A Global Plankton Diversity Monitoring Program

Batten, Sonia D.; Abu-Alhaija, Rana; Chiba, Sanae; Edwards, Martin; Graham, George; Jyothibabu, R.; Kitchener, John A.; Koubbi, Philippe; McQuatters-Gollop, Abigail; Muxagata, Erik; Ostle, Clare; Richardson, Anthony J.; Robinson, Karen V.; Takahashi, Kunio T.; Verheye, Hans M.; Wilson, Willie

Published in:
Frontiers in Marine Science

DOI:
10.3389/fmars.2019.00321

Publication date:
2019

Citation for published version (APA):
Batten, S. D., Abu-Alhaija, R., Chiba, S., Edwards, M., Graham, G., Jyothibabu, R., Kitchener, J. A., Koubbi, P., McQuatters-Gollop, A., Muxagata, E., Ostle, C., Richardson, A. J., Robinson, K. V., Takahashi, K. T., Verheye, H. M., & Wilson, W. (2019). A Global Plankton Diversity Monitoring Program. *Frontiers in Marine Science*, *6*(0). https://doi.org/10.3389/fmars.2019.00321

A Global Plankton Diversity Monitoring Program

Batten[*1], S.D., Abu-Alhaija[2], R., Chiba[3,4], S., Edwards[5], M., Graham[5], G., Jyothibabu[6], R., Kitchener[7], J.A., Koubbi[8], P., McQuatters-Gollop[9], A., Muxagata[10], E., Ostle[5], C., Richardson[11]A.J., Robinson[12], K.V., Takahashi[13], K.T., Verheye[14], H.M., Wilson[5], W.

[*1]CPR Survey, Marine Biological Association, Nanaimo, BC, Canada

[2] The Cyprus Institute, Nicosia, Cyprus

[3] JAMSTEC, Yokohama, Japan

[4] UNEP-WCMC, Cambridge, UK

[5] CPR Survey, Marine Biological Association, Plymouth, Devon, UK

[6] CSIR-National Institute of Oceanography, Regional Centre, Kochi, India

[7] Australian Antarctic Division, Department of the Environment and Energy, Kingston, Australia

[8] Sorbonne University, Paris, France

[9] Centre for Marine and Conservation Policy Research, University of Plymouth, Plymouth, Devon, UK.

[10] Laboratório de Zooplâncton, Universidade Federal de Rio Grande - FURG, Rio Grande, Brazil

[11] CSIRO Oceans and Atmosphere, Brisbane, QLD, Australia and University of Queensland, Brisbane, QLD, Australia

[12] National Institute of Water and Atmospheric Research, Christchurch, NZ

[13] National Institute of Polar Research, Tokyo, Japan

[14] Marine Research Institute, Department of Biological Sciences, University of Cape Town, Rondebosch, South Africa; formerly: Oceans and Coastal Research, Department of Environmental Affairs, Cape Town, South Africa

Correspondence

Dr Sonia Batten

sonia.batten@mba.ac.uk

Abstract

Plankton are the base of marine food webs, essential to sustaining fisheries and other marine life. Continuous Plankton Recorders (CPRs) have sampled plankton for decades in both hemispheres and several regional seas. CPR research has been integral to advancing understanding of plankton dynamics and informing policy and management decisions. We describe how the CPR can contribute to global plankton diversity monitoring, being cost-effective over large scales and providing taxonomically-resolved data. At OceanObs09 an integrated network of regional CPR surveys was envisaged and in 2011 the existing surveys formed the Global Alliance of CPR Surveys (GACS). GACS first focused on strengthening the dataset by identifying and documenting CPR best practices, delivering training workshops, and developing an integrated database. This resulted in the initiation of new surveys and manuals that enable regional surveys to be standardized and integrated. GACS is not yet global, but it could be expanded into the remaining oceans; tropical and Arctic regions are a priority for survey expansion. The capacity building groundwork is done, but funding is required to implement the GACS vision of a global plankton sampling program that supports decision-making for the scientific and policy communities. A key step is an analysis to optimize the global sampling design. Further developments include expanding the CPR for multidisciplinary measurements via additional sensors, thus maximising the ship-of-opportunity platform. For example, defining pelagic ecoregions based on plankton and ancillary data could support high seas Marine Protected Area design. Fulfilment of Aichi Target 15, the United Nation’s Sustainable Development Goals, and delivering the Essential Ocean Variables and Essential Biodiversity Variables that the Global Ocean Observing System and Group on Earth Observation’s Biodiversity Observation Network have respectively defined requires the taxonomic resolution, spatial scale and time-series data that the CPR approach provides. Synergies with global networks exploiting satellite data and other plankton sensors could be explored, realizing the Survey’s capacity to validate earth observation data and to ground-truth emerging plankton observing platforms. This is required for a fully integrated ocean observing system that can understand global ocean dynamics to inform sustainable marine decision-making.

Key Words

Continuous Plankton Recorder, zooplankton, phytoplankton, global monitoring, biodiversity, ocean observing, essential ocean variables

1. The need for global plankton observations

The pelagic zone is the largest biome on Earth. Plankton are found throughout the ~1 billion km^3 of living space in the pelagic zone, and are extremely abundant; one group, the copepods, could be three orders of magnitude more abundant than insects (Schminke, 1998). Plankton underpin almost all marine food webs and provide the link between the physical environment and the fish, marine birds and mammals that society values and which forms the basis of much of the blue economy. Furthermore, plankton are responsible for ~46% of the planetary photosynthesis, the first step in a series of complex biogeochemical processes in the ocean that make up the biological pump, which involves the export of carbon and other elements from the atmosphere via surface waters into the ocean’s interior. The many and varied roles of plankton make them essential candidates for measuring the health of our oceans in the Anthropocene.

There is an increasing emphasis on globally coordinated marine science strategies towards “conserving and sustainably using the oceans, seas and marine resources for sustainable development” as laid out in the United Nation’s sustainable development goal 14 (SDG14). Plankton are an ideal indicator for sustainably managing our oceans, as they are sensitive to the environment and they are not yet fished to any great extent, meaning that measured changes in plankton communities unambiguously reflect environmental changes and not the amount of harvesting, which complicates analyses of fish stock data.

1.1 Plankton: an essential ocean and biodiversity variable

The Global Ocean Observing System (GOOS) advocates for sustained observations that describe the current ocean state. The initial focus on physical oceanography now informs weather and climate forecasts through a suite of observing platforms (e.g., moorings, voluntary observing ships, satellites, Argo) to measure the temperature and salinity of the oceans. A more recent focus has been on the biological properties of the ocean, developed from the Framework for Ocean Observation (Lindstrom et al, 2012), with GOOS establishing a Biology and Ecosystems Panel in 2015. Its remit is to promote a global, sustained, and targeted ecosystem observing program based on essential ocean variables (EOVs). Plankton (abundance and diversity) were identified as EOVs with moderate to high relative impact for addressing societal drivers and pressures (Miloslavich et al., 2018).

The Group on Earth Observations Biodiversity Observation Network (GEO BON) has developed Essential Biodiversity Variables (EBVs) to “play the role of brokers between monitoring initiatives and decision makers” with a focus on the status and trend in biodiversity. EBVs include taxonomic diversity to inform policy makers on community composition and secondary productivity as well as plankton functional type variables to inform on ecosystem structure and function.

A key challenge in observing plankton in the pelagic zone over the vast expanses of the ocean is to estimate the zooplankton component. For nearly four decades, phytoplankton have been observed from space. Satellites not only provide estimates of phytoplankton biomass (chlorophyll-a), but also of some phytoplankton functional types (Brewin et al., 2010), although phytoplankton species composition remains elusive. However, zooplankton, the intermediate trophic link between phytoplankton and fish, cannot be observed from satellites. Zooplankton can readily be monitored over local scales using nets and modern imaging and laser systems, but sampling zooplankton over large spatial scales – both abundance and species composition – remains challenging.

1.2 Continuous Plankton Recorder Surveys

First routinely deployed in 1931 the Continuous Plankton Recorder (CPR) survey is the longest running, most extensive, marine biological sampling program (Richardson et al, 2006). Uniquely, the CPR collects *in situ* samples over large spatial scales, allowing species-level identification of plankton composition and abundance. This is possible because the CPR is sufficiently robust to be deployed from commercial ships (ships of opportunity), unaccompanied by researchers, making sample collection cost-efficient over large ocean tracts, although the species-level identification currently necessitates relatively high processing costs per sample. Full technical details of the CPR can be found in Batten et al. (2003a).

The first CPR sampling took place in the North Sea in 1931, followed by a network of transects around the UK which extended over the European shelf by the late 1940s. Further expansion to the western North Atlantic occurred next, followed by the first independent regional survey in 1961 off the east coast of the USA. Over time, additional regional surveys have extended CPR operations to northern and southern hemispheres, the North Atlantic and Pacific Oceans as well as smaller regional seas (Fig 1).

