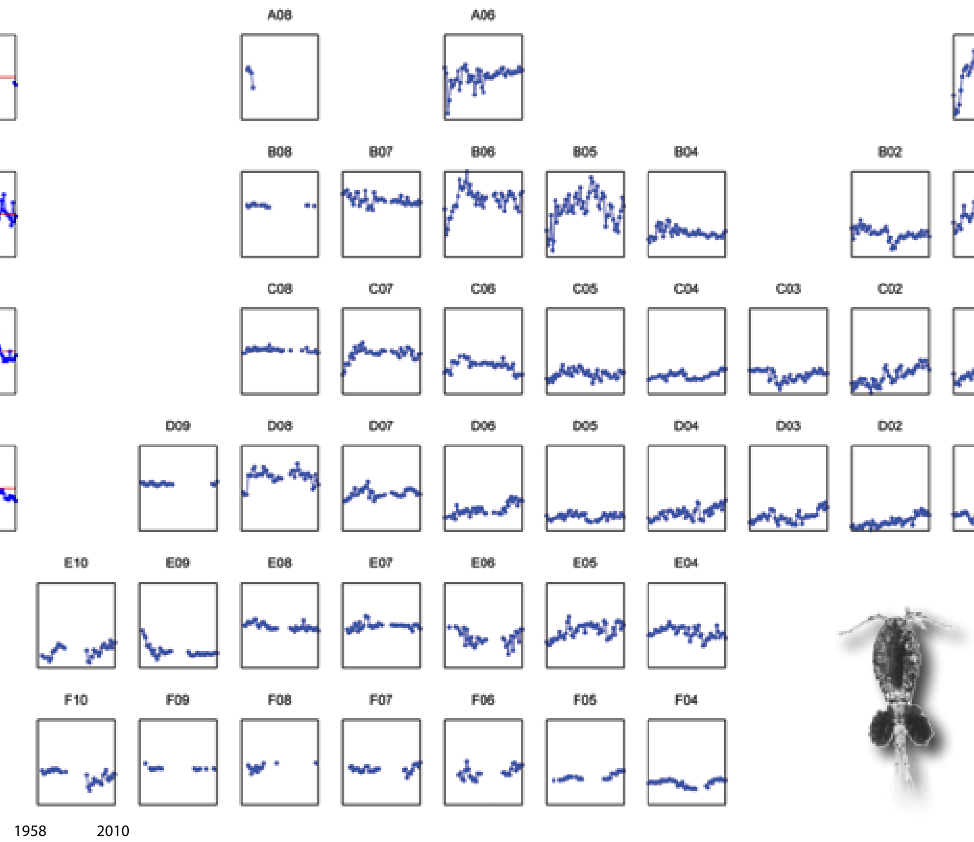


Fig. 15. Long-term trends in copepod abundance and copepod mean size in standard CPR regions of the North Atlantic from 1958-2010.

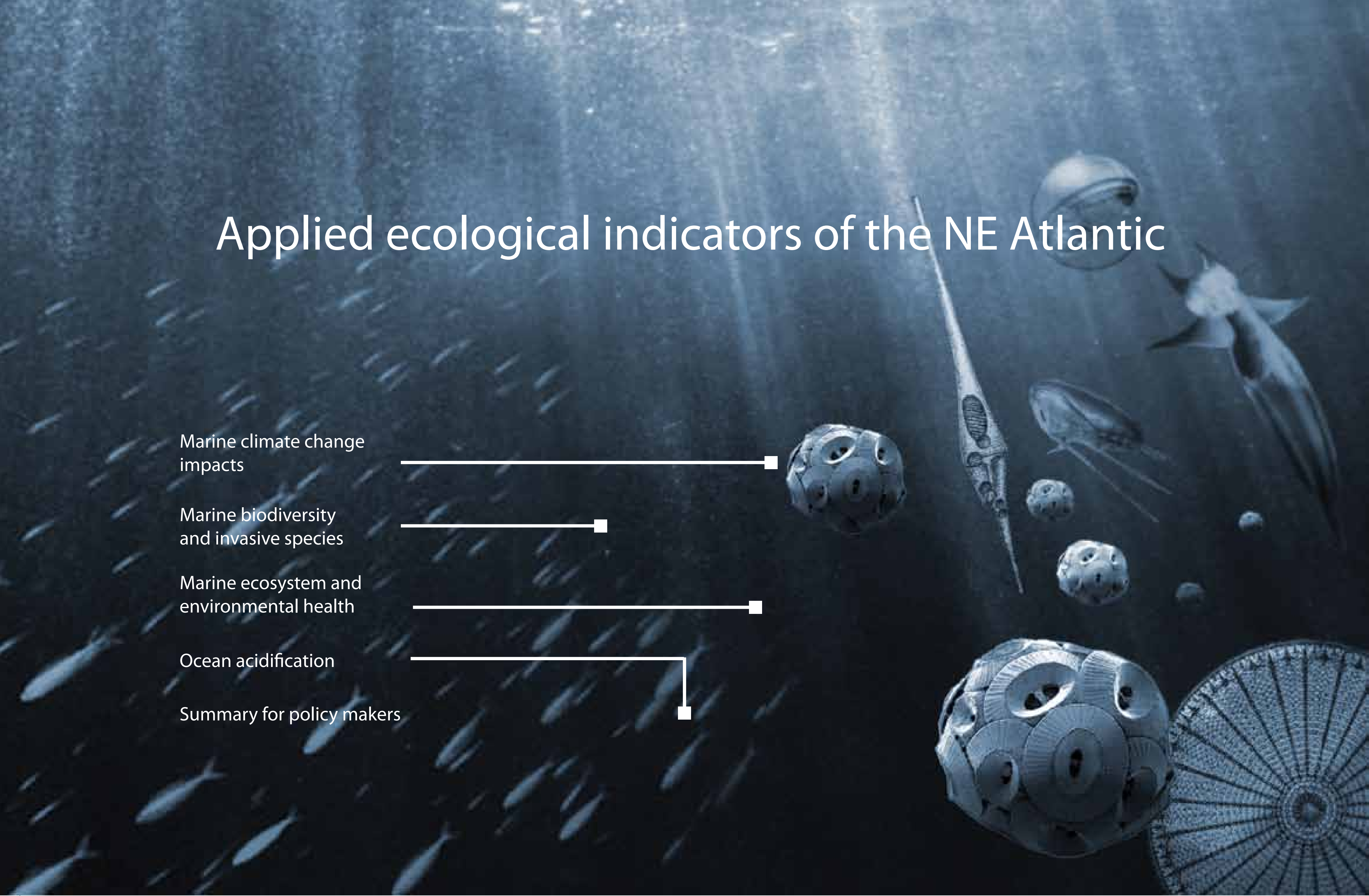
establishment in the North Sea and its probable spread to other regions.

