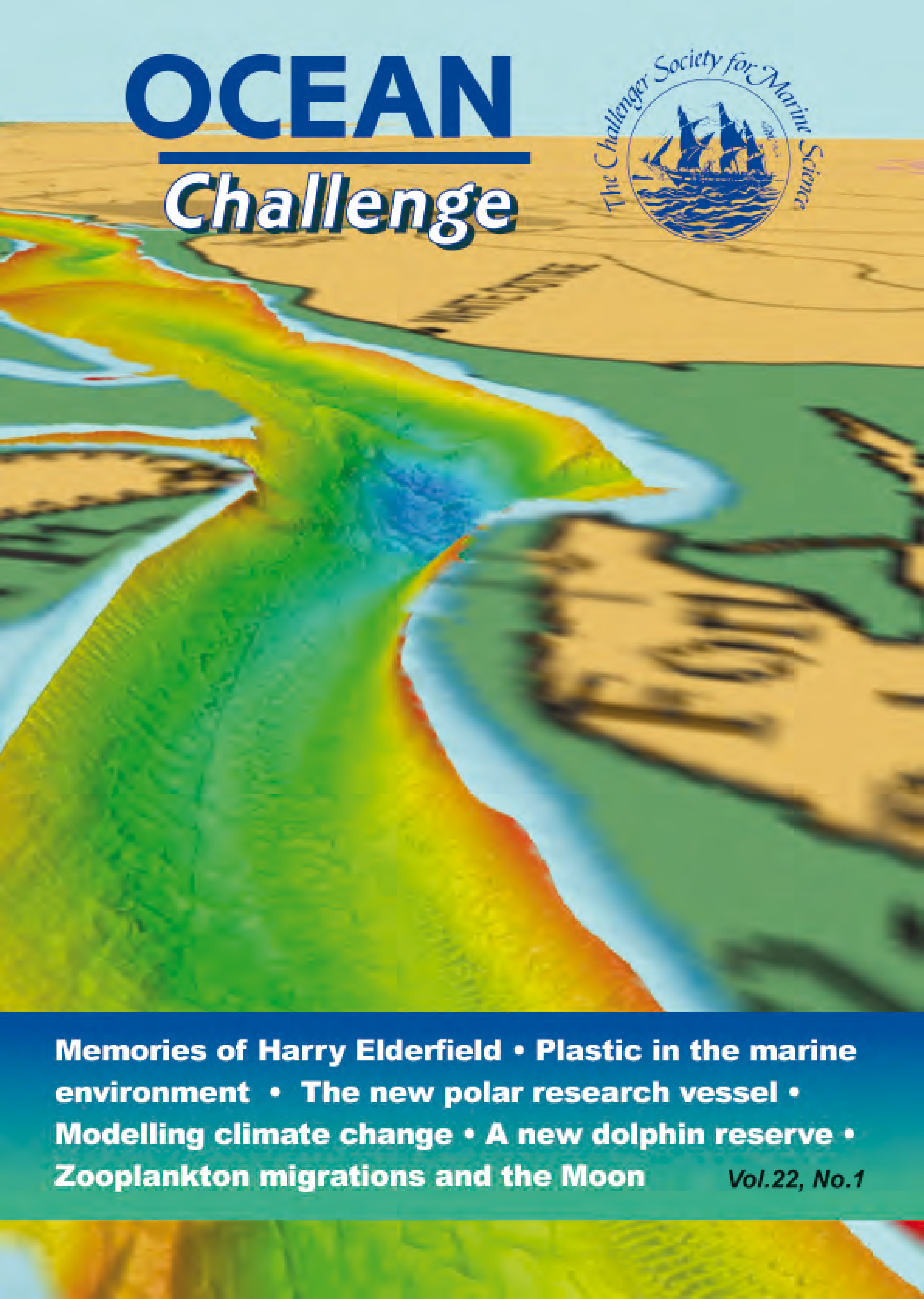

OCEAN Challenge

The Challenger Society for Marine Science

Memories of Harry Elderfield • Plastic in the marine environment • The new polar research vessel • Modelling climate change • A new dolphin reserve • Zooplankton migrations and the Moon

Vol.22, No.1

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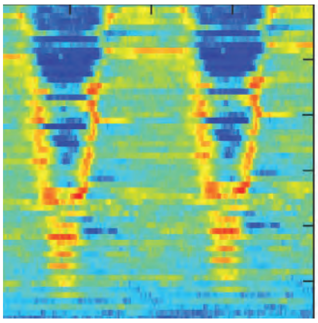

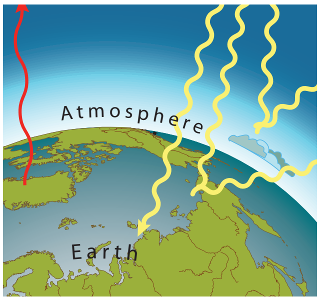

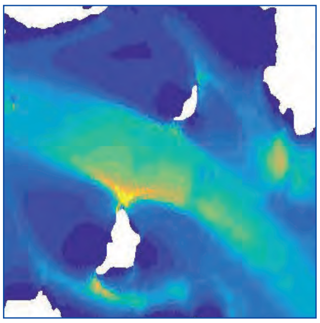

Most of the maps and diagrams were drawn by The ArtWorks.

The cover and heading graphics were designed by Ann Aldred.

Cover image by courtesy of School of Ocean Sciences at Bangor University (for full details, see overleaf)

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The cover image was generated from multibeam sonar data collected and processed by Jim Bennell, School of Ocean Sciences, Bangor University, through research undertaken via the Sustainable Expansion of the Applied Coastal and Marine Sectors (SEACAMS) project, Grant Number 80366.

Winners of the 2016 Challenger Society Conference Photographic Competition

Right
'Midnight nets, open ocean, beauty and utility, simplicity and complexity – a sea of questions'
by Corinne Pebody

Below
A bull southern resident killer whale (sometimes known as 'Onyx') off the coast of British Columbia
by Brittany Visona

Message from the Editor

Welcome to the latest issue of *Ocean Challenge*. Unusually, we have three articles that relate to modelling, including the results of the RAPID prediction competition. The impact of the ever growing amount of plastic in the marine environment is considered in a group of articles, the last of which describes an innovative and surprising approach to the problem. For those who enjoy the history of oceanography, Tony Rice brings us his latest installment in the story of the *Lightning*, a forerunner of HMS *Challenger.* And we have an article explaining why people on vessels in the middle of the South China Sea are receiving mobile phone messages saying 'Welcome to China'!

The polar oceans feature prominently in this issue – we have a report on the new polar research vessel, RRS *Sir David Attenborough*, an article on the Arctic's freshwater budget, and one whch explains why the French explorer Jean-Baptiste Charcot is fondly remembered in Iceland. In the feature article, Laura Hobbs explains why zooplankton in the darkness of the Arctic winter continue to migrate up and down in the water column.

There are also warm tributes to Harry Elderfield, a past President of the Society, and valued colleague of many in the marine science community, who died in 2016.

Angela Colling

Awards presented at the 2016 Challenger Society Conference

Last year's Challenger Society biennial conference was held in Liverpool. In the past, the best submitted reports of the conference were published in *Ocean Challenge*, but this time a group of accounts by enthusiastic young delegates who received Society funds to attend the conference can be found on the Challenger website.

As usual, awards were made at the Conference dinner, which on this occasion was held in the spectacular Anglican Cathedral. The Society's most prestigious award, the Challenger Medal, was presented to Professor Karen Heywood (University of East Anglia). The award is in recognition of her major contribution to physical oceanography in the UK and worldwide, notably her contribution to understanding physical oceanographic processes in the Antarctic, her work in applying novel techniques to understanding ocean processes, and her wider work in developing UK marine science, particularly within SCOR (Scientific Committee for Oceanographic Research).

A windswept Karen in the Southern Ocean

Challenger Society Fellowships were awarded to Nick Higgs (Plymouth University), Bee Berx (Marine Scotland Science, Aberdeen), and Alessandro Tagliabue (Universiy of Liverpool).

Malcolm Woodward (Plymouth Marine Laboratory) was awarded an Honorary Life Membership of the Society. The award reflects the enormous amount of work Malcolm has done for the whole marine science community in leading cruise logistics and planning, in helping design the operating space on several new and planned research ships, and in providing much of the nutrient data that has underpinned the UK community's biogeochemistry effort for the last 30 years (including major contributions to the development of high sensitivity measurement techniques and international nutrient quality control). We hope to publish an interview with Malcolm in a future issue of *Ocean Challenge*.

The Norman Heaps prize for the best early-career oral presentation was awarded to Shaun Fraser (University of Aberdeen) for his talk on 'Characterising turbulence in a tidal channel using observations from seabed platform deployments'. The Cath Allen prize was awarded to Anna Belcher (NOCS/University of Southampton) for her poster on: 'Can particle-associated microbial respiration help explain imbalances in the mesopelagic carbon budget?' The prize for the presentation with the biggest societal impact (sponsored by MASTS) was awarded to Ruth Paterson (Scottish Association for Marine Science) for 'Keeping shellfish safe: new technologies help protect consumers of cultured shellfish

Malcolm Woodward displays his Life Membership certificate

from toxic algae (*Azadinium spinosum* and azaspiracid toxins) in Scottish waters'.

The joint winners of the Presidents' Photographic Prize (chosen by both incoming and outgoing Presidents) were Corinne Pebody and Brittany Visona. Their winning photographs can be see opposite.

At the Challenger Society AGM, held during the Conference, Tim Jickells passed the Challenger gavel on to incoming President Rachel Mills. Tim is remaining on Council as Immediate Past President. Newly appointed to Council are Rob Hall (University of East Anglia) and Richard Sanders (National Oceanography Centre Southampton). Retiring Council members, Abigail McQuatters-Gollop and Chris Comyn were thanked for their hard work for the Society.

The 2017 AGM will be during the AMBIO VIII Conference, to be held in Oban in September. For more information, see p.31. *Ed*

Memories of Harry Elderfield

Many Challenger Society members will remember Harry Elderfield from his time as President of the Society (1998 to 2000), but not all will know of his enormous contribution to scientific research. Since Harry's death in April 2016, friends and colleagues have been recalling his achievements and how he impacted on their lives: four personal tributes are given below. For a more detailed discussion of Harry's wide-ranging research career, see the obituary by Rosalind Rickaby in *Nature:* https://www.nature.com/nature/journal/v533/n7603/full/533322a.html.

One of the great world-leading scientists

Harry was one of the great world-leading scientists, a true gentleman and the academic father of oceanic trace metal chemistry. He was awarded the Challenger Medal in 2012 for his sustained contributions to the Society and his field of research. Harry was one of the foremost scientists of his generation, as is reflected by the many honours he was awarded over his lifetime. He was recognised for his contributions with several notable awards including the Lyell Medal in 2003, the Urey Medal of the European Association of Geochemistry in 2007 and the V.M. Goldschmidt Award in 2013. He was awarded many Fellowships during his career and was elected as a Fellow of the Royal Society in 2001.

Harry was Professor of Ocean Geochemistry and Palaeochemistry at the Godwin Laboratory, Department of Earth Sciences, Cambridge University. His work has shown how and why the chemistry of the oceans, atmospheric carbon dioxide and global temperature have changed over time. One of his most important contributions was the establishment of new tools for analysing seawater through studying the chemistry of fossils buried in deep-sea sediments. His work has had a far-reaching impact on our knowledge of the Earth's make-up.

Like many of us in the field, I carried out my Ph.D under Harry's supervision. His mentorship, friendship and extraordinary intellect sustained my efforts for many years. One of the highlights of our work together was our British–Russian Atlantic Vents Expedition in 1994, where Adam Schultz and I served as co-Chief Scientists, and Harry was the Expedition Leader. Harry was an exceptional collaborator in the lab, on the ship, in the office – always bringing new insights, intellectual energy, and quiet challenge to the problem at hand. His legacies to marine science include the huge number of scientists whose careers he stimulated and the ideas that have transformed our understanding of the ocean and Earth system. His death is a great loss to the Challenger Society and to the world-wide community in which we carry out our work.

Rachel Mills
President of the Challenger Society

Harry receiving the 2012 Challenger Medal from President Hilary Kennedy

A long and wide-ranging career

I began working for Harry in March 1977 on his project to determine the rare-earth elements in seawater, then was privileged to work with him for thirty-nine years on a succession of projects and research grants. During this time I observed the progress of Harry's research and that of more than forty research students, the most recent being Lil Read, who continues at Cambridge under co-supervisor Simon Redfern.

Harry Elderfield's research was described succinctly by his title of 'Professor of Ocean Geochemistry and Palaeochemistry'. Harry was a chemist by training and a student of J.P. Riley and Roy Chester at Liverpool. His early work on ocean chemistry, beginning with his first paper in 1970 on chromium speciation in seawater, provided the framework for his later interests. During the 1970s Harry published papers on the mineralogy of iron–manganese oxides and sediments, followed by work on the rare-earth element geochemistry of ferromanganese nodules, sediments and seawater, which became a major focus of his research in the late 1970s and 1980s. In 1982 Harry moved to Cambridge and continued to work on rare-earth element geochemistry and the development of Cenozoic strontium isotope stratigraphy. The third major area of Harry's research was hydrothermal plume chemistry where, working with Adam Shultz and others, he linked physical models of plumes with chemical modelling to show that reactions in plumes cause hydrothermal systems to behave as a sink for many metals as well as a source for others.

Palaeochemistry became the dominant feature of Harry's research in the mid 1990s, when he was a pioneer in the use of chemical proxies from biogenic carbonates. Harry developed the Mg/Ca palaeothermometer with Gerald Ganssen and, with post-docs and students, developed and applied the Cd/Ca, Mg/Ca, Sr/Ca and B/Ca trace element proxies to explore the ocean carbonate system. In the midst of the activity in development of trace element proxies, Harry added a dose of realism when in 2002 he published the 'Paleoceanographic Proxy Confidence Factor Phase Chart', better known among the geochemical and palaeoceanographic community as the 'Elderfield curve'.

In 2011 Harry began a project linking geochemistry, biomineralisation and palaeoclimate. This combined development and refinement of analytical methods with investigation of biomineralisation of living calcifiers, and application of climate proxies. A major publication was Harry's 2012 paper in Science *on the evolution of ocean temperature and ice-volume through the mid-Pleistocene climatic transition, the culmination of twelve years' work on development and calibration of the Mg/Ca temperature proxy applied to benthic Foraminifera.*

Going to sea with Harry provided extra insights into his research and the way he worked. Harry was a practical chemical oceanographer who enjoyed seagoing research and participated in twenty research cruises during his career: to the Atlantic, Pacific and Indian Oceans, the Mediterranean Sea, the British Columbian Fjords (to study redox processes) and five cruises to the Mid-Atlantic Ridge to study hydrothermal processes, including expeditions to the TAG and Snakepit Vent fields on Alvin and the Russian Mir submersibles.

Harry left behind an enormous legacy. Many of his former students are established researchers, lecturers or professors at institutions in the UK and around the world. Among Harry's former graduate students, seven work at Southampton's National Oceanography Centre: Martin Palmer, Stephen Boswell, Rachel Mills, Paul Wilson, Rachael James and Matthew Cooper. Elsewhere in the UK, Hilary Kennedy is at Bangor, Rob Upstill-Goddard at Newcastle, Rosalind Rickaby at Oxford and Pallavi Anand at the Open University. Simon Wakefield, Caroline Lear and Stephen Barker are in Cardiff University's Earth Sciences Department, and David Thornalley is at University College, London. Sarah Bury became a lecturer in New Zealand and Samia Mantoura, Jimin Yu and Oscar Branson are in Australia. Chris German runs the deep submersible group at Woods Hole Oceanographic Institution, and Tim Conway is now at Florida State University.

Harry was always polite, courteous and knowledgeable. I had the pleasure and privilege of working with him for almost four decades.

Mervyn Greaves
Department of Earth Sciences
University of Cambridge

Harry, assisted by Laura Robinson, sampling deep-sea sediment from a box core, on RRS Charles Darwin

Harry in Florence for the Goldshmidt Conference in 2013

A 'scientific explorer' and remarkable analytical chemist

As an undergraduate at Leeds University (1968 to 1971) I was inspired by a series of lectures on aquatic hydrogeochemistry and chemical oceanography. The lecturer was a youthful Harry Elderfield who was just setting out on his lecturing and research career. I jumped at the chance to undertake a Ph.D with him when I graduated, and this set me towards a fulfilling life in freshwater environmental research.

It was immediately clear that I was working with a very deep-thinking and skilful researcher who was always modest, very positive and supportive. Harry's research was linked to the attenuation of transition metals from riverine sources to the estuary, the continental shelf and the open ocean, as well as diagenetic processes within bottom sediments, and my Ph.D fitted in with this. He started on the quest to address the profound issue of what hydrogeochemical processes might occur at mid-ocean ridges, and his work became central to the then emerging issue of how the oceans operate chemically, and how processes in the freshwater, estuarine and marine environments affect the behaviour of elements across the Periodic Table; it also became key in studies of climate change.