Strengths and limitations of CPR sampling are well documented in the CPR literature (e.g. Richardson et al. 2006) and will not be repeated here but its specifications mean that only a portion of the entire plankton community is sampled, a fact that is common to all plankton sampling strategies (Wiebe & Benfield, 2003). The CPR filters plankton from the seawater using a mesh with a nominal size of 270µm (although because of the silk weave it commonly captures phytoplankton down to ~10 µm {Richardson et al. 2006}). The seawater entrance aperture has sides of 1.2 cm. There are, therefore, upper and lower size limits of organisms that can be effectively captured and retained. The preservative used is formaldehyde which works well for some species, but not for others. The high speed of sampling (up to 25 knots) means that fragile and gelatinous groups are often damaged or destroyed. The CPR is towed at a fixed near-surface depth (5-10m) meaning it only captures those taxa that spend some of their time in the mixed layer. Despite these limitations the sampler has changed relatively little since its inception and is internally consistent. Many hundreds of taxa are routinely identified from CPR samples, resulting in a rich ecological dataset of unparalleled spatial extent allowing the identification of changes in plankton communities over large space and time scales, such as multi-decadal and ocean basin. There is a diverse scientific literature based on these data of over 1000 peer-reviewed publications (a selection is presented in Table 1). It should also be noted that the CPR is not an appropriate sampler for very shallow, near-shore regions, where transect lengths are less than about 100km or for station-based sampling. However, through collaborative approaches suggested in section 3, CPR data could provide larger scale context or link distant sampling locations where other samplers are used.

1.3 Initiating the Global Alliance of CPR Surveys

At the 2009 Global Ocean Ecosystem Dynamics (GLOBEC) Open Science Meeting in Victoria, Canada, CPR users from regional surveys met to examine new results and to begin discussions on stronger links between surveys and how it may be possible to integrate their products (Batten and Burkill, 2010). Two years later, in September 2011, the Global Alliance of CPR surveys (GACS) had its first meeting and signed a Memorandum of Understanding to work towards providing an integrated data set derived from the several national CPR Surveys that currently operated or were planned in the near future. It was anticipated that each of these surveys would continue to operate independently but with increasing emphasis for their contribution to the global perspective. There were 6 objectives that were laid out as targets;

1) A common aim “to understand changes in plankton biodiversity at ocean basin scales through a global alliance of CPR Surveys”.
2) Adoption of common standards and procedures wherever possible.
3) The generation of a plankton biodiversity database that would ultimately be made freely available to the science community.
4) The setting up of a website for publicity and data access.
5) The production of a regular Ecological Status Report on Global Plankton Biodiversity.
6) An interface between plankton biodiversity and other global ocean observation programmes.

2. Current status: Successes and stumbling blocks

Nine independent regional CPR surveys currently exist which are members of GACS (Figure 1, upper panel). One survey has ceased operation since GACS was formed (the east coast of the USA) but some sampling has been maintained there by the UK CPR survey. The proportion of collected samples that are analysed for taxonomic abundance differs between surveys but the lower panel of Fig 1 shows the annual total of analysed samples, globally, to the year when all surveys have reported data. Samples that are collected but not analysed are for the most part archived and can be used for additional studies. The total of collected and archived samples is about twice the number shown in Figure 1.

Many of the surveys have started relatively recently; however, there are now almost two decades with more than 5,000 analysed samples per year that are spread over at least 3 regions (regional seas or ocean basins) and both hemispheres. Funding is the largest limitation to further expansion of CPR surveys; there is strong competition for available funds and there is a (false) perception that it takes many years to realise the benefits of a new CPR survey. There are many issues apart from long-term changes that can be addressed by young CPR surveys (see Section 2.2 for examples). CPR surveys that have ceased operation have done so not because of lack of scientific merit, but because of a paucity of funding.

Resources have also limited the speed at which the global CPR database has been developed. Building the infrastructure to link the regional surveys relies not just on physical hardware and person-time in the GACS host institution but also person-time and expertise at each regional survey to format and deliver the data, some of which consist of only one Principal Investigator with many competing requirements for their time. While the benefits to participating in GACS and contributing to a global system are clear to all the scientists involved it is nonetheless not a small task for most to isolate resources for this process when the funding source may have an entirely national or regional focus. Creation of the CPR global database is a significant step for marine ecology as the only other plankton data at a similar spatial scale is currently from remote sensing. Although satellite data have global ocean coverage, they can only provide information on phytoplankton biomass and a few key functional groups, and cannot be used to examine oceanic or trans-oceanic changes in species and, therefore, biodiversity. Once the global CPR database is fully developed it can be interrogated to support integrated global analyses of CPR data, furthering understanding of near-global scale plankton dynamics and of inter-regional connectivity of pelagic habitats.

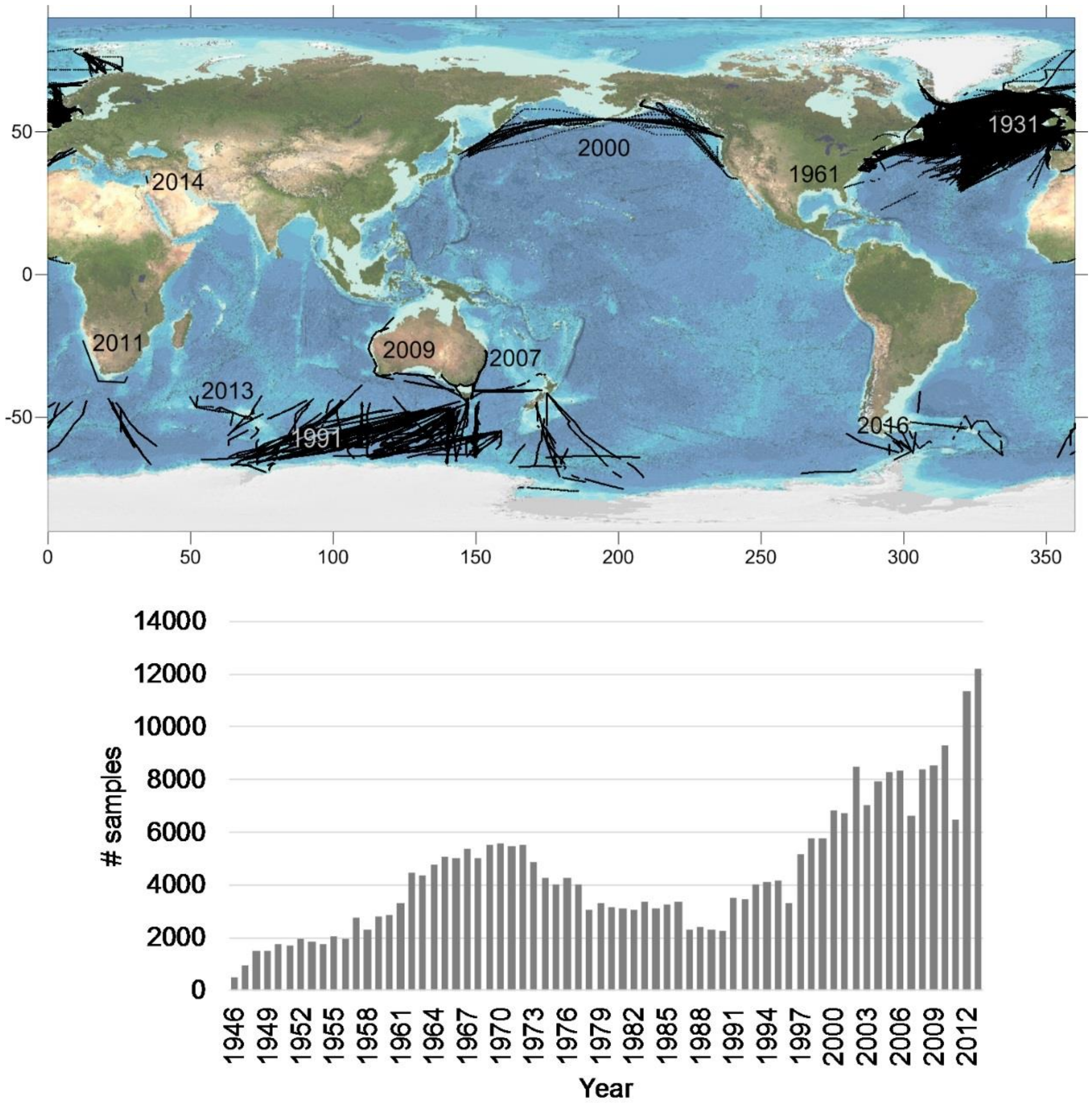

Figure 1. Upper panel shows the CPR transect locations together with the year of inception of that local survey. Lower panel shows the combined total number of CPR samples that have had plankton counts determined.

2.1 Defining best practices, capacity building and new surveys

CPR surveys share many methodological similarities. These include the CPR device itself (the same design is used by all surveys except the Southern Ocean (SO) surveys, which use a slightly modified version for deployment in sea ice), the silk mesh for capturing plankton (all sourced from the parent organisation), and methods for phytoplankton counting (see Richardson et al. (2006) for details). New surveys, however, are not constrained by maintaining the consistency of a time series and can modify the methods to better address their primary research questions. For example, surveys have different frequencies of deployment and this is not only related to cost: some surveys (e.g., in the North Atlantic) tow monthly to address questions concerning phenology and succession in temperate/polar regions, while other surveys (e.g., Australian CPR survey (AusCPR) tow every 3 months in (less seasonal) tropical regions to address inter-annual variation. Another difference among surveys is the method of zooplankton counting: some surveys in (diverse) tropical regions wash the plankton off the mesh for identification of taxa to a higher taxonomic level because the focus is on changes in diversity with climate change (e.g., AusCPR) or to avoid the need for a purpose-built microscope (e.g. New Zealand CPR and SO-CPR), while other surveys complete on-mesh analysis (which is more challenging for species-level identification of smaller species) that is well-suited to the larger organisms and lower diversity of temperate regions (e.g., the North Atlantic). Therefore, surveys in different regions have bespoke research questions, and thus some of the detailed methodology has been modified accordingly, precluding the use of identical methods across all surveys. However, these methodological differences can be viewed as being akin to measuring temperature in the ocean on different platforms (e.g., satellites, moorings, XBTs or Argo floats) at different spatial and temporal resolutions – each platform by itself is useful for answering specific questions, but their data can be successfully integrated into global temperature products. The similarity of the same sampling device – the CPR – and the species-level plankton identification – are key to the comparability of the data. This comes with some caveats though, as abundances from the CPR are semi-quantitative, providing consistent information on spatial and temporal variation, but not on absolute abundance, which is usually better measured with other sampling techniques (Batten et al. 2003, Clark et al. 2001, Richardson et al. 2004, 2006, John et al. 2001, Lewis et al. 2006).