Summary of plankton and environmental change

Natural variability versus anthropogenic warming: In the North Atlantic, at the ocean basin scale and over multidecadal periods, changes in plankton species and communities have been associated with Northern Hemisphere Temperature (NHT) trends, the Atlantic Multidecadal Oscillation (AMO), the East Atlantic Pattern (EAP) and variations in the North Atlantic Oscillation (NAO) index. It is estimated that 50% of the change is down to natural climate variability and the other due to forced anthropogenic warming. These have included changes in species distributions and abundance, the occurrence of sub-tropical species in temperate waters, changes in overall plankton biomass and seasonal length, changes in the ecosystem functioning and productivity of the North Atlantic (Beaugrand, et al 2003; Edwards, et al 2001; Edwards, et al, 2002; Reid & Edwards, 2001; Edwards & Richardson, 2004). Over the last five decades there has been a progressive increase in the presence of warm-water/sub-tropical species into the more temperate areas of the North-East Atlantic and a decline of colder-water species. The mass biogeographical movements are related to changes in sea surface temperature. A particularly interesting feature over the last five years is the decline in subarctic species to the south-east of Iceland and their movement to the north and west.

Biogeographical and phenology indicators: A useful indicator of the warming trend in the North Sea (a northward shift indicator) is the percent ratio of the cold-temperate *Calanus finmarchicus* and the warm-temperate *Calanus helgolandicus* copepod species (see section on applied ecological indicators). Although these species are very similar they do occupy distinct thermal niches. The thermal boundary for the arctic-boreal distributed copepod *Calanus finmarchicus* in the North-East Atlantic lies between ~10-11°C isotherm and is a useful indicator of major biogeographical provinces. *Calanus helgolandicus* usually has a northern distributional boundary of 14°C and has a population optimum lying between 10-20°C; these two species can therefore overlap in their distributions.

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 (Fig 16). This was a reflection of the particularly cold winter experienced in Northern Europe caused by a very low winter NAO index. During the last couple of years the NAO has been uncharacteristically 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 NE Atlantic. Similarly, this has had an effect on the timing of phenology in the North Sea for many species. The last couple of years have seen a later seasonality of plankton compared to the long-term trend which was a trend towards earlier seasonal cycles (see next section on applied ecological indicators). While Northern Europe was experiencing cold weather areas in Greenland, the Canadian Arctic and the Labrador Sea hit record temperatures in 2010 resulting in extended melt periods. Between the 1960s and the post 1990s, total *Calanus* biomass has declined by 70% due to regional warming. This huge reduction in biomass has had important consequences for other marine wildlife in the North Sea including fish larvae.



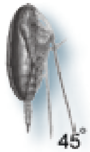
Applied ecological indicators of the NE Atlantic

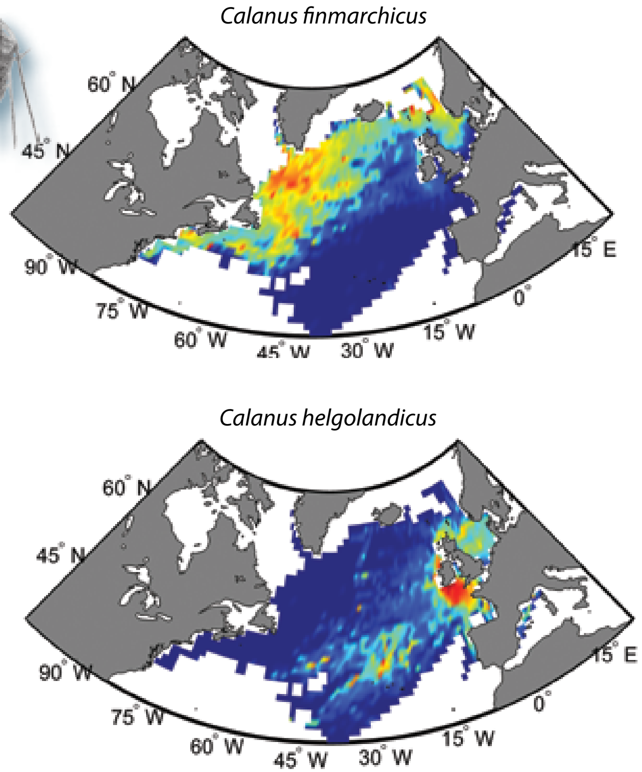
- Marine climate change impacts
- Marine biodiversity and invasive species
- Marine ecosystem and environmental health
- Ocean acidification
- Summary for policy makers

