OCEAN Challenge

The Challenger Society for Marine Science

Sailing in the virtual wake of HMS *Challenger*
The CoML and the CPR – so much more to be discovered
The complexities of coral conservation • Overturning ocean
Pioneering marine chemists remembered

Vol.18, Summer 2011

OCEAN Challenge

The Challenger Society for Marine Science

Volume 18, Summer 2011

The views expressed in *Ocean Challenge* are those of the authors and do not necessarily reflect those of the Challenger Society or the Editor.

SCOPE AND AIMS

Ocean Challenge aims to keep its readers up to date with what is happening in oceanography in the UK and the rest of Europe. By covering the whole range of marine-related sciences in an accessible style it should be valuable both to specialist oceanographers who wish to broaden their knowledge of marine sciences, and to informed lay persons who are concerned about the oceanic environment.

Ocean Challenge is sent automatically to members of the Challenger Society. For more information about the Society, or for queries concerning individual subscriptions to *Ocean Challenge*, please see the Challenger Society website (**www.challenger-society.org.uk**) or contact the Executive Secretary of the Society (see inside back cover).

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OCEAN Challenge

The Challenger Society for Marine Science

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of marine science through research and education.

To encourage two way collaboration between the marine science research base and industry/ commerce.

To disseminate knowledge of marine science with a view to encouraging a wider interest in the study of the seas and an awareness of the need for their proper management.

To contribute to public debate and government policy on the development of marine science.

The Society aims to achieve these objectives through a range of activities:

Holding regular scientific meetings covering all aspects of marine science.

Setting up specialist groups in different disciplines to provide a forum for discussion.

Publishing news of the activities of the Society and of the world of marine science.

Membership provides the following benefits:

An opportunity to attend, at reduced rates, the biennial UK Marine Science Conference and a range of other scientific meetings supported by the Society. Funding support may be available.

Receipt of our electronic newsletter *Challenger Wave* which carries topical marine science news, and information about jobs, conferences, meetings, courses and seminars.

The Challenger Society website is
www.challenger-society.org.uk

MEMBERSHIP SUBSCRIPTIONS

The subscription for 2011 costs £40 (£20.00 for students in the UK only). If you would like to join the Society or obtain further information, contact the Executive Secretary, Challenger Society for Marine Science, Room 251/20, National Oceanography Centre, Southampton, Waterfront Campus, Empress Dock, Southampton SO14 3ZH, UK;
Fax: +44(0)23-80-596149 **jxj@noc.soton.ac.uk**

ADVICE TO AUTHORS

Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. If at all possible, they should be well illustrated. Copy may be sent electronically.

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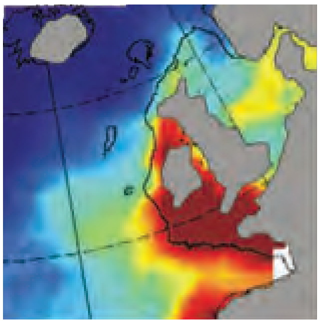

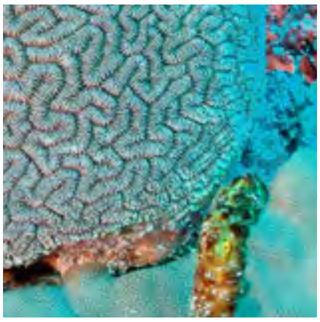

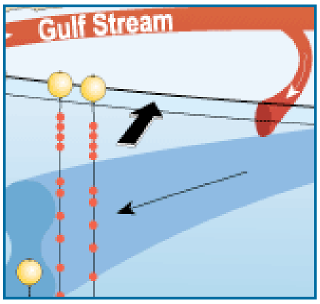

Most of the diagrams were drawn by The ArtWorks.

The cover was designed by Ann Aldred Associates.

Cover photograph © Ann Aldred

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Message from the Editor

Welcome to the latest issue of Ocean Challenge. *Featuring prominently in this issue is the science behind determining and protecting the ocean's biological diversity – including the future scope for learning more from data collected by the Continuous Plankton Recorder, designed by Alister Hardy more than 80 years ago, and from the Census of Marine Life, whose first phase was concluded in 2010. Two articles consider how best to protect corals, and the second of these, about the Chagos Archipelago, is followed by responses that have been submitted since the article was 'early online' at the Challenger website. If you would like to know more about this topic, see below for details of a meeting to be held in November.*

In addition, we have a feature article by Eleanor Frajka-WIlliams on the RAPID project, and information about how to get involved in an unusual activity relating to the Challenger Expedition, which may appeal to many Challenger Society members.

Challenger Society News

News from the Challenger SocietyAGM

The 2011 AGM was held during the AMBIO Special Interest Group meeting in Plymouth, and provided an overview of the Society's activities over the past year. We also waved goodbye to four Council Members: Carol Robinson, Claire Hughes, Elaine McDonagh and Andrew Davies. Clare Postle-thwaite and Hugh Venables were elected as new members of Council, Jaco Baas was elected as new Honorary Secretary and Hilary Kennedy as President Elect. The Society's Annual Report and minutes of the meeting will shortly be published online at www.challenger-society.org.uk

The Maritime Crossword Challenge

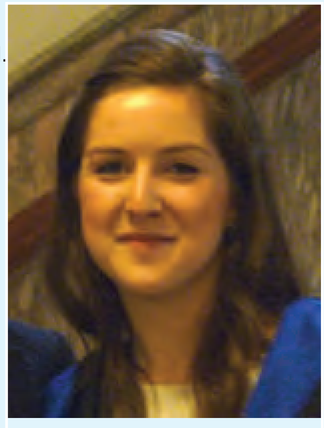
So far, no-one has sent in a correct solution to the crossword on p.56 of the last issue. It is now on the Challenger Society website. The prize of a £40 book voucher awaits collection!

Interested in the Chagos Archipelago?

On 24 November there is a joint one-day meeting in London of the Linnean Society and the Chagos Conservation Trust, starting at 10.00. The registration fee is £30 (£15 for students) which includes lunch and tea and coffee breaks. For more information, please contact: Events, The Linnean Society of London, Burlington House, Piccadilly, London, W1J 0BF; Tel. +44 (0)20 7434 4479 events@linnean.org To register please visit www.linnean.org and go to the 'upcoming events' page to download your registration form.

Co-culturing sea bass and sea cucumbers

We are proud to announce that the winner of this year's Tripartite IMarEST /CSMS/SUT award is Camilla MacDonald. Camilla is studying Marine Biology at the School of Marine Science and Technology, University of Newcastle upon Tyne. The title of her dissertation was 'European seabass (*Dicentrarchus labrax*) waste as a food source for the sea cucumber *Holothuria forskali*'. The primary aim of Camilla's dissertation was to investigate if the European sea bass could be co-cultured with the previously uncultured cotton-spinner sea cucumber in an Integrated Multi-Trophic Aquaculture (IMTA) system.



Specifically, Camilla examined the specific growth rates of the sea cucumber in response to being fed on waste from the seabass. The aquaculture approach examined by Camilla has the potential to alleviate problems associated with monoculture systems and reduces the impact of aquaculture on the surrounding environment. In addition, the outcomes have the potential to demonstrate the capacity to culture a previously uncultured species that could contribute to food security by providing additional economically valuable secondary aquaculture to an existing commercially cultured aquaculture species. Camilla's dissertation was well written and addressed important questions related to commercial aquaculture and food security.

Claire Mahaffey
University of Liverpool

__Left__ One of Camilla's sea cucumbers. The mouth, at one end of the ~ 20 cm body, is surrounded by small tentacles which the sea cucumber uses to collect sediment from which it extracts nutrients.

The Tripartite Prize is worth up to £500 for the winner. Application forms may be obtained from Heads of Departments, or direct from the websites of the Challenger Society, IMarEST and SUT.

Seeing the Future in Oceans Past

A warning from the IPSO Ocean Experts

Alex David Rogers, Charles Sheppard and Daniel Laffoley

In April, in the leafy grounds of Somerville College, University of Oxford, there was a gathering of ocean experts, including scientists with a range of different interests, policymakers, lawmakers, funders and communicators. The meeting, initiated by the International Programme on the State of the Ocean (IPSO), in partnership with the International Union for Conservation of Nature (IUCN), and its World Commission on Protected Areas (WCPA), was aimed at generating a synoptic picture of all human stressors on the oceans and in particular to examine the consequences of multiple or different impacts acting in concert. It was a fascinating meeting as world authorities on aspects of marine science were present and all could claim some level of expertise in the subject. However, at several points during presentations a silence fell across the meeting room and a speaker would be asked to repeat something that had surprised members of the audience. Over the course of three days we realised that although we were experts in our various fields, the high degree of focus demanded by modern research had, in some cases, blinded us to the broader aspects of marine and climate science. After three days of brainstorming, the findings of the meeting were subsequently drawn together in a synoptic report: *International Earth System Expert Workshop on Ocean Stresses and Impacts Summary Report*.

Some of the findings of the meeting were not surprising, for example, the extremely poor state of many of the world's fish stocks as a result of overexploitation. However, what *was* surprising was the extent of the profound changes in the structure of marine ecosystems that such impacts are causing and the consequences in terms of weakening resilience to other stressors. In other words, many human stressors are interacting with each other to generate what we termed 'negatively synergistic effects', where the net effects of two or more stressors are not simply a sum of the two but multiplied up to a larger overall impact. One example given was that corals are more prone to bleaching at high temperature in the conditions of lowered pH that may be expected as a result of ocean acidification. There is also the combination of overfishing, climate change and eutrophication acting in concert to make ecosystems more vulnerable to outbreaks of plagues of gelatinous organisms, or to drive those systems to create harmful algal blooms. The absorption of pollutants onto microplastic particles (making the poisons more available to marine organisms that ingest these fragments of human debris) was also raised, along with the effects of a new generation of endocrine-disrupting chemicals.

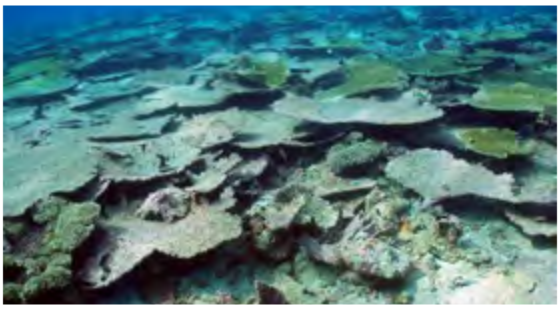
Another major finding of the meeting is the speed and extent of the changes now observed in marine ecosystems. Melting of the Arctic summer sea-ice is already proceeding at or worse than the worst-case IPCC scenarios, and rates of melting of the Greenland ice cap and Antarctic icesheets are accelerating. Dead zones and shifts in communities of marine organisms are occurring over large areas of the oceans, and things many of us did not expect to see for some time – such as changes in the distribution of water masses – are now being observed in the North Atlantic.

Perhaps the most worrying part of the meeting related to the rate of CO_2 emissions into the atmosphere and the corresponding decrease in ocean pH. Here, only a view on oceans past could really place into context the enormous experiment which we are subjecting planet Earth to. The nearest analogue for what we are seeing now are changes that occurred around the Palaeocene–Eocene Thermal Maximum (PETM), except it is estimated that we are releasing CO_2 at an order of magnitude faster than the rates estimated for that ancient event. The PETM was globally significant (though not one of the 'big five' extinctions) and it would appear that we are setting the scene for a globally significant extinction event in the oceans. It is notable that whereas past IUCN Red List assessments of marine species indicated that overexploitation was the main threat of extinction, the recent Red List assessment on reef corals now identifies threats associated with climate change as more significant.

There was, however, a message of hope from the meeting. We still retain much of the world's marine biodiversity and have a better idea than ever before about what is causing losses and changes to marine ecosystems. Another positive is that we have the knowledge and understanding to solve many of the problems we face. Underlying many of these issues are the questions of a large human population, poor governance and management of the oceans and, surprisingly, a lack of communication. During the meeting, Labour MP the Rt Hon. Barry Gardiner pointed out that as scientists we already had enough information to make the case for change in policy. The message simply was not getting out to the public or to the right policymakers. It was a rather shocking moment of truth for many of those in the meeting room.

The Workshop Report was launched in June at the United Nations Open Ended Informal Consultative Process (UNICPOLOS) and created a storm in the global media. Several of the experts from the workshop provided web-based interviews about the meeting and numerous radio, newspaper and television interviews. The report has now been raised by Members of Parliament at international meetings and also by US Senator Sheldon Whitehouse at a speech in the Senate. We are now writing a peer-reviewed volume setting out the findings of the meeting, as well as organising a follow-up workshop and activities aimed at engaging not only policymakers but also the wider public in all that matters in the oceans.

The Report of the Ocean Expert Workshop, along with video interviews and previous IPSO workshop reports, are available at http:www.stateoftheocean.org.



Corals face the 'double whammy' of climate change and ocean acidification. *The photo shows the aftermath of a mass mortality of table corals.*
(By courtesy of Charles Sheppard)

Alex David Rogers is the Scientific Director of the International Programme on the State of the Ocean. **Charles Sheppard** is Professor of Biological Sciences at.the University of Warwick. **Daniel Laffoley** is at the International Union for Conservation of Nature. Alex Rogers@zoo.ox.ac.uk
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The SAHFOS Continuous Plankton Recorder

A bright future built on 80 years of experience

Kelvin Boot

2011 sees the 80th anniversary of the Continuous Plankton Recorder (CPR) Survey operated from the UK by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) in Plymouth. During its eight decades of operation the survey has sampled just short of 6 million miles of ocean from 298 ships of opportunity, and while other marine technologies have come and gone the CPR remains 'fit for purpose' and has altered little during its lifetime. It is this consistency of sampling which ensures that the longest dataset of any marine biodiversity survey in the world is as relevant today as it was back in 1931 when it was established. Indeed, it is a testimony to the technical skill and foresight of its inventor, Sir Alister Hardy, that the basic mechanism remains unchanged, yet robust and reliable.

The idea first came to Hardy early in his career when illness of a senior colleague elevated him to the position of naturalist aboard the research trawler *George Bligh*. Good weather and an early completion of the research tasks gave Hardy his second piece of luck, allowing him time to indulge his own theories. He now had the luxury of staying on station, rather than taking samples and steaming on to the next station. Thus he made more samples throughout a 24-hour period, acknowledging that although the ship was on station, it was likely to have drifted slightly. The haul of post-larval herring, which were his target, fluctuated dramatically throughout the day, such that the difference between the smallest and greatest numbers at the one station was greater than that between the smallest and greatest numbers from any of the stations on the rest of the cruise! Hardy considered that this demonstrated just how patchy plankton and young fish can be, and that the single-point surveys gathered on the *George Bligh*, and on previous similar cruises, were valueless. He wrote later in the classic 'New Naturalist' volume, *The Open Sea; its natural history: Part 1, the World of Plankton*:

'It was this experience on the George Bligh in 1922 which led me to devise what I have called the continuous plankton recorder: a torpedo-shaped machine which can be towed like a tow-net but at full speed behind any ordinary ship. It automatically samples the plankton mile by mile as it goes along.

It is fitted with planes which, when it is towed, make it dive below the surface and ride at a depth which may be determined by the amount of towing cable veered out. As it is towed along, the sea enters the machine by a small hole in front, passes through it in a tunnel and out at the back; the cross section of the tunnel increases in size so that the water entering it at some 12 knots is slowed down as it passes along, to about a tenth of its original velocity. The plankton is sieved out from the slowed down water stream by a continuously moving banding of silk gauze which is slowly wound across the tunnel and into a storage tank of preservative fluid by a system of rollers geared to a propeller on the outside of the machine. As the gauze leaves the tunnel by a narrow slit it is joined by a second fabric which winds on with it on to the storage spool in the formalin tank. This prevents the plankton from being rubbed from one part of the roll to another.'

Hardy first deployed the CPR to obtain a continuous line of sampling through the sea on the 1925–27 *Discovery* Antarctic expedition, but it was not until he became Professor at University College, Hull (later University of Hull) that he contemplated a redesigned, smaller version of the CPR for use on merchant vessels running from Hull across the North Sea. Thus the Continuous Plankton Recorder Survey was born, with its first official tow taking place in September 1931, when the CPR was involved in its one and only accident as Hardy broke a finger during its launch; since then the safety record has remained clean. The CPR's work began in earnest in 1932 with a five-year survey over the southern half of the North Sea, on routes between Hull and the Skaggerak, Hamburg and Rotterdam. Hardy was quick to acknowledge the support from his University, but most importantly 'the generous cooperation of a number of different shipping companies and their officers'; an acknowledgement vigorously echoed by the CPR Survey's present Director, Professor Peter Burkill.

The first sortie into the Atlantic took place in 1939 from Europe to Iceland. As Peter Burkill observes: *'This was a major step forward with the realisation that one could look at plankton in the open ocean at scales that had not been thought of before. It was in a time before remote sensing; now we live in an era where one can remote sense phytoplankton when there is little cloud cover, but even today if one wants to carry out major surveys, or look at zooplankton there is only one way to do it and that's with the CPR.'*

1958 saw the survey expand into the western Atlantic through funding from the USA Office of Naval Research. This resulted in the compilation of a new *CPR Atlas*, showing the distribution of 255 taxa. Following a move to Leith under the auspices of the Scottish Marine

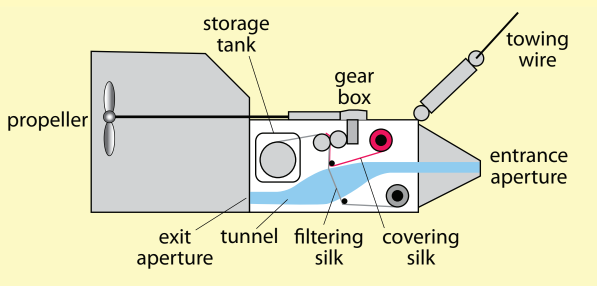
Robust and reliable, and still 'fit for purpose'

Alister Hardy deploying one of the first CPRs

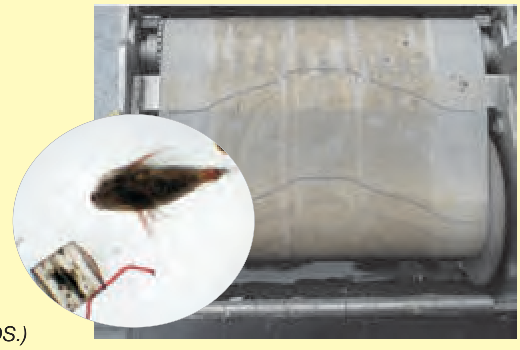
The CPR was originally made of gunmetal (phosphor bronze), but since 1997 has been made of stainless steel. The nose cone is filled with lead. The CPR is towed on a 10 mm diameter wire rope at a depth of about 10 m. It has been operated successfully at speeds of up to 25 knots, and its robust design allows deployment in rough seas. Successful tows have been continued in winds up to storm force 11.

A brilliant design that has stood the test of time

The CPR works by filtering plankton from the water on a moving filter band of silk (270 μm mesh size). The filter silk band is wound through the CPR on rollers turned by gears, which are powered by a propelller. A self-contained cartridge (*below right*) is loaded with the filtering silk at the laboratory and placed inside the CPR prior to deployment (ships may be supplied with several cassettes to increase the sampling range). A cross-section of the CPR, with cartridge in place, is shown below. See opposite for Hardy's own description of how the filtering system worked.



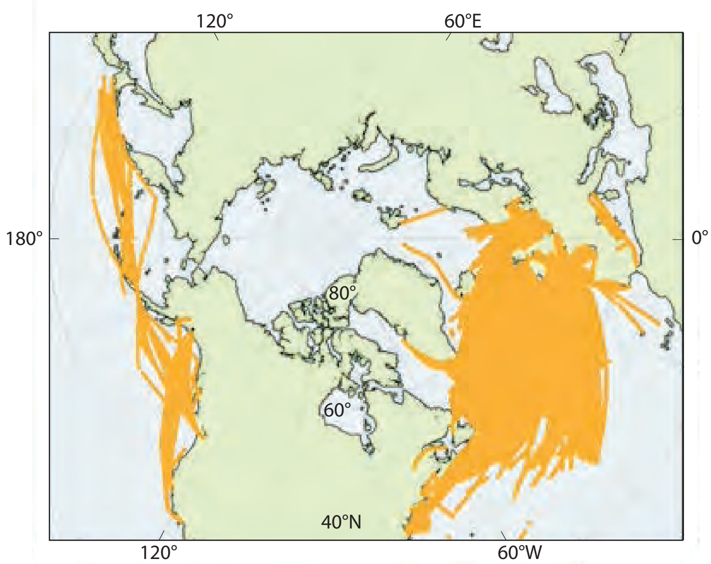
On return to the laboratory, the silk is removed from the cassette and divided into samples (or 'blocks') each representing 10 nautical miles of towing. The plankton on these samples are then analysed according to standard procedures.