An early focus of GACS has been to prepare manuals and materials to document the standard procedures used in all aspects of CPR deployment, maintenance and sample processing and archiving by the North Atlantic survey at the Marine Biological Association, UK (now home to the former Sir Alister Hardy Foundation for Ocean Science (SAHFOS) that also hosts GACS). Technicians from several nations that have subsequently initiated new surveys have attended training courses held by the North Atlantic survey. A short-term goal is to make those documents accessible to all through the Ocean Best Practices Repository.

2.2 The diversity of applications of CPR data

Continuous Plankton Recorder data have been used to study a multitude of scientific and societal questions (Table 1). The assessment of global issues such as climate change (e.g. Hinder *et al.*, 2014) and fisheries (e.g. Batten et al, 2018) provide the means to recognize similar trends in different areas. The survey has also been successful in evaluating regional stressors (e.g. Vezzulli *et al.*, 2016) or distinct events with globally applicable results or methodologies (Hallegraeff *et al.*, 2014). Here (Table 1) we do not aim to provide an exhaustive list of the CPR bibliography but rather a sample of the breadth and depth of knowledge produced through the various surveys.

Table 1. A selection of publications using CPR data to demonstrate the breadth of applications.

Subject	**Area/Timeframe**	**Main results**	**Reference**
Pollution	Irish Sea 1996 vs long-term	After the Sea Empress oil spill, a shift in zooplankton community composition and a decrease in population spawning was observed when comparing long term to post spill data.	(Batten *et al.*, 1998)
Pollution	North Sea, North Atlantic 1960s- 1990s	An increase of microplastics towards the end of the previous century was recorded from CPR samples, with oceanic areas having less microplastics than closed systems.	Thompson *et al.*, 2004
Bio-accumulation/Po lution	Northwest Atlantic	Methylmercury (MeHg), a harmful neurotoxin, concentrations as modeled from CPR phytoplankton data, predict that climate change forcing will have a profound effect in methylmercury concentrations and linear increases across trophic groups.	Schartup *et al.*, 2018
Alien species dispersal	English Channel to North-East Atlantic	*Coscinodiscus wailesii*, is a non-indigenous diatom, with detrimental effects to fish populations around the UK[1]. The survey tracks its appearance, dispersal, subsequent establishment as well as assesses and defines its interaction within the communities[2].	[1]Boalch and Harbour, 1977 [2]Edwards *et al.*, 2001
Fisheries	Bering Sea 2000-2014	A fifteen year CPR dataset revealed alternating patterns of zooplankton and phytoplankton abundances to be linked to the biennial Pink Salmon class strength. The evidence of a trophic cascade may be used as a predictor for future population trends.	(Batten *et al.*,2018
Fisheries	North Sea 1948-1997	Unsustainable fishing practices and the subsequent 1977-1982 ban on herring fishing[3] is reflected in changes within the planktonic community. The findings support the importance of top down regulation effect to ecosystem changes in complex ecosystems[4].	[3]Koslow, 1983 [4]Reid *et al.*, 2000
Fisheries	1951-2005	Blue-whiting spawning seems to be induced by a narrow window of conditions	Miesner and

	North Atlantic, North Sea	suggested to be optimal for the survival of the larvae (mainly salinity between 35.3 and 35.5psu). Predictive tools and CPR data could be used to map spawning distribution.	Payne, 2018
Fisheries	North Sea 1958-1999	Plankton composition changes in 1980's induced a decrease in cod populations. More importantly, abundance and diversity of the plankton community in any given year was found to be linked to next year’s cod stock.	Beaugrand *et al.*, 2003
Harmful Algal Blooms	North Atlantic, North Sea 1958-2004	Increasing temperatures are contributing to the increased frequency of the harmful algal blooms according to this study. A stepwise regime shift in the appearance and composition was also noted late 1988 with a high intensity of increasing HABs.	Edwards *et al.*, 2006
Climate Change	[1]North Atlantic 1960-2010 [2]North Sea, North Atlantic 1962-1992	The study of cold-water *Calanus finmarchicus* and warm water *C. helgolandicus* indicates ecological adaptations to climate change with implications to fisheries catches. The species have adjusted their geographical distribution towards respective optimal temperatures[5], while temporal investigation, shows *C. finmarchi*cus peaks in May, and *C. helgolandicus* peaks twice with the highest peak being in September[6].	[5]Hinder, *et al.*, 2014 [6] Planque and Fromentin, 1996
Climate Change	North Sea, North Atlantic 1960–1999	Community composition reflects plankton responses to the NAO and the increasing temperature regime, with associations of warm-water copepods expanding to the north.	Beaugrand *et al.*, 2002
Climate Change	North Sea North Atlantic 1958-2002	The study shows severe warming of 0.5°C in southern regions. Warming of waters coincides with phytoplankton abundance decreases which in turn create a cascading effect to zooplankton grazers and higher trophic groups.	Richardson and Schoeman, 2004
Pathogens/ Human health	North Atlantic and North Sea 1958–2011	The increase of environmentally transmitted Vibrio infections is linked to blooms of marine Vibrio, whose presence was genetically determined on CPR samples. The study stipulates rising temperatures could also increase Vibrio outbreak frequency.	Vezzulli *et al.*, 2016
Human Health	Labrador Sea,	Genetic evaluation of archived CPR samples identified the long-term presence	Cesare *et al.*, 2018

	North Atlantic, North Sea 1970-2011	of antibiotic resistance genes in marine plankton.	
Pathogens	Tasman Sea 2009	The pathogen, *Aspergillus sydowii*, was genetically identified from CPR samples after a dust storm event, Fungal cultures and field data of *A. sydowii* had adverse effects on mobility of the coral symbiont, Symbiodinium.	Hallegraeff *et al.*, 2014
Policy and management	Northeast Atlantic 1958-2017	Policy indicators at multiple taxonomic scales were developed to formally assess pelagic habitat biodiversity under the EU Marine Strategy Framework Directive. As a suite, the indicators inform on anthropogenically-driven change as well as changes caused by prevailing environmental conditions.	McQuatters-Gollop et al 2015 McQuatters-Gollop et al 2017 Bedford et al 2018
Eutrophication	North Sea 1958-2004	A new quantitative dataset created by integrating CPR and remotely-sensed chlorophyll data suggested that eutrophication is a local, coastal issue in the North Sea and climate change is the primary driver of increased productivity. Increasing water clarity and higher sea surface temperature has resulted in a longer growing season in coastal waters which are consequently now more sensitive to nutrient input.	McQuatters-Gollop et al 2007
Model assessment	North Atlantic, Australia	As biogeochemical and ecosystem models are increasingly used in marine management, CPR data are being used for model assessment. This is particularly true of zooplankoon data, which are not available from satellites.	Lewis et al. 2006; Skerratt et al. in press
Ecosystem assessments		Plankton indicators from the CPR are used in regional, national and international ecosystem assessments to describe the state and trends of marine systems.	Evans et al., 2016

2.3 Review of the different funding models

Historically, the major challenge facing sustained ocean observing programs is to attract long-term funding (Duarte et al, 2009; Koslow and Couture, 2013). Physical oceanographic components of GOOS have been funded by national governments rather than by international organizations such as the UN or World Bank, and this has also been the case for CPR surveys. CPR surveys have a range of successful funding models, but the most common is some type of funding by national governments through a dedicated program, supplemented by competitive grants and industry collaboration. One successful funding model within Australia has been for the small biological observing community to team up with the physical oceanographic observing community to push for a large and integrated observing system. Thus the Integrated Marine Observing System (IMOS) was born, with ~$US 11 million per year from the Australian Government and $US14 million per year in matching co-investment (Hill et al., 2010; Moltmann, 2011). All platforms, from physical to biological, have benefitted from being part of a larger integrated and coordinated system, allowing more direct lines of communication and influence with government. The disadvantage is that this single funding source means the program is vulnerable to fluctuating Government budgets.