Biogeographic shifts

Over the last five decades there has been a progressive increase in the presence of warm-water/sub-tropical species into the more temperate areas of the North-East Atlantic and a decline of colder-water species. This trend seems to be accelerating over the last five years. The mass biogeographical movements are related to changes in sea surface temperature. A particularly interesting feature over the last five years is the decline in subarctic species to the south-east of Iceland and their movement to the north and west.

A useful indicator of the warming trend in the North Sea (a northward shift indicator) is the percent ratio of the cold-temperate *Calanus finmarchicus* and the warm-temperate *Calanus helgolandicus* copepod species. Although these species are very similar they do occupy distinct thermal niches. The thermal boundary for the arctic-boreal distributed copepod *Calanus finmarchicus* in the North-East Atlantic lies between ~10-11°C isotherm and is a useful indicator of major biogeographical provinces. *Calanus helgolandicus* usually has a northern distributional boundary of 14°C and has a population optimum lying between 10-20°C; these two species can therefore overlap in their distributions. When these two species co-occur there is a tendency for high abundances of *C. finmarchicus* earlier in the year and *C. helgolandicus* later in the year. There is clear evidence of thermal niche differentiation between these two species as well as successional partitioning in the North Sea, probably related to cooler temperatures earlier in the year and warmer temperatures later in the year.





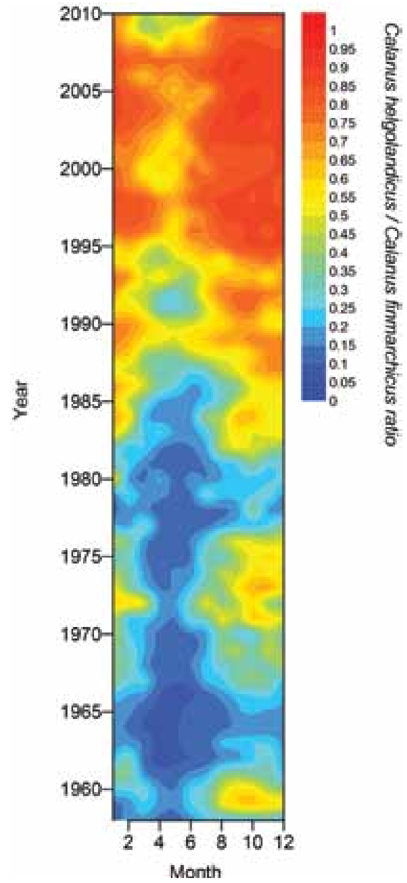


Fig. 16. A simple ratio between a warm-water species (*Calanus helgolandicus*) and a cold-water species (*Calanus finmarchicus*) per month from 1958-2010. Red values indicate a dominance of the warm-water species and blue values the dominance of the cold-water species. (0= total *C. finmarchicus* dominance, 1=total *C. helgolandicus* dominance)

The percentage ratio between *C. helgolandicus* and *C. finmarchicus* between 2009 and 2010 was for the first time in twenty years dominated by *C. finmarchicus* in spring. This was a reflection of the particularly cold winter experienced in Northern Europe caused by a very low winter NAO index. Between the 1960s and the post 1990s, total *Calanus* biomass has declined by 70%. This huge reduction in biomass has had important consequences for other marine wildlife in the North Sea including fish larvae larvae.

Phenology

Phenology - the study of natural phenomena that recur periodically, as migration or blossoming, and of their relation to climate and changes in season. Seasonal timing, or phenology, is occurring earlier in the North Sea and is related to regional climate warming. For example, some species have moved forward in their seasonal cycle by 4-5 weeks. However, not all trophic levels are responding to the same extent, therefore in terms of a productive environment, this change is considered detrimental because of the potential of mis-timing (mismatch) of peak occurrences of plankton with other trophic levels including fish larvae. There is a high confidence that these trends are related to regional climate warming. In particular, the trend towards an earlier seasonal appearance of meroplanktonic larvae over the last few decades is highly correlated with sea surface temperature. The trend in 2010, however, was later than the previous years due to the cold winter experienced in Northern Europe.