Before cutting, the colour of the silk is compared to a colour chart and given a 'green-ness' value of 0 (no greenness), 1 (very pale green), 2 (pale green) or 6.5 (green). This is a subjective analysis, with arbitrary values being allocated, but it can be the first indication that a phytoplankton bloom has been detected. *Continued in box overleaf*

(Technical details here and in box overleaf are by courtesy of SAHFOS.)

Biological Association (SMBA), and later to the Oceanographic Laboratory in Edinburgh, the Survey continued to expand in both expertise and geographical coverage, moving outside of its core area of the North Atlantic, even venturing into the Gulf of Mexico. Eventually, the Survey moved to the Institute for Marine Environmental Research (IMER) in Plymouth (later Plymouth Marine Laboratory) only to face impending closure and the cessation of its long-term data-collection, some years later in 1988. Following massive global support for its work, in 1990 a charitable foundation, the Sir Alister Hardy Foundation for Ocean Science, was established to operate the Survey into the future.



CPRs have been used extensively in the North Atlantic for more than half a century, and in the eastern and northern Pacific over the last 10 years; more recently they have been deployed in the European Arctic

The Future

The beauty of the CPR is that the technology is simple – it's the interpretation of that data that is hugely important. Many areas of marine science require the use of research ships that cost tens of thousands of pounds each day to run. One of the characteristics of the CPR programme is that Merchant Navy ships – ships of opportunity – are used, meaning that the basic costs are of the order of one or two hundred pounds per sample. But SAHFOS has ambitions for the future which embrace the possibility of building on the existing technology. Peter Burkill takes up the theme:

We call this part of our future strategy Going Complete. It accepts the existing CPR is inherently conservative but that much more information can be collected. One of the things we realised some years ago was that we should be looking at molecular taxonomy as well as the conventional microscope-based technology – we've worked closely with colleagues at the University of Plymouth and the Marine Biological Association and now we've appointed someone to do our own molecular taxonomy, in house. That recognises that by using molecular techniques we can analyse all sorts of plankton – for example, jellyfish, which get smashed up by the CPR. From the remaining small strands you can actually identify what they are, and get some reasonable idea of the numbers.

And we can go back in time! We are just in the process of establishing how these molecular techniques can be made operational through the back collection of samples – that is just going to be hugely important.

One of the other things we've done is – working closely with CEFAS and Defra – to get a water sampler, and we now have the capability of collecting water as well as the plankton that's retained on the silk. One of the great advantages of collecting water is that there is no selective filtration of the organisms, so we could look at viruses, fungi and bacteria as well as smaller planktonic organisms that escape the net. This is particularly important for our interests in Harmful Algal Blooms (HABs) with which there are huge economic consequences. So this looking at HABs is a major focus *for the molecular work, bringing together two new techniques there – molecular taxonomy and the water sampler.*

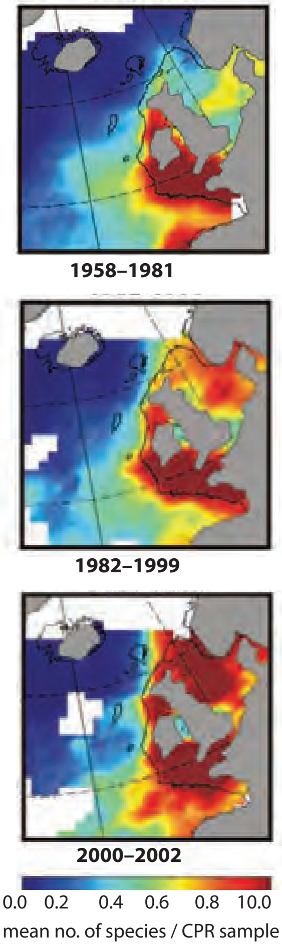
We have capitalised on work in the medical field. We use blood bags – they are sterile and a small motor opens the blood bag to allow it to sample and then the motor shuts the blood bag, capturing water samples in the order of 100 ml. The idea is that by using a fluorometer, which is a device for looking at chlorophyll fluorescence in the water, we can set the blood bags up to sample over the physical course of a bloom. You can use the fluorometer to open the blood bags once the concentration has got to a particular height. The next stage is to add flow cytometers; within the next five years we would hope to see these deployed in the CPR. At the moment the CPR is such that we have to bring it back to the lab for analysis; if we could get data in real time that would be a major force in terms of sampling.'

Going Global is the second thrust of SAHFOS's future strategy. The Survey began in the North Sea, moved into the Atlantic and about ten years ago started working in the Pacific. Now CPRs are being used in the European Arctic and there are plans to move even wider afield into areas relevant to global change processes. It may be climate, fisheries, pollution or eutrophication – there are a lot of drivers, and SAHFOS has an interest in understanding them all. Indeed, a recent discovery showed that a marine phytoplankter had moved through the newly opened North-West Passage to recolonise North Atlantic waters after an absence of 800 000 years. Changes in the distribution of phytoplankton could have serious consequences as they play such a key role in the biological pump that draws atmospheric CO_2 into the sea, as well as being the foundation for most ocean food chains. It is now essential to gain ocean-basin wide data, and as Burkill points out:

'In order to get that broad coverage we need a global perspective, and at SAHFOS we have 35 people so there's no way we can actually achieve that, so in the last few years we've had a very active programme to encourage other countries to start doing the work that we have been doing*. In fact, we are working very closely with South Africa, Namibia and Angola at the moment, helping them to get a survey going on the Benguelan system – that again is a very sensitive system, is hugely productive and so of great economic consequence to those countries. To aid this process we will be hosting a workshop in September whereby scientists from 12 different countries across the world, including New Zealand, Australia, Japan, China, South Africa, Namibia, Angola and the US and Canada will be discussing how we can produce a global alliance of CPR surveys. This will recognise that each of these surveys, run by these countries, will become eventually autonomous. Almost all of them have actually been started by SAHFOS in Plymouth over the period of the last 10–15 years or so.*

But it's my vision that we should be pooling our capabilities and recognising that in order to gain a global vision, it's in everybody's interest to continue working together, giving a little in order to gain a lot.

At the heart of this – and it's probably some years away – is the idea that we should come up with a global database reflecting the phytoplankton and zooplankton biodiversity globally. In order to do that, what we need is to agree common standards and formats and who has the intellectual property rights and so on. That's what we'll be discussing. It's extraordinarily exciting.'



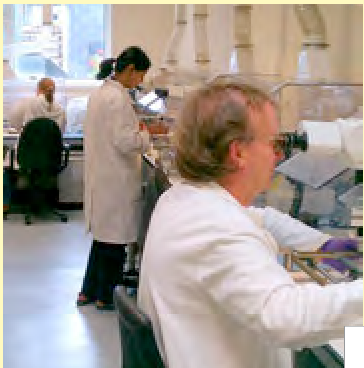
The change in the distribution of species of pseudo-oceanic copepods off north-west Europe between 1958 and 2002 – an example of the information that has been acquired using the CPR

From Beaugrand et al. *(2002) Science* **31**, 1692–4. *Courtesy of SAHFOS*

As the longest running biodiversity survey in the world, the CPR has become something of a gold standard, a perfect example of how long-term datasets can come into their own, and how the data can be used to address different problems or challenges, from fish stocks to climate change. The CPR is also an example of how collaborations can pay huge dividends. The key to SAHFOS's success is not simply the genius of an idea spawned decades ago, or the robustness of the mechanism, nor even the dedicated team that analyses the miles of silk from every tow, or the good will and enthusiasm of the 'ships of opportunity', their owners, masters and crew. It is the way these have all been brought together to answer questions over the last 80 years, while being ready and willing to face the challenges of the future.

Kelvin Boot is a Science Communicator working with SAHFOS. The article was written using additional materials supplied by SAHFOS. kelota@pml.ac.uk

Scrupulous lab work and the help of 'ships of opportunity' are both essential to the success of the CPR



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A sub-sample of each silk block (about 0.001 of the whole sample) is examined under high-power magnification to identify and count the phytoplankton species present. Another sub-sample analysis for small zooplankton is then carried out under a lower magnification, where all individuals seen in a traverse of the silk are identified and counted. (This sub-sample is about 0.02 of the whole sample.) In the last part of the analysis procedure, all zooplankton larger than about 2 mm are identified and counted from the whole sample. They are spotted by eye, but identified under the microscope. This is known as 'zooplankton eye count analysis'.

Marine Biodiversity: Where, What and Why?

Uncovering the patterns of diversity in the ocean

Tom Webb

The great fanfare that greeted the publication back in October 2010 of the first Census of Marine Life (CoML) (www.coml.org) was wholly justified. This is a landmark achievement in the study of marine biodiversity, and the Census has done a great deal to convey the sheer excitement of basic exploration that the marine environment still offers. Certainly, I have been charmed by photos of some of the weird and wonderful organisms discovered over the 10 years of concerted exploration of the depths and breadths of the oceans (Figure 1). But as a biodiversity scientist and macroecologist what excites me most about CoML is its vast potential as a source of data.

In particular, we now have an unprecedented opportunity to address fundamental questions in biodiversity science thanks to a concerted effort to collate and disseminate existing information on the geographic distributions of marine species. Perhaps the most profound of these questions is: *Where are you?* Or, to put it another way: *How is marine biodiversity distributed throughout the seas?* It is only once we have described such patterns that we can begin to try to explain them, and a promising way of doing this is to ask of the different species making up a community, *What do you do?* Using information on the biological characteristics of each species, we can begin to understand their particular ecological roles within the ecosystem. Finally, we can apply this understanding of marine macroecology to addressing some of the questions currently being asked by policy makers and society more generally, regarding for instance how best to weigh the needs of biodiversity against human requirements for food and energy. In other words we can ask of biodiversity: *Why do you matter?*

Figure 1 *The Census of Marine Life was responsible for discovering an estimated 6200 new species, including this new species of* Polybrachia *(a polychaete) from a mud volcano in the Gulf of Cadiz. Many of these new species may turn out to be widespread in the world's oceans, which highlights how little we still know about the distributions and basic biological characteristics of most marine organisms.*

(By courtesy of Ana Hilario, University of Aveiro, Portugal)

Where are you?

Knowing where a species occurs is fundamental to understanding its ecology. If all of the world's oceans had been sampled to an equal (and sufficient) extent, simply plotting on a map those locations at which a species had been recorded would tell us a great deal. We could immediately separate tropical from temperate, coastal from oceanic, cosmopolitan (i.e. widespread) from endemic, and (providing our map included a third dimension) benthic from pelagic species. Combining such information across numerous species provides the raw material for a 'macroecological' analysis of marine biodiversity, i.e. a study of patterns that only emerge at large spatial scales – for example, gradients in species diversity from the Equator to the poles, or from the shallows to the abyss.

Of course, it's highly unlikely that all the world's oceans have been equally and sufficiently sampled. In fact, *none* of the large marine ecosystems of the world has been sampled at a sufficient intensity to allow us to reliably assume that the absence of a species from a survey reflects a true absence in the environment. And it is certain that sampling of the marine realm has not been equal everywhere.

Although marine biologists would have been able to tell you this before the CoML (based on personal experience and general 'gut feelings'), we can now show systematically such spatial biases in sampling intensity. Largely, we can do this thanks to the Ocean Biogeographic Information System (OBIS, www.iobisl.org), which serves as the biogeographic arm of CoML. OBIS collates, standardises, and delivers to any interested party a vast collection of marine biodiversity 'records' – with each record representing the occurrence of a given taxon at a given geographic location. Currently, OBIS holds some 31 million records, for over 140 000 taxa (and – an invaluable service – each taxonomic name is checked against a standard taxonomy).

This phenomenal coverage means that we can start to identify those parts of the world that are particularly well – or particularly poorly – covered by OBIS. For instance, the 'state of knowledge' of marine biodiversity has recently been shown to be very variable across different regions of the world. Unsurprisingly, regions such as the Mediterranean and Atlantic Europe are typically far better known than the tropical East Pacific and tropical West Africa.

There is another yawning gap in our knowledge, which was revealed by an analysis I undertook together with Edward Vanden Berghe from OBIS and Ron O'Dor from CoML. Rather than split the world's oceans into geographic regions, we instead considered how OBIS records were distributed with respect to water depth. Specifically, we used only those records (about 7 million at the time) which reported the depth at which the specimen had been recorded. By comparing the depths of these records with the depth of the sea-bed at the same location, we were able to plot the distribution of recorded marine biodiversity through the water column (Figure 2).

The most striking pattern to emerge from this analysis is that the shallow waters of the continental shelf, which cover only about 10% of the area of the global oceans, together contribute more than 50% of the records stored in OBIS. But there is another important pattern too: when the deep seas *have* been sampled, this has typically occurred either in the surface waters, or on the sea-bed. The deep pelagic ocean, by a large margin the largest habitat on Earth and home to countless animals which never experience a hard surface, remains virtually untouched by biodiversity surveys.

So, while the CoML has compiled sufficient data on certain groups to enable global-scale analyses of their biogeography (examples include tunas, sharks, cetaceans and corals), it has also revealed the depths of our ignorance of other taxa, and of entire habitats such as the vast deep pelagic ocean. There are two positive sides to this newly-revealed ignorance. First, once you know what it is that you don't know, you

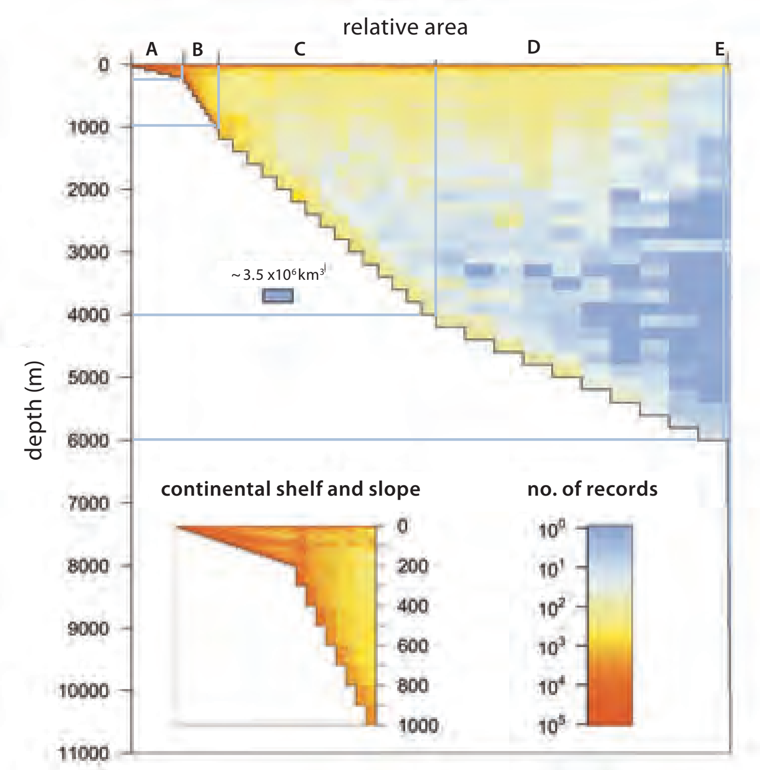


***Figure 2** **Global distribution within the water column of recorded marine biodiversity.** The horizontal axis splits the oceans into five zones on the basis of depth (A: continental shelf, B: continental slope/mesopelagic; C: continental slope and rise/bathypelagic; D: abyssal plain, E: hadal zone), with the width of each zone on this axis proportional to its global surface area. The vertical axis is ocean depth, on a linear scale. This means that area on the graph is proportional to volume of ocean. For instance, in the deep sea each cell of 200 m depth represents ~3.5 x 10^6 km^3 (see cell for scale). The number of records in each cell (each unique combination of sample and bottom depth) is standardised to the volume of water represented by that cell, and then log_{10}-transformed. The inset shows in greater detail the continental shelf and slope, where the majority of records are found. (From Webb* et al., *2010)*

can target future efforts to fill the gaps in your knowledge. And in the meantime, if you know about biases in your datasets, you can take steps to control for them in any analysis you may wish to conduct.

What do you do?

It is clear from the above examples that we remain a long way from knowing with any certainty where in the world the majority of marine species occur. Nonetheless, in some regions this basic knowledge is probably sufficiently complete to allow us to document macroecological patterns in more detail. The seas around the UK, for example, have been subject to exploration for scientific and commercial reasons for many decades, and so our basic knowledge of what occurs where is reasonably good. This means that we can start to ask more detailed questions such as, *Which kind of species occur where*, or *What kind of biological characteristics enable species to become widespread?*

Such questions require basic biological information across the range of species co-occurring across a set of sites. As we are discovering in an ongoing project, such information is, however, surprisingly scarce – even for relatively common British marine species. Even if we restrict ourselves to the macrofauna (organisms larger than about 1 mm or so), there is simply no documented knowledge of the ecology and behaviour of a large proportion of invertebrates. Basic information that would be required to construct simple models of population dynamics – things like the number of offspring produced in a year, or the typical lifespan of an individual – is incredibly scarce. We don't even know how big some species get.

With Lizzie Tyler at the University of Sheffield, and Paul Somerfield from Plymouth Marine Laboratory, I was able to collate sufficient information for nearly 600 species of bottom-dwelling invertebrates from the North Sea to perform some analyses. The results are intriguing, if rather subtle (Figure 3). Species which can grow to large sizes show a different kind of spatial distribution from smaller species: they tend to be more evenly distributed across their range, whereas small species are more clustered. We suspect that other traits – for instance, the presence or absence of a planktonic larval stage – will also influence spatial distribution. But before powerful statistical tests are possible, we need to obtain data on traits like this for more species.

Results like these suggest that a species' biology can affect its geographic distribution within a relatively uniform environment such as the North Sea, in a predictable way. This means that the macroecology of an entire assemblage will depend on the relative proportions of species displaying different collections of biological traits. In other words, in order to understand large-scale patterns in marine biodiversity, we really need to have some idea of what it is that the component species actually *do*.

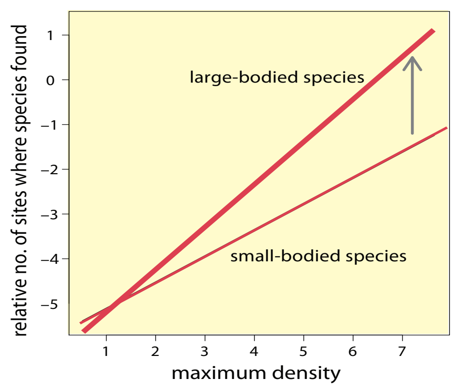
Unfortunately, an extended analysis of nearly 1000 species of common UK marine fish and invertebrates has shown that this basic knowledge simply doesn't exist for the majority of species. And there is little place in today's hectic research environment for the kind of basic natural history observation required to supply such information. It might be possible to fill some gaps by using statistical models which compare patterns of trait variation with the evolutionary relationships between species, but whether such models can cope with a situation in which the gaps outnumber the data remains to be tested.

Why do you matter?

It is tempting, when gazing out to sea, to imagine it as some vast, untouched wilderness. And yet with a little investigation the effects of human activity can be seen throughout the world's oceans, from the ravaged sea-beds of the heavily-trawled European continental shelf, to the accumulation of plastic debris in the central Pacific and the Deepwater Horizon oil spill, to bleached corals in the Indian Ocean.

Our dependence on marine ecosystems is also becoming ever clearer. Efforts to put a monetary value on the ecosystem services provided by the marine environment remain controversial, but it is undeniable that we benefit enormously from the seas – for example, from the food and raw materials that we extract, the carbon they absorb, and the pleasure that we derive from activities as varied as whale watching, wind-

***Figure 3** **Spatial distribution of North Sea benthic species varies with body size.** For a given population density (individuals m^{-2}) large-bodied species occur at more sites than small-bodied species, indicating a less aggregated distribution. (Simplified from Webb* et al., *2009)*



surfing and whispering sweet nothings in front of the setting sun.

The maintenance of these ecosystem services is at the forefront of efforts to mitigate some of the consequences of past and ongoing human activities. For instance, plans for the creation of substantial Marine Protected Areas, as well as for enormous offshore wind farms, are well advanced in the UK. The importance of aquaculture (which brings its own set of environnmental problems) is increasing as fast as wild fisheries are depleted. Vast geoegineering schemes no longer seem quite so far-fetched. Between unintentional environmental change, and concerted efforts to reverse such change, all we can say for certain about biodiversity is that it will be affected somehow.

What also remains very unclear is the role that biodiversity plays in the provision of this suite of services. The ecosystem is composed of communities of coexisting species, and it follows that all the different biological traits expressed by different species will interact to produce ecosystem-level properties – including those functions that we value highly. From this, it becomes clear that understanding which species occur where, and how they live their lives – which biological traits they possess – is fundamental both to understanding the functioning of ecosystems, and predicting the consequences of different kinds of environmental change.

These are the kinds of questions that are motivating an increasing number of marine ecologists. If my contributions appear somewhat negative – with too much emphasis placed on what we *don't* know, rather than what we *do* – then I apologise. But in my defence, I am firmly of the opinion that it is better to know what we don't know, and to take steps to incorporate this uncertainty into our models and predictions (if we're not in a position to fill in gaps in our knowledge), than it is to simply sweep the issue under the carpet. To paraphrase an accidental philosopher, better a known unknown than an unknown unknown.