Harry was an explorer – finding new things about how elements behave in the marine environment – and I tried to follow his example all through my career in freshwater science. A remarkable analytical chemist, Harry always had an eye to what equipment and techniques were available. He had a keen intuition about where to measure and what additional measurements might provide new insights into key environmental processes. When we were examining what the data showed and sharing new ideas, I found that there was no hierarchical separation between us, but I am sure that he steered me, imperceptibly, towards better avenues of thinking when needed.

It is clear that Harry was very astute in spotting talent. He had highly motivated and capable students and laboratory co-workers, underpinned by a remarkable laboratory in the Cambridge Department of Earth Sciences, which has produced a magnificent output over so many years.

Endeavouring to describe the hydrogeochemical and physical functioning of the vastness and diversity of the world's oceans was and remains daunting. Harry's skills – his strategic thinking and skill in planning, and his ability to encourage and unite researchers and obtain funding of ship-board time – were vital to the marine sciences as a whole . He deserves great praise for helping many become the next generation of researcher, actively promoting exciting new ideas at learned society meetings as well as dealing with the administration and vetting of the science.

Harry's humanity, tact, insight, honesty and sheer ability were inspirational to me. He will always be a great friend and colleague whom I greatly admire and love. No doubt many others will echo similar sentiments. Harry has now passed away, but his legacy and wonderful memories about him remain.

Colin Neal
Centre for Ecology and Hydrology, Wallingford

A great mentor and friend

My memories of Harry Elderfield – alongside all of his scientific accomplishments – are as a great mentor and friend. We first met in his first year in the Department of Earth Sciences at Cambridge, which coincided with my final year as an undergraduate there. I had just taken an intellectual leap away from my intended career path (Chemical Engineering) into Earth Sciences, on a gamble that there should be a way to blend the Advanced Chemistry courses that I had been taking under Part I Natural Sciences into a research career in Geochemistry. More than thirty years later, I am still pinching myself on both how well and how immediately that worked out, largely thanks to Harry. I remember that he really came alive in the one-on-one tutorials which we held every Wednesday starting at 4 p.m. in his office at the Bullard Labs – sessions that routinely continued until long after everyone else had gone home, all but the rear exit door had been locked and they had most definitely stopped serving dinner when I got back to college. Small prices to pay. I often think of how lucky I was to be in the right place at that perfect time. Surely, Harry's self-protection mechanisms would have cut in by his second year of teaching at Cambridge, but in that first year I enjoyed a rare privilege. When the Department messed up his paperwork for NERC Ph.D studentship funding that year, that was also my good fortune, as I got to apply for a Ph.D with him under 'late appeals'.

Over the following years, what really impressed me – and still seems unmatched 30 years on – was the grace and graciousness with which Harry conducted himself. We only disagreed once. Ever. I sought him out and apologised profusely the very next day, as soon as I wised up. And then he chose to do exactly the same, even when there was really no need. As a second example, if I find myself in a meeting or workshop trying to hone the arguments for new directions for research in which I am involved, I often find myself reflecting, perhaps even with reverence, on the way in which Harry used to be able to sit in the same room for two or three days at a time with more than a hundred individuals each clamouring for their piece of some intangible pie, and draw a coherent consensus from it all before the meeting ended, in a way that sent everyone home feeling good about both themselves and their new shared ambitions. A remarkable skill.

Of course, Harry also had a mischievous sense of humour, for sure. And a keen interest in the Arts. The first indication I had of the latter was when I found out that he was the only other person within a 10-mile radius of Great St Mary's Church who could tolerate listening to a favourite album of mine by the Talking Heads. Subsequently, it was interesting to perceive that his ability to write as elegantly as he always did stemmed not just from a keen scientific intellect but also a love of literature. It was Harry's example that taught me to read the 'classics' for pleasure – the kinds of books I had previously only associated with Eng. Lit. homework during my senior school years. It was also Harry who introduced me to the Impressionists. At the inaugural meeting of the Goldschmidt Conference in 1988, in Paris, it was Harry who encouraged me to goof off for an afternoon to visit the Musée d'Orsay which had not been open long. When I shared how much I had enjoyed that, he sent me next to the Orangerie. Was it a Ph.D I was undertaking, or finishing school??? Maybe both.

If I have to choose one favourite Cambridge memory it would be heading from a lock-in at the Eagle (where I used to work to subsidise my Ph.D) with Harry and Gary Klinkhammer (back, visiting from MIT) to catch a late-night showing of 'Stop Making Sense' at the Arts Cinema. But later this year, when I get to return to Paris for the latest Goldschmidt Conference, don't be surprised if I go missing for an afternoon. Consider it a pilgrimage.

Chris German
Woods Hole Oceanographic Institution

Marine Studies Group of the Geological Society

After a few years of dormancy, the MSG is back in action! The MSG is a network for the UK Marine Geoscience community, comprising Paleoceanography, Stratigraphy, and Marine Geology and Geophysics. If you would like to receive our newsletter or hear about upcoming workshops, or are planning an event within the field of Marine Geoscience, please visit our website and feel free to get in touch.

www://.geolsoc.org.uk/marine

SAVE THE DATE: Shackleton Conference: Marine Geoscience Past and Present will be held at The Geological Society, Burlington House, on Monday, 18 September 2017. The day's talks and keynotes will be split between Marine Geology and Paleoceanography with a focus on emerging technologies in Marine Geoscience. Further details will be on our website.

Saving space for white-beaked dolphins

Dan Smith

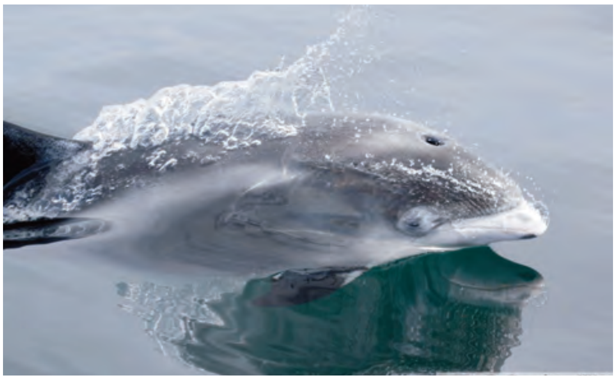
Protection of marine megafauna in UK waters is currently sporadic, and management of activities in 'hotspots' for large marine animals is very limited. Some cetaceans are European protected species, but others are not. The number of Marine Protected Areas (MPAs) designated primarily for large marine animals is limited to one Special Area of Conservation (SAC) in Cardigan Bay and one in the Moray Firth. So nature conservation organisations recognised an excellent opportunity in the summer of 2016 when Defra invited 'third-party' suggestions for new Marine Conservation Zones (MCZs) for 'highly mobile species'.

Fifty Marine Conservation Zones have so far been designated, with the majority of these sites being managed by the relevant authorities to protect particular named habitats and species (referred to in the relevant legislation as 'features'). But this number of MCZs falls short of the minimum required for a functioning network of Marine Protected Areas, and the existing sites focus on protection of features that are either static or move only short distances.

Back in 2014, The Wildlife Trusts identified protection of marine megafauna as a significant gap in the emerging network of Marine Protected Areas around the UK. In the report *Save our Ocean Giants,* The Wildlife Trusts listed 14 'hotspots', where cetaceans and other large marine animals gather to feed, breed and raise their young. For each of these areas, the report made one of three recommendations to government: the creation of a new MPA (either an SAC under the *EU Habitats Directive* or an MCZ under national legislation); the extension of site boundaries of an existing MPA; or the addition of the relevant species as a 'feature' of an existing MPA to ensure the site's management plan also takes conservation of the highly mobile species into account.

A white-beaked dolphin off the coast of Scotland

(Photo by courtesy of Caroline Weir/ Ketos Ecology)



A new MCZ in Lyme Bay?

One of the new MPAs recommended in the *Save our Ocean Giants* report was an MCZ in Lyme Bay, with the focal species being the white-beaked dolphin (*Lagenorhynchus albirostris)*. Thanks to an increase in surveys over the last decade (most of them co-ordinated by the charity MARINElife) an area to the south-west of the bay has been identified as particularly important for a population of these dolphins. In addition, this part of Lyme Bay, with a water depth ranging from 50 to 60 m and areas of high densities of sprat – a key prey species for cetaceans – has become known for regular sightings of harbour porpoise and common dolphin. The presence of locally to nationally important numbers of megafauna such as bottlenose dolphin, minke whale and basking shark as well as of several seabird species – razorbill, guillemot, great skua, Manx and Balearic shearwaters – also adds to the compelling case for a Marine Protected Area for highly mobile marine animals in Lyme Bay.

Located east of Torbay, the proposed Lyme Bay Deeps MCZ extends over 1055 km. This is an area of predominantly gently sloping sandy sea bed, distinct from those parts of the bay noted for their rocky reefs. A characteristic of the area is a large number of wrecks, mostly dating from the First and Second World Wars, which attract shoals of fish.

White-beaked dolphins can be up to 3 m long, and have dark grey bodies. The short thick beak patterned with fuzzy white patches gives the animal its common name, but white can also be seen on the sides and the back behind the dorsal fin.

White-beaked dolphins hunt in groups, using whistles, tail slaps and leaps to co-ordinate their search. Like other cetaceans, white-beaked dolphins are frequent 'bow-riders', surfing the waves created as a boat moves through the water. Usually recorded in pods of ten or so, they can also travel in groups several hundred strong in places where food is plentiful and threats are few. Mating is thought to take place in summer, with calves being born almost a year later.

Evidence from long-term surveys

Data on distribution and relative abundance of white-beaked dolphins in the English Channel were compiled from a programme of surveys by MARINElife using distance sampling methods (making sightings from fixed points or along transects). In total, 681 surveys from 606 days were analysed, with 70% of the data collected since 2006. During these surveys (which recorded both single dolphins and pods) there were 35 sightings of 402 individual white-beaked dolphins for the English Channel, with the vast majority being in Lyme Bay.

The boundaries of the proposed MCZ in Lyme Bay were derived from the main concentration of sightings in broadly similar habitat. White-beaked dolphins have been recorded inside this area every year since 2006. Most of the extensive survey work was carried out in this area in 2012, when

The main types of Marine Protected Areas in English waters

European Marine Sites (Natura 2000 Sites)

Special Areas of Conservation (SACs) to protect habitats and species of European importance, as listed under the *EU Habitats Directive*

Special Protection Areas (SPAs) to protect birds under the *EU Wild Birds Directive*

Marine Conservation Zones (MCZs) Protected areas that are important for the conservation of the diversity of nationally rare, threatened and representative habitats and species. Designation of these zones takes social and economic factors into account, alongside the best available scientific evidence.

Sites of Special Scientific Interest SSSIs with marine components giving protection to species and habitats of national importance.

Just under a quarter of English inshore waters are within Marine Protected Areas of some kind. Similar schemes are operating in Wales, Scotland and Northern Ireland.

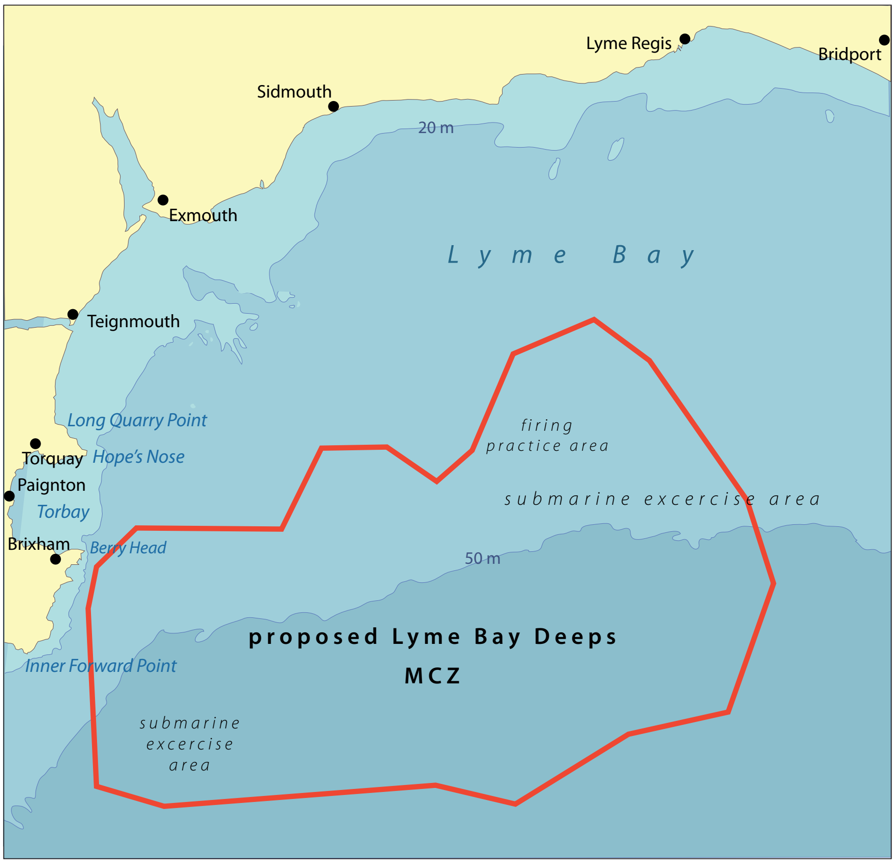
white-beaked dolphins were encountered on 85% of trips. The species has been recorded in all seasons including January and November, indicating their presence all year round.

50% of individually recognised white-beaked dolphins were re-sighted on one or more occasions. 32% of animals were sighted in multiple years, with three animals sighted in four different years. New individuals were regularly encountered from 2008 to 2012, though since 2013 very few new individuals have been encountered.

MARINElife surveys have thus confirmed the proposed area as a white-beaked dolphin hotspot between 2007 and 2014. The high recapture rates and the high degree of interchange of individuals between groups, along with the absence of matches with animals catalogued from other parts of UK waters, indicate that the population in Lyme Bay has a high degree of site fidelity.

Changing times

Lyme Bay is the most southerly known area in UK waters where white-beaked dolphins are regularly sighted and is therefore important in helping to maintain the species range. 'White beaks' have a more limited global range than most other UK cetacean species, being found only in cool temperate and sub-Arctic waters of the North Atlantic. There is evidence that its range is currently declining, with marked changes in occurrence along the west coast of the UK this century. As this hotspot for white-beaked dolphins is on the edge of their known range, it is especially important to protect it, particularly as not enough is known about the species to predict how they will respond to further rises in sea temperature.



The proposed location of the new MCZ in Lyme Bay off south Devon/Dorset.

Although there has been a decline in sightings of new individual white-beaked dolphins, the purpose behind designation of a Marine Conservation Zone is less to combat immediate threats to the population than to 'future-proof' the area by putting management measures in place to protect the population against threats that might develop over time. Potential threats include: damage by dredging or trawling of the wrecks that have become feeding habitat; increased fishing pressure in the event of relaxed fishing quotas leading to reductions in key prey items and hence the area's carrying capacity for the species; increased recreational disturbance – there is anecdotal evidence of motor boats pursuing groups of cetaceans in Lyme Bay for 'fun'; and future exploitation of the sea area for industry and military activity (cf. map).

The 2016 submission by The Wildlife Trusts and MARINElife of the proposed Marine Conservation Zone in Lyme Bay has led to a Devon Wildlife Trust (DWT) public engagement exercise – the Devon Dolphins campaign. DWT seeks to engage a wide audience in the effort to secure greater protection for our marine megafauna. Once Defra begins the public consultation on the final round of proposed MCZs – anticipated in late 2017/early 2018 – DWT hopes to inspire as many people as possible to take part, so the public can play a role in what would be a huge step towards a revitalised marine environment in English waters.

Readers can support the campaign at www.devonwildlifetrust.org/devon-dolphins

A white-beaked dolphin leaps off the coast of Northumberland

(Photo by courtesy of John Carnell)

Dan Smith is the Communications Officer at Devon Wildlife Trust.
dsmith@devonwildlifetrust.org

Modelling Scottish shelf seas

Rory O'Hara Murray

A new hydrodynamic ocean model of Scottish shelf seas – the Scottish Shelf Model (SSM) has been developed under the leadership of Marine Scotland Science (MSS). This work was conducted under contract by CH2M Hill (formerly Halcrow) and the National Oceanography Centre (NOC), Liverpool. The oceanography group at Marine Scotland Science has always used hydrodynamic model output as a research tool and to aid in providing scientific advice to the Scottish Government. In the past, we have used output from POLCOMS, HAMSON, NORWECOM and, more recently, NEMO (AMM7), to quantitatively describe circulation and hydrographic patterns and to drive other models, such as particle-tracking simulations to investigate the dispersion of pollutants and organisms, or connectivity between marine habitats. These hydrodynamic models were always run by third parties and the outputs shared through scientific collaboration or obtained through data-sharing initiatives such as the EU COPERNICUS Marine Environment Monitoring Service and its predecessor MyOcean.