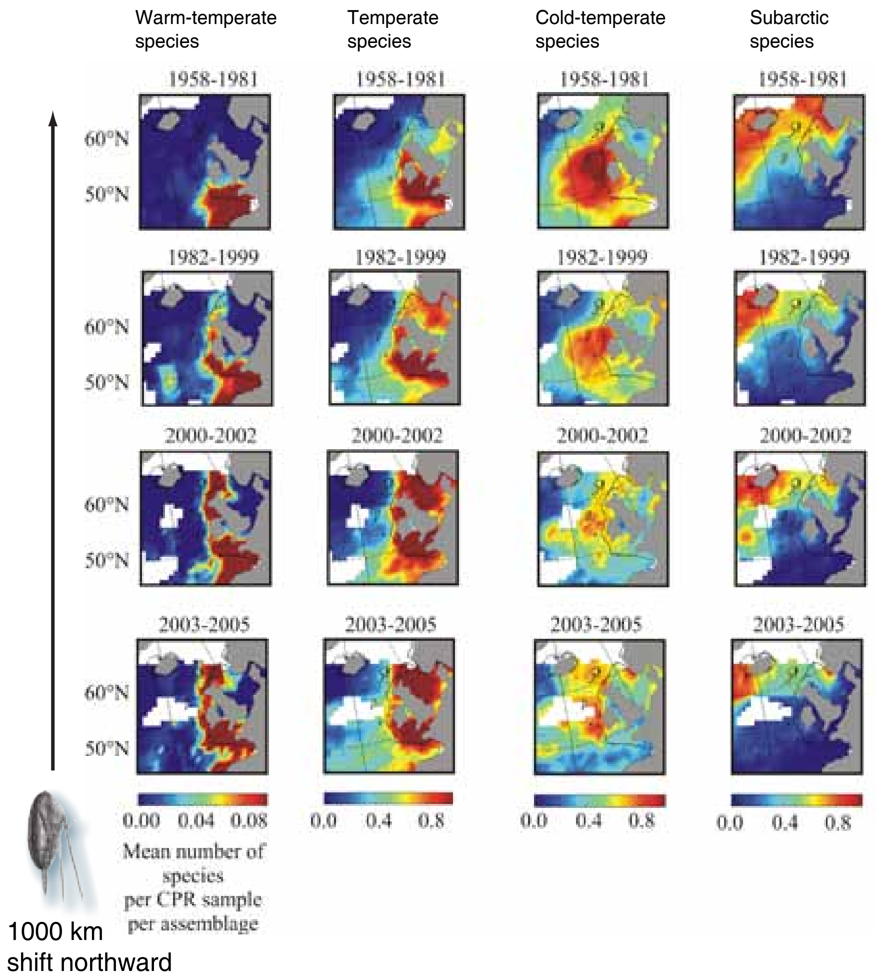


Fig. 17. Biogeographical changes in plankton assemblages spanning five decades. Warm-water plankton (e.g. warm-temperate species) are moving north and cold-water plankton (e.g. subarctic species) are moving out of the North Sea. Based on *Science (2002) 296: 1692-1694.*

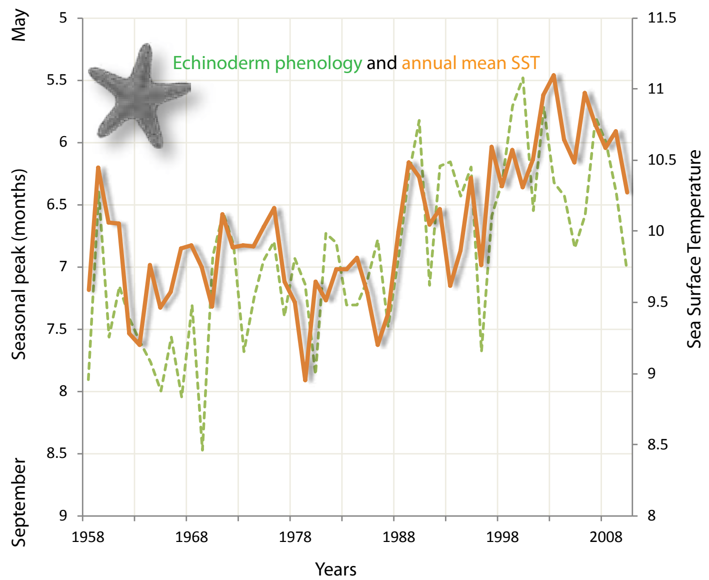


Fig. 18. Phenological shifts in echinoderm larvae and mean annual SST in the North Sea from 1958-2010. The main decadal trend is towards an earlier seasonal cycle, however, the year 2010 was later than the previous years. Based on *Nature (2004) 430: 881-884.*

Marine biodiversity and invasive species

Multi-decadal trends in ocean biodiversity

At the ocean basin scale studies on the pelagic biodiversity of zooplankton copepods are related to temperature and an increase in warming over the last few decades has been followed by an increase in diversity. There is also a direct link between diversity and the size-structure of the zooplankton community. The overall diversity patterns of pelagic organisms, peaking between 20° to 30° north or south, follow temperature gradients in the world's oceans. Similarly, phytoplankton show a relationship between temperature and diversity which is linked to the phytoplankton community having a higher diversity but an overall smaller size-fraction and a more complex foodweb structure (i.e. microbial-based versus diatom-based production) in warmer, more stratified environments. The parallel decrease in size-structure of pelagic organisms with increasing diversity may have implications for marine ecosystem services such as smaller-sized fish communities and reduced carbon drawdown *(PNAS (2010) 107: 10120-10124)*.