Further reading

Costello, M.J., M. Coll, R. Danovaro, P. Halpin, H. Ojaveer and P. Miloslavich (2010) A census of marine biodiversity knowledge, resources, and future challenges. *PLoS ONE*, 5 e12110 http://dx.plos.org/10.1371/journal.pone.0012110

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Webb, T.J. E. Vanden Berghe and R. O'Dor (2010) Biodiversity's big wet secret: the global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. *PLoS ONE*, **5**, e10223 http://dx.plos.org/10.1371/journal.pone.0010223

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The growing problem of 'green tides'

The mass blooms of seaweeds known as 'green tides' have returned yet again to Chinese coastal waters. In July 2011, the North China Sea Marine Forecasting Centre reported that green seaweeds could be found over 20 000 km^2 of the Yellow Sea, with a quarter of that area completely covered. A 'green tide' in China's marginal seas was first reported in 2007, and just a year later the area of ocean impacted by the bloom was ~40 000 km^2, making it the world's largest. This was very unfortunate timing as the green tide algae spread to the Beijing Olympics sailing venue adjacent to Qingdao. The authorities were left with no other option but to bring in 10 000 workers to clear away one million tonnes of algae from coastal waters and the shore in advance of the Olympic regatta.

China is by no means alone in its green tide problem. The incidence of these blooms has increased worldwide over the last 40 years, with annual green tides reported along the coastlines of countries including Denmark, the Netherlands, France and the UK. The culprits are ephemeral, fast-growing pale green seaweeds of the class Ulvophycae, such as *Enteromorpha* and *Ulva,* whose filamentous or sheet-like morphology allows rapid nutrient uptake. The high nutrient levels that permit these algae to reach the high biomass associated with green tides result from agricultural fertiliser application and other farming activities, waste disposal and aquaculture. Green tides are unsightly and when suspended in the water column interfere with recreational and fishing activities, but they also have a much more sinister side. When the seaweeds are washed up on the shoreline they start to decompose; the decomposition consumes oxygen and creates anoxic zones resulting in the production of the potentially lethal gas hydrogen sulphide (H_2S). Emissions of H_2S have been blamed for animal fatalities in areas impacted by 'green tides', including the deaths of 33 wild boar on the beaches of Saint-Brieuc in northern Brittany in July 2011, and they could potentially pose a threat to human health. This, together with other ecological implications – including wiping out indigenous flora and blanketing important bird-feeding grounds – means that green tides really are a problem.

The quandary is whether to try to reduce the severity and/or frequency of effects of the blooms or to manage (and possibly utilise) the huge amounts of biomass that they produce. Reducing the blooms would require reducing nutrient inputs to coastal areas by altering agricultural practices and adjusting the ways in which wastes are dealt with. One management idea is to allow the blooms to occur, 'mopping up' excess nutrients, and then to harvest the seaweeds for use as an agricultural fertiliser or in the production of animal feed. With increasing frequency of these events worldwide, understanding the environmental implications of green tides, and working out ways to deal with them, will remain high on the research and management agenda.

Claire Hughes
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The maintenance of these ecosystem services is at the forefront of efforts to mitigate some of the consequences of past and ongoing human activities. For instance, plans for the creation of substantial Marine Protected Areas, as well as for enormous offshore wind farms, are well advanced in the UK. The importance of aquaculture (which brings its own set of environnmental problems) is increasing as fast as wild fisheries are depleted. Vast geoegineering schemes no longer seem quite so far-fetched. Between unintentional environmental change, and concerted efforts to reverse such change, all we can say for certain about biodiversity is that it will be affected somehow.

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Sailing in the virtual wake of HMS Challenger

Documenting her ports of call, then and now

Gary McLeod

30th December, off the coast of Manila: *The weather during the run-up to Christmas day was frostier than anything experienced since we left. Things on board have therefore been much quieter, but it has certainly not dampened any spirits or crushed the hopes of what we are aiming to achieve. We have been at sea now for over a year, and only a quarter of our way through our voyage. We may still have much to do, but the scale of our task is not lost on me, as I strive to keep things moving along.*

Naturally the crew come-and-go, but this has been a maritime habit for some 200 years, and is to be expected. Nevertheless, the voyage remains firm in its ultimate objective, and we have sighted land in Gibraltar, Bermuda, Cape Town, and Manila, occasionally even sighting two places at once. In between sightings however, it seems as though our next heading is both somewhere and everywhere. This is because we are not sailing where others have sailed. We are sailing in what is arguably the sixth ocean: the World Wide Web.

Our ship is not a vessel made of wood or steel. It is a website that is made of 'code'. However, unlike most websites, which are virtual presentations of companies and individuals, this website is a Social Networking Site (SNS) and it allows people to join as members, and then communicate with other members wherever they are located in the world. It is this ability to communicate and share experiences on a global scale in one virtual location that makes the aim of our voyage feasible: to re-photograph the voyage of HMS *Challenger*.

While its scientific objectives are often revisited, its cultural position is less thought about, particularly from the perspective of an artist/photographer such as myself. The voyage produced five hundred official photographs taken during the three-and-a-half year voyage by three photographers (the first absconded in South Africa, and the second vanished in Hong Kong). In addition to the three photographers, there was the artist J.J. Wild, who was not only responsible for rendering the voyage in pencil and watercolour but was also secretary to Professor Charles Wyville Thomson. As can be seen from various diaries and albums of the crew, Wild and the official photographers had competition. Several of the officers were useful with a pencil and brush, and others (including the on-board scientists) had some knowledge of cameras. Considering that some of the shipmates also formed their own band (apparently woeful at first), HMS *Challenger* could arguably be considered in its totality as one very creative ship. Despite all the creativity, the various roles of the creative people on board overlapped and are difficult to distinguish, and the current climate for photographers, artists and designers is not that dissimilar. The one visual constant throughout *Challenger*'s voyage was the official photographs, which have been collated together by Eileen Brunton for the Natural History Museum.* Whilst in Japan, I came across the *Challenger* photographs that were taken there. Living near some of the places they visited, I wondered what the locations looked like today.

Undeterred by such vague captions as 'River Bed, Kobe' and 'Shinto Temple, Yokohama', I formed a small team and sought out the locations using local libraries, old visual references, and contempo-

*Brunton, E.V. (1994) *The Challenger Expedition 1872–1876: a visual index* The Natural History Museum, London: *Historical Studies in the Life and Earth Sciences* No. 2. ISBN: 0-565-0-1139-1. doi: 10.3366/anh.1995.22.1.139

***Challenger's* port of call in the Philippines**
Upper *'Bye-Street Canal, Manila' (1874–75) taken during the voyage of HMS* Challenger.
Lower *'San Fernando Bridge Canal, Manila' taken by Kathy Ponce in 2010 during the voyage of SNS Challenger.*

rary visual tools such as Photoshop and Google Earth. The search led us through local and national history, and when rephotographing the locations from the same position as the original photographer, I was deeply moved. This experience later directly influenced a series of photographs of the Japanese landscape that shared *Challenger*'s photographic objective. I had felt part of the voyage, albeit 130 years after the ship left, and this prompted me to wonder if it were possible to revisit every location photographed during the voyage of HMS *Challenger*. Moreover, I wondered what that would mean for me, and I sought to get institutional backing for what I wanted to do: build a team of online volunteers and collectively rephotograph the voyage of HMS *Challenger.*

A year on, our ship, SNS *Challenger* (the project's website), has welcomed over 3861 visitors from over 230 locations around the world. Amongst these are the 114 people who have become members of our 'crew'. It is through their efforts that we have managed to so far rephotograph 47 of the original *Challenger* images. In addition, like the crew of HMS *Challenger*, our crew has written about their experiences, which can all be found 'on board' (in the blog post section of the website). The adventures to be had in identifying the locations in the original pictures and going out into the landscape to rephotograph them have led some to reminisce about their childhood, and caused others to want to learn more about a place that they felt they knew. Connecting with history in such a way can lead to inspiration and creative pursuits, and SNS *Challenger* is the place to share them.

As an artist/photographer, I feel no concern about the ubiquity of digital cameras and amateur photography, but I am keen to help others to expand their creativite scope. Therefore my role aboard SNS *Challenger* is currently one of facilitating the transfer of information, supporting the crew and steering the ship – in the horizonless seascape of the Internet. J.J. Wild's role abroad HMS *Challenger* was as artist and secretary, and there are some who believe that he may have helped others to improve their skills and abilities onboard, but then got on with his paperwork in the evening. Only through lasting the voyage, will I know the outcome of my role, but my hope is that we will have collectively at least re-photographed the voyage in its entirety.

If you are interested in helping us with our voyage, SNS *Challenger* is looking for people to join the crew. Anyone is eligible to join the project, although it helps to be visiting one or some of the locations visited by HMS *Challenger*, as well as to have access to the Internet and a digital camera of some description. For a full list of destinations on our voyage, as well as more information on how to help, please visit SNS *Challenger* at: http://www.snschallenger.org or email me at: gary@snschallenger.org

Gary McLeod is the Captain, Navigator and Secretary of SNS *Challenger*, which forms part of his practice-based research degree at London College of Communication. He lived and worked in Japan for seven years before lecturing in visual communications/digital imaging at Loughborough University and Canterbury Christ Church University. His photographs have been exhibited internationally, and collections of his work are held at the Natural History Museum in London.

SNS Challenger

Pioneers in Marine Chemistry

John Riley 1922–2010

John Price (J.P.) Riley, who died in December 2010, could rightly be credited with being one of the founders of the science of chemical oceanography. He would never have claimed this for himself, however, because not only was he very modest about his immense achievements in the subject, but also he knew himself to be a very poor sailor. One (possibly apocryphal) story has it that whilst attending a scientific meeting held for some reason on one of the research vessels in Plymouth he distinguished himself by being seasick whilst the ship was still tied up at the quay. Recognising that his strengths lay in the laboratory, he was an indefatigable developmental chemist and his work laid the foundations of a great many principles and methods still widely used today.

J.P. was born in 1922 and attended schools in Southport and Cheltenham before joining the University of Liverpool in 1940. Here he obtained a First Class Honours degree in 1943, and in 1946 achieved his Ph.D, on oils and fats, under the supervision of Prof. T.P. Hilditch in the Department of Industrial Chemistry. He immediately obtained a Campbell Brown Fellowship and in 1947 became an Assistant Lecturer in that Department. In 1950 he joined Joseph Proudman and Leslie Fairbairn in the Department of Oceanography. He worked his way up the academic ladder and was eventually awarded a Personal Chair in Oceanography in 1972. After the retirement of Prof. Ken Bowden in 1987, J.P. took over the Chair of Oceanography – a post that he held until his retirement in 1989.

During his career he was editor of a number of journals bridging analytical chemistry and environmental chemistry. He published extensively but will probably best be remembered for the seminal works entitled *Chemical Oceanography*, which he co-edited with Dr Geoffery Skirrow of

John Riley photographed in 1987 on his appointment as Chair of Oceanography
(Photo courtesy of the University of Liverpool)

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A year on, our ship, SNS *Challenger* (the project's website), has welcomed over 3861 visitors from over 230 locations around the world. Amongst these are the 114 people who have become members of our 'crew'. It is through their efforts that we have managed to so far rephotograph 47 of the original *Challenger* images. In addition, like the crew of HMS *Challenger*, our crew has written about their experiences, which can all be found 'on board' (in the blog post section of the website). The adventures to be had in identifying the locations in the original pictures and going out into the landscape to rephotograph them have led some to reminisce about their childhood, and caused others to want to learn more about a place that they felt they knew. Connecting with history in such a way can lead to inspiration and creative pursuits, and SNS *Challenger* is the place to share them.

As an artist/photographer, I feel no concern about the ubiquity of digital cameras and amateur photography, but I am keen to help others to expand their creativite scope. Therefore my role aboard SNS *Challenger* is currently one of facilitating the transfer of information, supporting the crew and steering the ship – in the horizonless seascape of the Internet. J.J. Wild's role abroad HMS *Challenger* was as artist and secretary, and there are some who believe that he may have helped others to improve their skills and abilities onboard, but then got on with his paperwork in the evening. Only through lasting the voyage, will I know the outcome of my role, but my hope is that we will have collectively at least re-photographed the voyage in its entirety.

If you are interested in helping us with our voyage, SNS *Challenger* is looking for people to join the crew. Anyone is eligible to join the project, although it helps to be visiting one or some of the locations visited by HMS *Challenger*, as well as to have access to the Internet and a digital camera of some description. For a full list of destinations on our voyage, as well as more information on how to help, please visit SNS *Challenger* at: http://www.snschallenger.org or email me at: gary@snschallenger.org

Gary McLeod is the Captain, Navigator and Secretary of SNS *Challenger*, which forms part of his practice-based research degree at London College of Communication. He lived and worked in Japan for seven years before lecturing in visual communications/digital imaging at Loughborough University and Canterbury Christ Church University. His photographs have been exhibited internationally, and collections of his work are held at the Natural History Museum in London.

Pioneers in Marine Chemistry

John Riley 1922–2010

John Price (J.P.) Riley, who died in December 2010, could rightly be credited with being one of the founders of the science of chemical oceanography. He would never have claimed this for himself, however, because not only was he very modest about his immense achievements in the subject, but also he knew himself to be a very poor sailor. One (possibly apocryphal) story has it that whilst attending a scientific meeting held for some reason on one of the research vessels in Plymouth he distinguished himself by being seasick whilst the ship was still tied up at the quay. Recognising that his strengths lay in the laboratory, he was an indefatigable developmental chemist and his work laid the foundations of a great many principles and methods still widely used today.

J.P. was born in 1922 and attended schools in Southport and Cheltenham before joining the University of Liverpool in 1940. Here he obtained a First Class Honours degree in 1943, and in 1946 achieved his Ph.D, on oils and fats, under the supervision of Prof. T.P. Hilditch in the Department of Industrial Chemistry. He immediately obtained a Campbell Brown Fellowship and in 1947 became an Assistant Lecturer in that Department. In 1950 he joined Joseph Proudman and Leslie Fairbairn in the Department of Oceanography. He worked his way up the academic ladder and was eventually awarded a Personal Chair in Oceanography in 1972. After the retirement of Prof. Ken Bowden in 1987, J.P. took over the Chair of Oceanography – a post that he held until his retirement in 1989.

During his career he was editor of a number of journals bridging analytical chemistry and environmental chemistry. He published extensively but will probably best be remembered for the seminal works entitled *Chemical Oceanography*, which he co-edited with Dr Geoffery Skirrow of

John Riley photographed in 1987 on his appointment as Chair of Oceanography
(Photo courtesy of the University of Liverpool)

the Chemistry Department at Liverpool; the second edition was co-edited with Prof. Roy Chester. Other key publications included the hugely successful *Introduction to Marine Chemistry* (1971) also co-authored with Roy Chester which was the backbone of many undergraduate and graduate courses. Of his scientific papers, the one he co-authored with his chief technician Jim Murphy in 1986 on the analysis of dissolved phosphorus became a citation classic and the one marine chemistry paper that is known in marine laboratories worldwide.

In the early days, a major preoccupation of the Oceanography Department was the collection and analysis of many samples from the Irish Sea, obtained from the ferries – a practice that lives on through the Coastal Observatory programme run by the National Oceanography Centre Liverpool. In those days, the numerous salinities were calculated from titrimetric determination of chlorinity by J.P.'s research assistant John (J.M.) Bather. Under J.P.'s supervision, John Bather developed a potentiometric end-point determination that improved both speed and precision, freeing up Bather to work on sulphate in the Irish Sea. Bather wrote up this work which he was able submit as a MSc. thesis as J.P.'s first research student in oceanography.

The seminal phosphorus paper was typical of J.P.'s contribution to marine chemistry. He understood the essential attributes of a good analytical method, and the limitations of what was available, and could identify the most promising routes for improvements. J.P. was an early adopter of many techniques, perhaps most notably segmented flow analysis: thanks to his insight, a 'First edition' Technicon AutoAnalyzer, intended for use in hospital and quality control laboratories, became routinely used on board ships, a practice that continues to this day. It did not escape J.P.'s notice that not only was this type of machine more rapid and accurate than a manual operator but it also did not suffer from sea sickness, which in his mind was a major plus. He was not averse to making his own equipment, though it became well known in the university that his glassblowing skills were rather less than his ambitions. The university glassblower was willing to attempt to repair anything that a student had broken provided that J.P. had not tried to mend it first!

One of the features of working with J.P. was that he was always keen to know what was going on in your own research and, in the days before senior academics became totally swamped with bureaucratic nonsenses, would happily spend time looking over your shoulder telling how you could be doing things better. Attention to detail and quality control were hallmarks of this work and as a consequence much of the data produced with his co-workers – Fred Culkin, Manuwadi Tongudai, Roger Wilson, Peter Brewer, Fauzi Mantoura and Andy Dickson, to mention but a few – still underpin many fundamental principles of marine science. Perhaps it is in the areas of dissolved gas solubility and nutrient analysis that he will be best remembered, though there are other strong candidates.

Working on dissolved gases was not without its hazards. One of the idiosyncrasies of the old Oceanography building was that it was effectively a low-level adjunct to the mathematics tower. One of J.P.'s research students, Ali Douabul, was working on the solubility of H_2S in seawater when there was an irritated enquiry as to why all the tomato plants on a maths lecturer's windowsill had died. The cause was traced to the proximity of the relevant window to the vents of the fume cupboard containing the emissions from Ali's apparatus. (In the days before Health and Safety, the lecturer was probably advised to keep his window closed in the interests of scientific research!)

Whilst on the subject of experimental mishaps: J.P. was also a keep proponent of neutron activation analysis using the University of Liverpool's reactor at Daresbury. A lapse in communication between J.P. and a research student led to a seawater sample being encapsulated in Pyrex rather than quartz glass. When the sample returned from irradiation, J.P. was a little startled to receive it in a huge lead-lined container rather than the customary aluminium can. It was some time before the sodium-24 had decayed enough for anyone to get close to it.

Despite his adoption of numerous new analytical technologies there was one technical area in which J.P. was a complete luddite and that was in the use of computers. When the first desktop machines arrived in the university (with a massive 10 MB hard disk or 20 MB if you were a professor) a very patient technician from the computer service spent some considerable time instructing J.P. on the use of his new machine. At the end of the session he innocently enquired whether J.P. had any questions, to which the response was 'Yes, how do I turn it off?' Sadly, the machine spent the rest of its life gathering dust in the corner of his office, whilst J.P. stuck to the traditional 'cut-and-paste' method which involved scissors and a stapler. Those of us who worked with J.P. on his publications came to be familiar with page sizes that might be small fractions or large multiples of A4 (or probably quarto in the early days).

J.P.'s dedication to research was complete and he was never at a loss for new avenues to pursue. He worked his way steadily through the Periodic Table using whatever state-of-the art or original tools he could lay his hands on. He worked with colorimetry, segmented flow analysis, gas, liquid and gel permeation chromatography, fluorescence and emission spectrometry, electrochemistry and ultrafiltration, to name but a selection of techniques. However, he did not overlook the mundane. One method (that can now be safely revealed) for the analysis of a particular radio-isotope involved the discovery that the relatively new 2 pence piece was precisely the right diameter to be glued inside a plastic specimen tube. Treasonably grinding off the Queen's head resulted in a disk that was ideally suited for use as an electroplating substrate that could subsequently be inserted into a suitable radiation counter.

J.P. was a very modest and quiet man whose main interests were swimming, horse riding and the *Daily Telegraph* crossword which had to be completed as a lunchtime rite of passage before the afternoon's activities could begin. He was a notoriously reluctant traveller and could rarely be induced to stray far from home. His worst impressions of life outside Southport and Exmoor were confirmed when he and Jim Murphy worked in Kuwait in the midst of the Iran–Iraq war. Jim, who had travelled out a few days previously, was nearly blown up by a lorry bomb, and when J.P. arrived he found part of the airport on fire and pock-marked with bullet holes, on top of which the luggage had not arrived.

During his academic career J.P. influenced generations of marine scientists, all of whom regarded him with great respect as a scientist and mentor. In recent years, in retirement with his wife Dee, he still tried to stay in touch with current developments with occasional phone calls. His legacy lives on through his work and that of several generations of marine scientists, and for those of us who had the privilege of working with him he will be greatly missed.

Martin Preston
Roy Chester
Dennis Burton

Fred Culkin 1929–2011

Amongst the numerous tributes to Fred, a frequently recurring theme was that of his modest and unassuming manner. He was never one to boast or even mention his achievements if he felt it had no specific relevance to a conversation. Yet his work was always of the highest standard and his meticulous attention to detail in the chemical analysis of seawater has underpinned much of the modern understanding of ocean chemistry. An example of Fred's modesty came to light at his funeral: when discussing his passion for the game of rugby we discovered that during his youth he had been approached to turn professional as a rugby league player.

Fred started his academic journey in 1949 at the Mining and Technical College in his home town of Wigan where he studied full-time for a London External BSc. in Chemistry. It was that solid grounding in chemistry at Wigan which developed Fred's outstanding analytical skills which played such an important role in his subsequent career. Here he met up for the first time with his life-long friend and fellow chemist, Dennis Burton.