For a long time this approach served us extremely well, and we will always have a need for third-party model output, but in recent years it has become apparent that we need both a dedicated model of Scottish shelf seas and our own in-house modelling capability. Whilst many hydrodynamic models were available and were run routinely, and indeed operationally, there were none that covered the whole of Scottish waters with sufficiently high spatial resolution. For example, whilst models focussing on the North Sea highly resolve the Scottish east coast, the Scottish west coast does not lie within their domain. Similarly, models of the north-west European shelf, such as the operational 7 km Atlantic Margin Model (AMM7) and NORWegian ECOlogical Model (NORWECOM), include the whole of Scottish waters, but the horizontal resolution is often too coarse for many coastal applications, and such models were not necessarily designed with the intricate Scottish coastline in mind. This is especially true along the Scottish west coast which is characterised by many narrow lochs, with significant levels of freshwater input/runoff, as well as islands and complex bathymetry. Such a setting, whilst being a delight for sailing and diving, is incredibly challenging to model.

We chose to use the Finite Volume Community Ocean Model (FVCOM) developed at the University of Massachusetts Dartmouth, USA (see Further Reading). This open source model is being actively developed and has progressed greatly over the last few years. The most attractive feature of FVCOM is the unstructured grid composed of triangular model elements. This allows the grid resolution to change across the model domain and to take the shape of complex coastlines typical of many of the Scottish sea lochs and islands (e.g. Figure 1(a)). The model can also use terrain-following depth layers to discretise the vertical dimension and this suits shelf models, where the bathymetry can often vary rapidly, extremely well (Figure 1(b)). The depth layers occupy a constant proportion of the water column so that there is always the same number of modelled layers, for all model elements, no matter what the water depth is (e.g. Figure 1(b)).

FVCOM also has other features that are of interest to us, including sediment transport and spectral wave modules. The modular structure of FVCOM also allows for all features to be turned on or off depending on the model application. Also, as FVCOM is open source, users are able to probe the underlying code and either change or add to it so that it better suits their needs, and there is a growing group of users in the UK including groups at the Scottish Association for Marine Science (SAMS), Plymouth Marine Laboratory (PML) and NOC.

The SSM concept

An unstructured grid covering all of Scottish waters could, theoretically, be refined to have extremely high horizontal resolution at the coastline, and even go down to ~10 m in some areas. However, to run a model with such a grid would be extremely computationally demanding, and its benefit would be eclipsed by the computa-

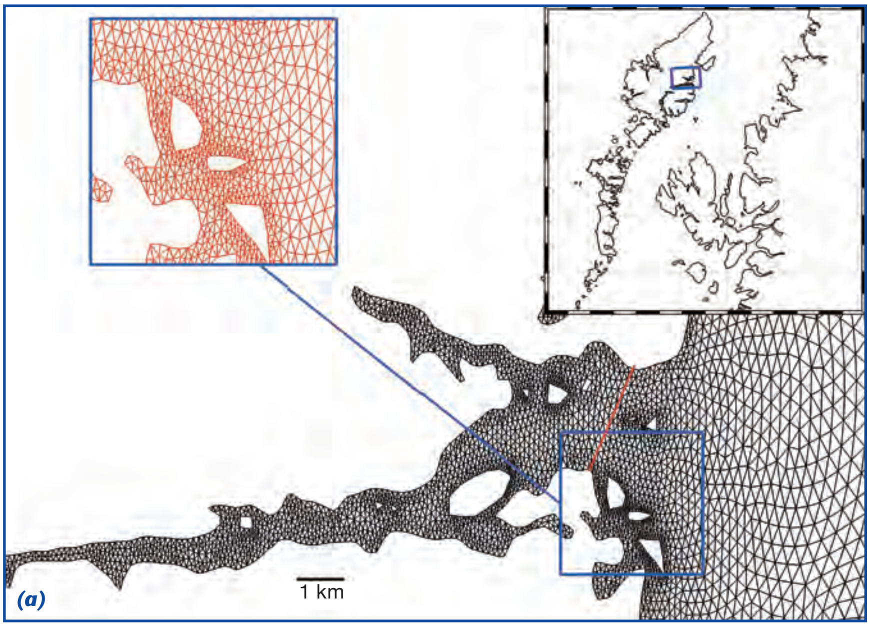
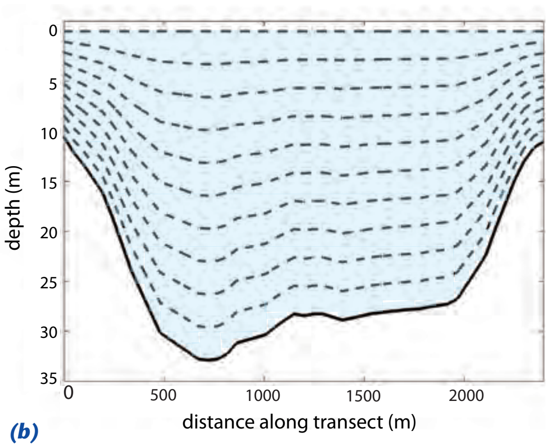


Figure 1 (a) *Example model grid for waters off the east coast of Lewis and Harris in the Outer Hebrides.* ***(b)*** *Example cross-section along the red line in (a) showing the ten terrain-following depth layers evenly distributed through the water column.*

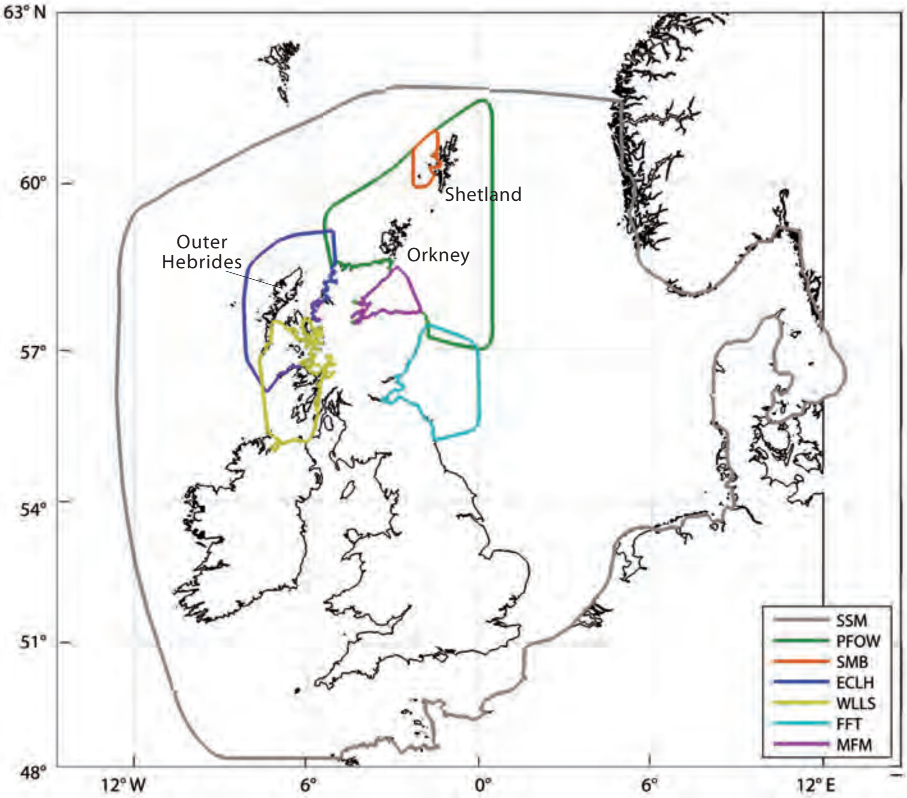


tional overhead. Even the unstructured grid would not be flexible enough to deal with such a scenario as the model would require a very small time step to remain stable at the smallest elements. A more efficient approach is to nest models with smaller domains, with small time steps, within a coarser model, with larger time steps, of the whole Scottish shelf. Thus, the Scottish Shelf Model is a suite of models composed of (1) a wider domain model with grid elements varying from approximately 10 km at the open boundaries to 1 km along the Scottish coastline; (2) a number of smaller domain 'case studies', nested within the wider domain mode, with extremely high horizontal resolution (down to 10 m in some areas); and (3) integrated model output combining the output from all the models to create extremely highly resolved model output for the whole of Scottish shelf waters. Figure 2 shows the domains of the wider SSM model and the nested case studies.

The third component of the SSM – the integrated model output – is an important aspect of the SSM because it enables other offline models, such as particle-tracking simulations, to be forced using extremely high resolution data across a very large spatial domain. Such model output was important for a particle-tracking study conducted as part of the initial SSM project investigating the spread of sea lice and disease agents between fish farms. The likelihood of lice or pathogens being carried in currents between 86 fish farm management areas along the west coast of mainland Scotland, the Outer Hebrides, Orkney and Shetland, was investigated using a large number of particle-tracking simulations forced by the integrated model output. The large domain of the integrated output enabled the particles to be tracked over great distances and yet the areas of interest were at the horizontal resolution necessary to resolve the complex hydrodynamic processes involved.

Typically, the model showed that there is a northward transport from the Outer Hebrides towards Orkney and Shetland, as the particles are carried by the Scottish Coastal Current. These passive particles represented sea lice (parasitic copepods, *Lepeophtheirus salmonis*) and two disease agents, and were assigned certain survival times and locations in the water column to represent simple aspects of their behaviour. We envisage using the integrated domain model output for similar applications in the future to provide an evidence base to support the sustainable management of the Scottish aquaculture industry. It is also being used, along with tagging experiments, to help understand the migratory patterns of salmon by ascertaining to what extent salmon migration routes are influenced by natural large-scale circulation. Other applications of the SSM are modelling the trajectory/dispersal of pollutants such as spilled oil, investigating the dispersal of oyster larvae, and the dispersal of non-intentional CO_2 releases from carbon capture and storage schemes.

Figure 2 *The Scottish Shelf Model domains: the coarser wider domain model (SSM) and the finer scale high resolution models: Pentland Firth and Orkney Waters (PFOW); St Magnus Bay (SMB), Shetland; East Coast of Lewis and Harris (ECLH); Wider Loch Linnhe system (WLLS); Firths of Forth and Tay (FFT); and Moray Firth Model (MFM).*



Identifying renewable energy hot spots and possible impacts

The SSM models have also been used to perform an assessment of the potential for tidal stream energy (i.e. renewable energy from tidal currents) in Scottish waters. This has been done with both the wider domain SSM and the Pentland Firth and Orkney Waters case study (cf. Figure 2 and Figure 3 opposite) as the Orkney Islands are an area of great tidal energy potential.

The Pentland Firth arguably has the largest tidal stream resource in the UK and there are currently plans for a number of small developments around the edge of the Firth, such as the Mey Gen development between the island of Stroma and the Scottish mainland. There are also developments planned in other channels in the Orkney Islands, such as the the Westray Firth and Lashy Sound. The European Marie Energy Test Centre (EMEC) has a test site in the south of the Westray Firth near the Island of Eday.

As well as particle-tracking applications the SSM models can be used to simulate the impacts of offshore developments on the physical marine environment. Tidal stream turbines generating renewable energy are a good example. Like any structure in the sea, tidal stream turbines will disrupt current flow and potentially cause localised changes in water elevation. However, unlike other offshore structures, turbines effectively impose an opposing thrust on the currents as a result of taking energy out of the water, and will slow down the flow. Large-scale arrays of turbines therefore have the potential to radically change current speeds and water levels in and around the array. Potential changes could operate at a variety of spatial scales and the SSM is well suited to studying spatial scales larger than 100 m, which corresponds to array-scale effects, rather than the small-scale effects that might occur around individual turbines. A recent study (see Further Reading) used the PFOW model to estimate the tidal stream resource in the Pentland Firth and to understand the impacts of a number of tidal stream renewable energy scenarios. To do this a simple tidal turbine module was added to FVCOM representing tidal

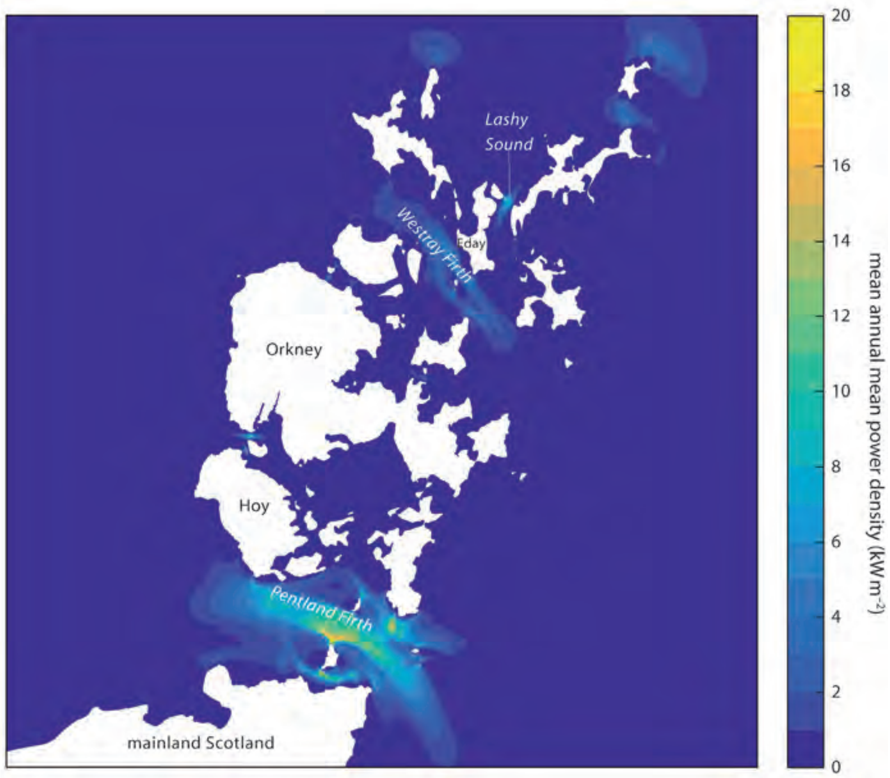


Figure 3 *The mean annual tidal power density around the Orkney Islands derived from a 1-year long Pentland Firth and Orkney Waters model run. Stroma, referred to in the text, is the island in the southern part of the Pentland Firth, off which power density values reach 20 kW m^{-2}.*

turbines as a momentum sink in selected model elements.

A climatological approach

The primary SSM output is a 1-year simulation forced with climatologically averaged data. 25 years of forcing data were obtained and then averaged to obtain a single year climatology representative of the 25-year period. The individual case studies have all been nested in the climatological SSM model run to provide higher resolution model output for these regions and the integrated model output. The principal forcing dataset was output from the AMM7 model, which is an implementation of the Nucleus for European Modelling of the Ocean (NEMO) model, a model of the north-west European shelf run operationally by the UK Met Office. These data include temperature, salinity, water level and 3D current velocities along the open boundary of the SSM. The atmospheric forcing (including wind velocities, solar heating, air pressure, precipitation and evaporation) came from the ERA-Interim reanalysis obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). It was also important to provide fresh water input at the locations of the Scottish rivers and sea lochs. We used output from the Grid-to-Grid hydrological model developed by the Centre for Ecology and Hydrology (CEH) that models not only river discharge but also diffuse runoff. The diffuse runoff component is important for the steep sided Scottish west coast, and can have a significant effect on the density structure in this region.

Future development and aspirations for a community model

Since the SSM contract was completed in 2016, we have been working with and developing the models. For example, the coarse SSM and four case study models (WLLS, ECLH, PFOW and SMB in Figure 2) were developed under contract, but MSS have since developed models of the Moray Firth and the Firths of Forth and Tay which we plan to nest within the SSM and assimilate into the integrated output. We also hope to incorporate an FVCOM model of the Firth of Clyde which has been developed in collaboration with the University of Strathclyde (see Further Reading). The ambition is for the SSM to become a continually developing shared resource that is both used and developed by the wider marine science community. Developments will include the implementation of new high resolution case studies, new hindcast, forecast and climatological runs, and the incorporation of output into the integrated grid. It is likely that the models will continue to improve and we foresee new updated versions being released over time. We would also like to develop the means to customise the integrated grid with selected case study regions highly resolved. It will be important for the developments to be well structured and quality-assured, and MSS aims to facilitate this. MSS also aims to help with the distribution of the model by developing the means for output to be downloaded, and for the model grids and input files to be shared in a coherent manner. MSS have recently gained funding to host a SSM workshop in Edinburgh early this summer to help set up an SSM community, provide networking and collaboration opportunities, and gain feedback from potential SSM users to help guide the direction of future developments.

Acknowledgements

I would like to thank all those involved in the SSM project to date, particularly Judith Wolf (NOC) and Hakeem Jonson and Darren Price (both CH2M Hill) who worked on the original contract; and Alan Hills (SEPA), Alejandro Gallego and Tracy McCollin (both MSS), for participating in the project steering group.