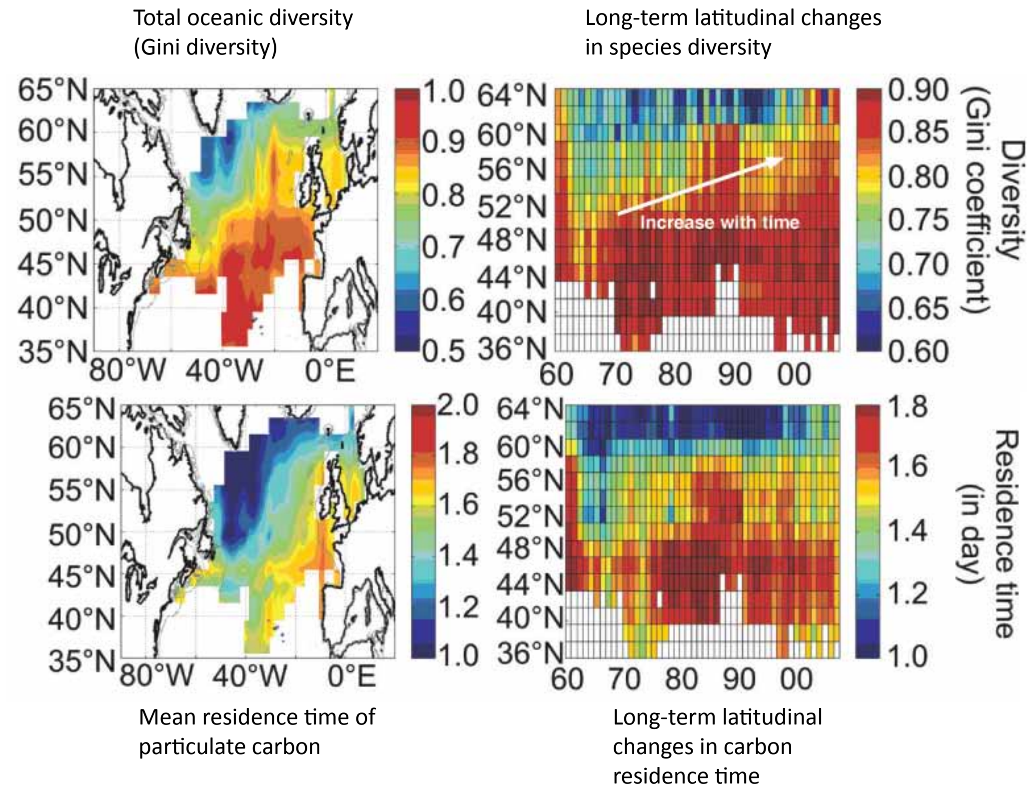


Fig. 19. Relationships between the spatial distribution and long-term latitudinal changes in the diversity and a size-derived functional characteristic of calanoid copepods in the extratropical North Atlantic. Diversity was measured by first-order jackknife performed on the Gini coefficient. Left panel: mean spatial distributions (1960-2007) of copepod diversity and mean residence time above 50 m of sinking copepod particles (in days). Right panel: long-term latitudinal changes in copepod diversity and mean residence time above 50 m of sinking copepod particles. Based on *(PNAS (2010) 107: 10120-10124)*.

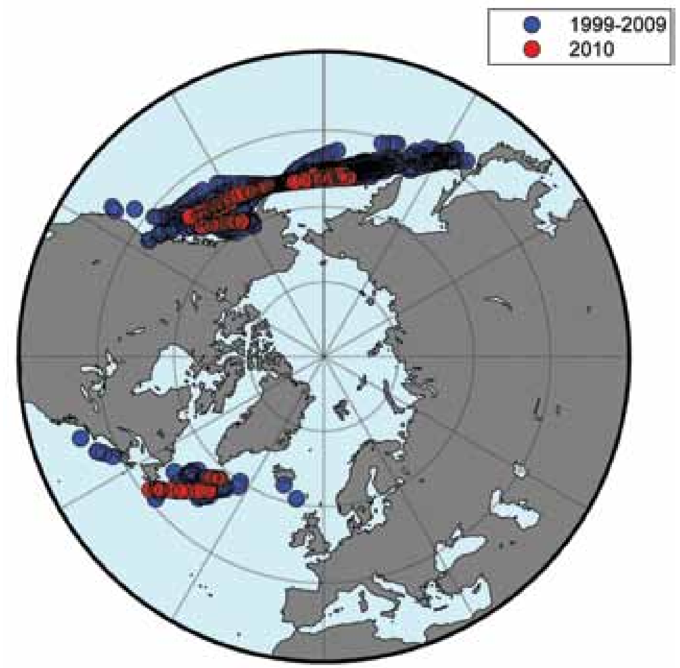


Fig. 20. It has recently been highlighted that Arctic ice is reducing faster than previous modelled estimates. As a consequence the biological boundaries between the North Atlantic Ocean and Pacific may become increasingly blurred with an increase of trans-Arctic migrations becoming a reality. The CPR survey has already documented the presence of a Pacific diatom, *Neodenticula seminae*, in the Labrador Sea since the late 1990s which has since spread southwards and eastwards. The diatom species itself has been absent from the North Atlantic for over 800,000 years and could be the first evidence of a trans-Arctic migration in modern times and be the harbinger of a potential inundation of new organisms to the North Atlantic. The consequences of such a change to the function and biodiversity of Arctic systems are at present unknown. Total records (blue), records in 2010 (red).