Another successful model has been industry collaboration. Individual routes in some surveys are supported by the oil and gas industry, in proactive collaborations. For example, British Petroleum has funded an AusCPR route across the Great Australian Bight in southern Australia – a region of developing oil and gas interests – to establish environmental baselines and understand ecosystem connectivity. In the North Atlantic, the CPR route from Aberdeen to the Shetland Islands is funded by the oil and gas exploration company Nexen because it passes close to their drilling platform. Arguably the most challenging pot of money to access is that of national competitive grants, but this has provided additional funding for specific hypothesis-driven research such as work on marine fungal blooms (Australian Research Council funding) and viruses in CPR samples (UK Natural Environmental Research Council). The North Pacific CPR Survey has been partially funded by the Exxon Valdez Oil Spill (EVOS) program for the past 16 years. This has provided sustained funding towards a North-South route along the US and Canadian west coasts. Although large-scale environmental disasters are thankfully rare, they do sometimes provide the opportunity for initiating long-term ocean observation. Supplemented by funding from the North Pacific Research Board and the Canadian Government’s Department of Fisheries and Oceans through a consortium the North Pacific Survey has maintained two lengthy transects (including a trans-Pacific route) for 19 years.

It is clear there is no single best way to fund CPR surveys, but having close links with the national research community involved in ocean observation, being responsive to short-term local funding priorities, and partnering with industry have all been fruitful approaches for long-term sustained funding.

2.4 The first CPR-based Ecological Status Reports

The translation of scientific jargon into non-technical language is an important challenge in disseminating scientific results to policy makers. An important driver behind the North Atlantic survey's strategy was to transfer scientific information revealed by CPR data to decision makers in an accessible and useful format. To address this challenge, in the early 2000's the CPR program (Sir Alister Hardy Foundation for Ocean Science Annual Report, 2002) published its first annual Ecological Status Report. The Ecological Status Reports apply an indicator approach to summarize the status of North Atlantic plankton using data and research from the CPR survey. The indicators were initially developed to monitor annual changes in key attributes of planktonic systems with a particular emphasis on indicators that were relevant to evolving UK policy and marine ecosystem management. This strategy of using indicators to clearly communicate the relevance of the CPR was particularly important to the funders of the North Atlantic CPR Survey such as the UK's Department of Environment, Food, and Rural Affairs (Defra). Defra continue to be the major funder of the North Atlantic CPR survey, with CPR data and science integral to informing UK and EU policy (see also policy section, 2.5).

Marine management drivers continue to influence research using CPR Survey data. Management and policy drivers have co-evolved with the survey, from purely a fisheries perspective in the 1940s to a whole ecosystem approach to management in the 21st century (Edwards et al. 2010). This close alignment with management and policy needs and the continued relevance of the CPR survey in providing large-scale evidence of marine ecosystem and anthropogenic changes (Figure 2) is one of the reasons why the North Atlantic CPR Survey has survived for 80 years, when many time-series have not lasted more than a decade (Koslow and Couture, 2013). CPR data (as summary metrics) from several regional surveys have also contributed to the International Group for Marine Ecological Time Series (IGMETS) report. An ongoing effort, this presents an analysis and overview of oceanic trends based on a collection of over 340 in situ marine ecological time series (see https://igmets.net/report), and supplemented with satellite-based spatio-temporal SST and chlorophyll background fields (UNESCO, 2017).

1. Societal drivers

Sustainable economic growth/development
Conservation/ biodiversity
Improved management/ ecosystem approach
Capacity building and technology transfer
Food security - fishing/aquaculture
Environmental quality and health
Energy production

2. Societal pressures

Climate change
Ocean acidification
Extreme weather events
Loss of resources/habitats
Overfishing
Seabed mining
Solid wastes/ marine litter
Pollution/eutrophication
Invasive species
Coastal development

3. Scientific questions

What is the current status of life and biodiversity in the oceans?
How is life in the oceans changing?
What are the natural and anthropogenic drivers of change?
Are HAB events increasing in frequency or spatial location?
Are invasive species increasing?
How does the changing life in the oceans affect ecosystem function (health and services)?

4. Biological phenomena to capture

Phenology
Occurrance of Harmful Algal Blooms (HABs)
Biogeographical shifts
Biodiversity/invasive species
Impact on calcareous organsims
Ecological regime shifts
Ocean productivity
Carbon sequestration

5. Spatial and temporal scale of biological phenomena

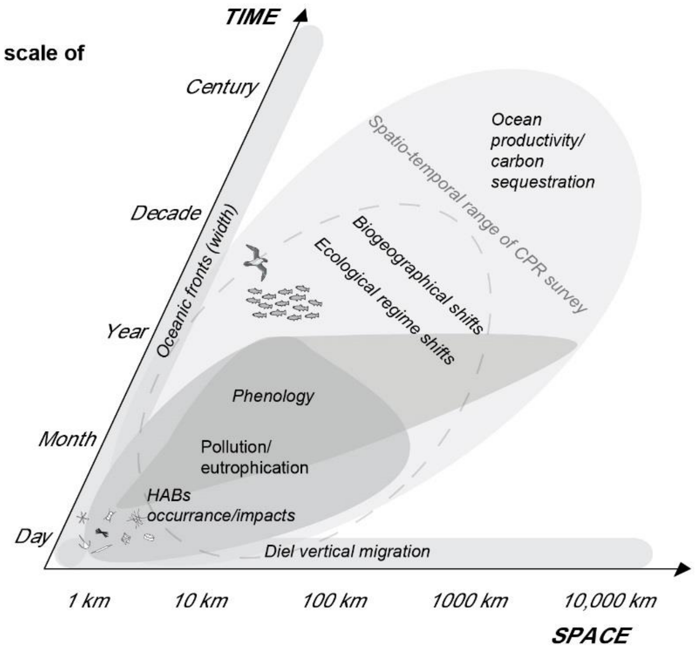

Figure 2: Key societal drivers and pressures on the marine environment and the aspects of plankton dynamics used to capture their impacts on the oceans. The aspects of plankton dynamics addressed occur at multiple spatial and temporal scales and therefore require monitoring by a system, such as the CPR survey network, which operates at similar scales. Based on Edwards et al (2010).

Since the formation of GACS in 2011 the CPR Ecological Status Reports have been used to report on changes by all the CPR regional surveys and give the international community a global perspective on plankton community change (Edwards et al. 2016). These Global Ecological Status Reports maintain the indicator approach, quantifying marine climate change impacts (biogeographical shifts, phenology), changes in ecosystem health (water quality, marine pathogens), changes in ecosystem state (biodiversity, invasive species). They continue to evolve and adopt new indicators, such as ocean acidification and marine microplastics, as new anthropogenic issues emerge (Edwards et al. 2016). Looking to the future, the Global Ecological Status Reports will be used to report metrics to global initiatives such as the EOVs and EBVs for GOOS, the marine component of GEO BON (MBON, Marine Biodiversity Observation Network) and the IPCC. They also support the recent recommendations made by G7 Ministers of Science which include to "Support an enhanced system of ocean assessment through the UN Regular Process for Global Reporting and Assessment of the State of the Marine Environment that would help develop a consensus view on the state of the oceans on a regular timescale. This would in turn enable sustainable management strategies to be developed and implemented across the G7 group and beyond.

2.5 CPR-derived metrics in marine policy

The CPR Survey has co-evolved with policy drivers and through the Survey's development of policy-relevant applied indicators, the CPR has played an integral part in providing relevant, targeted evidence for UK, European and international decision-makers (Edwards et.al. 2010). While CPR data and science have contributed to national ecosystem state assessments in the UK (UKMMAS 2010), USA (e.g. Zador and Yasumiishi, 2017), Canada (Chandler et al, 2017), and Australia (Evans et al. 2016; Richardson et al. 2015), the survey's transboundary nature has enabled it to play a key role in supporting regional policy and management initiatives. The European Union's Marine Strategy Framework Directive (MSFD) takes an ecosystem approach to achieving Good Environmental Status in Europe's regional seas. Uniquely, the CPR survey's pan-European nature supports collection of plankton data at this regional scale. CPR data were, therefore, fundamental to the conception, development, and delivery of two Northeast Atlantic-wide pelagic habitats indicators for the EU's Marine Strategy Framework Directive (OSPAR 2017). The first indicator uses plankton functional groups, or lifeforms, to reveal change in plankton communities while the second uses the Phytoplankton Colour Index and total copepod abundance to assess changes in plankton biomass and abundance (McQuatters-Gollop et al 2015). Both indicators are dependent on the taxonomic data collected by the CPR, with the underlying genus- and species-level information integral to interpreting indicator change to inform a program of management measures in the UK and the OSPAR (Northeast Atlantic Regional Seas Commission) region (McQuatters-Gollop et al 2017).

Another example of a CPR survey's contribution to regional decision-making is through the SCAR Southern Ocean CPR survey (SO-CPR), which is the major zooplankton monitoring program in the Antarctic region and supports the management of Antarctic biodiversity and resources. The SO-CPR survey includes members from Australia, Japan, Germany, New Zealand, France, South Africa, Brazil, Chile, UK, USA and Russia and, as of 2018, has collected over 250,000 nautical miles of zooplankton samples (see Hosie et al. 2014, and the SO-CPR Database metadata record at Australian Antarctic Data Center: https://data.aad.gov.au/metadata/records/AADC-00099). The Survey provides data and advice for use by the general Antarctic research community, notably via the Scientific Committee on Antarctic Research (SCAR) as well as to national and intergovernmental organisations within the Antarctic Treaty System such as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the Committee on Environmental Protection (CEP), the Southern Ocean Observing System (SOOS), the Monitoring program of the Japanese Antarctic Research Expedition (JARE); and the Ministry for Primary Industries project of New Zealand (Robinson et al. 2014).