Further information

SSM information website: http://marine.gov.scot/information/scottish-shelf-model

FVCOM website: http://fvcom.smast.umassd.edu/fvcom/

FVCOM wiki (UK user group): https://wiki.fvcom.pml.ac.uk/doku.php

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On belief and reason

Why we should trust the projections of global warming by climate models

Tom Anderson

Many people accept that the threat of climate change is real and, furthermore, take an interest in the underlying science. There are, however, those who remain unconvinced by the projections of climate warming to the end of this century, as made by the big Earth System Models (ESMs) run on supercomputers. I am referring here to the general public, noting that the doubters also include a small number of out and out sceptics who specialise in trying to find ways to discredit the evidence. Along with co-authors Ed Hawkins and Phil Jones, I have recently published an open-access article in the journal *Endeavour,* that describes the scientific case as to why we should trust the projections of warming by climate models, written for a general audience. I will come back to the article later.

First, I would like to take the opportunity to ponder how we form and maintain beliefs (here, I mean beliefs as in general knowledge about the ways of the world rather than, for example, religious beliefs) and thereby show how easy it is, based on our world view and natural instincts, to be sceptical of global warming. I will argue that scepticism about climate science can arise from a number of sources including inability to directly experience or sense long-term warming, prejudice based on a world view that does not welcome bad news, and intuition which tells us that complex systems, such as global climate, should be inherently unpredictable. I should emphasise from the outset that, although over the years I have done a good deal of reading about general science and how science progresses, I am an ocean scientist and not a psychologist. The ideas I present are therefore entirely my own personal opinions.

The importance of experience

A scholar might tell us that we form and maintain beliefs by achieving understanding about how the world works, in which case it is the reasons, or explanations, for things being and happening that provide the foundation of knowledge. While scientists certainly think like this, I doubt whether this is how everyday beliefs are generated. Consider a simple example: caffeine is disruptive to sleep. The scientific explanation as to why this is so is that caffeine increases adrenaline production and blocks sleep-inducing chemicals such as adenosine and melatonin. This is not, I would say, the reason why we believe that caffeine impairs sleep. I myself have not consumed coffee or tea for more than ten years because of developing an allergy to caffeine. Has my sleep improved during this time? Yes. The simple reason I believe that caffeine disrupts sleep is that it accords with my own experiences: I sleep better without it. Beliefs are thus primarily shaped by experience, without recourse to reason, despite the fact that much of our knowledge comes from things we have been told by other people, read in books, etc.

Let me relate another example, that of weather forecasts, which are the result of simulations run on supercomputers. When the ever-smiling weather lady tells us that it is 'probably' going to rain tomorrow, we will likely cancel that picnic to the beach. The forecast is accepted as trustworthy even if we have little understanding of the processes of weather, how they are represented in computer simulations, and the resulting sources of error. Why? We find by experience that, time and time again, the weather forecast is more or less accurate and does not let us down. When it comes to climate models, however, there is no such experience. We might frazzle on the beach during our summer holiday and be told by meteorologists that 2016 is the hottest year on record, but for many of us it is just another hot day. We do not directly sense, or experience, long-term climate change in our daily lives. The scientists can, of course, show us graphs of rising CO_2 and global temperature but, again, these can only be accepted as meaningful information by appealing to reason.

Advertisers know how to convince us ...

Our world view of beliefs

The second factor that shapes beliefs, I suggest, is our world view, in other words our beliefs as a united whole, such as what we think is good and bad, right and wrong, etc. We live our lives within a world view that leads, usually unconsciously, to prejudice on many fronts. For example, I generally trust the medical profession, and if doctors tell me that caffeine disrupts sleep, or dentists tell me that drinking sugary drinks causes tooth decay, I am inclined to believe them. I am likewise inclined to believe that any number of drugs may have therapeutic effects although, again based on experience, I am suspicious of possible side-effects.

What would we do without modern medicines, electricity, cars, computers and smart phones? Science has provided us with many benefits and so, based on our experience of these developments, surely we should trust scientists and believe their messages about global warming. Many people do, of course, but others think otherwise. The source of information is important. Advertising agencies can entice you to buy any number of products, providing they are made sufficiently appealing in context of our world view of 'likes'. How about, for example, the prospect of a little 'pep and vigour' from eating vitamin donuts: 'each ... fortified with a minimum of 25 units [!] of vitamin B1'. When it comes to articles about health in the newspapers, any number of conflicting stories may be found. For example, the benefits and dangers of consuming alcohol may be presented interchangeably from one week to another. The media struggle to accurately communicate climate science. Sceptical arguments may be introduced to achieve 'balance' but the result is often, as I wrote in the *Endeavour* article, 'an emphasis on confusion and uncertainty when presenting the climate change debate'.

There are two other factors, that again relate to our world view, which exacerbate the situation: the bad news mindset and intuition. Starting with the former, nobody likes to hear bad news. It is curious that the pain of losses is usually greater than the joy of equivalent gains, a phenomenon known as 'loss aversion', as demonstrated by the renowned psychologist Daniel Kahneman. The distress caused by having to pay an extra thousand pounds in tax is, for example, more extreme than the joy experienced when winning the same amount on the lottery. The same idea is often seen in the sporting arena. The 'golden goal' was introduced into association football in the 1990s as a means of increasing the drama in matches that end up in extra time. The first goal scored after the regulation 90 minutes would provide a golden moment of ecstasy as the opposing team was eliminated in an instant. At least that was the idea. A more apt term for golden goal might be 'sudden death', with obvious negative connotations. Instead of playing for glory and going all out for the golden goal, most teams mired themselves in defence, terrified of a swift exit. The golden goal was abandoned in 2004.

An unfolding disaster is only reluctantly included as a belief within our world view, and then only if it is readily experienced, or if there are simple remedies at hand (in which case it is no longer bad news). We believe, for example, in the deadly consequences of cancer because most of us have met people who have suffered and died, as well as because of the images seen on TV. Climate change is bad news, but news that may be conveniently disregarded in day-to-day life. We can't experience it and, anyway, it is all too easy to adopt a mindset that it does not matter because it will not affect us any time soon. The people most likely to believe in climate change are, I suggest, those who have experienced disasters such as hurricanes or floods, the frequency of which may be increasing with global warming.

Simplicity within complexity

Intuition is subtle, oblique knowledge that aids in problem solving. We use intuition to try and know or understand something without recourse to rational explanation. It is hunches and gut feelings, again based on world view. Even Einstein once said, 'The really valuable thing is intuition'. For most people, I suggest, intuition tells us that it is hard to make predictions about complex systems because there are so many interacting parts. The climate system is one such example. How is it possible to make projections of global warming when there are a myriad of processes in the ocean, on land and in the atmosphere, including the water cycle, ice, vegetation growth, cloud formation, etc., and all

Termites are driven by simple cues, but what they build is far from simple

acting in concert with human influences, notably atmospheric emissions of CO_2? In order to answer this question, I will briefly delve into complexity science, a discipline that arose to prominence in the 1980s. Complex systems are defined as those with many parts whose interactions lead to emergent outcomes that cannot necessarily be envisaged straightforwardly from a knowledge of the parts in isolation. A classic example is provided by termite colonies which build mound-like nests that can reach 20 feet or more tall (*see above*), encasing an intricate network of tunnels and chambers. This sophisticated architecture is the result of the collective behaviour of millions of termites, behaviour which is driven by apparently simple rules but which may actually be rather subtle involving, for example, reactions to various pheromones (chemical messengers) that are excreted by the termites as they go about their business. Mathematical models of termite mounds have been developed, with some degree of success. I would nevertheless say that this is an example of a complex system where it is difficult to make reliable predictions on the basis of mathematics as a consequence of the subtlety of the rules involved – a common characteristic of biological systems. So why should modelling climate be any different?

Complexity does not, I argue, necessarily mean unpredictability. There is the paradox that despite the complexity of the world, the rules of nature are simple. Well, maybe not for biology (especially behavioural biology, as with the termites), but for physics and chemistry, yes. Physical laws mean that we are able to achieve remarkable feats such as the European Space Agency mission in which the *Rosetta* probe made a successful rendezvous with comet '67P/Churyumov-Gerasimenko', a journey of ten years and four billion miles. It is the case, I argue, that simple physics is present at the heart of the climate system. Whereas weather is unpredictable beyond a few days or weeks because of its chaotic nature, we can reliably predict that summer will be warmer than winter, a consequence of the tilt of the Earth on its axis and the resulting geographical changes in radiation balance as the seasons pass by. Projections of climate warming are, in similar fashion, influenced by CO_2 in the atmosphere and its influence on radiative transfer. As the Intergovernmental Panel on Climate Change (IPCC) stated in its 2007 report:

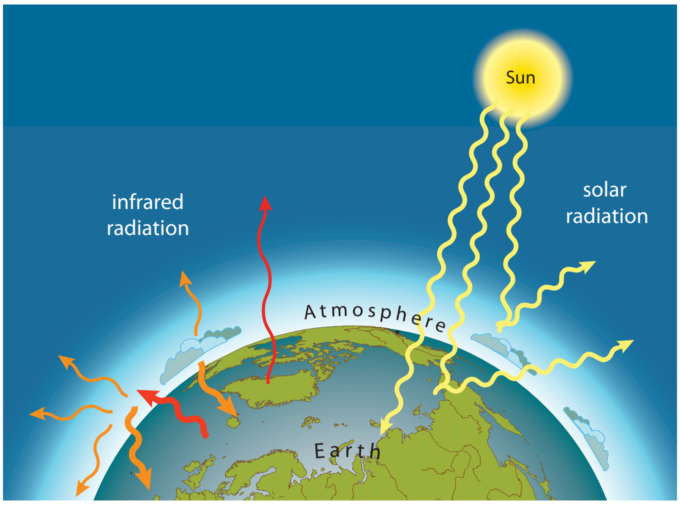
Projections of future climate are shaped by fundamental changes in heat energy in the Earth system, in particular the increasing intensity of the greenhouse effect that traps heat near the Earth's surface, determined by the amount of carbon dioxide and other greenhouse gases in the atmosphere. Projecting changes in climate due to changes in greenhouse gases 50 years from now is a very different and much more easily solved problem than forecasting weather patterns just weeks from now.

I return to this theme, namely simplicity at the core of the climate system, later.

Prejudice and probability

Before coming to the *Endeavour* article, I would like to illustrate just how easily we are prejudiced by our world view by comparing three uses of the word 'probably'. First, think back to the weather lady saying that it will 'probably' rain tomorrow, and how readily we believe this. Compare this with the statement made by the IPCC in their 2007 report that temperatures are 'probably' going to increase by between 1.8 and 4 °C by the end of the century. A similar statement is made in the 2013 IPCC report, namely that temperature increase will 'likely' exceed 1.5 °C. Yet, in complete contrast to our acceptance of the weather forecast, many apparently play down 'probably' and 'likely' in these instances and say it is not enough to warrant belief. Simple negative prejudice.

My final example is colloquial (rather than statistical) in nature and involves the unfortunate death of Mr Alexander Litvinenko by poisoning with radioactive polonium. On 20 January last year, Sir Robert Owen remarked: 'I have further concluded that the FSB operation to kill Mr Litvinenko was probably approved by Mr Patrushev, then head of the FSB, and also by President Putin.' That word 'probably' again, implying that the conclusion is consistent with the evidence, but without definite proof. While not wanting to make any judgement here, I reckon that many in the UK think it almost certainly the case that the statement is true, while doubtless the Russian public have no such belief given that the Russian media turned on the word 'probably' to discredit the statement as having insufficient basis in fact. This example again serves to show just how easily the communication of information is distorted by our world view of beliefs.



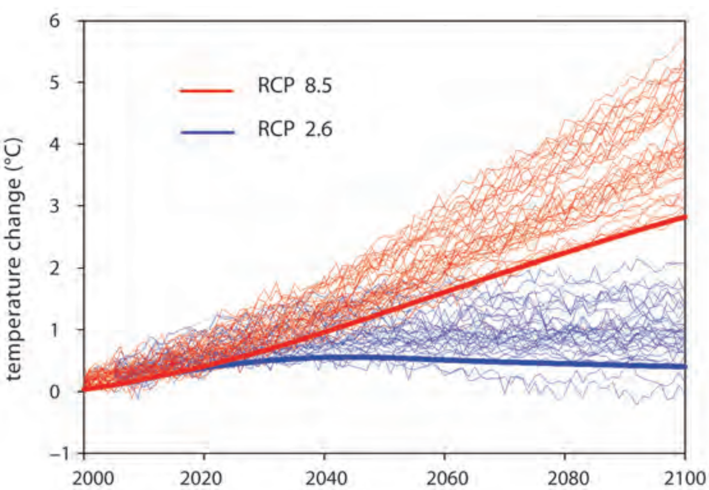
The 'greenhouse effect'

The radiative balance between incoming solar radiation (yellow arrows) and the absorption of re-emitted infrared radiation by the atmosphere (orange and red arrows) drive surface heating

Why we should trust the projections of climate models

Thus, I arrive at the finale: a summary of my thesis, as presented in the *Endeavour* article, as to why we should trust the projections of 21st century global warming by climate models. I am left with no alternative but to present the case by appealing to reason. Let me start by describing the well-known 'greenhouse effect'. Solar radiation passes through the atmosphere largely unhindered, warming the surface of the Earth. Energy is in turn re-emitted as infrared radiation (heat) which is absorbed by, and warms, the atmosphere. Most gases in the atmosphere, including oxygen and nitrogen, do not absorb infrared, but carbon dioxide (CO_2) does, as well as water vapour. Carbon dioxide is of course produced by the burning of oil, coal and gas and is increasing year-on-year in the atmosphere. And so the atmosphere traps more infrared radiation and, acting like a blanket, causes the Earth to heat up. This connection between CO_2 and anthropogenic warming was first made by Guy Stewart Callendar, a British steam engineer working in the 1930s. Callendar constructed a simple model of the radiation balance of the Earth and how it is influenced by atmospheric CO_2. The model might appear complex in that it had to take account of the seasonal variations in sunlight, pathways of radiation at different latitudes, reflectance of sunlight from clouds and ice, and heating within the atmosphere. In fact, however, this is all relatively straightforward physics and chemistry. I along with my co-authors formulated an empirical (mathematical) approximation of Callendar's model and, using observations of atmospheric CO_2, showed that the model successfully predicts the warming that was observed during the 20th century. Why is it successful? Because, as I argue above, simplicity exists within the complexity of the climate system, namely the physics of the greenhouse effect, as influenced by the concentration of CO_2 in the atmosphere.

Intercomparison of 21st century projections of Earth temperature from an ensemble of Earth System Models, for Representative Concentration Pathways (RCPs) 2.6 (low CO_2 emissions; blue) and 8.5 (high CO_2 emissions; red) scenarios (thin lines), with projections based on Callendar's model superimposed (thick lines). The RCP numbers correspond to radiative forcings in 2100 relative to the pre-industrial state, i.e. +2.6, +8.5 W m^{-2}.



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Ah, I hear the doubters say, but what about the climate feedbacks? These include melting of snow and ice, water vapour, changes in ocean stratification and changes in clouds. Climate feedbacks were not included in Callendar's model, with the exception of water vapour, and it would therefore appear that they were relatively unimportant during the 20th century given the successful prediction of warming using Callendar's model. This need not, however, be the case in future. We used the empirical approximation to Callendar's model again, but this time making projections of warming to the end of the 21st century (*see left*). Results are shown for two different CO_2 emissions scenarios, Representative Concentration Pathways (RCPs) 2.6 (low CO_2 emissions) and 8.5 (high CO_2 emissions), and are compared with the projections of an ensemble of climate models. These Earth System Models include not only the radiative transfer of the greenhouse effect, as in Callendar's model, but also a suite of climate feedbacks. The outcome: the projections of Callendar's model (the thick lines in the plot) are at the lower end of those of the ESMs. The explanation is straightforward. The simple physics and chemistry of the greenhouse effect, as represented in Callendar's model, give rise to quantitatively reliable baseline warming. The feedbacks add extra warming. There is uncertainty in the magnitude of the extra warming, but not in the sign:

positive, namely amplification of warming. Why should we believe that the feedbacks are positive? Heating causes melting of snow and ice meaning less sunlight is reflected back to space (if you've ever been out in the mountains in snow, you will know how bright that reflection is), thereby warming the Earth's surface. A warmer atmosphere holds more water vapour (it is why condensation appears when warm air is cooled on your car windscreen) and the water vapour in turn absorbs and re-emits infrared radiation, causing warming. You can see I am trying to promote reason by appealing to your experiences. Warming increases ocean stratification, resulting in less exchange between surface and deep waters and less uptake of CO_2 from the atmosphere. The stratification also reduces nutrient supply to the ocean surface, decreasing the 'biological pump' whereby phytoplankton growth leads to the production of particulate organic carbon that sinks into the deep ocean. Well, all I can say about our knowledge of these ocean feedbacks is that it is based on fundamentally sound principles accruing from decades of high quality research. At some point, we have to trust the scientists, at least in part, because science has been so successful in the past. There are other feedbacks also, notably those associated with clouds, that can act in either direction, positive or negative. There are uncertainties. Overall, however, the case that the combined action of climate feedbacks will be to amplify warming (over the baseline warming, as projected by Callendar's model) is overwhelming.