In 1955 Fred joined John Riley's group at the University of Liverpool to take over from a fellow Wigan student Robert Greenhalgh, and to study for his doctorate. He became reaquainted with Dennis who had been there since 1952. One of the functions of the department was to carry out long-term measurements on samples from the Irish Sea. Fred took on the task of the determination of salinity (by chlorinity titration) on thousands of seawater samples. As Dennis commented, 'It is interesting that at the very beginning of Fred's career he was so involved in seemingly meaningless measurements, not knowing that he would become the international authority on salinity.' Roger Wilson pointed out that the Standard Seawater calibrations which Fred carried out later for the Standard Seawater Service were probably the most precise measurements made in oceanography at that time, and required the highest degree of analytical skill and discipline.

In 1960 Fred joined the National Institute of Oceanography to work with Roland Cox. He headed up a small group which eventually developed into the Chemistry Department. When Roland died in 1967, Fred took young Bob Morris under his wing and Bob fondly remembers him as the person who 'was my teacher, my friend, someone who could and would tolerate my impatience and proper lack of discipline as an analytical chemist'.

Fred Culkin (left) and Paul Ridout, Chairman of Ocean Scientific International Ltd (OSIL), celebrate the naming of OSIL's new building in 2007

Fred pioneered work in ocean chemistry in the '60s and early '70s, publishing important texts which are still highly relevant. He worked with Steve Calvert and Mike McCartney in the NIO deep-sea chemistry group, and cruises included one in 1972 which was Dennis Burton's first on *Discovery*. As Dennis observed, Fred was not altogether comfortable with his time ashore in Tenerife. Already in pain with a foot injury, he then broke a tooth on a bread roll and attributed his bad luck to Dennis's presence on the ship. Several years later, Fred was in Tenerife supervising one of Dennis's students, as Dennis was committed to teaching in Southampton. Whilst unpacking boxes on the quayside with Fred, the student damaged her back and was unable to move until medical attention was received. Fred's dry sense of humour surfaced in the form of a postcard sent to Dennis that read 'That was a pretty good shot considering the distance but you missed me!' In fact, a subsequent cruise which included Dennis, resulted in us being 'stranded' in Barbados for 10 days, so maybe Fred had a point.

From 1975 until 1989 Fred was the Director of the IAPSO Standard Seawater Service and was a member of the Joint Panel of Oceanographic Tables and Standards (JPOTS) which introduced the Practical Salinity Scale 1978 (PSS78). The comparability of salinity data worldwide is largely due to the widespread use of this single-source calibration standard. It was typical of Fred that he recognised the importance of a single-source standard seawater and accepted the responsibility to continue its production even though it would not be a positive step with regard to his personal career. I joined him in 1977 to share the workload but he continued to be actively involved so that I could develop a research career at IOS. He was unselfish to a fault and I will always be grateful to him.

On his retirement from the IOS Deacon Laboratory in 1989 he joined Ocean Scientific International Ltd (OSIL) as a consultant, and so remained actively involved in standard seawater developments. In 2007, in recognition of his contribution to OSIL and to the marine scientific community as a whole, the company's new building in Havant was named 'Culkin House'.

Fred made a significant contribution to oceanography. He will be remembered around the world by friends and colleagues who recognised his extensive knowledge in marine chemistry and appreciated his warm and friendly manner.

Paul Ridout

RAPID

Monitoring the meridional overturning circulation at 26°N

Eleanor Frajka-Williams

The ocean conveyor is a term used to describe how a parcel of water initially at the surface in high northern latitudes might travel at depth to the Southern Ocean, and then return in surface currents (see Figure 1). The conveyor belt idea made its Hollywood debut in the film 'The Day after Tomorrow' in which a palaeoclimatologist shows a similar diagram to politicians. Soon after, large drops in temperature are recorded by weather buoys off Greenland — a warning that the world is undergoing a massive climate shift due to a shut down of the conveyor belt. In the film, the shutdown of the circulation plunged the world into a new ice age, with glacial conditions spreading equatorward more quickly than cars could drive. While the details of the film are only loosely based on science, it raises a valid question: could the conveyor shut down and what would be the consequences to the Earth climate system if it did?

*Meridional = north–south, as opposed to zonal = east–west

While the conveyor belt analogy is a popular choice for science communication, it is somewhat notorious among scientists because it greatly simplifies the state of knowledge about the ocean circulation. The conveyor belt is a representation of the ocean meridional overturning circulation (MOC), a global three-dimensional web of currents driven by winds and spatial variations in water density. Some of the general 'conveyor belt' ideas are broadly true – warm water moves northward, contributing to more temperate winters in the British Isles and north-western Europe. Winter temperatures in the British Isles are at least 10 °C higher than at similar latitudes on the North American or Asian continents. This heat transport is one of the roles that the MOC plays in the global climate system. However, the term 'conveyor belt'

The elegant simplicity of the 'ocean conveyor' hides the complexity of the meridional overturning circulation which it represents

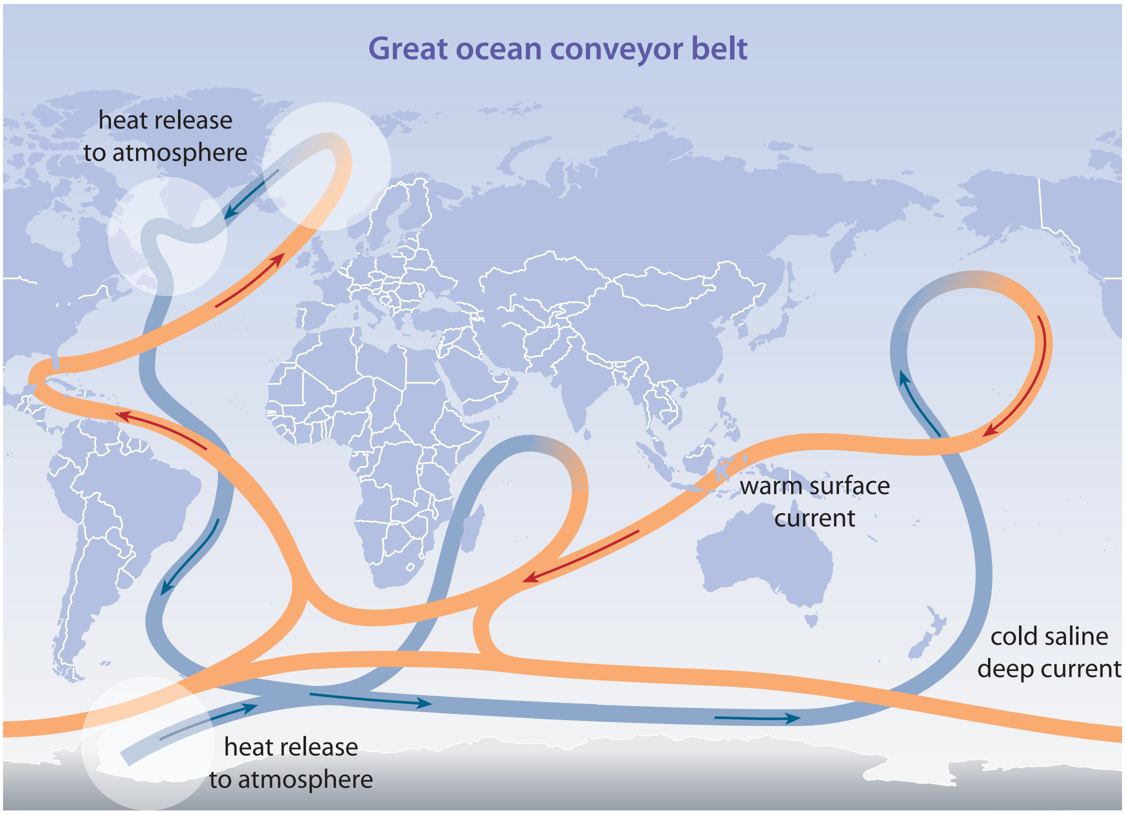


Figure 1 *The ocean conveyer belt. Red indicates warm currents, typically at the surface; blue indicates deep currents. Downwelling occurs through the process of deep convection in particular high-latitude regions, while upwelling is more spatially diffuse. The main regions of deep convection, indicated on the map, are the Greenland and Norwegian Seas, the Labrador Sea and the Weddell Sea. (Source: IPCC)*

suggests the presence of localised streams of water moving around, which in turn suggests that a slowdown of the belt in one region directly translates to a global slowdown everywhere. In truth, the web of currents making up the MOC is not only diffuse but dynamic. The positions of currents can change and they are subject to fluctuations on a range of time-scales. It is the potential for large-amplitude fluctuations – including a complete cessation of of the overturning circulation and its associated heat transport – that worries scientists, politicians and other informed people today.

Palaeo evidence and modelling

Palaeo evidence has shown that rapid shifts in climate are possible, and that the most likely culprits in large-amplitude global shifts are changes in the ocean circulation. One such event was the 8.2 kyr climate event during which glacial Lake Agassiz, in North America, drained into the subpolar North Atlantic, releasing roughly 9500 km^3 of fresh meltwater, the equivalent of a local rise in sea-level of 25–50 cm. In the present-day climate, cold winds blowing across the high-latitude Atlantic cool surface waters so that in certain locations (Figure 1) they become denser than the layers beneath and sink, forming the deep 'limb' of the conveyor.

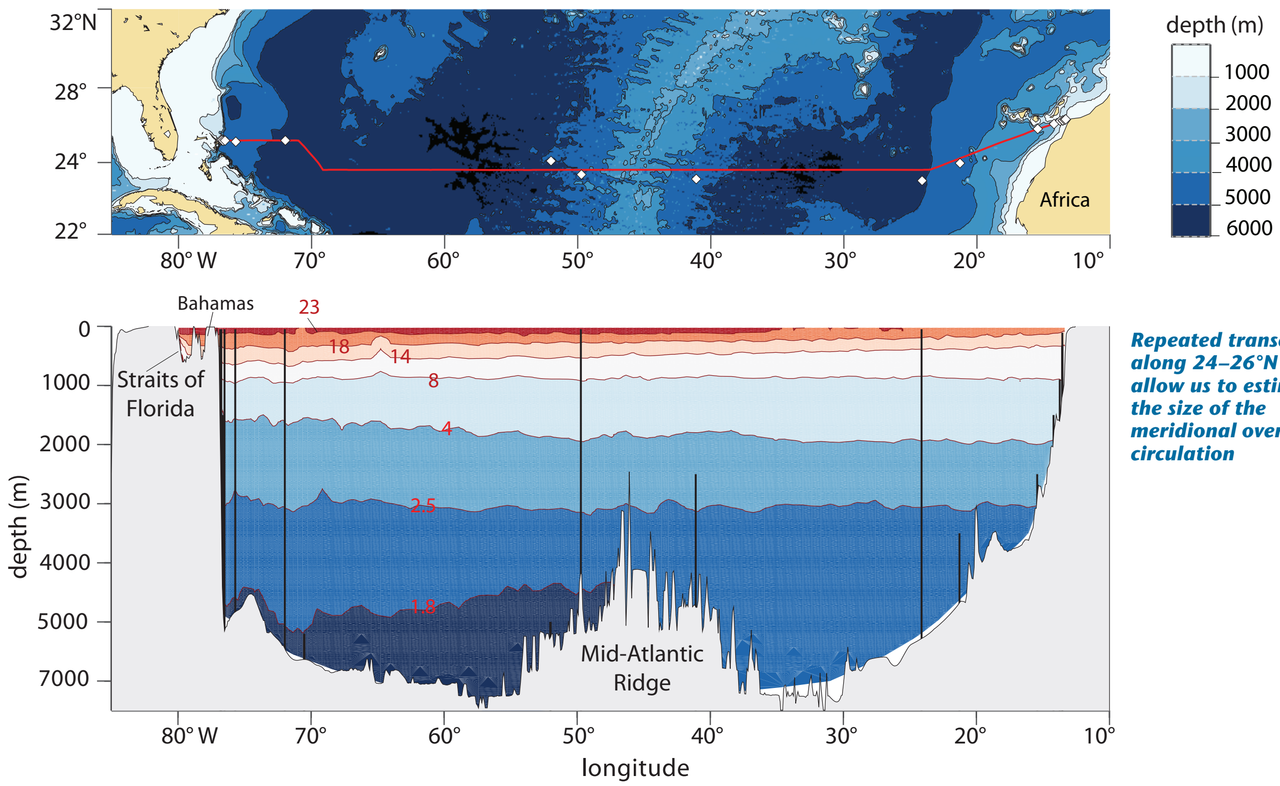
However, in the 'glacial Lake Agassiz' scenario, fresh water capped the regions where deep convection had previously occurred, so that the surface waters were too buoyant to sink. The result was a break in the conveyor, effectively shutting down the MOC and causing a cooling of the northern high latitudes.

Global numerical models have shown similar processes: large inputs of fresh water to the northern North Atlantic can reduce deep convection, and thus slow the MOC. The adjustment of the MOC to changes in northern latitudes can be quite quick, on the order of one month (see Further Reading) as a result of wave processes travelling down the coast and resetting the stratification.

Observations of the MOC

Observational estimates of the MOC are sparse due to the global nature of the circulation and the expense of making large-scale measurements. However, repeat observations *have* been made along ~ 26° N in the Atlantic. To the west, Florida and the Bahamas confine the very fast, northward-flowing Gulf Stream in the Straits of Florida, where it has been measured since 1982 by recording the voltage induced across a submarine telephone cable. Since seawater is a conductor, as it moves through the Earth's

Figure 2 Upper *Bathymetry of the North Atlantic beneath the southern part of the subtropical gyre. The red line from the Bahamas to Africa represents the track of the 2004 hydrographic section whose temperature distribution is shown in the panel below. This transect, and other ocean-wide transects just to the north and south of it, made since 1957, are allowing us to estimate meridional overturning transport.* ***Lower*** *The temperature distribution for the transect shown above. Also shown, to the west of the Bahamas, is the temperature distribution within the northward-flowing Gulf Stream in the Straits of Florida. In the Atlantic above 1000 m, the isotherms sloping up to the east are indicative of the southward flow of surface and thermocline water in the subtropical gyre (cf. Figure 3).*



Repeated transects along 24–26°N allow us to estimate the size of the meridional overturning circulation

magnetic field, it induces an electric field. The strength of the field varies with the speed of the Gulf Stream, and can be detected in the telephone cable as changes in voltage, which have been extensively calibrated with direct velocity measurements in the Gulf Stream. Ship-based observations of density structure along 25° N have been carried out six times (in 1957, 1981, 1992, 1998, 2004 and 2010). As the vessel crosses the Atlantic, salinity, temperature and pressure (depth) profiles are retrieved at a number of hydrographic stations. From these data, density is calculated, and by assuming geostrophic balance, meridional currents and volume transports between stations are estimated. Surface Ekman transport (flow in the wind-driven layer, at right-angles to the wind) is estimated using the zonally-integrated wind stress from QuikSCAT satellite data. Combining the zonal integral of geostrophic transport estimates with estimates of Gulf Stream transport and the meridional component of Ekman transport, gives us an estimate of the amount of water that is moving meridionally, either northward or southward. Since mass is assumed to be conserved across the 26° N section (the amount of water that flows north must equal the amount that flows south), the total integrated transport is adjusted to be zero. The resulting quantity of interest is the overturning – the amount of water going north at shallow depths, and the equal amount of water going south at greater depths.

A recent paper using the sections up to 2004 indicated that the MOC had slowed by 30% in 40 years, from 22.9 Sv in 1957 to 14.8 Sv in 2004 (1 sverdrup (Sv) = $10^6\,m\,s^{-1}$) (see Further Reading). For comparison, the River Amazon transport is roughly 1/6 Sv. This apparent slowdown caused quite a stir. If transport has reduced by 30% in 40 years, are we in the middle of a dramatic shift in ocean circulation? At the brink of a global 'ice age'? How will we know? This controversial paper set the stage for the long-term observational project RAPID-MOC, now RAPID-WATCH (Will the Atlantic Thermohaline Circulation Halt?).

The National Oceanography Centre is one of the major partners in the RAPID 26° N monitoring system, which is a joint US/US project. The mission of RAPID is to develop a cost-effective system to monitor the Atlantic MOC continuously for a decade, from 2004 to 2014. From the observations, we then quantify the MOC and determine the major drivers of its variability. This monitoring system can be used to diagnose the state of the MOC, improve climate models, and refine risk assessments for a marked slowing of the MOC.

Rather than ship-based observations, this system is based on estimates of density from arrays of moorings at the eastern and western boundary of the Atlantic at 26°N (Figures 3 and 4). The same principle of geostrophic balance is applied to the moorings, but instead of calculating transports between multiple pairs of hydrographic stations, the zonally integrated transport is calculated between a single pair of density profiles created by combining density estimates from the mooring arrays off the Bahamas in the west and those off the Canary islands in the east. These data are combined with direct current measurements within 25 km of the Bahamas. Once a year, moorings are recovered and data are downloaded before moorings are redeployed for the following 12 months.

The benefit of using moored instrumentation is that it measures water properties very frequently (every 30 minutes) and continuously (since 2004). Ship-based hydrographic measurements

At 26°N, the surface and deep components of the MOC are both concentrated in western boundary currents

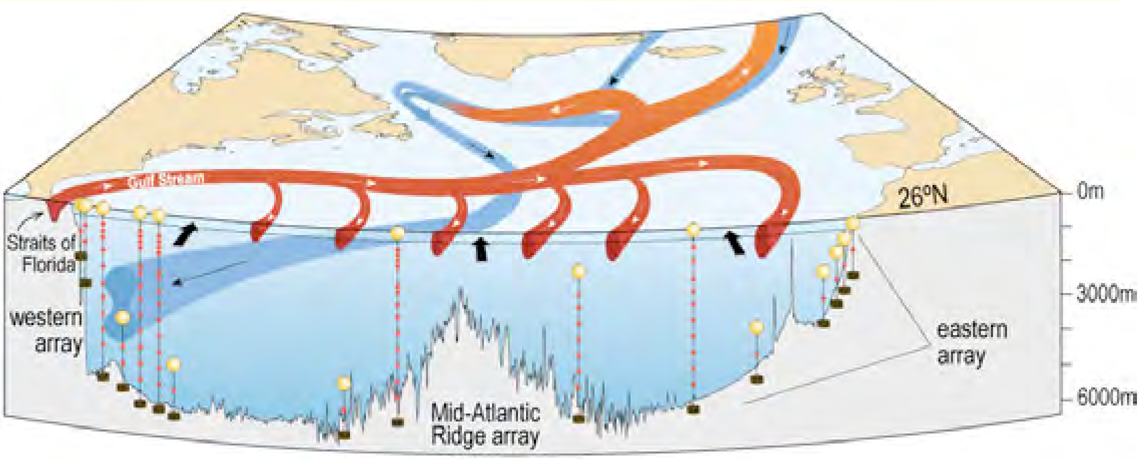
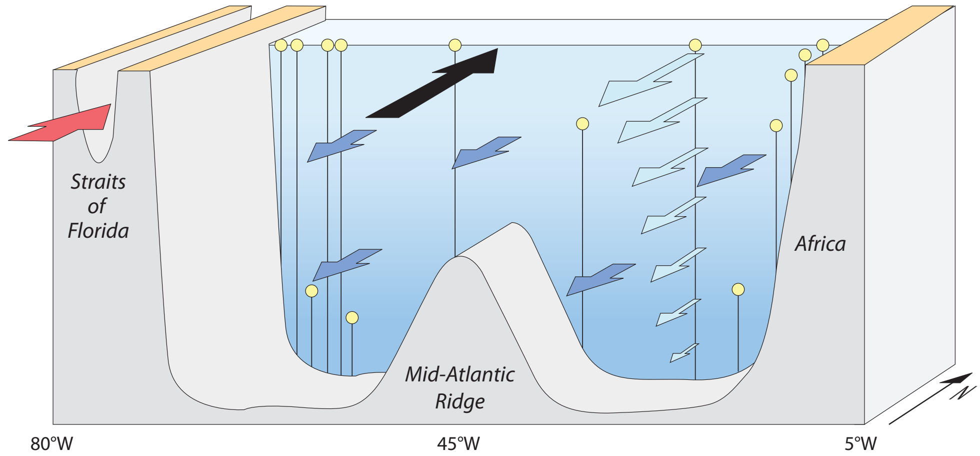


Figure 3 *Schematic representation of the MOC in the North Atlantic, consisting of (red) flow in the Gulf Stream/North Atlantic Current and the subpolar and subtropical gyres, (blue) the deep return flow concentrated along the western boundary, and (broad black arrows) near-surface wind-driven Ekman transport arising from the zonal wind stress. Also shown are the RAPID mooring arrays along ~26° N. Note that in the eastern and western Atlantic, where the continental slope and rise are relatively steep, the observations from a number of moorings (an array) are 'stitiched together' to provide a longer profile than would otherwise be possible.*

(Modified from an original figure by Neil White and Lisa Bell, CSIRO)



To obtain an estimate for the overturning transport at 26°N, we need to quantify four different flow components

Figure 4 *The various components of the zonal transport across 26°N: Gulf Stream transport through the Straits of Florida (red), wind-driven Ekman transport (broad black arrow) arising from the zonal wind stress, and the contribution from geostrophic currents (pale blue arrows), calculated between adjacent pairs of 'moorings' (vertical lines). Mid-blue arrows indicate a spatially constant velocity correction that ensures mass balance across the section.*

(By courtesy of Joël Hirschi)

are high-quality, revealing full zonal and depth structure, but they are expensive and slow. For the most recent transect undertaken in 2010, the ship took 55 days to cross the ocean, while measurements were being made at a total cost of tens of thousands of pounds per day. As a result, transects across the Atlantic can only be undertaken infrequently, and it is difficult to deduce long-term changes in the MOC from six estimates. However, unlike hydrographic estimates, the moored technique provides little zonal structure of the MOC transport.