More information: *Global Change Biology (2007)13: 1910-1921*

Invasive species

Because of its extensive geographical coverage and long time frame, data from the CPR have provided invaluable information on the spread of non-native plankton. For example, the invasive diatom *Coscinodiscus wailesii*, which has become a persistent and significant member of the plankton community, has spread from its first record off Plymouth in 1977 throughout all coastal waters of northern Europe and out into the Atlantic in a matter of only 30 years.

A recent review of non-native marine species around the British Isles that includes plankton and HAB species provides more detail on planktonic introductions. The discovery of the comb jelly *Mnemiopsis leidyi* in North Sea waters is of particular concern, even though it has not yet been recorded in the British Isles, because of the very marked impact it appears to have had on fisheries and the general ecosystem when it has appeared in other parts of the world.

Climate warming will open up new thermally defined habitats (see section on habitat expansion of temperate province) for previously denied non-indigenous species (e.g. sub-tropical species in the North Sea) and invasive species allowing them to establish viable populations in areas that were once environmentally unsuitable. Apart from these thermal boundary limits moving progressively poleward and in some cases expanding, the rapid climate change observed in the Arctic may have even larger consequences for the establishment of invasive species and the biodiversity of the North Atlantic (see figure 20 left).

New copepod species found in the southern North Sea

A new invasive copepod species has been found in the North Sea. The copepod species *Pseudodiaptomus marinus* naturally occurs in east Asiatic waters but has been subsequently spreading more widely in the Indo Pacific region over the last decade. The first record of the species in European waters comes from its discovery in the Adriatic Sea in 2007. In October 2011 the species was recorded on CPR routes operating in the southern North Sea (Jha et al. In prep). The present records extend the known distribution of *P. marinus* across the southern Bight from the Netherlands to the British coast and to the German Bight. It is highly probable the species presence is due to human activity linked to ballast water release or aquaculture. The CPR survey will continue to monitor its establishment in the North Sea and its probable spread to other regions.

Unusual biodiversity records in 2010/11

Two rare species of calanoid copepods from the North Atlantic were found in 2010: last recorded in 1974, *Euchirella amoena* was found in July in the middle of the subtropical Atlantic and off the coast of New York; on the same coastal sample a *Scaphocalanus echinatus* was also identified. Although not unusual in their distribution these copepods are scarce in the CPR survey having only previously been recorded 3 and 19 times respectively. Similar in size to the aforesaid copepods, *Calanus finmarchicus* is contrastingly one of the most abundantly found copepods on North Atlantic CPR samples and is associated with the Atlantic polar biome. However, in March 2010 there were 2 occurrences of *C. finmarchicus* in oceanic subtropical waters. During the last 30 years *C. finmarchicus* has only been identified 8 times in this region and is typically replaced by its warmer-water-loving sister species *C. helgolandicus*. *Calanus* species are important food items for higher marine animals including fish. *Pacillina arctica incertae sedis*, an organism of uncertain taxonomic placement, was recorded in July 2010 stretching some 80 miles along the coastline of New York. These are the most westerly sightings ever of this suspected ciliate cyst in the CPR survey.

Marine ecosystem and environmental health

Eutrophication and Habs

There has been a considerable increase in phytoplankton biomass (Phytoplankton Colour Index) over the last decade in certain regions of the North-East Atlantic and North Sea, particularly over the winter months. Increased phytoplankton biomass may be an indicator of eutrophication; however, similar patterns of change have been found in both coastal and offshore waters. In the North Sea a significant increase in phytoplankton biomass has been found in both heavily anthropogenically-impacted coastal waters and the comparatively less-affected open North Sea despite significantly decreasing trends in nutrient concentrations. The increase in biomass appears to be linked to warmer temperatures and evidence that the waters are also becoming clearer (i.e. less turbid), thereby allowing the normally light-limited coastal phytoplankton to more effectively utilise lower concentrations of nutrients (*Limnology and Oceanography (2007) 52: 635–648*). These results may indicate that climatic variability and water transparency may be more important than nutrient concentrations to phytoplankton production in the North Sea. Despite the overriding influence of climate, elevated nutrient levels may be of concern in some localised areas around European seas. In general, HABs are naturally occurring events although some exceptional blooms have been associated with eutrophication in coastal waters. HAB taxa are generally most numerous along the Dutch coast and off the northern Danish coast. In particular the red-tide forming species *Noctiluca scintillans* naturally forms extensive blooms during the summer period in these areas as well as in the Irish Sea. Large HABs during 2010 occurred within the range of natural variability and were similar to the long-term average occurrences. However, the large blooms of *Pseudo-nitchia* spp. that occurred in the southern North Sea were particularly numerous in 2010 and are becoming more common in the North Sea over the last decade.

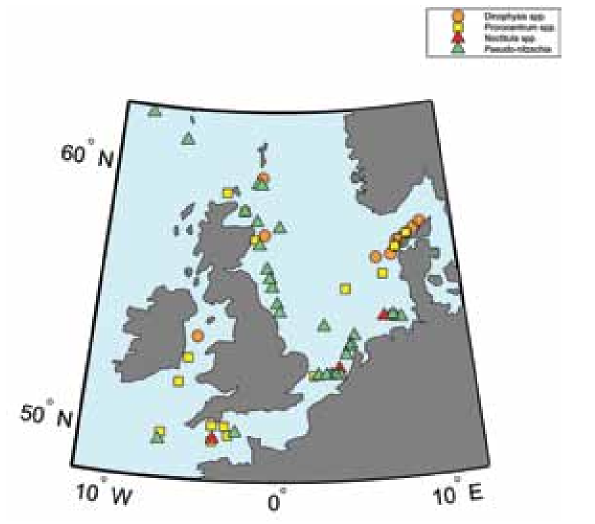


Fig. 21. The distribution of large HAB blooms in Northern European waters in 2010. Large or exceptional HAB blooms are equivalent to 4 standard deviations above the long-term mean (1958-2009).