I finish by quoting directly from the *Endeavour* article:

The projections of end-of-century global warming by ESMs are fundamentally trustworthy: quantitatively robust baseline warming based on the well understood physics of radiative transfer, with extra warming due to climate feedbacks. These projections thus provide a compelling case that global climate will continue to undergo significant warming in response to ongoing emissions of CO_2 and other greenhouse gases to the atmosphere.

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Another telling of the inconvenient truth

'Before the Flood' is a documentary directed by Fisher Stevens and starring Leonardo DiCaprio. It was released in October 2016 and is available online.* In the film, Leonardo DiCaprio rings the alarm bell on climate change, using Hieronymus Bosch's allegorical painting, *The Garden of Earthly Delights*. The issue of climate change is one we've been aware of for some time now, but can a film by a Hollywood movie star cause a dramatic change in how we address this challenge?

A decade or so on from Al Gore's 'An Inconvenient Truth', this movie similarly aims to increase public engagement in the subject. To paraphrase DiCaprio, if you give people the data, you empower them. The narrative is clear, and highlights climate change as the global challenge it is – a challenge greater than individuals and countries can address independently, and impacting most on those who contributed the least to the problem. This is, however, where similarities between the two movies end: 'Before the Flood' is a fast-paced, high-drama movie. As might be considered typical of visual media today, it races along with flashing images, spectacular scenery and suspenseful music, but the 1½ hour run-time still made it feel a little too long.

Exploiting his role as UN Messenger of Peace, Leonardo DiCaprio calls in a stream of A-list friends to help deliver his message, including Barrack Obama, Elon Musk and Pope Francis. The movie is packed with information on issues and potential solutions, from the impact of cattle-rearing and what we eat, to our electricity-hungry society and 'gigafactories', and latency in policy making and who we choose as our political leaders. Only the narrative on the palm oil industry felt like distraction from these main issues, and came to what seemed a dead end. Honouring its by-line, *'The science is clear. The future is not',* the film does not spend a great amount of time presenting the scientific evidence or details. As a scientist, I still found it interesting viewing, particularly the socio-economic and political aspects of the climate change challenge. Personal highlights included the amazing demo of the NASA 'Hyperwall' (if you find the opportunity to see it in real life, do – It is even more brilliant), and the insight provided by Michael E. Mann on how a single graph could change your career and have a dramatic influence on your personal life.

As scientists, we can fall in the trap of 'doom and gloom thinking', and the movie's overall message remains hopeful. It suggests both small changes individuals can make to their life styles (eat less red meat, for example), and larger ones which will require buy-in at all levels of society across the globe, and a great political drive (including implementing carbon taxes). We are 'humankind before the flood', and this is a renewed call to action.

Bee Berx
Marine Scotland Science

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The RAPID challenge

Observational oceanographers challenge their modelling colleagues

David Smeed

Since 2006 there has been a biennial conference on the theme of the Atlantic Meridional Overturning Circulation (AMOC), organised jointly by the NERC RAPID-AMOC programme (RAPID = rapid climate change) and the US-CLIVAR AMOC Science Team (CLIVAR = the World Climate Research Programme's Core Project on Climate and Ocean: Variability, Predictability and Change). The latest of these biannual conferences was held in Bristol in the summer of 2015. Some presentations of model studies at the meeting suggested a growing confidence in the capability of models to predict future changes in the AMOC. These studies were based on comparisons of hindcast simulations with time-series of historical data. But could models make predictions for the future? The RAPID 26° N team decided to throw down the gauntlet! What started as light-hearted competition soon became the stimulus for some interesting science.

AMOC and the RAPID time-series

When compared with the other ocean basins the North Atlantic has an unusually large poleward transport of heat. In the subtropics almost all of this heat transport is carried by Atlantic Meridional Overturning Circulation (AMOC). The AMOC is composed of a poleward flow of relatively warm near-surface water above a colder equatorward deep return flow. At high latitudes the warm waters give up heat to the atmosphere resulting in the formation of the dense water that feeds the return flow.

Climate simulations have linked decadal scale changes in the AMOC with a pattern of sea-surface temperature variability in the North Atlantic known as the Atlantic multi-decadal oscillation (AMO). The AMO is known to have important impacts on surface temperature, precipitation and sea level in regions bordering the ocean. These impacts include the frequency of hurricanes and the amount of rainfall in the African Sahel as well as the weather in western Europe and sea-level on the eastern seaboard of the USA. The AMOC is also thought to have played a key role in rapid climate change in the past, and model simulations predict a decrease of the AMOC in the 21st century in response to increasing greenhouse gases.

The result of a collaboration between NERC, the US National Science Foundation (NSF) and NOAA, the RAPID 26° N array has been measuring the overturning circulation since April 2004. The location of the array was chosen to be close to the latitude of maximum meridional heat transport. Typically, this transport is 1.3 petawatts (1 pW = 10^{15} W), about 25% of the total (atmosphere plus ocean) poleward transport at these latitudes. At 26° N most of the Gulf Stream flows through the Straits of Florida where it is monitored using sub-sea cables calibrated by frequent hydrographic measurements. East of the Bahamas the flow is measured by an array of moored instruments. Current meters are used over the Bahamian continental slope, but across the rest of the basin transport is estimated on the basis of geostrophic balance, so it is sufficient to measure only temperature and salinity along the boundaries and over the Mid-Atlantic Ridge. It is also necessary to take account of the wind-driven Ekman flow in the surface layers, and this is quantified using surface wind velocities obtained from satellite scatterometer measurements.

Over the last 12 years, data from the RAPID array have given great insight into the structure, mechanisms and variability of the AMOC. Most notably, a sharp downturn in the AMOC was observed in 2009–2010, and many subsequent studies have documented the climate impacts of this reduction which was maintained over about one year. A sustained reduction of about 15% has been observed since 2010 and it seems that the North Atlantic may now be entering a relatively cool phase compared with the rest of the global ocean (see Further Reading).

The RAPID challenge

The RAPID time-series of the AMOC is updated following the servicing of the moorings once every 18 months. The challenge to the modellers in summer 2015 was therefore to estimate the AMOC over the 18 months from the last turnaround in March 2014 up until the next in October 2015. The closing date was the end of the year and before the new data were published. So strictly speaking this was a hindcast challenge and not a prediction challenge; however, the competitors did not know the values of the AMOC when they made their estimates.

Figure 1 *The overturning circulation and the RAPID array. Relatively warm water flows poleward in the Gulf Stream; much of this water recirculates in the subtropical gyre but some continues northward into the subpolar gyre. Heat loss to the atmosphere results in deep water formation that feeds a cold deep equatorward return flow primarily in the deep western boundary currents. This circulation is monitored by an array of moored instruments over the western boundary, the Mid-Atlantic Ridge and the eastern boundary. Flow in the Straits of Florida is monitored by submarine cables. Ekman transport at right-angles to the prevailing winds is shown by short black arrows.*

For more on RAPID see the article by Eleanor Frajka-Williams in Ocean Challenge ***18****, 14–18*

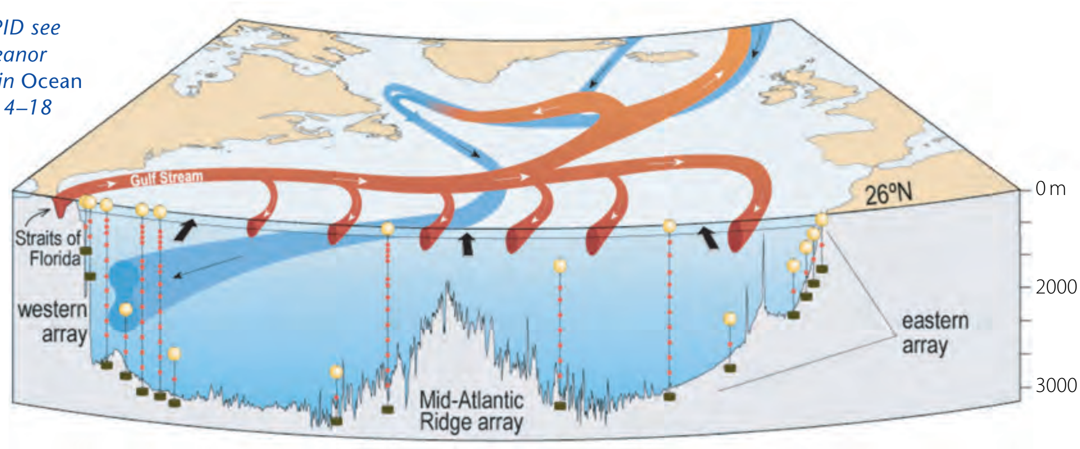


Table 1 *Details of the six entries for which the methodology was put on the RAPID blog; see http://rapidchallenge2015.blogspot.co.uk/ Papers describing some details of the techniques are given in Further Reading.*

	Team	Technique
CX	Helen Johnson and colleagues, University of Oxford	An ocean model and its adjoint were used to determine the sensitivity of the AMOC to surface wind, heat and freshwater forcing over the entire globe during the preceding 15 years. Then observed forcing anomalies were projected onto these sensitivity patterns; only those forcing anomalies which project strongly in space and time onto the sensitivity fields would generate variability in the AMOC. No quarterly values were supplied, but the method resulted in an accurate prediction.
C1	Laura Jackson and colleagues, UK Met Office	The AMOC was calculated from the GloSea5 ocean reanalysis. This ocean reanalysis assimilates temperatures, salinities, sea-ice concentrations and sea-surface heights, and uses the ERA interim atmospheric reanalysis for surface forcing. The model was only run to May 2015, so was missing the last 4 months which were created by adding a seasonal climatology onto the mean anomaly from the previous 12 months.
C2	Peter Challenor and students of statistical modelling	A purely statistical approach that used only the previous measurements in the RAPID time-series. Two techniques were employed. The first was to fit an AutoRegressive Integrated Moving Average (ARIMA) model to the data. The second used dynamical linear model. This incorporated two parts: a random walk that picked up the slow underlying evolution of the overturning and a seasonal part. http://www.rapid.ac.uk/challenge/Exeter_Rapid_prediction.pdf
C4	Grant Bigg and colleagues, University of Sheffield	A control systems modelling approach using knowledge of changing oceanic and meteorological conditions. Nonlinear Auto-Regressive Moving Average with eXogenous inputs (NARMAX) system was used to produce a model for the observed variation of the AMOC using two large-scale environmental variables as inputs. To represent atmospheric variability, the North Atlantic Oscillation index was used, while for oceanic variability a linear measure of the surface density of the northward-flowing Gulf Stream was combined with a linear measure of the likelihood of deep-water formation based on the surface density of the Labrador and Norwegian Seas.
C7	Nick Foukal, Duke University	Another statistical approach using only the previous measurements in the RAPID time-series. In this case a state-space analysis was used to build a statistical model. The basic tenet of the state-space model is that the future state is a function of the current state. http://www.o-snap.org/predicting-the-next-18-months-of-the-amoc-at-the-rapid-line-with-a-statistical-model/
C9	Eleanor Frajka-Williams, University of Southampton	Anomalies relative to the seasonal cycle were calculated using correlations between the non-Ekman component of the AMOC and sea-surface height anomalies in the western part of the subtropical gyre. To these were added the mean seasonal cycle from previous data and the Ekman transport from satellite scatterometer measurements.

Ten teams ventured to predict the AMOC in the RAPID challenge. Six of them submitted an article to the RAPID blog to explain how their estimates were made, and these are listed in Table 1.

Estimation methods

The great variety of techniques used can be divided into three broad categories:

- **Prognostic forward models** such as the forced ocean model run at the UK Met Office (C1 in Table 1). Note these models require forcing fields. For hindcasts the forcing is usually derived from reanalysis. For a true forecast an estimate of the forcing can be provided from climatology or coupled model forecasts.
- **Statistical models that exploit correlations with other known data.** For example, regression with sea-surface height data was used in C9. The entry C4 used a nonlinear technique with the North Atlantic Oscillation (NAO) index and other indices based on surface density. For CX an adjoint model* was used to derive the correlations with global wind and buoyancy surface forcing. The extent in time of the forecasts depends upon the AMOC's 'memory' of the forcing.
- **Purely statistical models that used only the previous data in the RAPID time-series.** These models also have an inherent time-scale over which the AMOC remembers its previous states.

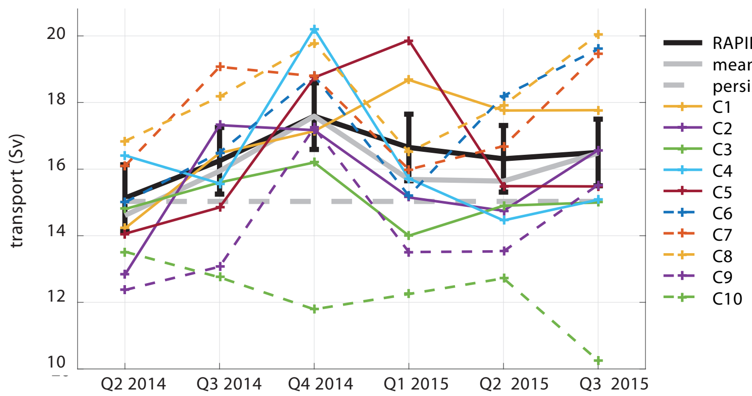
All three types of estimation method produced results of a similar accuracy.

Results

Competitors were asked to estimate what the mean AMOC would be in each of six quarters, starting with April to June 2014 and finishing with July to September 2015. But the organisers did not state how the winner would be determined, so how can we select the best prediction?

The true AMOC measured by RAPID is shown in Figure 2 along with the ten estimates. The measurement error in the

Figure 2 *Quarterly average values of the AMOC from spring 2014 to summer 2015. The black line shows the RAPID data with an error bar of 1 Sv. Each of the 10 estimates entered in the competition is shown by a coloured line. The average of the estimates is shown by the grey line and the dashed grey line is an estimate based on persistence (i.e. it is the value for the first quarter of 2014 extended over the whole period).*



The entries are ranked according to the root-mean square error (RMSE) of the estimates when compared with the RAPID data

*The output variables of a forecast model are dependent on the inputs (initial conditions, forcing variables, model parameters). An adjoint model is an efficient technique that allows calculation of the sensitivity of the output variables to the inputs without the forecast model having to be run many times.

RAPID calculations has been estimated to be about 1 sverdrup (1 Sv = $10^6 m^3 s^{-1}$) (see Further Reading). Over the time of the challenge the AMOC had an average value of 16.4 Sv and a standard deviation of just 0.7 Sv. This was a relatively stable period compared with the previous 18 months when the standard deviation was more than 2 Sv, as it was for most of the 11-year time-series.

Common measures of the 'skill' of a model compare the errors in the forecast with the variability of the observed data. So an accuracy of 1 Sv seems a good benchmark. Another useful benchmark is a prediction based on persistence, i.e. the last measured value. The absolute error of the persistence value was below 1 Sv for the first three quarters but rose after that.

The two quantities used to evaluate the estimates are shown in Figure 3. Evaluated over all 6 quarters, the root-mean-square error (RMSE) of the entries ranged from 1.1 Sv to 4.5 Sv. Also shown in Figure 3 is the number of months for which the error remained less then 1 Sv. Four of the ten entries had an absolute error less than 1 Sv for the first quarter. This suggests a significant skill when predicting three months ahead. After 9 months things were very different with just one prediction bettering persistence for each of the first three quarters.

For both measures of skill – RMSE compared with data variability, and how well model results compare with persistence – the best performing model was the UK Met Office entry from Laura Jackson.* However, if we make an estimate of the AMOC based on the mean of all the entries then it performs much better than any of the individual estimates and has an error of less than 1 Sv for all 6 quarters. This should perhaps not be a surprise. In ensemble simulations of climate variables the ensemble mean often outperforms all the ensemble members, as recently highlighted by Rougier (see Further Reading).

* This differs from the result on the RAPID blog published before the full dataset was available, when a provisional estimate of the AMOC was used.