The extensive spatial scale, multi-decadal time-series, and taxonomic richness of the CPR survey have placed CPR science at the forefront of evidence provision for high-level policy and management advice. Data and research from the survey have informed high profile and strategic global marine assessments such as the IPCC status reports (Pörtner et al 2014) and the United Nations World Ocean Assessment (Innes et al 2016). These international assessments are key to raising the profile of marine ecosystem change and are widely read by those on both sides of the science-policy interface. Integrating and analysing data holistically across the GACS network through a global database with open access to data products would further increase the global impact of CPR data and research.

2.6 Instrumenting the CPR

The CPR surveys are best known for taxonomic plankton data based on microscopy including many phytoplankton, hard-shelled microzooplankton and meso-zooplankton. With the developments in technology that have occurred during its history, most notably in the most recent two decades, there has been a push to add supplemental instrumentation which can also collect oceanographic data. Using the CPR itself as a platform takes full advantage of the sampling infrastructure already in place and can extend the types of data collected, both enhancing the understanding of *in situ* conditions for the plankton communities sampled and maximizing the information that can be gained from having the instrument in the water.

The North Atlantic CPR survey has developed and used a water sampler installed on the CPR body, so far the only automated water sampler that can be deployed on a vessel, external to the ship, whilst still moving. The water samples thus obtained from the English Channel were used to successfully identify planktonic organisms using metagenetic approaches (Stern et al. 2015), revealing a range of unseen diversity not detected by microscopic methods. Additionally, abundance of different size-classes of plankton from flow cytometry analysis of the water samples has been shown to be robust and has revealed new patterns of abundance. Genetic and size-classified biomass data can enhance existing CPR datasets to better model biotic responses to the environment. Alongside a range of “PlankTags” (self-powered instruments that can telemeter data in real-time) and off-the-shelf CTD instruments that measure temperature, salinity and fluorescence, there are a number of biogeochemical sensors that are being tested on the CPR, which can, for example, measure the concentration of carbon dioxide in the seawater.

3. The future

3.1 Synergies with satellite observations

CPR surveys are the program that can provide basin-scale data similar to satellites, but although the temporal scale is far less frequent, CPRs have the advantage of providing species-level taxonomic data. Studies have been carried out that combine CPR and satellite data. Batten et al. (2003b) and Raitsos et al. (2013) used satellite fluorescence data to positively validate the CPR’s Phytoplankton Colour Index, showing that although a simple index, it reveals seasonal and long-term trends in phytoplankton communities. Reve-Lamarche et al (2017) used CPR diatom taxonomic data to associate diatom assemblages with specific spectral anomalies (from PHYSAT) for regions of the English Channel and North Sea. The ability to ground-truth satellite-derived phytoplankton functional groups from different regions around the world sampled with CPRs is an attractive idea. Through collaboration with groups such as the International Ocean-Colour Coordinating Group (IOCCG) this is an area that should be further exploited as a short-term goal.

3.2 Adding value to development of new sensors and platforms

There are other simultaneous efforts to improve and extend the measurement of global plankton. The Scientific Committee on Oceanic Research (SCOR) Working Group 154 “Integration of Plankton-Observing Sensor Systems to Existing Global Sampling Programs”, for example, is reviewing the current inventory of state-of-the-art, validated, plankton-related measurements and off-the-shelf sensors. This review will identify those that could be implemented/installed on board research vessels that are operating on other globally coordinated ocean monitoring networks (Boss et al., 2018) such as the Global Ocean Shipped-Based Hydrographic

Investigations Program (GO-SHIP), http://www.go-ship.org/ and OceanSITES, http://www.oceansites.org/. GOSHIP co-ordinates trans-basin ship surveys that are repeated at least once every 10 years per transect (frequency of sampling varies). OceanSITES co-ordinates full ocean depth time series observations from moorings and repeat ship visits. The WG will also identify the required resources to support those measurements, as well as the data-dissemination infrastructure, and make recommendations. The WGs approach is to minimize the impact on these existing sampling programs that do not yet record plankton by using self-contained instrumentation. GACS data will be invaluable in providing links between such new measurements that may be temporally sparse (GO-SHIP) or spatially restricted (OceanSITES) with nearby well-established CPR time series as well as provide an historical context. CPR data also provide the species-level information that is often missing with more automated approaches. Many of the developing autonomous systems (boats, gliders, subs, underway systems etc.) still require a significant amount of person time to set-up, supervise and recover. Emerging plankton observing technologies are quickly developing but are often not (yet) robust enough to operate at vessel speeds of more than a few knots, or be deployed unattended for thousands of kilometers. The time will come when they are ready to complement traditional observation systems, but collaboration between networks is essential if we are to link existing and new time series to fully recognize the magnitude of pelagic ecosystem changes.

3.3 Instrumentation and analyses achievable in the next decade

The CPR Survey has already developed qualitative and quantitative assays for microbial pathogens, harmful algae and overall plankton diversity that can be used for indicator development of water quality and ecosystem health. Additionally, assays have been developed to genetically capture plankton diversity from CPR samples, despite their preservation in formaldehyde, allowing for greater scope to fully detect pelagic biodiversity (e.g. Vezzulli et al, 2016). Using an improved filter-based capture method will allow the sampling of greater water volumes which will improve detection rates of species, together with metagenetic detection methods, would provide a new automated method for rapidly monitoring diversity.

The CPR Survey currently deploys PlankTags on nine routes within the North Sea, English Channel and in the N.E. Atlantic. The next generation PlankTags will be able to measure a greater suite of biogeochemical proxies (Conductivity, Temperature, Depth, Chl-a fluorescence) and are designed for trans-oceanic deployment. A methodology for “Macro” FlowCam processing is also being developed in order to explore the size and abundance spectra of zooplankton and plastics from CPR samples (or discrete water samples).

Quantifying the distribution and abundance of plastics within the world ocean has become a necessary demand due to increased concern over potential marine and human health impacts. GACS provides a promising platform to achieve the global coverage required and to develop the CPR protocol further for monitoring large and small plastics that get caught within the CPR. As new technologies capable of identifying the composition of microplastics continue to develop (such as the use of hyper-spectral cameras), these may be able to provide a method to retrospectively analyse historic CPR samples and create a more complete picture and consistent monitoring of the global plastics problem.

3.4 Becoming truly global

3.4.1 New surveys to fill gaps

A frequently asked question of members of existing CPR surveys is why you would choose to use a CPR when there are many newer plankton samplers in use and under development? The CPR is the method-of-choice for large-scale plankton surveys, which is what is needed for a global program, and no other device currently available delivers similar information at a similar cost. There are four main reasons:

a. **Cost:** Research vessel costs for large-scale surveys, (e.g. fisheries surveys) are tens of thousands of dollars a day in most countries. Other than a small gratuity to the crew of the merchant ships, CPR sampling is essentially free. Most current plankton samplers are far too fragile for Ships of Opportunity (SOOP) and require dedicated research ship time, making them far too expensive for long-term, large-scale surveys. While autonomous samplers that can cover reasonably large distances are in the pilot phase (e.g. Ohman et al., 2019) there are still significant start-up, maintenance, and data processing costs. The expense of microscopy required to process CPR samples is offset by the longevity of the instrument. With servicing, the CPR can last decades even when it is deployed monthly on SOOPs and it is highly reliable with a success rate of over 90%. It can also easily be moved between vessels since only a towing point needs to be added, there is no alteration of a ship's water intake system. Many modern instruments require regular calibration and technician time. Longevity, reliability and low-cost sampling make the CPR particularly good value-for-money.
b. **Species-level taxonomy:** Most other modern instruments for zooplankton or phytoplankton do not collect species-level taxonomy. No autonomous vehicle can currently identify phytoplankton or zooplankton to species level. Molecular approaches can identify species, but cannot estimate abundance very well, which is relatively easy with microscopy. Molecular approaches also do not distinguish juveniles from adults, and females from males, which is relatively straightforward with microscopy. So, whilst somewhat labour-intensive, the CPR approach provides highly-resolved taxonomic data together with abundances. This is essential for effective biodiversity monitoring.
c. **A physical sample:** Many other plankton sampling techniques, such as the Video Plankton Recorder, Optical Plankton Counter, autonomous vehicles, and Imaging Flow Cytobot, extract a measure of the plankton community, but do not collect a sample. Having a physical sample, especially when archived and curated, allows for many additional analyses such as molecular studies, other biochemical assays (stable isotope measurement for example), as well as analyses of taxa that were not able to be counted at

the time of sample processing. There are very likely new techniques in the future that are not currently imagined that can also be applied to an archive of physical samples.

d. **Comparative analyses:** There is an archive of standardized samples and data from other CPR surveys around the globe for comparison with new results. Wiebe and Benfield (2003) reported that there were then over 150 different zooplankton samplers, with no acknowledged global standard other than the CPR. The ability to place a new regions' results into a global context will increase the ability to understand a local system.

For all of these reasons, the CPR is the only reliable, robust sampler that can be used over large space and long-time scales – and remains the method-of-choice for new plankton surveys.