Trends in marine pathogens

As sea surface temperatures increase, predictions favour an increase in number and range of pathogenic micro-organisms. Such changes are difficult to determine over short time periods that cannot separate short-term variations from climate change trends. In a unique long-term time study, Vezzulli et al. (2011) investigated the spread of the pathogenic bacteria, *Vibrio,* the causative agent of cholera in the North sea over 54 years, between 1961-2005, and revealed that *Vibrio* bacteria are increasing in this region. The VAI was found to steadily increase over four decades which was linked to temperature and copepod abundance but not PCI. The Rhine area was significantly correlated with VAI, which has higher summer SST over 18˚C, where *Vibrio* thrives best (Vezzulli et al. 2004), and was especially marked in the late 1980s when step-wise increase in SST was reported in the Southern North Sea. No significant increase was found in the Humber, which never exceeds 18˚C. *Vibrio* attaches to chitin surfaces, so the relationship with Copepods, may reveal the mechanism by which this pathogen spreads.

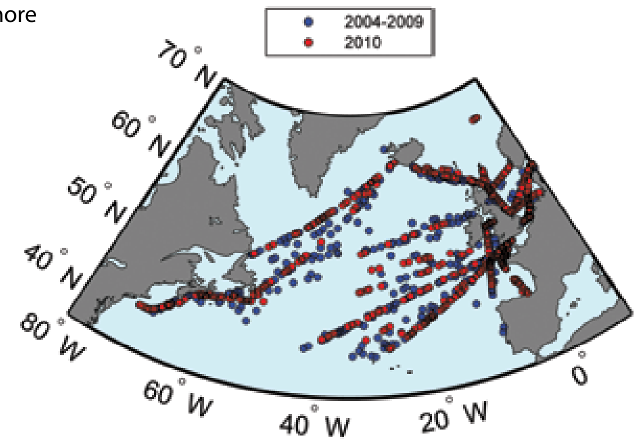


Fig. 22. The geographical distribution of microplastics recorded on CPR samples in 2010 and between 2004-2009. While the distribution largely reflects CPR sampling frequency it does show that microplastics are widely distributed in the North Atlantic including the offshore oceanic environment.

Marine microplastics

From the presence of microplastics that have been recorded on CPR samples it is clear that microplastics are widely distributed in the North-East Atlantic with the frequency of microplastics increasing towards the coasts (particularly in the southern North Sea). From retrospective analysis of some CPR samples spanning three decades it appears that microplastics are increasing in frequency through time (*Science (2004) 308:834*). The incidence of monofilament netting snagged by the CPR towed body also seems to be increasing, particularly in the southern North Sea.

Ocean acidification

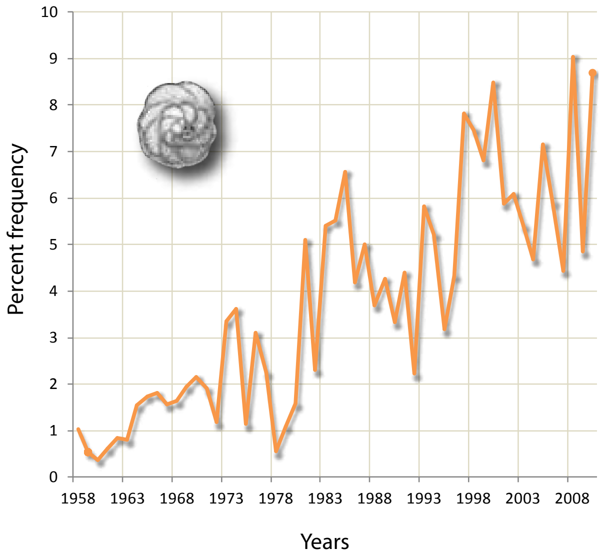
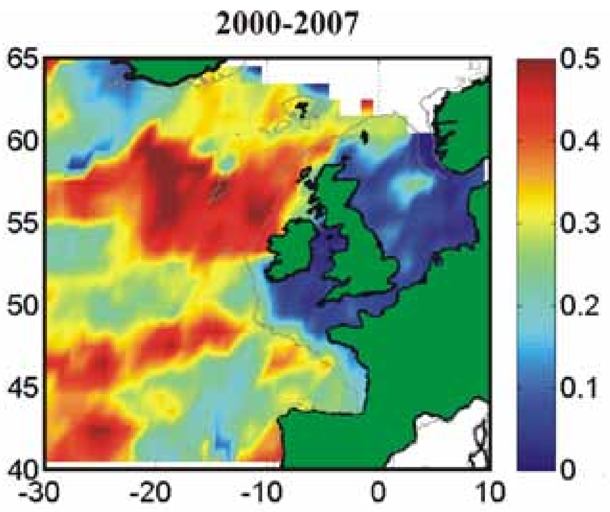