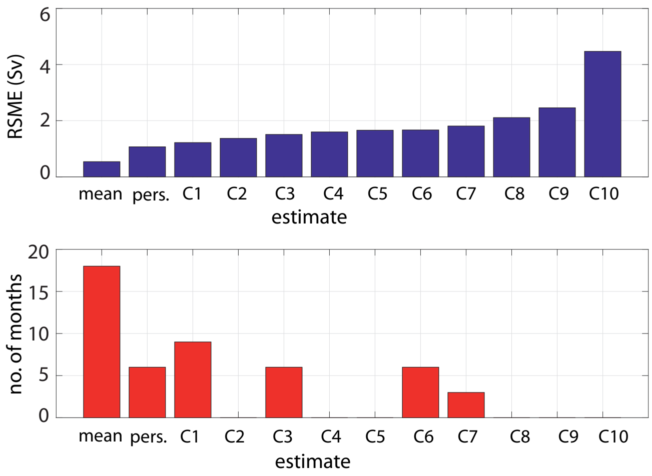


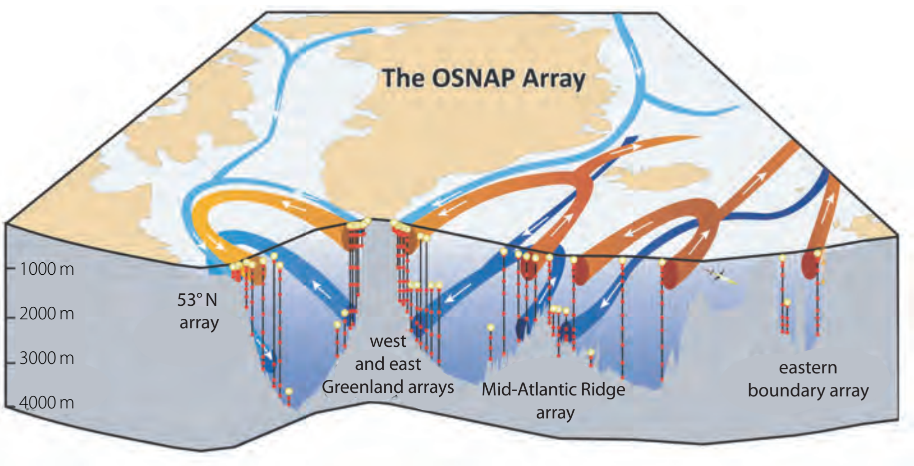
Figure 3 ***Upper*** *The RMSE for each of the 10 submitted entries, as well as for the mean of all entries (mean) and the persistence value (pers.).* ***Lower*** *The number of consecutive months for which the error remained less than 1 Sv.*

More challenges

This has not been a rigorous study but the results suggest that there is some predictability in the AMOC over time-scales of at least a few months and perhaps longer. But with none of these hindcasts showing skill beyond 9 months, the need for observations is clear and the RAPID team will be going to sea in spring 2017 to retrieve the next measurements of the AMOC.

If you would like to test your skill at predicting the AMOC then take a look at the OSNAP website (*see the related links*). The AMOC research community is eagerly waiting for the synthesis of the first two years of data from the OSNAP array (Sept 2014 – Aug 2016) and the OSNAP team has announced a competition to predict their results.

Figure 4 *The OSNAP array in the subpolar North Atlantic. OSNAP seeks to quantify the AMOC across the whole of the subpolar gyre, and is a collaboration between the USA, UK, Canada, China, France, Germany and the Netherlands.*



Related links

The RAPID 26°N data are available from http://www.rapid.ac.uk/rapidmoc/

The RAPID Challenge blog is at http://rapidchallenge2015.blogspot.co.uk/

The OSNAP Challenge http://www.o-snap.org/osnap-challenge

Further reading

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The RRS Sir David Attenborough

The UK's new polar research vessel

Ray Leakey

The RRS *Sir David Attenborough*, due to enter service in summer 2019, will be the UK's most advanced research vessel and represents the largest UK investment in polar science since the 1980s. In this article I will summarise why we need it, what it will do, and the implications for conducting marine science in polar waters.

An artist's impression of RRS Sir David Attenborough *in polar waters (© Rolls Royce)*

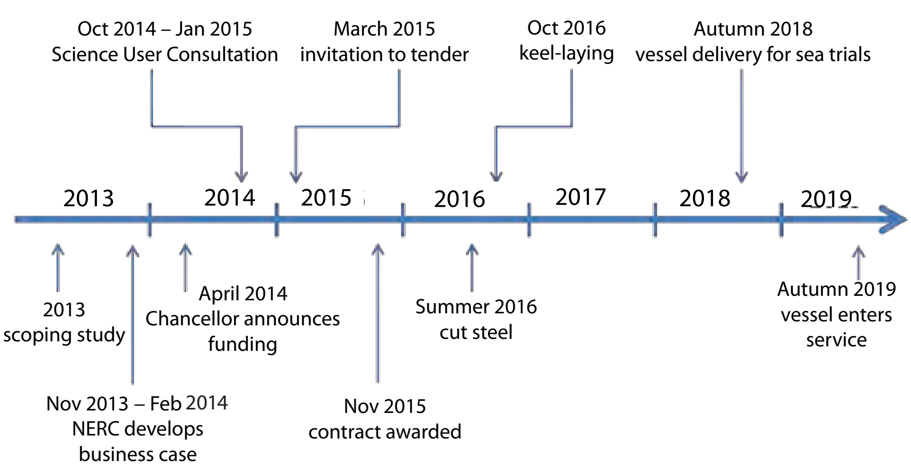
The polar regions are of great scientific interest and importance. They cool the planet, drive global ocean circulation, act as a net sink for carbon dioxide, contain valuable climate records and natural resources, and are home to unique flora and fauna as well as indigenous peoples. They are also the most rapidly warming regions of the planet, exhibiting changes which exert profound global environmental and socio-economic impacts.

The UK has a long history of conducting world-leading research in both the Arctic and Antarctic, supported by land, sea and airborne research platforms. These include two ice-strength ships operated by the British Antarctic Survey (BAS): the research vessel RRS *James Clark Ross* and logistics support vessel RRS *Ernest Shackleton*. For more than 20 years these two ships have performed an outstanding service enabling research in both polar oceans and resupplying UK Antarctic stations; however, they are now reaching the end of their scientifically useful lives.

In April 2014, the UK Department for Business, Energy and Industrial Strategy announced £225 million funding for a new dual purpose polar research vessel to replace the RRS *James Clark Ross* and RRS *Ernest Shackleton*. The ship will be owned by the Natural Environment Research Council and operated by BAS in support of the UK polar and marine science communities. The 'two-ships-to one' strategy of procuring a single, new, state-of-the-art vessel to undertake both a research and logistics role will enable the UK to enhance its polar science capability while at the same time achieving a significant reduction in running costs (~ £100 million over the life-time of the vessel). The new ship has been designed by Rolls Royce and is currently being built by Cammell Laird in Birkenhead. Following a public call for suggested names, which attracted unprecedented media engagement (including the popular '*Boaty McBoat Face*'), the ship will be named *Sir David Attenborough*, a name that captures the ship's scientific mission and celebrates the broadcaster's contribution to natural science.

Designing and building a dual-purpose, state-of-the-art, ice-strength research vessel is no easy task and the design team have had to address several major challenges. First, the ship has to safely and comfortably deliver its large cargo of supplies and scientists to the world's most remote and hostile waters. To achieve this it needs to navigate from pole to pole across tropical and temperate waters, as well as polar oceans. It also has to be able to break sea-ice up to 1 m thick and be self-sufficient in terms of cranes, cargo tender and workboats to resupply remote Antarctic stations lacking any port infrastructure. Secondly, the ship has to act as a multidisciplinary research platform to support the diverse range of marine science undertaken by the UK community. To achieve this, it has to be very quiet when in transit to allow environmental monitoring, have good dynamic positioning to enable instrument deployment, and be able support a large number of scientists at sea for long periods of time. Thirdly, the ship has to

The RRS Sir David Attenborough *time-line*



The performance of the vessel's hull design in sea ice was tested using a 6.5 m (1 : 20 scale) model in the large ice tank at Hamburgische Schiffbau-Versuchsanstalt, Germany. Conditions in the tank can be varied to produce different kinds and thicknesses of ice.
(© Cammell Laird)

be fuel efficient, with minimum environmental impact, and with the flexibility and adaptability to meet future scientific requirements during its 30-year life. These include developments in remotely operated and autonomous instruments, and in data-handling and communication. Last but not least, the ship has to be delivered on time and within budget.

Meeting these scientific and operational challenges requires a very big ship and the RRS *Sir David Attenborough* will be the UK's largest research vessel and also the largest civil ship to be built in the UK since the 1980s. It will be 129 m long with a breadth of 24 m, a draught of 7 m, and ~15 000 tonnage with cargo (approximately three times the tonnage of the RRS *James Clark Ross*) (*see right*).

This large size has helped address some of the design challenges, enabling a wide range of science capabilities to be supported. All the existing science activities currently undertaken on the UK's blue water research fleet will be supported by the new ship along with several new capabilities. These include: a helicopter deck and hangar to deploy field parties and instruments on sea-ice and to remote coastal locations; a moonpool to enable the safe deployment and retrieval of instrumentation in rough seas and ice-covered waters; a 10 m hard-hull workboat to enable near-shore research; a giant (42 m) piston corer so longer sediment cores can be retrieved, thereby extending palaeorecords from poorly sampled ice-covered waters; a dedicated trace-metal-free CTD rosette and winch to enable biological studies in iron-limited offshore waters; a science hangar housing up to six laboratory containers (this in addition to further laboratory container positions on the aft-deck, fore-deck and helicopter hangar); and large spacious laboratories including dedicated aerosol, atmospheric, clean chemistry and controlled-temperature experimental facilities.

A major priority has been to design the ship so that it can break ice, yet at the same time operate quietly and efficiently – requirements which place conflicting demands on hull design. Extensive hydrodynamic model tests have therefore been undertaken to attain an optimal hull design, including computational fluid dynamic modelling, and physical model trials undertaken in an ice tank where real sea-ice conditions can be simulated (*see above*). Air flow over the ship's superstructure has also been modelled to optimise the design for atmospheric measurement and sampling.

The use of a single larger ship to support UK polar science will result in a ~15% reduction in science days and presents several new operational challenges. An extensive programme of enabling works is being undertaken at the UK Antarctic research stations to support the new one-ship operation model. These include

RRS Sir David Attenborough *Technical Specifications*

Length 128.9 m, breadth 24 m, draught 7 m
~15 000 tonnage with cargo
Scientific cargo volume of approximately 900 m^3
Endurance for up to 60 days in polar regions
Range 19 000 n.m. (~ 35 000 km) at 13 knots transit
Ice breaking capability: up to 1 m thick at 3 knots (PC5)
30 crew and officers
60 scientists and support staff

RRS* James Clark Ross *for comparison

Length 99m, breadth 19 m draught 6.4m

5732 tonnes

Sir David Attenborough and Cammell Laird CEO John Syvret CBE with a model of the new ship at the Cammell Laird shipyard
© Mills Media

Left *Part of the keel of the RRS* Sir David Attenborough*, ready to be lowered at the keel-laying ceremony in October 2016*

Right *The man himself at the keel-laying ceremony*

(Both photos © Cammell Laird)

Right *Artist's impression showing how the RRS* Sir David Attenborough *superstructure (decks 7 to 12) will be placed on to the main body of the vessel at the Cammell Laird shipyard in Birkenhead*

(© Roll Royce)

the extension of the wharf at Rothera station (on Adelaide Island to the west of the Antarctic Peninsula) to accommodate the larger ship, and installation of more efficient cargo-handling and storage systems. However, the move to a one-ship operation also presents new science opportunities. In addition to its enhanced science capabilities, the ship will be able to accommodate up to 60 scientists at sea continuously for up to 60 days. This will have significant implications for the way in which the UK science community organises its polar ocean fieldwork, with a greater emphasis placed on undertaking large, long-duration, multidisciplinary expeditions.

The design of the RRS *Sir David Attenborough* was completed in spring 2016, after extensive consultation with the science user community, and the ship is now being built in Cammell Laird's huge construction hall. The first steel was cut in summer 2016 and a ceremony was held on 17 October 2016 to mark the traditional 'laying of the keel', with Sir David Attenborough as guest of honour. After completion in summer 2018 the vessel will conduct a year of ship trials in the North Atlantic and Arctic before entering service with its first trip to the Antarctic in autumn 2019.

The UK oceanographic community has a long and outstanding record of scientific achievement supported by some of the world's finest research vessels. The RRS *Sir David Attenborough*, along with the RRS *James Cook* and RRS *Discovery*, will help ensure that the UK continues to be a world leader in marine and polar environmental science, and is well placed to address the challenges presented by a rapidly changing planet.

Acknowledgements

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Further information

https://www.bas.ac.uk/polar-operations/sites-and-facilities/facility/rrs-sir-david-attenborough/

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• Wave Radar
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• Irradiance
• Nitrates, Phosphate
• Transmissometers
• Turbidity
• LISST Particle analysers
• Mooring recovery Systems
• CO2, CH4
• Sediment Monitoring
• ARGO Floats
• Absorption and Beam Attenuation
• Spectrophotometers
• CTD - Multi-parameter systems
• Miniature Data loggers
• Ice keel Profilers
• Water Column Profiler
• Push Corers
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• Tracking Beacons
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Studying the Arctic Ocean's freshwater budget by seeing under the ice from space

Tom Armitage

The Arctic Ocean represents just 4.3% of the global ocean area, making it the smallest of the world's major ocean divisions. It is largely enclosed by land, limiting interactions with the global ocean, and sea ice, which covers between 5×10^6 km^2 (in summer) and 15×10^6 km^2 (in winter), acts as a barrier between the ocean and the atmosphere. This sea-ice barrier not only limits the exchange of heat between the atmosphere and ocean, it also limits the exchange of momentum, which results in relatively low surface current speeds. Further, the Arctic Ocean surface layer stores a large amount of cool and buoyant freshwater (somewhere in the region of 80 000–90 000 km^3) in the form of both ice and liquid; cool, low salinity water overlies warmer, more saline water at depth, and the resulting stratification limits vertical mixing between the surface and deep ocean, preventing momentum transfer from the surface to the deep ocean, but also preventing upward mixing of heat from depth (there is enough heat in the deep Arctic Ocean to melt the Arctic sea ice several times over).

But despite this, the Arctic Ocean is an important component of the global ocean. Excess freshwater outflow from the Arctic has the potential to slow convection in the Nordic Seas by acting as a cap which insulates the warm and saline northward flowing Atlantic water from the atmosphere, reducing heat and moisture loss, and limiting the formation of dense North Atlantic Deep Water (NADW). The formation and subsequent sinking of NADW is a driver of the large-scale thermohaline circulation in the North Atlantic (the so-called North Atlantic conveyor) and the global overturning circulation. It is thought that large freshwater pulses into the North Atlantic have in the past dramatically reduced the strength of the North Atlantic overturning, and hence the northward transport of heat, leading to low Northern Hemisphere air temperature anomalies that persist for centuries. The so-called 'Great Salinity Anomaly' of the 1970s – at the time labelled 'an extreme variation in ocean climate' – was caused by an excess outflow of just over 2% of the freshwater stored in the Arctic Ocean surface layer.

Thus, a picture emerges of the Arctic Ocean and its role in the global climate: it is an isolated, stratified and sluggish ocean, but one that is in a delicate balance with the global ocean and could have a significant impact on Earth's climate if that balance is disrupted.

An important question then arises: what is happening as the sea-ice layer recedes, thins and weakens under a changing climate, and the underlying ocean becomes more exposed to the atmosphere and wind? Without its protective sea-ice layer is the Arctic Ocean becoming more like a conventional ocean?

Over the global ocean, sea-surface height is an important parameter for measuring the impact of climate change. Tide gauges have been used to estimate global mean sea level since the late 19th century and satellite radar altimeter missions have provided near-global maps of sea-surface height since the early 1990s. However, sea-surface height is poorly measured in the Arctic Ocean. The coverage of tide gauges is poor in space and time and conventional satellite altimeter missions do not cover the polar oceans. Furthermore, even polar-orbiting satellite altimeter missions cannot routinely estimate sea-surface height in the large areas of the Arctic Ocean that are covered by sea ice.

In an article published in *JGR: Oceans* in 2016, my colleagues and I aimed to reveal seasonal and interannual variability in sea-surface height of the Arctic Ocean, to examine the role of freshwater exchanges at different time-scales and to demonstrate the role that satellite altimetry can play in monitoring this important component of the global ocean in a changing climate (see Further Reading).