The MOC at 26° N consists of broadly southward flowing water (pale blue arrows in Figure 4), the northward flowing Gulf Stream (red) and Ekman transport (black arrows), and a barotropic compensating flow (mid-blue). As before, the Gulf Stream contribution is estimated by means of the telephone cable across the Straits of Florida, and Ekman transport is estimated from QuikSCAT wind data. The compensating flow is derived from the measurements by assuming mass balance every 10 days. Together these data produce a daily estimate of overturning strength, providing an unprecedented look at the temporal variability of the MOC at 26° N.

Findings so far

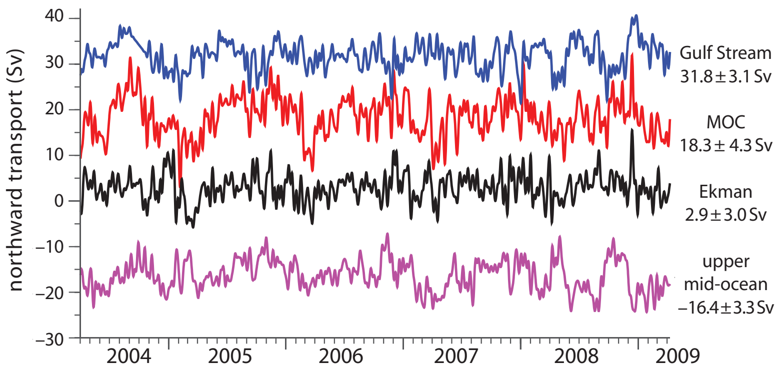
The findings to date have been surprising, and overturn the view of the ocean conveyor belt as in a relatively steady state. In the first year alone, the average overturning was 18.7 Sv but with a range of 4.0 to 34.9 Sv. This easily encompasses the entire range measured from hydrographic sections between 1957 and 2010. The MOC time-series up to April 2009 is shown in Figure 5. The MOC is the overturning transport, corresponding to approximately 18 Sv of net northward transport above 1000 m and 18 Sv of net southward flow below 1000 m. In the first 5-year period, all components varied on a wide range of time-scales, but there is no compelling evidence for a large reducing trend.

One striking finding of the observations is the strength of the seasonal cycle of the MOC. The seasonal range in the MOC is roughly 6.7 Sv (cf. Figure 5), itself a large fraction of the the range in the MOC from 1957 to 2004. In fact, a comparison of the seasons in which these hydrographic sections were occupied, indicated that most of the reducing trend was simply an aliasing* of the seasonal cycle into the long-term trend (Figure 6, overleaf). Part of the seasonal cycle is due to the influence of eastern boundary upwelling on the MOC. When the eastern and western density contributions to the zonal density gradient were examined separately, it

*Aliasing occurs when the spacing of observations is such that the deduced variability is not a true representation of reality.

Figure 5 *Time-series of Gulf Stream, Ekman, upper mid-ocean and MOC transport from 29 March 2004 to 10 April 2009. The mid-ocean contribution includes both the current meter measurements within 25 km of the Bahamas and the geostrophic contribution between arrays on the western and eastern boundaries. RAPID moorings provide the upper mid-ocean transport as the vertical integral of transport per unit depth down to the deepest northward velocity (~1100 m). MOC transport (maximum northward transport of upper-layer waters on each day) = sum of the other three components.*

The MOC time-series suggests an overturning volume of ~18 x 10^6 $m^3 s^{-1}$



An apparent decline in the strength of the MOC was actually a reflection of the times of year that measurements had been made

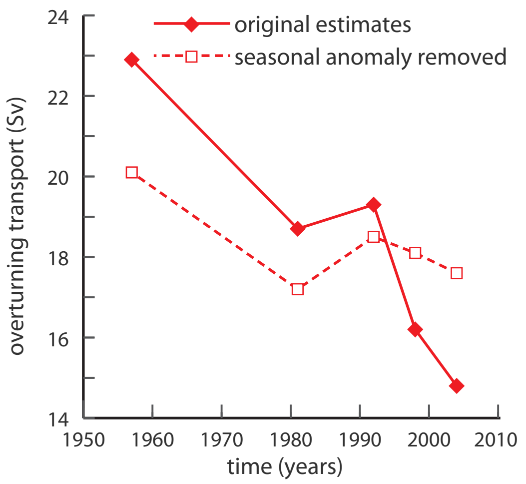


Figure 6 *Red diamonds: The overturning transport inferred from five hydrographic sections carried out in autumn 1957, summer 1982, summer 1991, winter 1998 and spring 2004. Open squares: The overturning adjusted to take into account the seasonal cycle measured by the RAPID arrays.*

(Based on a figure by Torsten Kanzow)

was found that the annual cycle of overturning is phase-locked with the variation in wind stress at the eastern boundary. In particular, upwelling-favourable winds raise the isopycnals at the boundary, increasing the net density gradient between east and west, and hence intensifying deep southward geostrophic currents.

On even shorter time-scales, large-amplitude, high-frequency variability abounds. Westward propagating Rossby waves encounter the coast near the mooring locations, and topographic waves travel rapidly northward and southward along the boundaries. The impact of eddies on the MOC is debated, however. One recent paper suggested that all variability in the MOC was due to eddy activity, and any longer term fluctuations are simply the superposition of different eddies, just as the 'beating' between two semidiurnal tides can produce the lower frequency spring–neap cycle. A second paper showed that eddy variability at the mooring locations very close to the boundaries is actually relatively weak. Modelling studies suggest that eddy energy or Rossby waves may contribute to feeding the meridional currents, in which case they are part of the signal. (See Further Reading for details of all these papers.)

Challenges ahead for RAPID

The more we learn about the MOC, the more complexity we uncover. We have made leaps in our understanding of the variability of the MOC and its seasonal cycle, and are unravelling the dynamical sources of large, high-frequency variability. However, we are only beginning to understand the low-frequency interplay between components of the MOC. For example, we do not understand why the 2008 seasonal pattern of the mid-ocean geostrophic transport deviated from previous years' observations: in 2008, it was dominated by a semiannual cycle, which was out-of-phase and significantly anticorrelated with the Gulf Stream, whereas in (all) previous years there was no relationship between the Gulf Stream and mid-ocean transport.

Adjustments in one or more components of the MOC in response to changes in another, and intrinsic seasonal and eddy variability, all modulate the behaviour of the MOC. These fluctuations directly impact the meridional heat transport which further influences sea-surface temperature and atmospheric circulation. Rapid climate change pervades palaeoclimate records, and were it to occur in the present-day world, would have devastating effects on human civilization. The global change in these palaeo scenarios appears to be due primarily to shifts in the MOC and its redistribution of heat in the climate system. The goal of RAPID is to observe the MOC strength and structure continuously, and to improve models and our understanding of the dynamics controlling MOC variability. As the record-length increases, we will have more confidence in determining longer term changes in the MOC, in particular whether it is speeding up, slowing down, or changing its basic ciirculatory pattern altogether.

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How will coral reefs respond to climate change?

David J. Suggett and David J. Smith

Shallow tropical and subtropical coral reefs are considered flagship ecosystems of both coastal and oceanic environments because of their disproportionately high diversity and productivity, but they are also a cause for concern because of their extreme sensitivity to environmental (climatic) change. Localised impacts, such as pollution and unsustainable harvesting, as well as broad-scale changes, such as ocean warming and acidification, have intensified over the last few decades; simultaneously, very visible declines in 'reef health', in particular the diversity and abundance of species that are present, and consequently the ecosystem services that are afforded, have been observed worldwide. Such continued declines carry potentially immeasurable impacts for humanity: over ¼ billion people worldwide, including some isolated indigenous populations, are entirely dependent on viable coral reef ecosystems for subsistence and coastal protection. Reef biodiversity may also contain (as yet untapped) potential bio-medicinal and bio-technological applications. Much rests on understanding how continued environmental change will further alter coral reefs and consequently what efforts and investments are needed to effectively manage and conserve these key ecosystems.

Developments in coral research

Research into coral reefs and climate change has been intensifying, with recent efforts focussing on related processes acting at different operational scales: biologists continue to examine the mechanisms that determine how individual organisms respond to environmental change but, as with other fields, are turning towards molecular scales (and 'omics' techniques supported through bioinformatics); ecologists now rely on remotely sensed information, algorithms and models to explore larger scale community and ecosystem patterns. Research groups from various Institutes across the UK have been playing a critical role in these efforts, in part by capitalising on in-house coral husbandry facilities and/or access to field sites through the UK's responsibility to its British Overseas Territories,* as well as long-term collaborations (in particular in the Caribbean, Indian Ocean and Indo-Pacific; cf. Figure 1, overleaf). These various research groups are also aligned with (and exchange knowledge with) the UK's thriving coral aquarist industry.†

Until recently, much of our understanding of how coral-reef systems would respond to further environmental (and climatic) change has come from quantifying the effects of 'natural experiments', such as extreme thermal events and severe storms, and applying these observations to climate models. The El Niño–La Niña (EN–LN) of 1998 was considered to be the greatest thermal anomaly in recent history and many coral reefs worldwide were irreversibly damaged through thermally induced coral bleaching. Thus observing the nature of the damage, and the extent to which different reefs were impacted and subsequently recovered, has been an area of intense interest for both scientists and managers. For many reefs in the Indo-Pacific, an EN–LN throughout 2010 seems to have been even greater in extent and duration than that in 1998, but initial observations suggest that many (but not all) reefs have only been moderately

*E.g. reefs in the Chagos Archipelago; see pp. 26–31.

†UK Knowledge Exchange has been facilitated through a three year NERC funded KE programme: Coral Aquarists Research Network (CARN: www.carn.org).

impacted at most.* Whilst this comes as a relief, how such contrasting results will be interpreted (in light of past impacts) will no doubt fuel the research community for months if not years; have some reef systems demonstrated some capacity to adapt to anomalies post 1998? Regardless of the answer to this question, these 2010 observations demonstrate that if we are to make accurate predictions we need to understand much more of the heterogeneity of reef systems, and consequently their diversity of responses to environmental change.

Reef-building corals are conventionally associated with clear blue waters of low latitudes where combined conditions for coral growth, primarily light, temperature and degree of saturation of aragonite (the form of calcium carbonate used by corals) – are optimal (e.g. Figure 1, upper). However, some calcifying coral species can thrive outside of this 'environmental envelope' to form what are termed *marginal reefs*. Many marginal reefs exist worldwide effectively at the latitudinal limits for coral growth (~ 20–30 °N and S); key examples include those of the Persian Gulf and Red Sea where water temperatures vary widely (~20–40 °C) over the course of the year, and Brazil's southern Atlantic coast where seasonal extremes in river run-off and wind-driven re-suspension routinely modify the light environment, by turning clear blue waters to a murky brown (Figure 1, lower). In both cases, whilst coral cover can remain high, diversity of the corals and associated reef fauna is typically lower than that for lower latitude reefs. Importantly, marginal coral reefs are not purely confined to higher latitudes but also occur, albeit at a smaller localised scale, in association with lower latitude reef complexes, in particular, the shallow-water fringing mangrove and seagrass environments that border reefs (Figures 2 and 3). Such environments are extremely dynamic, with strong currents and continual and intense sediment resuspension, yet some coral species still thrive, but as patches rather than a true reef.

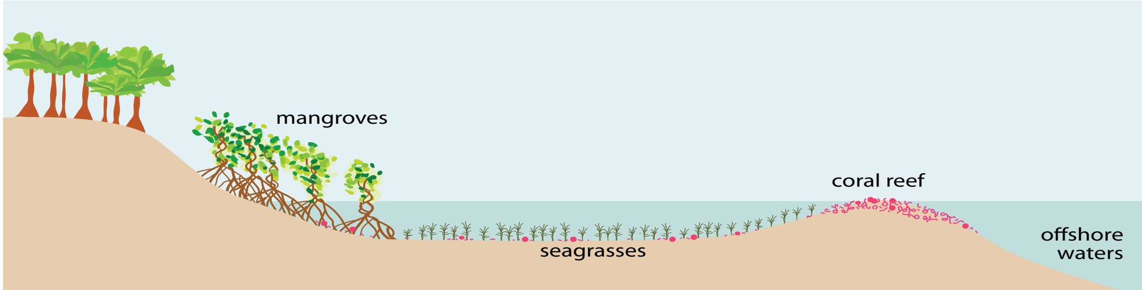
Corals in marginal environments tend to be less species-rich than those living under optimal conditions

Figure 1 Upper *A relatively pristine tropical reef off Indonesia and* ***Lower*** *a high-latitude marginal reef off Brazil. The two sites both exhibit relatively high coral cover (~ 30–40%) but the diversity for Brazil's reefs is considerably less and characterised by many endemic species (such as* Mussimilia hartii*, with large tubed formations). (This image was taken during the dry season, when waters are clearest.)*

Survival of coral communities within relatively extreme environmental conditions under present-day climates provides good evidence that corals and coral reefs can be resilient when growth conditions become sub-optimal. The question is whether such resilience can be maintained as reef environments undergo the current period of rapid change Environmental models certainly suggest that in the next 50–100 years many of the world's reefs will exist in marginal conditions of aragonite saturation and temperature†; thus, a core component of our research is now focussing towards: (1) how and to what extent corals can thrive in marginal reef systems (exteme environments)? (2) to what extent are present-day marginal reef systems an analogue for many future reefs worldwide? and (3) what lessons can be learnt about environmental management from observations of reef viability under marginal (sub-optimal) conditions?

*Examination of thermal anomalies (and associated remote-sensing products) have demonstrated that 2010 has exceeded 1998 for many regions, especially in the Indo-Pacific (http://coralreefwatch.noaa.gov/satellite/virtual_stations); our observations (article in preparation) demonstrate that many coral reefs throughout Indonesia and the Seychelles have been impacted to some extent, with less than ~20% mortality (i.e. substantially less than during 1998). That said, some reefs areas (e.g. Aceh in Indonesia) have still experienced high mortality and we will not fully understand the impact of the 2010 EN–LN until more data from reefs worldwide are collated.

†See Guinotte *et al.* (2003) in Further Reading.



Corals survive amongst mangroves and in seagrass beds

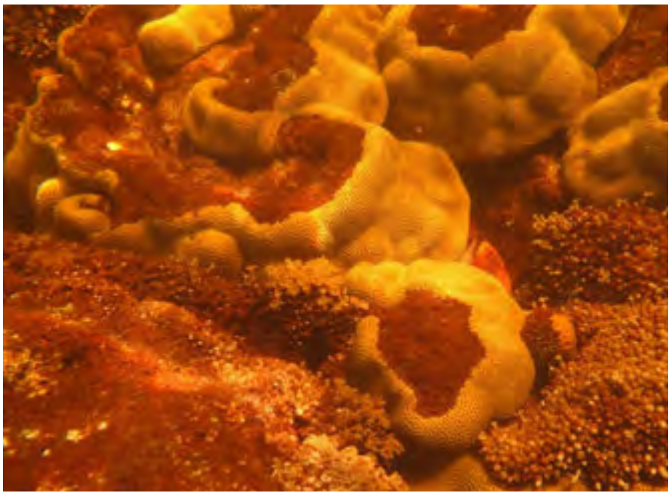
Figure 2 *Mangroves and seagrasses are often found between a fringing reef and the land, and both may provide marginal habitats for corals.*

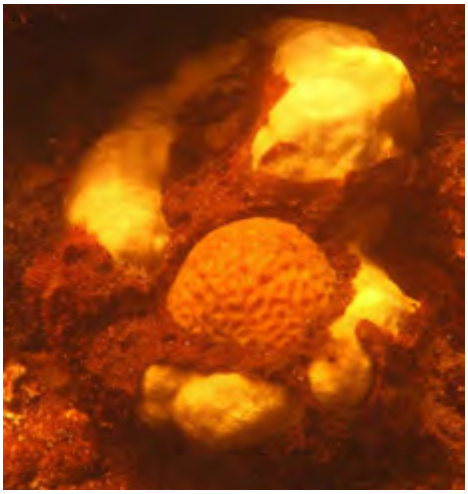
Acclimation or adaptation?

Whether present-day marginal coral systems represent an analogue for future reefs under rapid environmental (climatic) change ultimately depends on whether survival in marginal environments occurs via high physiological flexibility (acclimation) or distinct specialised genetic selection (adaptation). Unfortunately, climate-change scenarios may not give corals the time needed to 'adapt' (whether this is the case remains a key unknown). Acclimation might result in a more positive outcome for corals worldwide as (in theory at least) all coral populations should have the capacity to track environmental change; in contrast, adaptation may limit only specific populations, already within marginal environments, to seed future reef communities. Under adaptation, the capacity to successfully respond to environmental (climatic) change will most likely rest on the extent of connectivity between marginal and non-marginal populations, i.e. physical connections, such as currents, that link habitats to one another – a subject that is little known. Engineering better connections by transplanting coral could therefore perhaps afford a greater capacity for reef populations to adapt to rapid environmental change but is impossible to even consider until pathways and rates of connectivity between key coral populations within and between bio-regions are much better understood. Gaining such understanding will inevitably require much closer collaboration between reef biologists and oceanographers.

Acclimation requires species to repond physiologically to their changing environment (within the constraints of their existing genetic blueprint) over the

Figure 3 *Corals living in sub-optimal (marginal) conditions near to an Indonesian offshore reef.* ***Above right*** *Coral patches within a seagrass bed on a near-shore reef flat.* ***Below*** *Corals living within the highly turbid mid-channels of a mangrove forest. Both populations are found in ~1 m of water and colonies can range in size from 5 cm to 1 m in diameter.*





Corals living under sub-optimal conditions often form patches rather than substantial reefs short term but ultimately may give rise to adaptation where conditions remain altered over the longer term. Our recent research following coral communities along environmental gradients (from clear-water reefs to mangroves) in Indonesia clearly demonstrates that with increasing proximity to mangroves corals modify their underlying physiology for acquiring energy by increasing the proportion of energy they obtain by taking in nutrition themselves and reducing their reliance on their symbiotic microalgae; at the same time they modify their genetic make-up in terms of the symbiotic algae that they are compatible with so that they favour more stress-tolerant types of algae.* A particularly extreme example occurs for the coral species *Goniastrea aspera*. This species conforms to the model of regulating energy acquisition and symbiont genotype across reef environments but also invests heavily in protection against stress, e.g. in the production of proteins for protection against heat shock, in pigments to protect them against ultraviolet radiation, and in molecules that scavenge free radicals. As a result, *G. aspera* colonies can happily survive in rock pools (Figure 4) or even completely emerged from water at low tide under the most extreme tropical temperatures/sunlight. However, identifying the extent to which the physiological changes truly represent adaption or acclimation will ultimately require further examination through population genetics.

Selection for physiological and genertic traits along environmental gradients does in fact appear key in determining the extent to which species withstand anomalous environmental conditions. For example, recent research on coral reefs of the Indo-Pacific highlights the fact that the degree of variability of sea-surface temperature (SST) that a coral reef has lived through – i.e. its environmental history – determines how susceptible it is to thermally induced bleaching, and subsequent mortality.† Coral bleaching has been a major topic of interest to reef researchers and managers over recent years when widespread paling, and in turn mortality, of entire coral communities (at local to regional scales) has occurred during EN–LN events. Over relatively small scales, corals that live in environments with greater SST variability (but generally similar light regimes) are much more tolerant of further temperature anomalies. Perhaps more intriguing is that the same appears to be true when comparing reef systems with greater SST variability (but generally similar light regimes) at different latitudes. In both cases, acclimating or adapting to highly variable conditions clearly pre-arms corals with the physiological flexibility needed to tolerate further change (within reason). Coral reefs 'naturally' bleach every year as seasonal changes in light and temperature require that corals downregulate their ability to harvest light by losing pigments and/or numbers of symbiotic algae (Figure 5), and those reefs/coral species equipped to undergo the strongest seasonal bleaching may ultimately be the most tolerant of more extreme thermal stress. Such emerging concepts are important to how we view the conservation of reefs since corals that bleach most regularly may ultimately have the greatest conservation value. This should apply for marginal reef environments, which are extremely variable over time, and should enhance their (currently highly underrated) 'value'.