3.4.2 Designing the sampling.

An important current gap in the GACS vision of having a global CPR survey is the sampling design. One way to envision such a design is to consider the different bioregions of the ocean. There are several classification systems in use that define marine biogeochemical provinces for the pelagic realm in terms of major oceanographic and ecological patterns: (a) the Longhurst Biogeochemical Provinces (BGCP; Longhurst, 2007), (b) the Marine Ecoregions of the World (MEOW; Spalding et al., 2007), (c) the Large Marine Ecosystems (LME for coastal systems; Sherman, 2005) which also includes socio-economic factors in the delineations. Adding ecological complexity and dynamics to such essentially static systems by combining satellite data and in situ observations has been proposed by Kavanaugh et al (2016). However, probably the most currently accepted global bio-regionalisation for the open ocean sampled by the CPR is the "Longhurst Provinces" (first presented in Longhurst, 1998), which are 56 ecoregions based primarily on the major oceanographic regimes (Fig 3). For a global plankton survey, we might aim for a network that covers all of these provinces. Currently, CPRs sample provinces in the North Atlantic (e.g., NECS, NADR, SARC, NASE), the Southern Ocean (SANT, ANTA, NEWZ), around Australia (AUSE, AUSW, TASM), and the North Pacific (CCAL, PSAE, NPPF). These are relatively well sampled, but most of the biogeographical provinces are not sampled (Fig 3), including whole parts of the ocean including the South Pacific (SPSG) and the southern Indian Ocean north of the Southern Ocean (ISSG). Coverage of CPR sampling will continue to grow, but we can stimulate its development by learning from the approach of the physical oceanographic research community to building the global observing system for climate. Beginning in 1997, the community released a blueprint for what the global observing system for ocean climate would look like, detailing the needed temporal and spatial coverage of its major platforms (National Research Council, 1997). Not only was this global system designed through community discussion, but by simulated sampling of temperature and salinity by different platforms from output of hydrographic models. This enabled an objective design of the system, based on the needed precision of the data products. It also provided a target that could be tracked through time – motivating the research community and focusing the attention of funding bodies. For example, the ARGO network, which had only 544 floats in 2002, reached its design specification of 3,000 floats globally in 2007, and has maintained this coverage ever since.

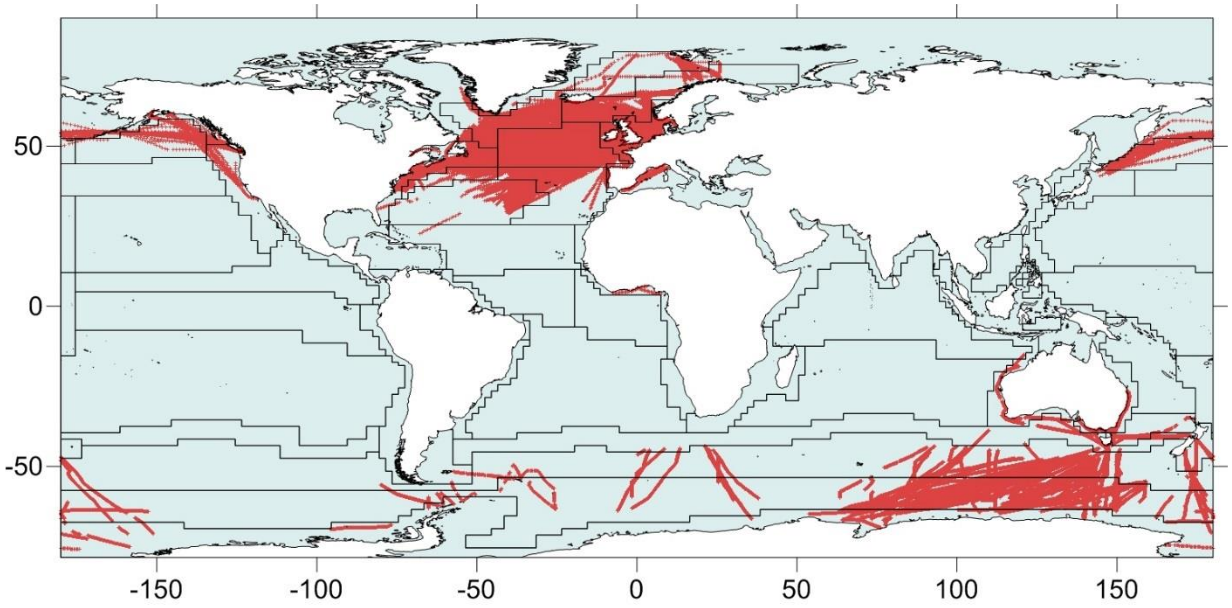

Figure 3. Longhurst Provinces (Flanders Marine Institute, 2009) overlaying CPR sample locations (red). Names of provinces are not shown to avoid clutter but can be found at http://www.marineregions.org/images/boundaries/Longhurst_crop.png

As the physical oceanographic research community used hydrodynamic models that capture the time and space scales of variation in temperature and salinity to design the physical components of GOOS, so the biological oceanographic research community can use global biogeochemical and ecosystem models that incorporate plankton functional types to inform the design of a global plankton observing system. There might be different designs for different objectives. For example, a key objective might be to measure the planktonic component of the carbon cycle, and we could use biogeochemical models to estimate the global coverage and frequency of observations of the critical zooplankton functional groups. Another key objective might be to measure zooplankton productivity supporting fisheries and we could use ecosystem models that include plankton and fish for this purpose. In this way, we could develop a design – or an amalgamation of a few designs – for a global plankton observing system. Different plankton sampling methods (say time series from nets or zooplankton size spectra from LOPC) can be integrated into a global observing program, although they each measure different yet complementary aspects of the zooplankton community, as do the different oceanographic platforms that currently measure temperature and salinity in GOOS. The key might not be the design itself, but that there is a coherent, defensible vision that the international community could own and promote. Such a design would also provide target against which progress could be measured.

3.5 Delivering indicators for global marine policy

The CPR survey's scale is approaching global coverage and so the survey is uniquely placed to inform transboundary, basin-scale, ocean-scale, and even global-scale management efforts. Besides climate change impacts, which are indeed global, many human induced pressures on the marine environment and biodiversity are transboundary across the EEZs of multiple-countries and from EEZs to the high seas as well, e.g. chemical and debris pollution, fisheries, maritime operations and offshore industries. International policy mechanisms should be established to ensure effective conservation and management planning of global marine ecosystems. The need for such a globally integrated mechanism has been further recognized since the Ocean Summit in 2017 where the UN agreed their commitment to maintain and achieve a "healthy ocean". The spatial extent of the Global Alliance of CPR Surveys enables coherence between different projects for assessments contributing to international high-level policy and management initiatives.

Several opportunities for contributions of the CPR to global policy mechanisms exist in UN led agendas such as the 2030 Agenda on Sustainable Development Goals (SGDs; https://www.un.org/sustainabledevelopment/sustainable-development-goals/), Convention of Biological Diversity (CBD) post-2020 global biodiversity framework (Convention on Biological Diversity, 2017), and the conservation and sustainable use of marine biological diversity Beyond Boundaries of National Jurisdiction (BBNJ; https://www.un.org/bbnj/). For SDG14: Life Below Water, CPR data can provide scientific evidence useful in development of global indicators to report the achievement for the Goal 14.1 on pollution, 14.2 on ecosystem-based approaches, 14.3 on ocean acidification, and 14.5 on marine protected areas. Such indicators could be developed and assessed at the regional or basin scale and reported through national mechanisms, enabling direct comparability between seas and national waters and allowing examination of change in a global context. Plankton information including the CPR data are currently not used in the global indicator suites of the current CBD framework or Aichi Targets despite the fact that the CPR's scientific quality and data coverage could exceed the requirement of these indicators (Chiba et al, 2018). This issue may be solved in the post-2020 framework in which a more harmonized collaboration of different UN organizations, such as IOC-GOOS and UNEP, will be expected.

It is worth noting that both in the SDGs and CBD many of the established or proposed global indicators are to indicate the "response" of society, while the development of robust "state" indicators to indicate the status of the ecosystem and biodiversity, and which are needed to fill the gap of the indicator suites particularly in the marine realm, have not yet been specified. One way to promote this will be by establishing protocols that streamline GOOS EOVs to global indicators. Robust indicators will be developed by coupling plankton EOVs and physical and biogeochemical EOVs (part of the GOOS 2030 strategy, in prep.). This will also strengthen the current Framework for Ocean Observing scheme of global ocean observation (Lindstrom, 2012), which has not yet identified the explicit methodology/strategy in feedback of the observation outcome (data) to policy.

Finally, global CPR data can provide scientific evidence useful for negotiating BBNJ where a lack of biodiversity data in the High Seas makes assessment of ecosystems in the High Seas difficult (United Nations, 2017), and has been one of the obstacles for establishment of the internationally agreed (Wright et al, 2016), effective conservation and management policy of BBNJ.

Conclusion

"Locally Strong, Globally Connected" is the rationale that underpins GACS and it remains the best way to develop a global plankton diversity monitoring network. The decade since OceanObs 2009 has seen dramatic changes in the coverage of CPR surveys, collaborative studies and in the degree to which the data are applied to marine resource management policies. As the biological focus of the GOOS matures during the next decade, and with the UN Decade of Ocean Science for Sustainable Development (2021-2030) about to start, the importance of extending GACS and realising its full potential could not be greater, nor more timely. A global network of CPR surveys has been initiated. What is needed now is a coordinated approach; to fill gaps in current coverage of large ocean tracts, integrate with other plankton sampling programs that operate in regions not appropriate for CPRs, ground-truth emerging technologies and satellite observations, and integrate with other Essential Ocean Variables to build an efficient global observing program for the open ocean.

Acknowledgments

The authors are grateful to the past and present volunteer ships, their officers and crews, that have towed CPRs and contributed to the GACS dataset. Comments made by three anonymous reviewers and the Editor have considerably improved the manuscript.