Specialised data processing

To do this, we applied specialised processing of satellite altimeter data to estimate sea-surface height in the ice-covered portions of the Arctic Ocean. This involved identifying data that originate from leads (cracks) in the sea-ice cover, where the sea-surface is exposed (Figure 1). Sea-surface height from leads was then combined with sea-surface

Figure 1 *A lead in the sea ice in the Lincoln Sea, north of Greenland, March 2014. Altimetry data from leads can be used to estimate sea-surface height in the ice-covered portions of the Arctic Ocean.*

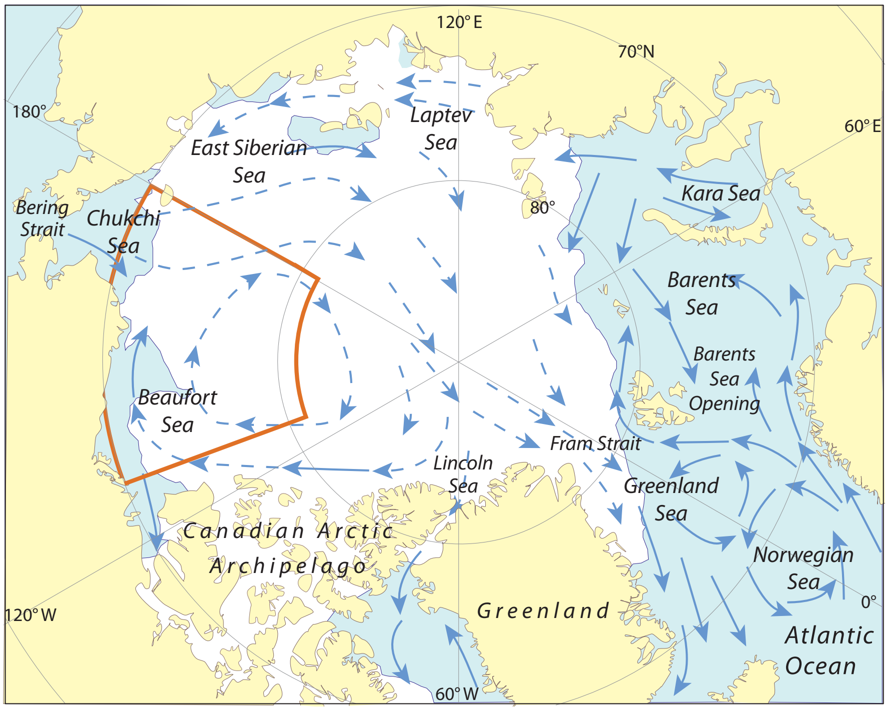


Figure 2 *Generalised pattern of surface currents in the Arctic Ocean and Nordic Seas. White = area covered by sea-ice in July 2016; in ice-covered areas, surface currents are mirrored by the large-scale ice-drift. The area outlined in red is the region for which the freshwater budget was esimated (cf. Figure 4; see Armitage* et al. *(2016) in Further Reading).*

height from open water, and we stitched together data from two European Space Agency satellites (*Envisat* and *CryoSat-2*) to get a monthly record of sea-surface height in the ice-covered and ice-free Arctic Ocean between 2003 and 2014.

Over decadal time-scales, global sea level varies for two main reasons: first, due to changes in the total amount of water in the ocean (the ocean mass) which can change due to exchanges of water or ice with the land, for example, and secondly, due to changes in the ocean density (steric sea-level change) which depends on the temperature and salinity of the seawater. At a regional scale, the relative contributions of these effects to the total variation in sea-level can inform us about ocean processes and dynamics. Sensors carried by the NASA Gravity Recovery and Climate Experiment (GRACE) satellites measure changes in the ocean mass and it is possible to estimate steric sea-level changes by combining the GRACE data with the altimetry data. This allows us to study the role of freshwater in the Arctic Ocean because at low temperatures, as in the Arctic, changes in the density of seawater are almost entirely caused by variations in salinity.

What makes the Arctic Ocean breathe?

Our observations reveal a large seasonal cycle of Arctic sea-surface height which is dominated by variations in sea level resulting from changes in the density of the upper ocean (Figure 3). This seasonal cycle in sea level is driven by the input of freshwater into the Arctic Ocean, which has a strong seasonal variation.

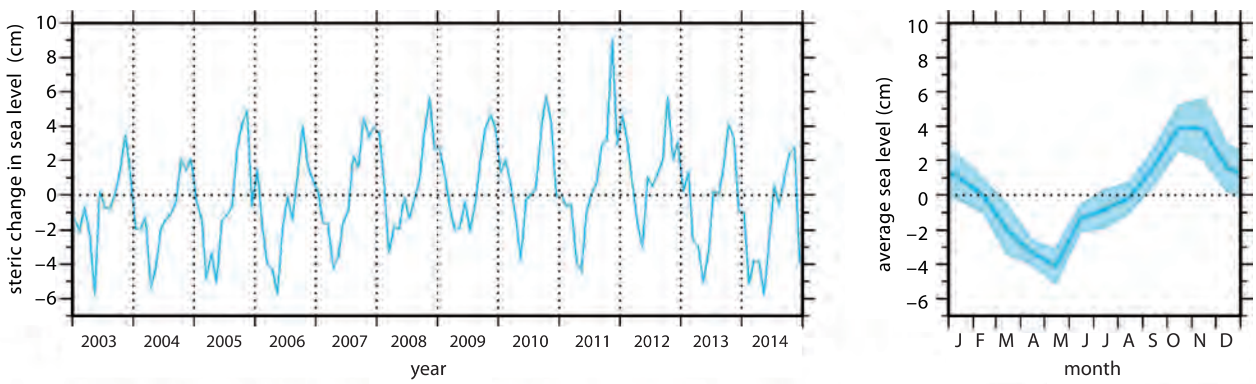
Every year there is a large input of freshwater to the Arctic Ocean during summer. In May and June the terrestrial Arctic thaws and a vast amount of meltwater flows into the large Siberian rivers from where it eventually flows into the Arctic Ocean. Overall, whilst the Arctic Ocean represents just 1.4% of the global ocean volume, around 11% of global river runoff ends up in it. At the same time, during summer, precipitation exceeds evaporation over the central Arctic and there is a peak in the flow of relatively fresh Pacific water through the Bering Strait into in the Arctic.

These inputs of freshwater push more saline seawater out through the openings of the Arctic Ocean (the Fram Strait, the Bering Strait, the Barents Sea Opening and narrow straits through the Canadian Arctic Archipelago; Figure 2); this, combined with summertime melting of sea ice, freshens the upper ocean. Sea level thus rises during the summer as the seawater becomes fresher and less dense, with sea level peaking in October and November, with typical heights of 4 cm above the annual average (Figure 3, right). Sea level then falls during winter as newly forming sea ice rejects brine (making the ocean more saline and hence denser again) and is exported from the Arctic to the Nordic Seas.

Regional freshwater exchanges

During the period of our study, there was an accumulation of freshwater in the Beaufort Sea Gyre, which appears in our data as a bulge in sea level in the western Arctic, north of Canada and Alaska. Strong anticyclonic winds, particularly in late 2007, in combination with receding, thinning and weakening sea ice, saw the enhanced 'spin up' of the Beaufort Gyre, and resulted in an accumulation of freshwater due to increased Ekman convergence of surface waters (Figure 4).

Figure 3 ***Left*** *Steric sea-level variation in the central Arctic Ocean between 2003 and 2014.* ***Right*** *The average seasonal sea-level cycle during this period, relative to the 2003–2014 average. The pale blue envelope indicates the standard deviation of the seasonal cycle.*



We estimate that, on average, between 2008 and 2010 the freshwater content of the Beaufort Sea region was 4300 km^3 greater than it was between 2003 and 2006 (Figure 5).

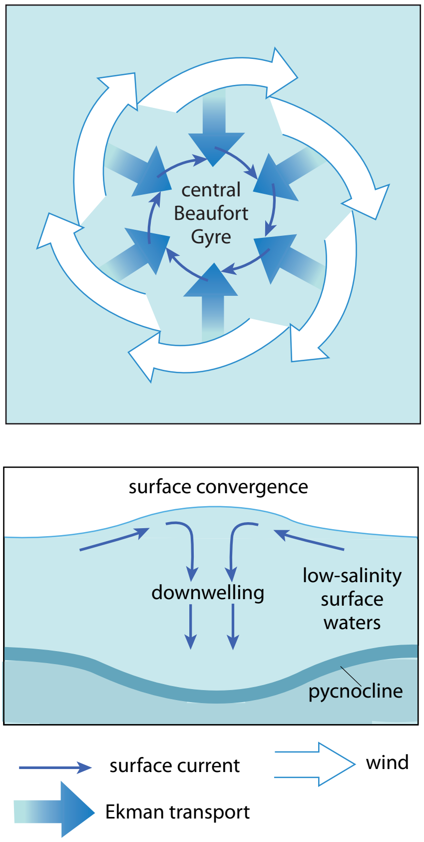


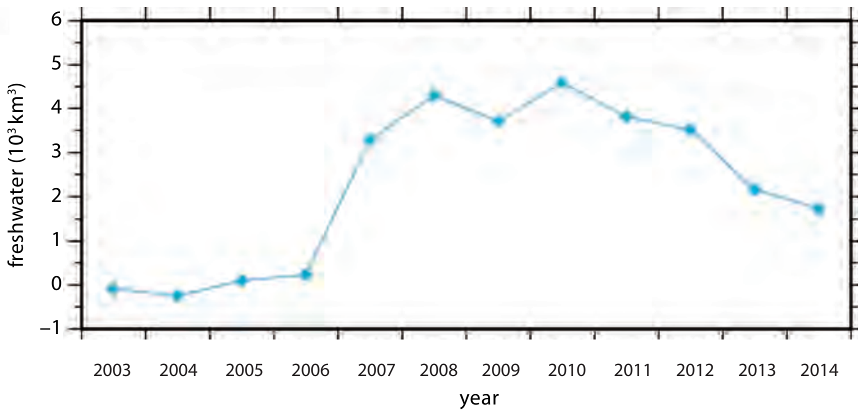
Figure 4 ***Upper*** *Anticyclonic winds over the Beaufort Gyre lead to transport of relatively fresh surface water at right angles towards the centre of the gyre (Ekman transport) in the wind-driven layer.*
Lower *Cross-section of the Beaufort Gyre, showing the resulting upward bulge in the sea-surface and the accompanying depression of the pycnocline. Note that although the bulge is initially partly the result of a piling up of water (extra ocean mass), the upper ocean quickly adjusts, and the longer term increase in sea-surface height is a result of the low density of that extra water (i.e a steric effect).*

Our data show that the increase in sea level in the Beaufort Sea was concurrent with drops in sea level in the adjacent East Siberian and Laptev shelf seas. This is to be expected as the Beaufort Gyre draws in water from the surrounding shelf seas. We calculate that around 200 km^3 of freshwater was drawn off the Siberian shelf seas over the course of the study period.

The amount of freshwater redistribution within the central Arctic – i.e. transfer of freshwater between different regions of the Arctic Ocean – is small compared wth the total accumulation of freshwater seen in the Beaufort Gyre. For example, the Siberian shelf seas contribute just under 5% of the total accumulation of 4300 km^3. Other sources of freshwater for the Beaufort Gyre (river runoff, melting of sea ice, precipitation, inflow of Pacific water) cannot account for the increase in freshwater content in this period – there must have been a reduction in freshwater outflow. A reduction in outflow of just 15% over a few years could account for the accumulation of freshwater seen in the Beaufort Gyre during the late 2000s.

It remains an open question as to what will happen if the wind forcing supporting the increased volume of freshwater in the Beaufort Gyre weakens. Our data show drops in the freshwater content of the Beaufort Gyre towards the end of the study period and other studies have linked the storage and release of freshwater in the Beaufort Gyre with salinity anomalies in the North Atlantic. So, it is possible that the reduction in Beaufort Gyre freshwater seen in our data between 2012 and 2014 could show up in the North Atlantic over the next few years. We wait to see if other data corroborate our observations.

Figure 5 *Change in freshwater content of the upper ocean in the western Arctic region outlined in red in Figure 2.*



Arctic monitoring

We believe that our work has demonstrated the potential for satellite altimetry to augment existing observational networks, and contribute to monitoring the freshwater balance of the Arctic Ocean. Automated buoys tethered to sea ice floes provide high-frequency detailed information about the temperature and salinity of the Arctic Ocean at depth but their spatial coverage is relatively sparse. Satellites don't provide the same detailed information as buoys but can detect changes in the Arctic freshwater distribution with better spatial coverage than buoys. Moorings across the main openings of the Arctic Ocean give us information about the water flowing in and out of the region. By combining these complementary data it will be possible to start to build a more complete picture of Arctic Ocean freshwater exchanges.

We will continue to develop and extend the sea-surface height data to establish a long-term record of ocean change in the Arctic. We are now using these data to study changes in Arctic Ocean circulation and changes in the interaction between the atmosphere and ocean. By removing the sea-ice layer of the Arctic Ocean, humans are currently performing one of the largest (if unintended) experiments ever conducted in oceanography. We hope that by using the sea-surface height data, and making it available to other researchers, we can contribute to determining how the Arctic Ocean is responding.

Further reading

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A new stamp for Iceland – and why not?

Jörundur Svavarsson and Tony Rice

On 16 September 2016 the Icelandic Post Office issued a new stamp to mark the 80th anniversary of the sinking of the French exploration vessel *Pourquoi pas?* and the tragic loss of all but one of her complement of 41, including the French polar explorer Jean-Baptiste Étienne Auguste Charcot. Charcot is well known in Iceland, where he has two memorial monuments, one of which is in Reykjavik, but he is otherwise largely forgotten except amongst marine scientists and polar exploration enthusiasts, despite at one time being as famous in France as Robert Falcon Scott was in Britain.

Charcot was born in 1867 in Neuilly-sur-Seine, the son of Jean-Martin Charcot, a celebrated pioneer neurologist. Like his father, Jean-Baptiste initially studied medicine, but his real passion was marine exploration and to this end, between 1893 and 1901, he bought three successively larger vessels to all of which he gave the enigmatic name *Pourquoi pas?* (meaning 'Why not?'), supposedly the question that, as a small boy, he painted on the side of a soapbox in which he sailed, and sank, in a local pond. As a privately financed amateur he gained a considerable reputation as an Arctic navigator, so much so that when he financed the building of a new 250-tonne vessel, designed specifically for polar waters and patriotically named *Français*, he received sufficient official support for him to command the ship in what became the official French Antarctic Expedition from 1903 to 1905 (*see photo opposite*). Unfortunately, the venture was inadequately funded and the ship, particularly her engine, proved less than satisfactory, and she was sold to the Argentine government on her way home. Nevertheless, the expedition was considered a great success, having charted some 600 miles of previously unknown Antarctic coastline on the western side of the Antarctic Peninsula, and bringing home large geological and biological collections.

On the back of the expedition Charcot had become something of a national hero. As a result, he ordered the fourth *Pourquoi pas?* (the one commemorated in the new stamp) to be built at the shipyard of François Gautier at Saint Malo. Financed by Charcot himself and by public subscription, and launched in 1908, the new *Pourquoi pas?* was rigged as a three-masted barque and had a displacement of 450 tonnes, almost twice that of the *Français*. She was also fitted with a more powerful 450 h.p. engine and carried a crew of 35 plus five scientists.

The first cruise of the new vessel, from 1908 to 1910, was again to the Antarctic, where Charcot and his crew overwintered for a second time. She returned to France again having made many scientific and

The commemorative stamp, depicting the forepart of the ship (the bowsprit and foremast) with a black-legged kittiwake flying above, was issued within a larger image showing the vessel about to strike the reef on which it was wrecked, off the coast of Álftanes Peninsula (Iceland). This is superimposed on a more or less contemporary map of the Álftanes Peninsula and offshore islands. The stamp is to be used for packages up to 1000g in weight. The sheet was designed by Hany Hadaya.

geographical discoveries, including the discovery of a new island which had been named Charcot Island in memory of Charcot's father. Over the next three decades, eventually financed by the French government, the ship made numerous scientific cruises in Arctic waters, as well as in the North Atlantic and Mediterranean, carrying out geological, physical, chemical and biological studies. Initially, Charcot was almost invariably in command, though in the 1920s, with increasing age, he handed over command to younger men while often retaining overall leadership. The *Pourquoi pas?* made several visits to Iceland and Greenland, and in the 1930s was involved in setting up and servicing an ethnographic mission in Greenland in collaboration with the ethnographer and explorer Paul-Emile Victor. It was during the return voyage after supplying scientific material to the mission in 1936 that the ship was lost. After visiting Reykjavik to re-provision and refuel on 13 September, the *Pourquoi pas?* sailed for Copenhagen in very calm weather on 15 September but was caught in a violent storm during the evening and was lost on the reefs off the Álftanes Peninsula (about 35 km north-west of Reykjavík) in the early hours of the following morning. With the single exception of master helmsman Eugene Gonidec, all those on board were lost, including the 69-year-old Charcot.

Photograph taken during the first Antarctic Expedition on the Français*, showing two of the scientists having a glass of champagne, reflecting the spirit during the Expedition. (By courtesy of the Charcot family)*

The loss of the *Pourquoi pas?* was a national tragedy in France and the recovered bodies were given a state funeral at Notre Dame in Paris. But it was also a great shock to the people of Iceland where Charcot and the *Pourquoi pas?* had become well known because of her many, possibly 40, visits to Icelandic ports over the years. When the recovered bodies were transported from the Catholic church in Reykjavik to a French vessel, to be carried to France, all the shops in Reykjavik closed and most of the city's inhabitants came to show their respects. Even today, the memory of Charcot and his ship is strong amongst older Icelanders and there is currently a small exhibition about Jean Charcot and the *Pourquoi pas?* at the Suðurnes Sciences and Learning Centre in Sandgerði in south-west Iceland in collaboration with the University of Iceland.