Several key factors moderate corals' susceptibility to stress: these are primarily light and temperature (and in turn oxygen and nutrient availability), and the physical processes that regulate exposure. These factors certainly don't operate in isolation and can trigger numerous 'vectors' of stress; for example, elevated temperature stress can directly affect the functioning of corals' symbiotic algae (and be exacerbated if light intensities are higher). Simultaneously, elevated temperatures can increase microbial activity, which in turn will locally decrease oxygen concentrations around the coral tissue, and leave the coral susceptible to pathogens. Therefore, any point in space or time that acts to reduce the net effect of these stressors effectively affords a refuge for the coral.** Our work from reefs of the Seychelles and Brazil demonstrates how local environments that diminish light availability to corals via enhanced sedimentation/resuspension, can result in highly successful and flourishing reef systems with a potentially high conservation value.

Corals can thrive in the hottest of rock pools

Figure 4 Goniastrea aspera *in a rock pool at low tide. The upper surface of the coral has died off, presumably through exposure to air combined with high temperatures and light levels. This surface is replaced by a build-up of silt and sand, but the coral remains healthy. Water temperatures in these pools regularly exceed 40 °C.*

*See Hennige *et al.* (2010) in Further Reading,

†Several recent papers hypothesise and/or demonstrate a relationship between the extent of intra-annual SST variability and species tolerance of anomalous temperature stress, including Suggett and Smith (2011) and Ateweberhan and McClanahan (2010); see Further Reading.

**See West and Salm (2003) in Further Reading.

The surprising protective effect of turbidity

Small island states such as the Seychelles are critically dependent upon income generated by their natural resources, in particular coral reefs. Unfortunately, the 1998 El Niño thermal anomaly heavily impacted the Seychelles' coral reefs; up to 95% of all corals at some sites underwent thermally induced bleaching mortality and the reefs are still recovering today, against a backdrop of continued environmental change. The present-day coral communities are generally characterised by species now with mostly small/young colonies which suggests recent colonisation. This observation suggests significant differences in thermal tolerance amongst species within the coral communities: species now with mostly small/young colonies must have been most susceptible to bleaching-induced mortality, and have since begun repopulating the community with larval offspring.* Discrete lab-based stress experiments on the various species have since confirmed this hypothesis.

However, at some reef sites, there were exceptionally large colonies (> 2 m) of the apparently most thermally susceptible species; the water at these sites was very obviously turbid, with determinations of light attenuation much greater than in neighbouring highly impacted reefs; these sites were either shallow lagoons or embayments where wind and tidally driven mixing appear to continually resuspend the sediments. Most likely in these turbid environments, less (light) is more: as alluded to above, less light can (1) dampen the thermal stress response of corals, and (2) encourage corals to switch towards a more heterotrophic lifestyle, which ensures that where function of corals' symbiotic algae is compromised by higher temperatures, the corals can still acquire enough energy to resist (and subsequently recover from) thermal stress. Furthermore, waters where sediment is continually resuspended have a highly variable light environment which may encourage corals to pre-arm their physiology against subsequent anomalous stress. Regardless of the mechanism, turbid waters may have thus enabled thermally susceptible species to persist through the 1998 EN–LN (and hence subsequently repopulate neighbouring highly impacted reefs post-1998). Importantly here, these highly turbid sites (Figure 6) were originally targeted as having less (obvious visible) appeal to tourism and hence lower conservation value in the longer term; in fact our original surveys that identified these turbid refuge zones were prompted by demands to build a new hotel adjacent to the surrounding embayment.

Other researchers in the Seychelles have further observed that not only reductions in light *quantity* but also a change in *quality* may have afforded sensitive corals a refuge from the 1998 EN–LN.* Large colonies of thermally susceptible species have also been found in lagoons that are clear but have a large amount of seagrass. Optical measurements demonstrated that the high concentrations of dissolved organic matter produced by the seagrasses filtered out ultraviolet light that would have exacerbated any thermal anomaly effect. Such examples have now stimulated intensive research efforts to identify other such refuges throughout the Seychelles.

Unlike the Seychelles, Brazil's southernmost reefs are almost entirely marginal as they are relatively high-latitude (~ 17–19° S) and located in shallow waters at the mouths of extensive estuaries; consequently, corals here must tolerate substantial seasonal variability of light, temperature and rainfall (and in turn riverine outflow) for

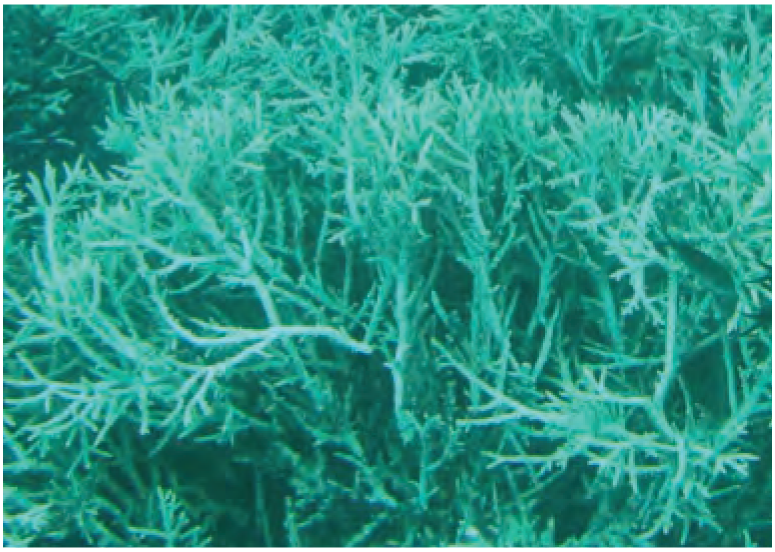


Figure 5 *Indonesian* Acropora *reefs that underwent sublethal thermal bleaching in 2010.*

Seasonal bleaching may equip corals to cope with more extreme thermal stress in the future

*For examples see Smith *et al.* (2008) and Iluz *et al.* (2008) in Further Reading.

Figure 6 Acropora *reefs ('thickets') found flourishing in turbid waters within embayments of the Seychelles.*

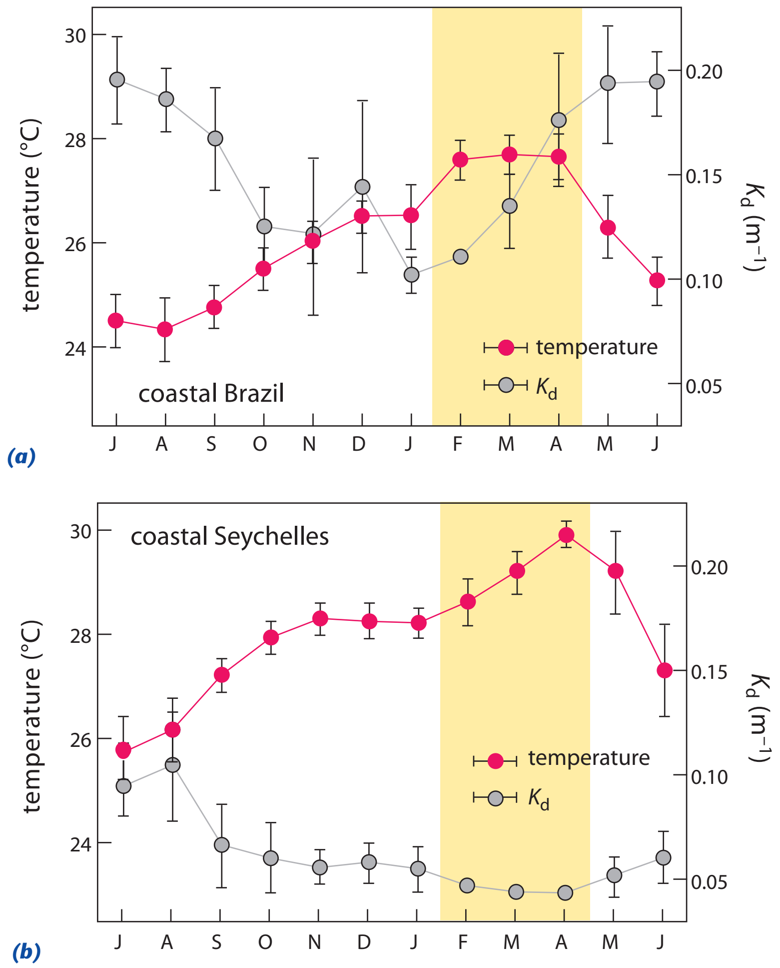
Turbid waters may protect reefs now and enable them to survive in the future

the reefs to remain viable. Importantly, a high proportion (~ 35%) of the reef-building coral species here are endemic only to Brazil, perhaps reflecting long-term adaptive pressure to survive within highly variable (yet marginal) conditions and in relative geographical isolation. Compared with other reefs of the Atlantic, Brazil's corals have received little attention but clearly thrive within highly variable environmental conditions that would again suggest corals here should be highly tolerant of (transient) stress. However, controlled lab-based stress studies (and also some general observations across the reef sites) suggest that many species are highly susceptible to anomalous temperatures and/or light; most worryingly, that the endemic species appear most susceptible.

These reefs have indeed routinely experienced anomalous light and temperatures in the past, but relatively little bleaching (or bleaching-induced mortality) has been observed. Analyses of long-term light and temperature records may in fact hold the key here. We have begun examining records of remotely sensed water-column light attenuation, K_d (a measure of how clear or turbid the water is). Many reefs are characterised by high co-variability between K_d and SST throughout the year, i.e. waters warm as they become clearer (and/or become clearer as they become more thermally stable). Such a pattern carries a high potential for high light/temperature stress; however, Brazil's reefs do not follow this pattern. Closer inspection of the data suggests that periods of high rainfall/onshore winds (that increase K_d/turbidity) could provide a 'seasonal refuge', protecting the corals when waters are warmest, and the potential for thermal stress is greatest (Figure 7). Such theories are still being tested.

Brazil's reefs may be protected from anomalously high temperatures by increased turbidity, as summer is also the rainy season

Figure 7 *Variation over the course of a year of temperature and remotely sensed light attenuation (K_d)* ***(a)*** *for marginal reefs off Brazil and* ***(b)*** *for a typical reef in the Seychelles. Off Brazil, the warmest part of the year coincides with a period of rising turbidity, which may buffer the corals against light-enhanced thermal stress, whereas for the Seychelles reef, the water is at its clearest during the warmest months.*



The two examples above clearly demonstrate that examining marginal reefs, i.e. reefs often perceived as being of 'lower quality', in fact returns a wealth of information as to how coral communities can remain resilient by exposure to sub-optimal growth conditions. The understanding we gain from such observations will no doubt help to ensure that predictions of the future form and function of reefs are as accurate as possible. Perhaps more importantly, our observations demonstrate how critical *light* is, as perhaps the primary variable, when considering how corals and coral reefs will respond to environmental change. Most research on corals and climate change understandably focusses on temperature and aragonite saturation but we need to contextualise this focus with how future light environments of coral reefs will also change: where are these predictive models for light? Without this knowledge we will be left with extremely limited predictive power, and ultimately limited accuracy, with which to make critical (often sensitive) management decisions.

Future directions for coral research

In looking to the future, the structure (form and function) of coral-reef communities will inevitably change as *all* reef environments become increasingly marginal; the challenge today is, as ever, to accurately understand the implications for productivity and biodiversity and in turn *how* reefs can continue to support the ¼ billion (and growing) dependent people worldwide. Both the examples highlighted above, from the Seychelles and Brazil, highlight emerging concepts on the capacity of reef systems to absorb change. Perhaps most critically, coral reefs perceived as being of lower environmental quality (and hence often having less conservation value) may still carry key untapped information about how reef systems can ultimately respond to environmental change. What is clear is that with environmental change comes a need to shift priorities in reef research.

Knowledge of the oceanography and biogeochemistry of many reef systems is still sorely lacking. Surprisingly, we still know very little about the most basic reef processes, including primary productivity, growth rates and in turn framework development, which are all regulated by environmental conditions. Without a better handle on such fundamental processes, we cannot confidently move to the next step in modelling of reef systems, where parameterising ecological networks and physiological traits will no doubt become key; the rate at which these emerging concepts can be developed will probably depend on integration of the expertise of biogeochemists, oceanographers and modellers. However, the UK is exceptionally well placed to capitalise on possible opportunities by drawing on already close links between disciplines and emphasis on technological development and, perhaps most importantly, a growing emphasis on exchange of knowledge.

Acknowledgements

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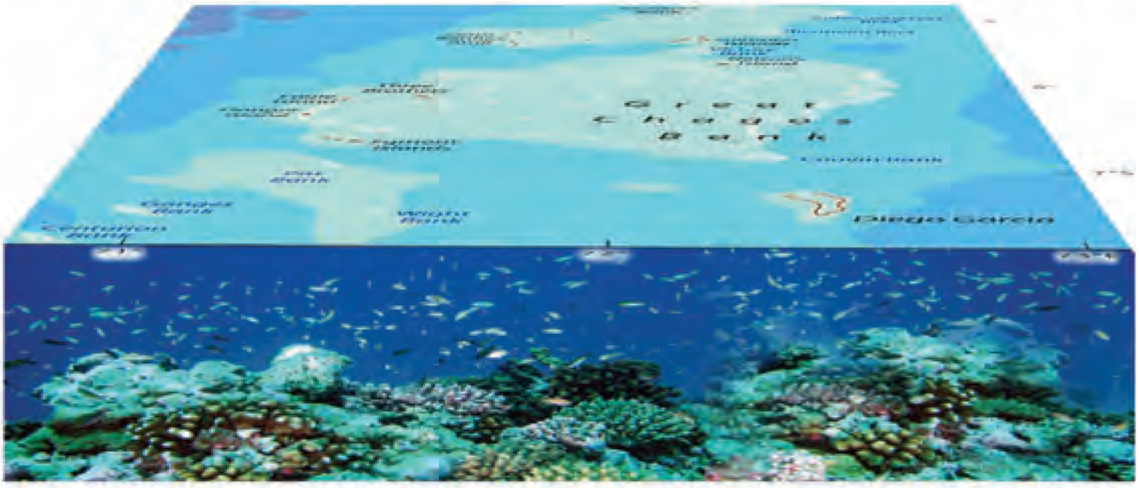
Vivid Porites *coral species (left) and* Acropora *coral species (right) thriving on brightly lit shallow intertidal reef flats. At low tide, the corals can be in less than a metre of water, and at very low tide completely out of the water, making this a marginal environment.*
(These and all other photos were taken by Dave Suggett.)

Protecting the Chagos Archipelago

– a last chance for Indian Ocean reefs?



Charles Sheppard

The Chagos Archipelago lies in the middle of the Indian Ocean (Figure 1). Its exclusive economic zone (EEZ) of over half a million km^2 encompasses about 60 000 km^2 of shallow coral reefs, and in April 2010 these waters were declared a Marine Protected Area. Because of the over-exploitation and decline of coral reefs throughout the Indian Ocean, the Chagos reefs could represent as much as half of that ocean's reefs remaining in good condition. The reason for this is simple: except for one side of the island of Diego Garcia, which has a military facility, the archipelago has for about 40 years been remote from human exploitation. I would argue that Chagos is one of a few 'legacy' areas which, on the one hand, are in good condition now (for whatever reason) and on the other have a good chance of remaining so, benefiting the greater region in perpetuity.

Returning to paradise?

For at least 150 years many of the larger islands were inhabited, during which time their native vegetation and most birds and other wildlife were displaced by coconut plantations. All five atolls were affected by this, but in the 1930s the plantations on two of them were wound up because of economic and social problems, while plantations on the remaining three continued until the early 1970s. In the last few decades of cultivation there was continued decline, partly because of the archipelago's remoteness and partly because of a boom in the rival palm oil crop which by the 1970s had overtaken coconut oil; today it has all but replaced other such foodstuffs. But complete evacuation was a result of the archipelago being made into the British Indian Ocean Territory (BIOT), to be used for the defence purposes of the USA and UK.

Despite its tiny land area, the Chagos Archipelago's EEZ is > 500000 km^2

Thus, while the last 40 years have seen most parts of the tropical oceans suffer massive environmental decline from pollution, over-exploitation and various unwise forms of development, the Chagos Archipelago has been in a sort of time-capsule, in which its rich coral reefs have survived in a way no longer seen in most parts of the world. Even the land has started to see recovery from past depredations.

Figure 1 *The remote location of the Chagos Archipelago in the middle of the Indian Ocean. The red line is the boundary of the exclusive economic zone and the previous Fisheries Conservation and Management Zone, as well as the boundary of the new Chagos Archipelago Marine Protected Area/no-take zone.*

Figure 2 *The Chagos Archipelago contains ten Important Bird Areas, including places that are home to ground-nesting birds, which do not survive on islands that have had human presence and rats.* ***Above left*** *A masked booby with her single egg.* ***Below left*** *A nesting noddy tern.* ***Above right*** *A colony of sooty terns.*

Ground-nesting birds thrive on many of the Chagos islands

In comparison with the reefs, the islands are relatively tiny, being just 60 km^2 in total, spread across the 55 islands of the five atolls (Figure 4, overleaf). On many of the islands, especially those which were too small to have been converted into coconut plantations, wildlife thrives. The result is that today in the Chagos Archipelago you will see coral reefs and small tropical islands as they would have looked a century ago, and observe scenes which today are found only in a diminishing number of locations which man has passed by. Not many places look like this now; there are scattered patches in some remote parts of the Seychelles and Maldives, for example, but there are certainly no other areas with concentrated richness over such a large area. Chagos's tiny islands contain ten internationally designated Important Bird Areas, for example, and even the turtles, once nearly extinguished for food and their shells, are coming back (Figures 2 and 3).

The reason for its present great biological wealth is, of course, its lack of development, lack of overfishing and exploitation, and its distance from all the other disturbances that accompany humanity. The evacuation of the remaining settlements in the early 1970s was controversial, and probably nobody would argue that the now well-known eviction was handled well, or was fair, or that the islanders were not subsequently subjected to distressing conditions. I don't know anyone who thinks that those who went to Mauritius fared other than badly – whatever aid was given at the time, they appear to have had a miserable time of it.

Protection for Chagos's reefs

While Chagos' reefs have been protected since the creation of the British Indian Ocean Territory, this protection was *ad hoc* to a degree, and measures evolved over many years. In April 2010 the UK government declared that the whole region, extending out to the 200 nautical mile limit, would be a Marine Protected Area and no-take zone. The existing 200 n.m. Fisheries Conservation and Management Zone was, from that time, a no-take zone.

Some Chagossians want to return now and are taking actions to try and do so. The key questions from a conservation perspective are: How many

Figure 3 *A hawksbill turtle on a Chagos reef. Both this species and the green turtle are becoming more common, and both species breed on several Chagos islands.*

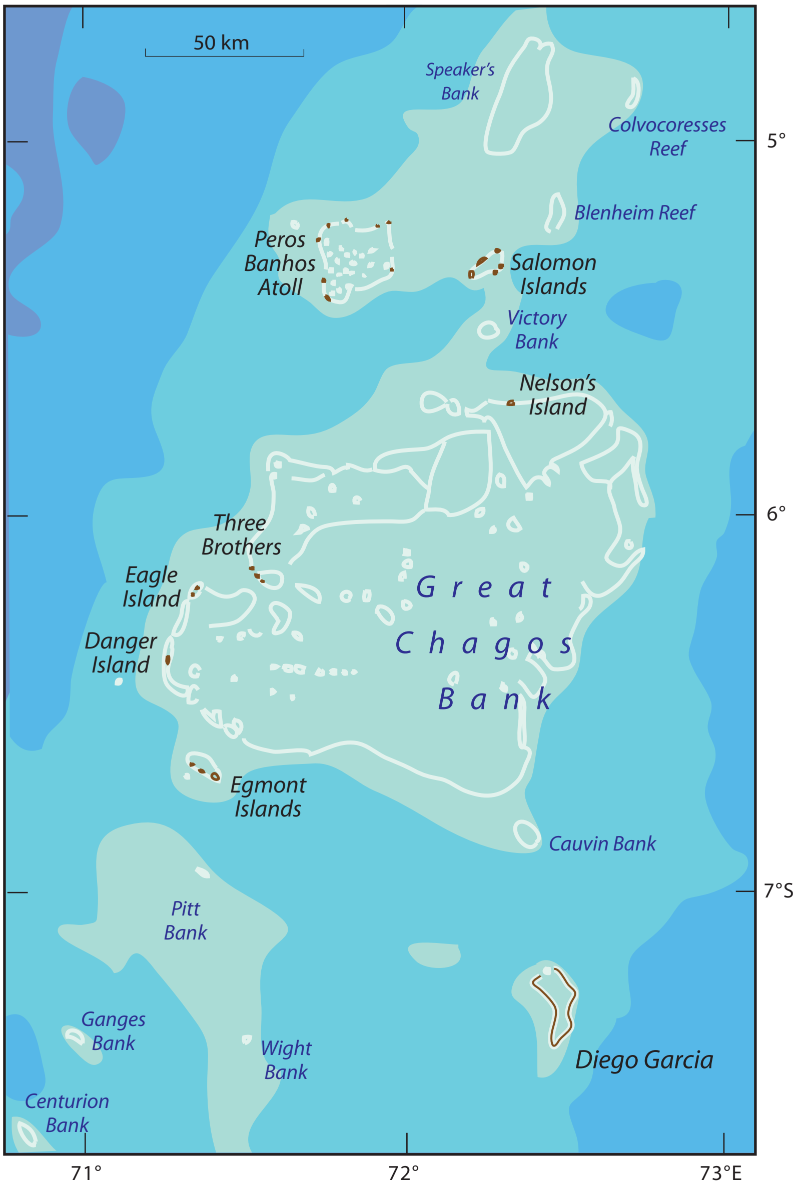
Turtle numbers are increasing in Chagos waters following heavy depletion in plantation days

people? And to do what? There is no infrastructure on those uninhabited islands, after all. There have previously been two proposals or suggestions. One put forward by the Chagos Conservation Trust several years ago advocated an 'Aldabra solution', namely a small group of 'wardens', supported from outside, who would help maintain conservation needs. The other proposal, by a Chagossian group supporting return, envisaged a massive development whose airport and port alone would have cost $100 million or more, with hotel, fish-processing plant, and more. So far, there have been no proposals for anything in between.