Author Contributions Statement

Significant pieces of text were contributed by: SB (throughout) AMcG, and SC for the policy sections, ME for the ESR section, RA for Table 1, AR for sections 2.3 and 3.4. Shorter contributions were made by GG, RJ, JK, PK, EM, CO, KR, KT, HV and WW to sections throughout.

Conflict of Interest Statement

There are no personal, professional or financial relationships for any authors that could result in any conflict of interest.

References

Batten, S.D. and Burkill, P.H. (2010) The Continuous Plankton Recorder: towards a global perspective. Journal of Plankton Research 2010 32: 1619-1621

Batten, S. D., Allen, R. J. S. and Wotton, C. O. M. (1998) 'The effects of the Sea Empress oil spill on the plankton of the Southern Irish Sea', Marine Pollution Bulletin. Pergamon, 36(10), pp. 764–774. doi: 10.1016/S0025-326X(98)00039-3.

Batten, S.D., Walne, A.W., Edwards, M. and Groom, S. B. (2003b) Phytoplankton biomass from Continuous Plankton Recorder data: An assessment of the phytoplankton colour index. Journal of Plankton Research 25, 697-702.

Batten, S.D., Clarke, R.A., Flinkman, J., Hays, G.C., John, E.H., John, A.W.G., Jonas, T.J., Lindley, J.A., Stevens, D.P., and Walne, A.W. (2003a) CPR sampling – The technical background, materials and methods, consistency and comparability. Progress in Oceanography, 58, 193-215.

Batten, S. D., Ruggerone, G. T. and Ortiz, I. (2018) 'Pink Salmon induce a trophic cascade in plankton populations in the southern Bering Sea and around the Aleutian Islands', Fisheries Oceanography, (March). doi: 10.1111/fog.12276.

Beaugrand, G., Brander, K. M., Lindley, J. A., Souissi, S. and Reid, P. C. (2003) 'Plankton effect on cod recruitment in the North Sea', Nature, 426(2001), pp. 661–664. doi: 10.1038/nature02164.

Beaugrand, G., Reid, P. C., Ibanez, F., Lindley, A. J. and Edwards, M. (2002) 'Reorganization of North Atlantic marine copepod biodiversity and climate', Science, 296(May), pp. 1692–1694.

Bedford, J., Johns, D., Greenstreet, S. and McQuatters-Gollop, A., (2018). Plankton as prevailing conditions: a surveillance role for plankton indicators within the Marine Strategy Framework Directive. Marine Policy, 89: 109-115.

Boalch, G. T. and Harbour, D. S. (1977) 'Unusual diatom off the coast of south-west England and its effect on fishing', Nature. Nature Publishing Group, 269(5630), pp. 687–688. doi: 10.1038/269687a0.

Boss, E. , Waite, A. , Muller‐Karger, F. , Yamazaki, H. , Wanninkhof, R. , Uitz, J. , Thomalla, S. , Sosik, H. , Sloyan, B. , Richardson, A. , Miloslavich, P. , Karstensen, J. , Grégori, G. , Fennel, K. , Claustre, H. , Cornejo, M. , Berman‐Frank, I. , Batten, S. and Acinas, S. (2018), Beyond Chlorophyll Fluorescence: The Time is Right to Expand Biological Measurements in Ocean Observing Programs. Limnology and Oceanography Bulletin, 27: 89-90. doi:10.1002/lob.10243

Brewin, R.J.W., Sathyendranath, S., Hirata, T., Lavender, S.J., Barciela, R., and Hardman-Mountford, N.J. (2010) A three-component model of phytoplankton size class for the Atlantic Ocean. Ecological Modelling 221, 1472–1483.

Cesare, A. Di, Petrin, S., Fontaneto, D., Losasso, C., Eckert, E. M., Tassistro, G., Borello, A., Ricci, A., Wilson, W. H., Pruzzo, C. and Vezzulli, L. (2018) 'ddPCR applied on archived Continuous Plankton Recorder samples reveals long-term occurrence of class 1 integrons and a sulphonamide resistance gene in marine plankton communities'. doi: 10.1111/1758-2229.12665.

Chandler, P.C., King, S.A., and Boldt, J. (Eds.). (2017) State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3225: 243 + vi p.

Chiba, S., Batten, S., Martin, C.S., Ivory, S., Miloslavich, P., and Weatherdon, L.V. (2018) Zooplankton monitoring to contribute towards addressing global biodiversity conservation challenges, Journal of Plankton Research, https://doi.org/10.1093/plankt/fby030

Convention on Biological Diversity (2017) Recommendation adopted by the subsidiary body on science, technical and technological advice. CBD/SBSTTA/REC/XXI/1, pp. 5. https://www.cbd.int/ doc/recommendations/sbstta-21/sbstta-21-rec-01-en.pdf.

Duarte, C.M., Conley, D.J., Carstensen, J. and Sánchez-Camacho, M., (2009) Return to Neverland: Shifting Baselines Affect Eutrophication Restoration Targets. Estuaries and Coasts, 32: 29-36.

Edwards, M., John, A. W. G., Johns, D. G. and Reid, P. C. (2001) Case history and persistence of the non-indigenous diatom Coscinodiscus wailesii in the north-east Atlantic. Journal of the Marine Biological Association of the UK, 81(02), pp. 207–211. doi: 10.1017/S0025315401003654.

Edwards, M., Johns, D. G., Richardson, A. J., Leterme, S. C., Svendsen, E. and Richardson, a. J. (2006) Regional climate change and harmful algal blooms in the northeast Atlantic. Limnology and Oceanography, 51(2), pp. 820–829. doi: 10.4319/lo.2006.51.2.0820.

Edwards, M., Beaugrand, G., Hays, G.C., Koslow, J.A. & Richardson, A.J., (2010) Multi-decadal oceanic ecological datasets and their application in marine policy and management. Trends in Ecology and Evolution,25: 602-610.

Evans K, Bax NJ, Smith DC (2016) Australia State of the Environment. Marine Environment. 226 pp.

Flanders Marine Institute (2009). Longhurst Provinces. Available online at http://www.marineregions.org/. Consulted on 2018-10-26.

Griffiths, H.J., Danis, B.,David, B., De Broyer, C., d'Udekem d'Acoz, C., Grant, S., Gutt, J., Held, C., Hosie, G., Huettmann, F., Koubbi, P., Post, A., Raymond, B., Ropert-Coudert, Y., Van de Putte, A.P. (2018) Antarctic Environments Portal DOI: 10.18124/D4F04J

Gutt, J., Constable, A., Cummings, V., Hosie, G., McIntyre, T., Mintenbeck, K., Murray, A., Peck, L., Ropert-Coudert, Y., Saba, G.K., Schofield, O., Schloss, I., Stefels, J., Takahashi, K. (2016) Antarctic Environments Portal DOI: 10.18124/D46P48

Hallegraeff, G., Coman, F., Davies, C., Hayashi, A., Mcleod, D., Slotwinski, A., Whittock, L. and Richardson, A. J. (2014) 'Australian Dust Storm Associated with Extensive Aspergillus sydowii Fungal "Bloom" in Coastal Waters'. doi: 10.1128/AEM.04118-13.

Hill K, Moltmann T, Proctor R, Allen S (2010) The Australian Integrated Marine Observing System: delivering data streams to address national and international research priorities, Mar Tech Soc J 44: 65–72. doi:10.403/MTSJ.44.6.13.

Hinder, S. L., Gravenor, M. B., Edwards, M., Ostle, C., Bodger, O. G., Lee, P. L. M., Walne, A. W. and Hays, G. C. (2014) Multi-decadal range changes vs. thermal adaptation for north east Atlantic oceanic copepods in the face of climate change. Global Change Biology, 20(1), pp. 140–146. doi: 10.1111/gcb.12387.

Hinder, S. L., Gravenor, M. B., Edwards, M., Ostle, C., Bodger, O. G., Lee, P. L. M., Walne, A. W. and Hays, G. C. (2014) Multi-decadal range changes vs. thermal adaptation for north east Atlantic oceanic copepods in the face of climate change. Global Change Biology. Wiley/Blackwell (10.1111), 20(1), pp. 140–146. doi: 10.1111/gcb.12387.

Hosie, G., Mormede, S., Kitchener, J., Takahashi, K., Raymond, B. (2014) Near Surface Zooplankton Communities. In: De Broyer, C., Koubbi, P., Griffiths, H., Danis, B., David, B., Grant, S., Gutt, J., Held, C., Hosie, G., Huetmann, F., Post, A., Raymond, B., Roper-Coudert, Y., Van de Putte, A., (eds) The CAML/SCAR-MarBIN Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, UK.

Innes L., Simcock, A (Joint Coordinators), Amanuel Yoanes Ajawin, Angel C. Alcala, Patricio Bernal, Hilconida P. Calumpong, Peyman Eghtesadi Araghi, Sean O. Green, Peter Harris, Osman Keh Kamara, Kunio Kohata, Enrique Marschoff, Georg Martin, Beatrice Padovani Ferreira, Chul Park, Rolph Antoine Payet, Jake Rice, Andrew Rosenberg, Renison Ruwa, Joshua T. Tuhumwire, Saskia Van Gaever, Juying Wang, Jan Marcin Węsławski. (2016) The First Global Integrated Marine Assessment: World Ocean Assessment 1. United Nations. http://www.un.org/Depts/los/global_reporting/WOA_RegProcess.htm

Kavanaugh, M.T., Oliver, M.J., Chavez, F.P., Letelier, R.M., Muller-Karger, F.E., and Doney, S.C. (2016) Seascapes as a new vernacular for pelagic ocean monitoring, management and conservation, ICES Journal of Marine Science, 73, 839–1850, https://doi.org/10.1093/icesjms/fsw086

Koslow, J. A. (1983) Zooplankton Community Structure in the North Sea and Northeast Atlantic: Development and Test of a Biological Model. Canadian Journal of Fisheries and Aquatic Sciences, 40(11). doi: 10.1139/f83-222.