Fig. 23. The percent frequency of foraminifera recorded on CPR samples

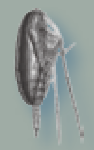


Changes in temperature have direct consequences on many physiological processes (e.g. oxygen metabolism, adult mortality, reproduction, respiration, reproductive development) and control virtually all life-processes from the molecular to the cellular and from the regional ecosystem level to biogeographical provinces. Temperature also modulates species interactions (e.g. competition, prey-predator interactions and foodweb structures) both directly and indirectly; ultimately, changes in temperatures caused by climate change can lead to impacts on the biodiversity, size structure, carrying capacity and functioning of the whole pelagic ecosystem. While temperature has direct consequences on many biological and ecological traits it also modifies the marine environment by influencing oceanic circulation and by enhancing the stability of the water column and hence nutrient availability. Under many climate change scenarios, oceanic primary production is predicted to decline due to nutrient limitation.

While temperature, light and nutrients are probably the most important physical variables structuring marine ecosystems, the pelagic realm will also have to contend with, apart from global climate warming, the impact of anthropogenic CO_2 directly influencing the pH of the oceans. Evidence collected and modelled to date indicates that rising CO_2 has led to chemical changes in the ocean which has led to the oceans becoming more acidic. Ocean acidification has the potential to affect the process of calcification and therefore certain planktonic organisms (e.g. coccolithophores, foraminifera, pelagic molluscs) may be particularly vulnerable to future CO_2 emissions. Apart from climate warming, potential chemical changes to the oceans and their effect on the biology of the oceans could further reduce the ocean's ability to absorb additional CO_2 from the atmosphere, which in turn could affect the rate and scale of climate warming.

Presently in the North Atlantic certain calcareous taxa are actually increasing in terms of abundance, a trend associated with climate shifts in the Northern Hemisphere temperature (see above figure of foraminifera frequency). However, there is some observed evidence from the Southern Ocean that modern shell weights of foraminifera have decreased compared with much older sediment core records with acidification being implicated *(Nature Geoscience (2009) doi:10.1038/ngeo460)*. It is not yet known how much of an effect acidification will have on the biology of the oceans in the 21st century, whether rapid climate warming will override the acidification problem, and whether or not species can buffer the effects of acidification through adaptation. The CPR survey is providing a critical baseline (both in space and time) and is currently monitoring these vulnerable organisms in case in the future these organisms begin to show negative effects due to acidification.

Summary for policy makers



Marine climate change impacts: Northward shifts

Warmer-water species are currently increasing in the North Sea due to regional climate warming and the NAO. In terms of a productive environment this change is currently considered detrimental because the warmer-water species are not replacing the colder-water species in similar abundances which may negatively impact other trophic levels including fish larvae. For example, an important zooplankton species has declined by 70 % in the North Sea. There is a high confidence that these trends are related to regional climate warming.

Marine climate change impacts: Changes in seasonality and phenology

Seasonal timing, or phenology, is occurring earlier in the North Sea and is related to regional climate warming. For example, some species have moved forward in their seasonal cycles by 4-5 weeks. However, not all trophic levels are responding to the same extent; therefore in terms of a productive environment, this change is currently considered detrimental because of the potential of mis-timing (mismatch) of peak occurrences of plankton with other trophic levels including fish larvae. There is a high confidence that these changes are associated with regional climate warming.

Marine biodiversity and invasive species

Oceanic plankton biodiversity is increasing in the North Atlantic associated with temperature increases. There is a strong relationship between biodiversity and size-structure in pelagic communities. Increasing biodiversity is associated with a decreasing size-structure of the community. This in turn may have implications for marine ecosystem services such as smaller-sized fish communities and reduced carbon drawdown.

Marine ecosystem health and water quality

At the regional scale, it has been found that most phytoplankton trends are related to hydro-climatic variability as opposed to anthropogenic input (e.g. nutrient input leading to eutrophication). This means that the North-East Atlantic as a whole is generally considered to be fairly healthy. This is not to say, however, that certain coastal areas and the southern North Sea are not vulnerable to eutrophication and climate change may also exacerbate these negative effects in these vulnerable regions. It has also been found that the number of microplastics collected on CPR samples is increasing and the frequency of occurrence and bloom timing of some Harmful Algal Bloom species are related to regional climate warming.

Ocean acidification

Organisms that could be particularly vulnerable to acidification are the calcifying organisms such as coccolithophores and foraminifera. The CPR survey is proving a critical baseline and is currently monitoring these vulnerable organisms in case these organisms start to show any negative effects due to acidification in the future. Over the last few decades trends in calcifying organisms recorded by the CPR survey have been correlated with changes in Northern Hemisphere Temperatures rather than changing pH. However, acidification may become the main driver of change in the future.

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The Sir Alister Hardy Foundation for Ocean Science (SAHFOS) is an internationally funded charity (Canada, Norway, UK and the USA) that operates the Continuous Plankton Recorder (CPR) survey. The Foundation has been collecting data from the North Atlantic and the North Sea on biogeography and ecology of plankton since 1931. More recently, work has been expanded to include other regions around the globe including the Arctic and Southern Ocean. The results of the survey are used by marine biologists, scientific institutes and in environmental change studies across the world. The SAHFOS team is based in Plymouth, England and consists of analysts, technicians, researchers and administrators, who all play an integral part in the running of the survey.

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