Given this difference in approach, and the desire of some to return and to undertake considerable development, what is the best thing to do about Chagos today, in the context of the whole Indian Ocean? The Chagos Archipelago is in the best possible condition in the increasingly overexploited and populated Indian Ocean and I would argue that every ocean really needs at least one surviving remnant of a large reef system in good condition, a legacy of the world's past. On the basis of research by myself and 50 others over several decades, I have argued that the Indian Ocean needs Chagos intact.

The Chagos islands are the exposed parts of coral atolls, but there are numerous other submerged atolls

Figure 4 *The Chagos Archipelago consists largely of the exposed parts (red) of coral atolls (white). Here submerged features are labelled in blue; land (red) is labelled in black. The land areas are on five different atolls; half of the land is the island of Diego Garcia which became a military facility in the early 1970s.*



Most reasons for this conclusion are scientific, but several are very pragmatic. The rich biological wealth of the Chagos Archipelago would certainly not survive the sort of fishing pressure and hotel, airport and port development that are typical of many Indian Ocean islands. How, therefore, could the reefs 'pay their way'? Does everywhere actually have to pay its way in fact, or can the world afford to retain a small number of such legacy sites? Today even most World Heritage Sites and Ramsar sites have extensive human habitation, and while some are more or less successful in combining human activities with the natural world, most now have a condition which is far from 'natural'. The Chagos Archipelago is one of very few tropical marine areas where, under water at least, conditions remain which are not affected by the distorting effects of over-extraction, local disturbance and pollution.

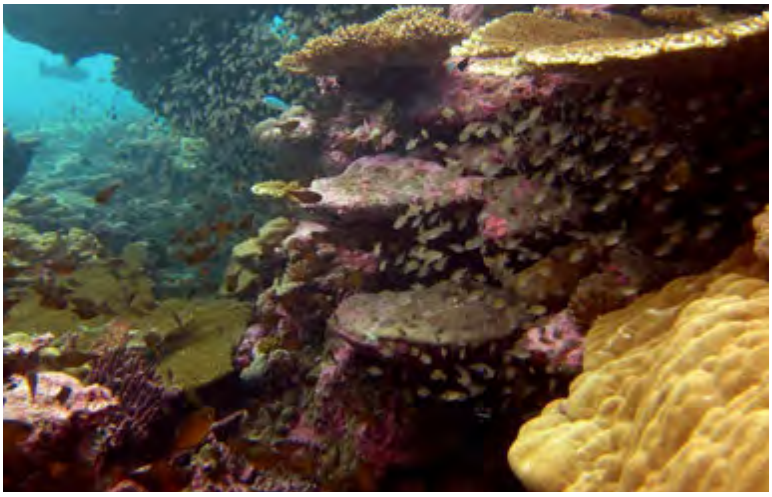
A third of the world's reefs are already dead, mainly because of overfishing, pollution and misuse. Reefs need to be cherished simply because they house the world's richest marine biodiversity, they provide essential protein for countless millions of people, and for many entire nations they provide even the land itself (which does not exist long if their component corals don't survive). For many countries they also provide important breakwaters which, when damaged, can no longer protect them from flooding and erosion – an important concern when much of that land is scarcely above sea-level. In short, coral reefs are needed, but today their prognosis is grim.

Conservation choices

The Indian Ocean does not provide many good examples of how to conserve the wealth of coral reefs for the benefit of people. This is because reefs don't tolerate well the impacts and insults inflicted upon them by people wanting or needing to be supported and fed from coastal habitats. Many countries in and around the Indian Ocean have a population-doubling time of little more than a decade; furthermore, when trouble strikes – wars or declining agriculture, for example – inland people commonly migrate or flee to coastal areas, making the population-doubling time shorter still.

It is said often enough that conservation is littered with examples of failure and destruction of resources because local people have not been properly engaged in the process. But while this is sometimes true, most conservation failures are of course caused by the people themselves, whether engaged or not: too many, too hungry, taking too

Figure 5 **Top** *Chagos has by far the highest recorded fish biomass in the Indian Ocean.* **Middle** Ctenella chagius*, the endemic brain coral of Chagos. There are few endemic species, probably because of the high interconnectivity of Chagos with the western Indian Ocean.* **Bottom** *Table corals were killed in large numbers in 1998, but have recovered well.*



Chagos's reefs consist of a wide variety of coral species, and support an enormous biomass of fish

much, so that the capacity of the habitat to support people is exceeded. Given human needs and behaviour, what can be done?

Conservation theory seems to go in cycles. One hundred years ago, westerners (including 'great white hunters') thought it best to exclude local people in order to conserve or preserve the habitats (or perhaps just the big game). This was unfair, and didn't usually work very well in any case. Then it was thought that the best way was to engage people in husbanding their habitats. This was socially nicer, but whether it worked any better or not may be judged by the results: the fact is that this recent phase has seen the greatest deterioration of natural habitats ever. Things may have been worse otherwise of course, but clearly conservation practices as carried out today are not working overall. As a result, examples of good habitat like that in Chagos are running out.

Candidate 'legacy' sites, which could have a good chance of remaining healthy in the future, are few and diminishing, and we must remember that once reefs are gone, all past evidence shows that we cannot get them back. Several 'targets' have been declared over the past few years concerning the amount of marine protected area that the world needs, declared by various entities such as the Convention on Biological Diversity, World Summit on Sustainable Development, World Parks Congress, and the like. All have failed by huge margins to reach the targets recognised as being essential for sustained human wellbeing. Chagos is perhaps the only large site in the Indian Ocean where it is still possible to retain sufficient example of what a natural reef complex should look like. The associated social dimension may still need a solution, but the science is pretty clear – the ocean needs Chagos as it is.

Chagos: precious reservoir of biodiversity

Corals throughout the Indian Ocean died in huge numbers in 1998 from an exceptional warming episode. Many complete reefs died and have remained useless to people. Chagos bounced back like almost nowhere else, because it suffers no extraction of key components such as fish, and because humans don't add other stresses to it either. New results on the biomass of reef fishes show that Chagos has the highest amount known in the Indian Ocean, dwarfing that of most other coral reef locations in the world, and only paralleled by some very remote unfished locations in the Pacific Ocean. This exceptional biomass is probably also the main reason why Chagos reefs bounced back so well after the 1998 warming, when so many other areas of that ocean still remain in a highly degraded state with a productivity which is incapable of supporting human needs.

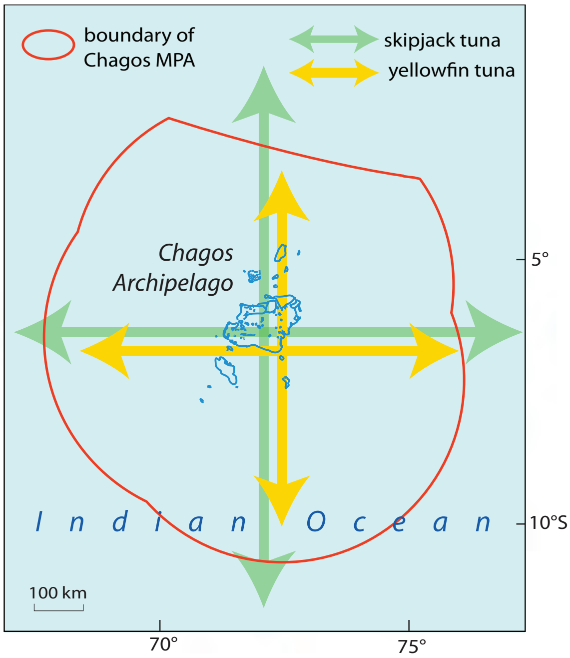
It is suggested too that Chagos is an important larvae source and sink for the western Indian Ocean, or at least an important biological 'stepping stone' for east–west movement of larvae. For four months of the year, currents flow from west to east across Chagos and for eight months they are mixed or flow from Chagos to the western Indian Ocean where many of the countries are amongst the poorest in the world. Early results of a genetic programme started a few years ago all show connectivity between Chagos and the western Indian Ocean for several groups, including turtles, the coral predator Crown-of-Thorns starfish, and several reef fish, with many more species being worked on now. The importance of this may be immense – not because there is some sort of 'current conveyor belt' taking fish from Chagos to depauperate African reefs; this is not the case, and nor is it necessary. All that is needed (given how fish breed) is the occasional transport of larvae to areas where they can grow and reproduce.

We do not yet know the rate at which this happens, but we are now clear that it is the case. Also, Chagos receives larvae from further west.

The new no-take zone will protect and conserve Indian Ocean tuna and other pelagic fish too (the by-catch from the tuna industry was immense). The pelagic situation in the Indian Ocean is not good: for oceanic fish like tuna, multinational fisheries laws are inadequate and fisheries practice is deficient, and of course fisheries companies are profit-seeking businesses. The Indian Ocean Tuna Commission has admitted its own deficiencies and in 2010 its performance was still lamentable. The fished skipjack and yellowfin tuna species have declined to the point where they have breached the conservationist benchmarks of concern and would qualify for listing by the IUCN Red List as being Vulnerable, a category meaning the species is considered to be facing a high risk of extinction in the wild. Using results from the Pacific (there are inadequate Indian Ocean data), it can be shown that the range of about half these fish throughout their lifetime is about the same as the diameter of BIOT's EEZ. That means that while half will leave (there is a large migratory route around the Indian Ocean), about half probably stay put, and thus Chagos will act as an important conservation area. The no-fishing rule causes substantial loss of revenue to BIOT, and of course is unpopular with some tuna-fishing organisations, but it is likely to be of immense value to the Indian Ocean fishery as a whole over the longer term. The clear no-take rules declared in 2010 also encompass about 300 seamounts whose different and rich biodiversity are increasingly targeted by gigantic trawls which can now extend to depths of kilometres. This large

Figure 6 *The median lifetime ranges of the two main tuna species that used to be caught around Chagos: skipjack and yellowfin. The area corresponding to these ranges is approximately the same as that of the Chagos MPA.*

Half the tuna found around Chagos may have spent their entire lives there



Marine Protected Area therefore provides a good basis for conservation of many key species and habitats in the Indian Ocean.

The special case of Diego Garcia

For military reasons, the waters within 3 n.m. of the atoll of Diego Garcia are not part of this huge MPA, but being able to conserve 99% of the area is still a major achievement. Two-thirds of Diego Garcia has its own network of Strict Nature Reserves requiring human exclusion, and most of it is a Ramsar site whose protective measures are enforced far more strictly than is the case for most such sites around the world – enforcement is a relatively simple matter in a military area. As a result, Diego Garcia's red-foot booby population has expanded to become the largest in the Indian Ocean (Figure 7), and the coconut crab is found there in densities averaging 300 per hectare, which is the highest in the world for these highly desired but Red-Listed species (Figure 8).

Furthermore, routine analysis of over 100 potential pollutants shows Diego Garcia to be probably the least polluted inhabited atoll in the world. In some respects, the military presence makes it a reference site for Chagos as a whole, in that no poachers go near that atoll, something reflected for example in its higher numbers of the highly targeted sea-cucumbers (much favoured by Asian consumers), which have been poached from more northerly parts. In addition, experimental work is underway in Diego Garcia to speed up the slow recovery of native hardwood trees where they were replaced by coconuts, to the benefit, we hope, of natural vegetation and birds.

A unique conservation opportunity

It was the accumulation of many scientific reports that led eventually to the creation of the Chagos MPA. The Pew Global Ocean Legacy programme selected a half-dozen sites around the world that fulfilled all of several criteria: they must be areas worth preserving; they must be large enough to make a global difference; they must have a governance which would be able to administer it appropriately – after all, with the best will in the world, nobody can ensure this kind of protection if the location has thousands of hungry mouths to feed. Formation of 'legacy' sites is therefore emphatically not a model for conservation generally, but rather is one component in a global network of diverse conservation measures. With the Chagos Archipelago properly protected, there will be at least one site where effects of global climate change can be studied without the confounding and confusing effects from factors such as overfishing, sewage and other disturbances caused by people. A range of science bodies and individuals supported the MPA creation, and at the same time an open letter from about 260 of the world's leading marine scientists was published, calling for more large MPAs.

Also recently formed is the Big Ocean Network, an informal (so far) network of scientists and managers of the world's largest half-dozen MPAs (more than a quarter of a million km^2) for the purposes of exchanging information and ideas for solving problems that are unique to such large areas; the median size of the world's other MPAs is less than 10 km^2 so they do not form a useful model for management.

The British Indian Ocean Territory came into existence in the first place because of perceived military needs during the Cold War. Then, no thought at all was given to other aspects – human or biological. Chagos is needed now for many more reasons than could have been envisaged back then, including its use as a reference site for other parts of the Indian Ocean that that are the subject of costly but largely ineffectual attempts at conservation. The Chagos reefs recovered from recent climatic fluctuations because they did not also suffer from local forms of degradation, and this is why it is thought that Chagos is amongst those sites that will survive global warming for longest. For these reasons and more, its scientific value is incalculable. Enormous care, not just hopeful aspirations, is now needed to ensure that its value survives. Most of the world does not have the luxury of time in this regard.

Some parties are hostile to the no-take MPA. For tuna fishers for example there is an obvious short-term commercial reason; Mauritius has a sovereignty claim on the area; some Chagossians want to return. The issues of the protected area have been confused in the past 18 months with issues of Chagossian settlement by those who claim that the new conservation measures are simply a ruse to keep Chagossians away. But this is nonsense: for the first 38 years since Chagossians were removed, 'conservation' was neither invoked nor needed. Only since the MPA declaration in 2010 was this removal conflated with conservation.

British Overseas Territories (OTs) occupy an unusual political niche, quite different from, say, the French model where the islands in question are more essentially part of France. In the case of the UK, 'Environment', for example, is delegated to each OT

Figure 8 *A coconut crab; some areas of Diego Garcia support an extraordinary 600 individuals per hectare. Though highly prized for eating, these crabs thrive in Diego Garcia, especially its Ramsar site. The adults reach 4 kg, and have a 90 cm leg span.*

A red-foot booby – the iconic species of Chagos

Figure 7 *A red-foot booby: the Indian Ocean's largest colony is on Diego Garcia, but there are also large numbers on many small northern islands of Chagos. These large seabirds feed on the abundant fish and squid in surrounding waters.*

government. Each OT government may or may not sign up to various international conventions, and Chagos has not done so in the case of the World Heritage Sites. The British Indian Ocean Territory government has instead agreed to treat the whole area 'as though it were' a World Heritage Site, but points out that the reason for its existence is military, and it might not accept all conditions should they arise. In the case of the no-fishing declarations which came into force in 2010, the government has also stated that any such decisions are 'without prejudice' to Chagossians, so that should policy change and some resettlement take place, the issue of fishing would be revisited. But here too we can see a minefield of conflict of needs: the commonly used phrase 'artisanal fishing' conjures up visions of people fishing with hooks or nets to feed a family. But 'artisanal fishing' now also means catching enough fish to export to pay for housing and infrastructure, an airport, a harbour, and a fish-processing plant. The dilemma has not been solved anywhere else so far!

For the Indian Ocean, there are perhaps no second chances. Because of its history, Chagos is its insurance policy. From the perspective of people in the Indian Ocean, an intact Chagos is needed. With declining ecosystems and with degrading and diminishing natural resources in most Indian Ocean littoral states, this need is pressing today.

Charles Sheppard is a Professor of Biological Sciences at the University of Warwick. He has visited Chagos for research for 35 years, and has led several international science expeditions. He is also the government's environmental advisor for BIOT. Charles.Sheppard@warwick.ac.uk

Return to Chagos

conservation and humanity can go hand-in-hand

Richard P. Dunne and Magnus Johnson

Charles Sheppard argues that the Indian Ocean needs the Chagos 'intact' – a euphemism for 'uninhabited' – to ensure the best chance for its survival 'in good condition' to benefit the region in perpetuity. We question this proposition on several evidential grounds.

The argument that the Chagos is 'an important larval source and sink for the western Indian Ocean' is a gross overstatement of the scientific evidence that exists. The ocean current patterns around the Chagos which would carry these larvae are complex and poorly understood. The known 'connectivity' so far is limited to a clustering of coral species similarity for the Chagos–Seychelles–Maldives which was interpreted as representing a stepping stone between western Australia and the Red Sea over geological time; the possible dispersion of the goldrim surgeonfish by larval transport from the eastern Indian Ocean to Diego Garcia; unpublished reports of genetic similarity in the crown-of-thorns starfish; indications that the Seychelles may provide recruitment of hawksbill turtles to the Chagos; and for populations of the brown surgeonfish, a genetic similarity between the Seychelles and Diego Garcia. Additionally, the fishes of the Chagos have been shown to be most similar to the Maldives but have only 7% of the species in common with the wider western Indian Ocean. Sheppard suggests that 'the importance of this may be immense' but the evidence remains very sparse and contains some contradictions. Furthermore, it still remains to be determined whether these genetic linkages were made in recent times or several thousands of years ago, and whether they represent ecologically relevant exchange as opposed to the level to maintain genetic homogeneity.

Secondly, Sheppard highlights one reason for the present great biological wealth as a 'lack of overfishing'. If this is indeed the case, then it is testament to the enforcement of fishing licences and conservation in the Chagos over the past decades. The Chagos has had fisheries legislation in place governing a sea area out to 200 nautical miles (n.m.) since 1991. In 2003 this became a more general Environment (Protection and Preservation) Zone. On paper, the protection is comprehensive, covering every marine organism. The more recent declaration of the Marine Protected Area (MPA) in April 2010 contains nothing new. The cessation of fishing licences in November 2010 was permitted by virtue of the earlier legislation. So, if the existing fishery under licence has resulted in the present 'great biological wealth' at the same time as feeding people then is there not a balance to be struck between the two purposes, one that is not recognised by a blanket 'no-take' area? Furthermore, there is no consideration of whether the Chagos 'no-take' area may simply result in a displacement of fishing effort which may be detrimental to other areas. The resources allocated to enforcement of the new MPA are also unchanged from what has existed over the last two decades. What has been lost, however, is the ability to monitor and analyse catch statistics. Ironically the complete ban on licensed fishing in the area will take away the one source of information that has been available. We would like to be able to report that there is to be a scientific programme in the British Indian Ocean Territory to monitor the effect of the new 'no take' area on the fish stocks, but unfortunately there is none.

Thirdly, in relation to the 'special case of Diego Garcia' the reality is that the US Military occupy the island – they demand a 3 n.m exclusion zone around the atoll so that no-one may enter without their permission. They have invested over US$3 billion since 1971, and built what is undoubtedly their most important overseas military base. With a UK/US treaty in force until at least 2036 (*Treaty Series No 15 (1967)*), they are not going to allow anyone, Chagossian or scientist, to meddle in this state of affairs. Let us also not pretend that Diego Garcia is a nature reserve or that it is pristine or unpolluted. Four-and-a-half million cubic metres of coral reef was blasted and removed in the construction of the base in the 1970s and '80s. Massive areas of the island were levelled and transformed, the lagoon was and continues to be dredged. Millions of gallons of jet fuel have been spilt into the island freshwater lens over the years. Huge military transport ships lie at anchor in the lagoon. Nuclear (SSGN, SSN) submarines dock alongside the USS *Emory S. Land*, a submarine support-and-repair ship on permanent station. Whilst Chagossian-crewed fishing vessels are no longer allowed to fish in other parts of the territory, foreigners on Diego Garcia (which they call 'Fantasy Island') plunder the seas with an annual catch of 46 tonnes of tuna and reef fish, purely for recreation.

Finally, the Chagossians' demand for a right to return to the islands does not make them 'hostile to the no-take MPA', and those that support them are not anti-conservationist. It is not the case that those who think the MPA has been used as a ruse to impede resettlement are confused, as Sheppard contends. It is an undeniable fact that the Foreign and Commonwealth Office told US Embassy officials in no uncertain terms that it would serve this purpose. It is equally clear that FCO policy has long been driven by opposition to resettlement and thus denial of the fundamental right of the Chagossians to go home.