Koslow, J.A. and Couture, J., (2013) Ocean sciences: Follow the fish. Nature online, 502: 163-164.

Lewis K, Allen JI, Richardson AJ, Holt JT (2006) Error quantification of a high resolution coupled hydrodynamic-ecosystem coastal-ocean model: Part 3, validation with Continuous Plankton Recorder data. Journal of Marine Systems 63: 209-224

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., & Glover, L. K. (2012) A framework for ocean observing. By the task team for an Integrated Framework for Sustained Ocean Observing. Paris, France: UNESCO.

Longhurst, A.R. (1998) Ecological Geography of the Sea. Academic Press, San Diego. 397p

Longhurst, A.R. 2007. Ecological geography of the sea. London: Academic Press.

McQuatters-Gollop, A., Edwards, M., Helaouët, P., Johns, D.G., Owens, N.J.P., Raitsos, D.E., Schroeder, D., Skinner, J. and Stern, R.F., (2015) The Continuous Plankton Recorder survey: how can long-term phytoplankton datasets deliver Good Environmental Status? Estuarine, Coastal and Shelf Science, 162: 88-97.

McQuatters-Gollop, A., Johns, David G., Bresnan, E., Skinner, J., Rombouts, I., Stern, R.F., Aubert, A., Johansen, M., and Knights, A., (2017) From microscope to management: the critical value of plankton taxonomy to marine policy and biodiversity conservation. Marine Policy, 83: 1-10

McQuatters-Gollop, A., Raitsos, D.E., Edwards, M., Pradhan, Y., Mee, L.D., Lavender, S.J. and Attrill, M.J., (2007) A long-term chlorophyll dataset reveals regime shift in North Sea phytoplankton biomass unconnected to nutrient levels. Limnology and Oceanography, 52: 635-648.

Miesner, A. K. and Payne, M. R. (2018) Oceanographic variability shapes the spawning distribution of blue whiting (Micromesistius poutassou)’, Fisheries Oceanography, p. In Press. doi: 10.1111/fog.12382.

Miloslavich P, Bax NJ, Simmons SE, et al. (2018) Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. Glob. Change Biol. 2018;24:2416–2433. https://doi.org/10.1111/gcb.14108

Moltmann T (2011) Ocean observing systems a national perspective from Australia. IEEE 10.1109/GEOSS-XLII.2011.6105429

National Research Council. (1997). The Global Ocean Observing System: Users, Benefits, and Priorities. Washington, DC: The National Academies Press. https://doi.org/10.17226/5580.

OSPAR, (2017) Intermediate Assessment 2017. Available at: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017.

Ohman, M. D., Davis, R. E., Sherman, J. T., Grindley, K. R., Whitmore, B. M., Nickels, C. F. and Ellen, J. S. (2019) Zooglider: An autonomous vehicle for optical and acoustic sensing of zooplankton. Limnol Oceanogr Methods, 17: 69-86. doi:10.1002/lom3.10301

Planque, B. and Fromentin, J. M. (1996) Calanus and environment in the eastern North Atlantic .1. Spatial and temporal patterns of *C-finmarchicus* and *C-helgolandicus*. Marine Ecology-Progress Series, 134(1–3), pp. 101–109. doi: 10.3354/meps134101.

Pörtner, H.-O., Karl, D.M., Boyd, P.W., Cheung, W.W.L., Lluch-Cota, S.E., Nojiri, Y., Schmidt, D.N. and Zavialov, P.O., (2014) Ocean systems. In: C.B. Field et al. (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,, pp. 411-484.

Raitsos, D.E., Walne, A., Lavender, S.J., Licandro, P., Reid, P.C., and Edwards, M. (2013) A 60-year ocean colour data set from the continuous plankton recorder, Journal of Plankton Research, 35, 158–164, https://doi.org/10.1093/plankt/fbs079

Reid, P. C., Battle, E. J. V., Batten, S. D. and Brander, K. M. (2000) Impacts of fisheries on plankton community structure. ICES Journal of Marine Science, 57(3), pp. 495–502. doi: 10.1006/jmsc.2000.0740.

Rêve-Lamarche, A.-H., Séverine, A., Racault, M.-F., Dessailly, D., Guiselin, N., Jamet, C., Vantrepotte, V., and Beaugrand, G. (2017) Estimation of the Potential Detection of Diatom Assemblages Based on Ocean Color Radiance Anomalies in the North Sea. Frontiers in Marine Science, 4; 408 DOI=10.3389/fmars.2017.00408

Richardson, A. J. and Schoeman, D. S. (2004) Climate impact on plankton ecosystems in the northeast Atlantic. Science, 305(August), pp. 1609–1612.

Richardson A.J., Eriksen, R.S. & Rochester W. (2015) Plankton 2015: State of Australia’s oceans. CSIRO Report. ISBN 978-1-4863-0565-0.

Robinson, K.V., Pinkerton, M.H., Hall, J.A., Hosie, G.W., (2014) Continuous Plankton Recorder Time Series. New Zealand Aquatic Environment and Biodiversity Report No. 128. Ministry for Primary Industries, Wellington. 74 pp. ISBN 978-0-478-43226-8

Schartup, A. T., Qureshi, A., Dassuncao, C., Thackray, C. P., Harding, G. and Sunderland, E. M. (2018) A Model for Methylmercury Uptake and Trophic Transfer by Marine Plankton. Environmental Science & Technology. American Chemical Society, 52(2), pp. 654–662. doi: 10.1021/acs.est.7b03821.

Schminke, H.K. (2007) Entomology for the copepodologist. Journal of Plankton Research 29: i149-i162.

Skerratt J.H., Mongin M., Wild-Allen K.A., Baird M.E., Robson B.J., Schaffelke B., Soja-Wozniak M., Margvelashvili N., Davies C.H., Richardson A.J., Steven A.D.L. (in press) Plankton and nutrient dynamics on the Great Barrier Reef: Skill assessment and analysis of the eReefs biogeochemical model. Journal of Marine Systems.

Sherman, K. 2005. The large marine ecosystem approach for assessment and management of ocean coastal waters. In T. Hennessey, & J. Sutinen (Eds.), Sustaining large marine ecosystems: the human dimension (pp. 3–16). Amsterdam: Elsevier.

Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdaña, Z. A., Finlayson, M.A.X., Lourie, S. A. 2007. Marine ecoregions of the World: A bioregionalization of coastal and shelf areas. BioScience, 57, 573–583.

Stevens, D., Richardson, A. and Reid, P. (2006) Continuous Plankton Recorder database: evolution, current uses and future directions, Marine Ecology Progress Series, 316, pp. 247–255. doi: 10.3354/meps316247.

Stern, R. F. Picard, K. T., Hamilton, K. M., Walne, A., Tarran, G. A., Mills, D., McQuatters-Gollop, A., Edwards, M. (2015) Novel lineage patterns from an automated water sampler to probe marine microbial biodiversity with ships of opportunity. Prog. Oceanogr.137,409–420.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Steven, J., John, A. W. G., Mcgonigle, D., Russell, A. E., Science, S., Series, N. and May, N. (2004) Lost at Sea: Where Is All the Plastic? Science, 304(5672), p. 838.

UNESCO (2017) What are Marine Ecological Time Series telling us about the ocean? A status report, pp. 171–190. Ed. by T. D. O'Brien, L. Lorenzoni, K. Isensee, and L. Valdés. IOC-UNESCO, IOC Technical Series, No. 129. 297 pp.

United Kingdom Marine Monitoring and Assessment Strategy, (2010) Charting Progress 2: The state of UK seas. An overview. Defra, London, UK.

United Nations (2017). The First Global Integrated Marine Assessment. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108186148

United Nations General Assembly (2017) Resolution adopted by the General Assembly on 6 July 2017. A/RES/71/313. Work of the Statistical Committion pertaining to the 2030 Agenda for Sustainable Development. https://undocs.org/A/RES/71/313

Vezzulli, L., Grande, C., Reid, P. C., Hélaouët, P., Edwards, M., Höfle, M. G., Brettar, I., Colwell, R. R. and Pruzzo, C. (2016) Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. Proceedings of the National Academy of Sciences, 113(34), pp. E5062–E5071. doi: 10.1073/pnas.1609157113.

Wiebe, P. H., and M. C. Benfield. (2003) From the Hensen net toward four-dimensional biological oceanography. Prog. Oceanogr. 56: 7–136. doi:10.1016/S0079-6611(02)00140-4

Wright, G., Rochette, J., Druel, E., & Gjerde, K. (2016) The long and winding road continues: Towards a new agreement on high seas governance. IDDRI Study, (1).

Zador, S., and Yasumiishi, E., 2017. Ecosystem Considerations (2017) Status of the Gulf of Alaska Marine Ecosystem, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501