There are many benefits that may accrue from the Chagos MPA, but let us not inflate its value, or misrepresent the facts in order justify the complete exclusion of Chagossian habitation of any sort whilst tolerating the presence of a foreign power and of wealthy yacht owners who use the northern islands as their playground. Five years after the last of more than 1150 islanders were deported in 1973, the first environmental survey recorded exceptionally high coral cover and healthy reefs. Despite 40 years of depopulation, this condition has deteriorated. Furthermore, all Chagossian groups have stated their commitment to conservation of their islands, even whilst in exile. The rights of the Chagossian people need to be recognised and they should be involved in the management decisions regarding the seas surrounding their homeland.

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Magnus Johnson is a lecturer at the Centre for Environmental and Marine Sciences, University of Hull. m.johnson@hull.ac.uk

For a fully referenced version of this article, please contact either of the authors.

Letters to the Editor

The preceding article, by Charles Sheppard, has been online at the Challenger Society website for some time, and in response to it we have received the article on the previous page and the letters reproduced below. *Ocean Challenge*'s interpretation of the thrust of the article differs from that of the critical correspondents, but in the interests of open debate we are happy to publish these contributions, especially as there seems to be much common ground. *Ed.*

Controlled resettlement could contribute to the protection of the marine environment

I refer to the article 'Protecting the Chagos Archipelago ...' by Charles Sheppard who is the Conservation Adviser to BIOT (Chagos Islands) and has, over the years, made a considerable contribution to the research and protection of the marine environment of the Chagos Archipelago. But his article goes beyond the purely scientific since it discusses the history and politics of the expulsion of the Chagossian people from their homeland.

The tenor of the article suggests that as a result of the expulsion of the Chagossians in 1968–73, and because so far they have not been allowed to return, the Archipelago survives as a pristine paradise with some of the richest biodiversity in the world. The article thus appears to argue against any return of Chagossians to their homeland. I am advised by scientific experts that some of Prof. Sheppard's evidence in support of his contentions is questionable. As Ocean Challenge *does not require supporting references* unsubstantiated claims can be made as if they were established scientific fact.*

The Chagossian people have declared their intention to be the custodians of their precious environment and with suitable training could fulfil such a role. Sheppard juxtaposes his 'Aldabra solution' with a 'massive development whose airport and port alone would have cost $100m or more, with hotel, fish processing plant, and more. So far there have been no proposals for anything in between'. He exaggerates this much earlier scenario but in any case is fully aware of a proposal 'in between' which emerged from a conference on 19 May at the Royal Geographical Society to which he was invited. This is for a Marine Park Base and Scientific Research Station which would be serviced by Chagossians, living in an eco village nearby. This proposal was put to the Foreign Secretary on 27 June by the novelist Philippa Gregory and broadcaster Ben Fogle, both Patrons of the UK Chagos Support Association, when they called on him to discuss the outcome of the conference and the way forward.

The Chagos Islands All-Party Parliamentary Group, of which I am the Coordinator, believes that environmental protection and resettlement can be compatible and planned in such a way that the environment may actually benefit.

The article contains doubtful assertions on the historical, political and defence background. Its underlying purpose appears to have been to raise alarm about the prospects of resettlement.

David Snoxell
Deputy Commissioner of BIOT, 1995–7; British High Commissioner to Mauritius, 2000-04; Coordinator of the Chagos Islands (BIOT) All-Party Parliamentary Group from 2008.

Chagos MPA: an achievement to be proud of

The article ' Protecting the Chagos Archipelago ...' by Charles Sheppard is, I believe, a good reflection of what Chagos needs in the era in which we are living. The removal of the natives of the archipelago was indeed amongst the most sad episodes in British Foreign policies history, which the last and the actual Government of the UK have both regretted openly.

I am proud that the Chagos Conservation Trust, the Chagos Environment Network (which includes many eminent science bodies and many other supporters including several who have given and are giving practical assistance to Chagossians), and Professor Charles Sheppard and the 100 scientist collaborators he has engaged in Chagos, came up with the idea of the Marine Protected Area.

The UK government launched a consultation process in which my people have participated fully to declare this protected zone. We are being trained to work in conservation and play our role although we live outside of our homeland. I have personally led a team of young people on a mission to Diego Garcia where we have done some conservation work in June this year.

The situation regarding return is a complex one. There are many questions which have not been addressed, such as how many people would return and where would they want to return? I have pioneered the resettlement of my people in the UK from 2002; some would want to return while others would want to remain permanently in the UK. I can say from experience that this is a complicated issue. There are many people outside of our community who want to lead us in what they believe is good for us, but it's up to the Chagossian people to say what they want to happen.

There are two most significant steps that we have made as a people – our move to the UK and the establishment of the Marine Protected Area of Chagos.

President Allen Vincatassin
Diego Garcia and Chagos Islands Council
The Provisional Government of Diego Garcia and Chagos Islands (in waiting)

****Editor's Note*** Ocean Challenge *does not use references as it aims have an accessible style. Articles are read carefully by Editorial Board members and when necessary checked for accuracy with the help of other experts. This particular article came to us via the British High Commision in the Seychelles.*

Book Reviews

Synchronised swimming in the sea? It's not all moonshine

Chronobiology of Marine Organisms by Ernest Naylor (2010) Cambridge University Press, 242pp. £45 (hard cover, ISBN-10: 0-521-76053-4; ISBN-13: 978-0-521-76053-9; also available as a Mobipocket eBook from ebooks.com, ISBN-13: 978-0-511-68242-1).

I look over the first-year students gathered in the lecture room, take a deep breath, and begin with an ice-breaker my old professor used: 'What I am about to tell you is either wrong, or will, in time, be proven to be wrong, or perhaps if you're lucky, will be found to be only partially correct'. This raises eyebrows and murmurings which I particularly enjoy since this information flies in the face of what most students believe they are coming to university for. In a similar vein, Ernest Naylor's latest book, *Chronobiology of Marine Organisms,* starts by telling the reader that some of the pioneers of modern chronobiology were not only howling up the wrong tree, but in the wrong forest altogether. I do apologise: this is my analogy, not Naylor's, though the irony in the title of the first chapter, 'Moonshine', was not lost on me.

The early pioneers of chronobiology (the study of biological clocks) had correctly identified that nearly all organisms they maintained in the laboratory under constant conditions, without day/night or tidal cycles, displayed innate biological rhythms. However a prominent selection of researchers were insistent that these behaviours were controlled by external environmental factors, such as lab-penetrating cosmic rays, rather than what we now know to be internal physiological clocks. Although their laboratory observations were entirely correct, their conclusions were most certainly not. It took a concerted effort by co-workers to change this view with meticulous experiments leading to the eventual discovery in 1971 of the molecular basis of the endogenous circadian clock.

Naylor's book provides its readers with a fantastic insight into the link between those (to many oceanographers at least) nebulous biological processes and the highly quantifiable physical environment the organisms inhabit. I have often heard oceanographers exclaim – I am a biologist, incidentally – that when we drop our instruments into the sea, biology just gets in the way – not only do critters stick to our sensors but other dubious looking small beasts migrate around in the water column spoiling an otherwise clear view of what the ocean is doing. Naylor informs us that these same organisms have a fabulous ability to use the ocean currents as a highway, turning up in all sorts of places, tens, sometimes hundreds of kilometres from where they originated. They undergo surprisingly precise daily vertical migrations, familiar to any scientist working with acoustic data, and those that live mainly in estuaries are perfectly able to stay put or migrate for tens of miles inland in a clearly orchestrated manner. Naylor's book informs us that many organisms that live in the sand or mud in the intertidal zone know not only when the tide comes in but how the tidal ebb and flow changes over the lunar month. The worms, crabs and even some plants on the shore understand (to be horribly anthropomorphic) about spring and neap tides and they adjust their activities accordingly.

Sally Lightfoot crabs on the shores of the Galapagos, dancing to the rhythm of the tides (taken from the book's cover)

Perhaps the greatest surprise to the chronobiologically uninitiated comes when Naylor explains that one polychaete worm in particular has a tremendous time-piece. The Pacific Palolo worm will spawn on only a few nights every year in either October or November, depending on the timing of the third quarter of the Moon. In what has been dubbed a 'nuptial dance', the headless tails of the worms, both male and female, swarm in the water column releasing sperm and eggs. Astonishingly the Palolo's sexual activity can be tracked with a 19-year period, also called the metatonic cycle, which must certainly be one of Nature's finest examples of long-term time-keeping.

So what is the time-piece of such a natural feat of synchronicity? Naylor explains that the internal clocks are made up of a suite of genes that control their own expression with complicated feedback loops, and which are set by the environmental inputs from the Sun, Moon, tides and their various associated harmonics of which there are probably hundreds. Once the clocks are set or entrained, they will provide temporal information to their owner much like a wrist watch does to you or me. This clock will allow the organism to accurately navigate, migrate, and reproduce etc. with astonishing synchrony. The behavioural and physiological consequences of having an internal clock provide highly orchestrated and quantifiable results – if you are clever enough to design the experiments, and patient enough to gather the data!

This book is primarily aimed at a scientific readership or, at the very least, those who are familiar with interpreting graphs. It is easy to follow and reasonably self-explanatory though I do feel a glossary of terms would have been useful. I think it would be highly valuable to any budding marine biology undergraduate and anyone involved in the field of purely terrestrial circadian biology. Finally, I think it would also be of interest to those oceanographers who may have wondered why their backscatter data look funny at night. Indeed, whatever your speciality, I suggest you pack a copy of Naylor's book for your next cruise!

Kim S. Last
Scottish Association for Marine Science (SAMS)

Going up?

Understanding sea-level rise and variability edited by John Church, Philip Woodworth, Thorkild Aarup and Stanley Wilson (2010) Wiley– Blackwell, 428pp. £40 (flexicover, ISBN 13: 978-1-4443-3452-4).

This collection of 13 papers arising from the World Climate Research Programme (WCRP) meeting in 2007 is an excellent introduction to the subject of sea-level science. Rarely have I sat and read such a text from beginning to end, yet doing so in this case was very enlightening and well worth the effort. Few areas of oceanography are as multidisciplinary as sea-level change and this book reflects the breadth of the work that is currently being undertaken. This is no simple review of the subject though. It is self-consciously a look at the state of the art and the open questions facing climate scientists.

The book is generally of a high quality and well presented with few weak papers. Most subjects are covered, with a comprehensive review of existing sea-level observing systems, including a critical review of their strengths and weaknesses; there is also an appraisal of what needs to be done to improve each of these systems in order to reduce the uncertainties in the various contributions to sea-level change, both positive and negative.

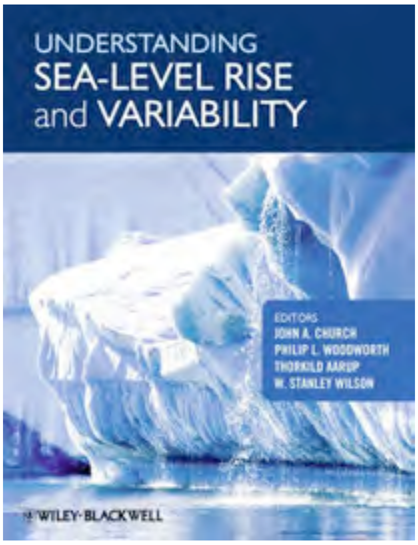
The opening chapter provides a high-level overview of the problems facing society as a result of increasing sea-level. The chapter also explains the context of the WCRP and how it complements the IPCC process. As the chapter states, the meeting started 'with the IPCC uncertainties and focusses on the scientific and observational requirements needed to reduce those uncertainties'.

The chapter on mitigation of, and adaptation to, sea-level rise was interesting for the emphasis on relative sea-level change. Too often, scientists and the media focus on global mean sea-level which hides the wide range of sea-level change experienced at the coast – in many places where the land mass is rising, sea-level is actually falling relative to the land. Most damage is also caused by extreme sea-levels rather than changes in mean sea-level itself, although an increase in mean sea-level makes those extremes more likely to occur. However, the effects of sea-level on the sinking megacities of Asia is particularly important. This process is going on regardless of anthropogenic climate change due to a variety of causes ranging from groundwater extraction to the compaction of delta sediments. There is a particularly arresting image of submerging telegraph poles, now a kilometre out to sea, south of Bangkok in Thailand. This local rise in sea-level has severe implications for the 12 million inhabitants of the Greater Bangkok area, where subsidence rates of more than 100 mm per year are observed in some localities.

There is a dedicated (if rather thin) paper on offshore structures and oil refineries, which obviously are of very significant economic importance. For me, this was the weakest part of the book, though it is quite clear why it is there. The punchline of the paper? There is very little impact from sea-level rise on offshore structures due to their short life-span and largely floating nature in deep water. The main impact on offshore structures is likely to come from any change in extremes. For shore-based infrastructure the story is a little different since the time-scale of operation is much longer, but the estimated global cost (of US $4–6 billion for a 50 cm rise in sea-level) is negligible for the industry as a whole.

The next chapter is a thorough review of palaeo-environmental data and methodologies, with a useful examination of the limitations of present data. There are pointers to where improved data would be most effective, and an exploration of the main modelling issues to be resolved. Again, the point is made that most places do not experience the global mean rate, and that local and regional departures are often more important and scientifically more interesting.

There follow interesting chapters reviewing the significant steps forward in recent estimates of sea-level change (using altimetry, tide gauges and saltmarsh proxies) and steric (density-related) contributions from temperature and salinity changes. Then there comes a paper dedicated to cryospheric contributions to sea-level change. I found the sections on the limitations of data-coverage relating to glaciers and ice caps (both those at low latitudes and those associated with ice sheets) particularly compelling. However, this chapter also felt the most uneven in the book, perhaps due to the large number of contributing authors.



The size of the terrestrial water-storage contribution to sea-level change was a nagging concern to the community even before the Third IPCC report in 2001 showed that this aspect dominated our uncertainty in the sea-level budget. I found this section of the book fascinating and, more than any other paper in the collection, it demonstrates the limitations of our current knowledge. The overall contribution from water storage could be huge – it appears to be so on annual time-scales, but over decades the residual trend appears to be small. Terrestrial water is hard to measure, and even harder to model due to the lack of knowledge of subsurface processes. The hydrologic processes in which the authors feel they have 'medium confidence' actually sum to $0\,mm\,yr^{-1}$. However there are substantial remaining uncertainties and many potential contributions for which only very poor estimates are available.

I found the chapter on geodetic observations enlightening but also the most challenging, perhaps due to my own lack of familiarity with much of the material. This is a crucial and often overlooked aspect of sea-level science. With both land-level and sea-level changing at the same time we need a stable 'reference frame' in which to place our observations. So many of our measurements are made by satellites that interpretation is impossible without it.

There are further stimulating chapters on the important aspects of surface mass-loading effects and on past and future changes in extreme sea-levels. The latter section was especially noteworthy in that the most recent results seem to suggest that future climate will not change extremes or significant wave height to any great extent. However, the probability of a given level being exceeded will increase simply due to the higher mean sea-level. For this reason, increasing mean sea-level will lead to more extreme sea-levels and therefore increased losses due to flooding.

After a chapter on the observing systems needed to address sea-level rise and variability, the book ends with a synthesis and outlook. Clearly, there is a need for continuity in observational programmes, and in a time of constrained expenditure the challenges for maintaining expensive space-based measurements are considerable. However, I finished the book with a strong feeling that without these programmes the considerable threat to society from rising sea-levels would cost vastly more than any short-term cuts would save.

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Oceans, weather and life

The Dance of Air and Sea: how oceans, weather and life link together by Arnold H. Taylor (2011) Oxford University Press, 288pp. £16.99 (hard cover, ISBN 13: 978-0-19-956559-7).

Arnold Taylor regales us with a tour through atmosphere–ocean interactions and the climatic, societal, and ecological impacts of these interactions. The book's strap line is 'how oceans, weather, and life link together' and for anyone looking for in a readable account on this topic, I'd highly recommend this book. Taylor's style is broadly in the popular science category, with science progress described very much though key protagonists (from the 17th century to the 21st) and numerous anecdotes about their lives and careers. In general, these stories are engaging, often fascinating. Some of the stories I was familiar with, others I was not. For topics I was familiar with I would say the author has done a very good job of presenting a balanced account of the science, and added enough 'colour' to make the book an enjoyable read for someone knowledgeable in that area. For topics further from my expertise (for example, the ocean–atmosphere impacts on ecosystems such as Lake Winderemere or the North Sea) I found the author's account truly engaging and learnt a lot.

One of the central themes of the book is the North Atlantic Oscillation, what it is, how it was discovered, and the many and diverse phenomena that are directly or indirectly (strongly or weakly) affected by it – the list is long! The book is not broken down into discrete topics. Rather it is more of a tour through the subject, with particular focus points on aspects that the author clearly finds fascinating or has a great deal of expertise in. Hence it is rather pointless to outline the content of each chapter, so to give an idea of the topics covered I'll list a selection – plankton, ocean circulation (focussing on the North Atlantic and the thermohaline circulation), weather and climate of the North Atlantic–European region, chaos theory as applied to simple nonlinear ecosystems, global circulation with a focus on maritime weather, teleconnections or climate modes, ecosystem 'bellweathers' for climate, past climate changes and future climate change, with both the latter two chapters taking more of an anecdotal approach and so covering a few areas briefly. In other words, this is not a book about climate change; it's a book about the Earth system, and in particular how the atmosphere–ocean system works, and its impact on ecosystems and society.

The book has ten chapters, but as mentioned above these are not on discrete topics. They are more like parts of a journey. The text is illustrated with black and white graphs and schematic diagrams, typically just a few in each chapter, which certainly aid the reader's understanding and provide quantitative information. However, many of the graphs are simply time-series style plots, often illustrating the correlation of something with some aspect of the ocean–atmosphere circulation. So although useful, they are not extraordinary. There is a comprehensive referencing of the text using numbered citations and endnotes collected by chapter at the back of the book. Being a researcher by nature, I found myself flipping to the back of the book throughout many chapters, and certainly at the end of each chapter, and thinking some of these references may be useful in my own research. Especially as, from what I can tell, Taylor has stuck mainly to references that are specific to the points he makes, often in more generalist journals such as *Nature* or *Science*, or to readable science journalism pieces from *New Scientist,* for example. Also at the back of the book is a short glossary, certain to be very useful to some, and of course a decent index.

The Dance of Air and Sea comes across as a personal book written by a highly knowledgeable first-rate scientific researcher with the knack for telling stories. The stories do tend to jump around quite a bit, rather like a vibrant party conversation – you have to be ready for rapid changes and this can on occasion get a little tiring. However what it occasionally lacks in smooth story-telling, it makes up for with interest and enthusiasm. All in all, I would definitely recommend *The Dance of Air and Sea*, both to readers with a professional interest and to those who are simply fans of popular science – I think I'll be lending my copy to my Dad (who's in the latter camp).

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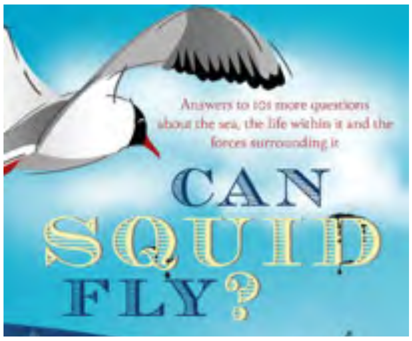

More quirky Q&As

Can Squid Fly? Answers to 101 more questions about the sea, the life within it and the forces surrounding it by Tony Rice (2010) A & C Black Publishers Ltd, 160pp. £9.99 (paperback, ISBN 13: 978-1-40-813320-0).

He's done it again. Tony Rice has returned and is pulling us back into the ocean. When we thought he'd exhausted his treasure-trove of sea-faring knowledge, he sails back bearing more questions and quirky answers. *Can Squid Fly?* is here to whet your appetite for the sea or quench that thirst that's been lingering since you turned the last page of *Do Whales Get The Bends?*

The author returns like an old friend, chatting as if he's never been away. *Can Squid Fly?* is really an extension of *Do Whales Get The Bends?* with all the best bits plus more. As before, this book covers a wide spectrum of topics from the g's of geology and geography to the p's of pastimes and physics. Who knew there were so many questions to be asked?

An attractive and enlightening addition to the book (which I originally took to be only for children because of the humorous title and colourful cover – how wrong was I?!) are photos from Tony Rice's personal photograph collection. He takes pride in being an amateur photographer and allows us for once to feel a little superior. Mixed in with the sketches and graphs we saw in *Do Whales*, the photographs convey even more excitement about the fascinating things we might see if we were to follow in Tony Rice's 'wake' onboard a fishing boat or cruise ship.

Thankfully, one thing that hasn't changed from the first instalment is Tony Rice's knack of providing answers to technical questions in digestible portions for those of us who are landlubbers. With the addition of the further reading section and related website addresses, Tony Rice welcomes us into his world of whales and squid with open arms.

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