Contemporary painting of Charcot by Marin-Marie (By courtesy of the Yacht Club de France)

Although Jean Charcot seems to be not very well known by the general population in France today, he is still remembered and revered by the oceanographic community. In 1965 a French survey vessel was named after him and operated initially by CNEXO (later IFREMER) and the French Post Office. One of us (TR) has fond memories of the *Jean Charcot* when she hosted a gear inter-calibration cruise in the early days of European collaboration in deep-sea biological research. Late in her life, but still carrying her original name, she operated as a fishery patrol vessel under the flag of Vanuatu. Continuing the remembrance of Jean Charcot, a current research vessel, launched in 2005 and operated jointly by IFREMER and the French navy, was also given the name *Pourquoi pas?* This vessel appropriately paid a courtesy visit to Reykjavik on the 80th anniversary of her namesake's loss and acted as a temporary post office for the issue of the first day covers.

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A ‘cranky little vessel’: The story of HM steam vessel Lightning

Part 2 The navy enters the steam age

Tony Rice

In the previous issue of *Ocean Challenge* I published the first of a series of articles based loosely on the story of HMS *Lightning*, the little Royal Naval paddle steamer that, towards the end of her career, undertook a fairly disastrous six-week oceanographic cruise which led ultimately to the *Challenger* Expedition. That article dealt with *Lightning*’s connection with Deptford Dockyard, where she was launched, and the origins of the expression ‘Sweet F.A.’ in a gruesome murder in the summer of 1867. Here I go back to *Lightning*’s very earliest days, before she entered the *Navy List* in 1828, when the Navy didn’t quite know what to do with her and her steamer contemporaries, and certainly didn’t yet have qualified officers and men to operate them.

The beginning of a new era

The *Lightning* was launched at Deptford Dockyard on Friday, 19 September 1823. She was by no means unique, but simply one of a number of steam vessels built for the navy in the 1820s, all with ‘power’ names like *Comet* and *Meteor.* At the time they were built, every one of the one hundred or so ships in the *Navy List*, the official catalogue of the Royal Navy’s ships and officers, was a conventional sailing vessel. Compared with the hugely impressive line of battleships in the post Napoleonic war navy, *Lightning* and her contemporary steamers were pretty unprepossessing and received a lukewarm reception from many naval men. Twenty years later, J.M.W. Turner captured the nostalgia for sail in his famous painting ‘The Fighting Temeraire’, depicting the old ship as she was being towed to a breaker’s yard at Rotherhithe in 1838. The 98-gun *Temeraire* was regarded with great fondness by the British public because of her role at the battle of Trafalgar where she came to the timely aid of Nelson’s *Victory* as the flagship was in danger of being boarded by the crew of the French *Redoutable*. As if in tribute to the ending of a romantic and elegant era and the beginning of a much more workaday and less attractive one, Turner’s painting shows the tall and stately *Temeraire* in a ghostly silvery livery, being towed towards the viewer by a dark, squat tug with huge paddle boxes on either side and a tall black funnel belching smoke and flames: an ignominious end to a national icon that would have resonated with many retired naval officers – and quite a few who were still serving.

In Turner’s ‘The Fighting Temeraire’ (National Gallery), painted as the age of sail was being overtaken by steam, the graceful **Temeraire** *is partly obscured by the dark steam-driven tug (though Turner has moved the tug’s funnel forward for a better effect).*

But there were a few forward-looking naval officers who embraced the new technology enthusiastically and realised that steam would totally transform sea-going. One of these was Captain (later Admiral Sir) John Ross, the uncle of the much better known James Clark Ross of Antarctic surveying fame. In 1818, five years before the *Lightning* was launched, John Ross, accompanied by James, had led a naval expedition to Baffin Bay and Lancaster Sound in search of the North-West Passage, under sail of course. Although it brought back some interesting oceanographic data (see Further Reading) the expedition was an almost total failure and ended in controversy that more or less ended John Ross’s naval career. But partly as a result of his difficulties, he became convinced that steam propulsion would greatly assist Arctic exploration.

He was so keen to spread his enthusiasm that he wrote *A Treatise on Navigation by Steam*, published in 1828, in which he not only extolled the virtue of the new technology, but also made many recommendations on how best to employ it in a naval setting. Inevitably, however, a good deal of Ross’s *Treatise* was taken up with details of how he thought steam vessels should be rigged and how they should be sailed with or without using the engines. This was because early steam engines were inefficient and far from reliable, as Ross was to discover all too painfully himself the following year when he led an Arctic expedition financed by the gin king Felix Booth and employing an ex Isle of Man ferry, renamed *Victory,* probably the first steam vessel to enter Arctic waters (see Further Reading). The ill fated expedition eventually spent a record four and a half years in the Canadian Arctic before being rescued, amazingly, by the Hull whaler *Isabella* – the very same vessel hired by the Admiralty and commanded by John Ross in 1818. Its main, and very significant, achievement was the first location of the North Magnetic Pole by James Clark Ross, some hundreds of miles south of where it is today. But John Ross’s faith in the *Victory*’s steam engine had been totally dashed. It was so inefficient and unreliable during the early part of the expedition that at the end of September

1829, as they were preparing for their first Arctic winter, Ross decided that it was a waste of space, literally, and had the machinery and boilers dismantled.

Although Ross seems to have been particularly unlucky with the engine fitted to the *Victory*, it would be many years before the navy risked steam vessels totally devoid of masts and sails, the very first being the turret ship *Devastation* launched at Portsmouth in 1871. In the meantime, steam propulsion in the navy was always an adjunct to wind and sails, as in the case of the 226 feet long HMS *Challenger*, launched in Woolwich in 1858 and technically a steam-assisted screw corvette. *Challenger*, like the much larger and near contemporary *Warrior*, was primarily a sailing ship, and her funnel could be laid flat on the deck and her screw raised clear of the water to increase her efficiency under sail. The *Lightning*, on the other hand, was primarily a steam vessel. Only 126 feet long and with a beam of 22 feet, she was fitted with two simple paddle wheels about 18 feet in diameter driven by two side lever engines, each of 50 nominal horse power, occupying the whole of the middle one third of the vessel's hull. Side lever engines were modifications of the conventional beam engine used in many land-based applications, reducing the overall height of the engine and lowering its centre of gravity to make it more suitable for maritime use. But although they provided her main propulsion, she also had a jib and two masts carrying a range of both square and fore and aft sails which would undoubtedly have been used wherever possible to conserve her coal fuel, though the shape of her hull and her paddles would have made her a rather inefficient sailing vessel.

Lightning and her steamer companions were very definitely innovations for the navy at the time, but they were considered to have a restricted and specialised role. Although not named as such, they were all in essence tugs, their main role being to tow sailing warships in and out of harbours against contrary winds or tides, and to undertake similar tasks in action, particularly towing large men-o-war into position for land bombardment. But accounts of these duties by steam vessels before they entered the *Navy List* are scarce, either because their crews were not required to keep the conventional log books and muster books kept by all commissioned vessels or, if they did keep such records, they do not seem to have been preserved in the naval archives. Consequently, the story of the first few years of the *Lightning*'s history has to be put together from a variety of sources, often not very clear.

Although fitted with a steam engine, HMS Warrior *(now at Portsmouth) was primarily a sailing vessel*

Initially she was certainly used mainly for towing duties and Simon Goodrich (1773–1847), the Navy Board's civilian senior engineer, based in Portsmouth, recorded that in May 1824 he had accompanied her to tow in HMS *Niemen*, a 6th rate 28-gun vessel and that 'The engines perform remarkably well' (see Further Reading). Four months later he received a report from Joshua Field, a partner in the engineering firm of Maudslay, Sons and Field which had built the *Lightning*'s engines, that the vessel was capable of 11 miles per hour while towing a frigate with a following wind and with the paddles revolving 26 times a minute.

However, in between these two somewhat mundane events *Lightning* was employed in a quite different role, to accompany naval warships to Algiers to remonstrate with the ruler for several acts of piracy by Algerian vessels, culminating in the seizure of two servants from the British Consulate. Initially, just two ships were sent out, the 5th rate 46-gun frigate *Naiad* and the 12-gun brig sloop *Cameleon*. Between January and May 1824 these two vessels had blockaded the Algerian coast and, amongst other things, had captured the 20-gun Algerian corvette *Triopoli*, one of the known pirate vessels. One of the *Naiad*'s lieutenants was George Evans who had already had a good deal of seagoing experience both in action and in surveying. Although he was not to know so at the time, Evans would eventually command *Lightning*, becoming the very first commissioned naval officer to command a steam vessel. And he was about to see this strange new vessel for the first time though there is no record of what he thought of her.

A new breed of seaman

But until she entered the *Navy List*, command of the *Lightning* was in the hands of non-commissioned officers, or even civilians. For the Algerian expedition, for example, she was under the command of a Mr Gage, master attendant at Portsmouth, while her engineers would have probably been from Maudslay's. Her complement, that is the number of men of different ranks deemed necessary to operate her efficiently, was changed several times during her career, ranging from as few as 12 to as many as 25, though for efficient working the minimum seems to have been about 15, consisting of three 'deck officers' (a master and two mates), two engineers assisted by two boys or engineering apprentices, one steward, one cook, and six others made up of seamen and boys to undertake all the basic tasks ranging from rope and sail handling to coal trimming and stoking.

Despite being at the cutting edge of contemporary nautical technology, the engineers had rarely received what we would now consider a significant general education and were understandably not nearly as literate as most naval officers of the day. Nevertheless, by early 19th century standards they were quite

Sir – I should have wrote to you before our arrival at Deptford but have been so bussey imployed in towing ships about that I have had not a hour since I left Cronstead in Rusia we left in on the 1 July in company with the Gloucester 74 after beatin [beating, that is heading into the wind] and towing her at time we was ten days and nights before we made Copheagen after working that time my water in the boilers did not exceed the tempeture 216 Deg. by my blowing some water from the boilers several times a day. We took our departure from Copheagen on the 13th inst. and then whent into a port in Norway in a gale of wind on the 17th inst at this place Biggs Departed on 19h Inst this life and was buried their the tempeture of the water in the boilers did not exceed 216 Deg. Took our departure from Egersound in Norway on the 21 Inst and made Sheerness on the 24 Inst which made our running better then two hundred miles in four and twenty hours when We came to Sheerness we run to Chatham and then towed a 74 from Sheerness to near Chatham left Sheerness for Deptford on the 24 Inst and then the next day towed a ship from Woolwich to the Nore and then back to Deptford tomorrow we towes a barge from this to the Downs or Deptford immedently Sir the tempeture of the warter in the North sea his 214 and the tempeture in my boilers did not exceed 218 so that I never put my fire out nearly the old of the voage and when I took my man hole of the boilers of was as clean as a pair of new ones my Engins his in as good repair as when I left England the main pipe joint under the boilers give way but I repaird that so that it his as tite as ever but my front plates round the fire doors his gitin bad and my Clutch on the paddle Wheels his git lose by been in such evey seas. Mr. Mosely [Maudslay] have been on board and it give him grate pleasure to see the Engins in so good a state after such a long journey Sir I hope that you will send to the Board to know if I am to have the boat or know as we belong to your department for I have had know time to see them or write to them I hope that you will do me the favour and let me know Sir as soon as posable or some recompence for bring home the Vessel as I am at Deptford I have two or three places to go to if the don give me the situation. I have had charge of the Engins from the 4 of June when we left Cronstead to look for the Duke I have had a fertigen time of it Algers was nothing to compair with this journey.

Sir,

I remains your most humble and Obedgent Servent
John Chapender, Acting Engineer of H.M. Ship Lightning

John Chapender's letter to the navy's senior engineer, Simon Goodrich, written on Lightning's return from Saint Petersburg

capable of making themselves understood, as illustrated by the correspondence of one of *Lightning*'s engineers, John Chapender, with Simon Goodrich.

Chapender was in *Lightning* in 1824 for the expedition to Algiers and was still with her when she visited the Russian naval base at Cronstadt (or Kronstadt) in 1826. She had been sent to the Baltic as an escort to the 74-gun *Talavera* and other vessels taking British representatives, including the Duke of Wellington, to the funeral of Tsar Alexander I who had died suddenly, and rather mysteriously, in the southern city of Taganrog in December 1825 and was interred in Saint Petersburg in March 1826. Chapender's letter to Goodrich from *Lightning* after the vessel's return to Deptford in August has already been published at least twice, but it is so emotive that it deserves another airing – warts and all.

Chapender's frequent references to water temperatures highlight one of the big concerns of engineers looking after these early steam engines: the density or salt content of the boiler water. The boilers of seagoing steam vessels were, of course, fed with seawater, but as the steam boiled away the remaining water became more and more salt. This could result in salt deposition within the engine which might clog up pipes and valves, including the 'blow down' cocks which were used periodically to discharge the old, very salt water and replace it with new seawater. The density of the water in the boiler, and hence the salt content, was tested by drawing off a sample and determining the temperature at which it boiled, the saltier the water, the higher the boiling point. Fresh water was known to boil at close to 212 °F, whereas normal seawater containing about 35 grams of salts per litre would boil a couple of degrees higher, hence Chapender's note that 'the tempeture of the warter in the North sea his 214'. In comparison, he reports that the highest boiling point he recorded from samples taken from the boiler was 218° and was usually considerably lower.

Of course, Chapender's main reason for mentioning these details was to impress Goodrich with how solicitous he had been in his care of the 'engin' and how, as a result, his 'Engins his in as good repair as when I left England', despite having had such a 'fertigen time'*. He was

* I have been unable to find out what 'fertigen' means or meant, but I suspect it was not complimentary!

successful in the short term, being confirmed in his appointment to *Lightning* in November 1826. But Goodrich apparently suggested that he should be replaced by someone called Jenman in the following June (see Further Reading), though I can find no evidence of such an appointment. Certainly, by December 1827 when she first appeared in the *Navy List*, her muster book (ADM 37, 7571) gives her first engineer as Robert Rastrick and her second engineer as John Dinnon (sometimes also spelt Dinnen). These engineers were to become particularly significant because the navy, and the *Lightning*, were entering an important period in the history of steam. But before this could happen, steam vessels and the men who built and ran them needed support in high places. The next chapter in the story will describe how our little *Lightning* earned that support from no less than a future monarch and the Lord High Admiral.

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Advances in Marine Biogeochemistry Conference VIII (AMBIO VIII)

To be hosted by the Scottish Association for Marine Science (SAMS) in Oban

6 to 8 September 2017

This is the biennial meeting of the Challenger Society's Marine Biogeochemistry Forum. It attracts early-career researchers from institutions across the UK, and provides a fantastic opportunity for networking and forming new collaborations.

The conference aims to present the state of the art in research and technology in the field of marine biogeochemistry in the UK.

Day 1 will cover currently emerging and highly topical aspects of research, with a line-up of exciting keynote speakers.

Day 2 will be dedicated to celebrating Peter Statham's career, with notable keynote speakers reflecting the highlights and diversity of his research interests. Speakers will include Martyn Tranter (University of Bristol), Hélène Planquette (Université de Bretagne Occidentale, Brest) and Ian Hall (University of Cardiff).

Day 3 will be devoted to topical workshops which will provide the opportunity to focus on subject-specific collaborations to target funding and research outputs.

Registration and abstract submission are open! Submit your abstract at www.sams.ac.uk/ambioviii. To present your research at AMBIO VIII, please register online and email your abstract as a Word document to ambio@sams.ac.uk. Deadline for abstract submission: 23 June 2017.

Organisers

AMBIO Chair: Gary Fones, University of Portsmouth
AMBIO VIII Co-convenors: Kirsty Crocket and Natalie Hicks, SAMS

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Geopolitics, greed and environmental vandalism in the South China Sea

The South China Sea has been the subject of territorial claims for centuries, but tension has been steadily increasing in recent years. The 3.6 million km^2 of tropical waters linking the Indian Ocean and the Pacific Ocean make up the second most heavily trafficked sea in the world, with over half the global annual merchant fleet tonnage passing through the Strait of Malacca, the Sunda Strait and the Lombok Strait. Over 1.6 million m^3 (10 million barrels) of crude oil are shipped through the Strait of Malacca, every day. However, there is more at stake than trade.

Some legal background

The red lines in Figure 1 show the limits of the 200 nautical mile (n.m.) exclusive economic zones (EEZs) of the states around the South China Sea, according to the 1982 *UN Convention on the Law of the Sea* (*UNCLOS*). China has ratified *UNCLOS*, so why does it feel justified in claiming such a large proportion of the sea, including areas which overlap the EEZs of other states, most notably Vietnam and the Philippines, but also Malaysia, Brunei and Indonesia?

China's extensive claim can be traced back to 1278, when it drew up a map of its influence, including the whole of the South China Sea. Since then, influence in the region has passed between regional powers and, later, colonial states. The fractious situation today owes much to the fact that in surrendering after in World War II, Japan gave up its right to islands in the South China Sea, and no one nation was explicitly given sovereignty over the waters, effectively leaving a power vacuum. In 1946 China took advantage by seizing islands and publishing a U-shaped boundary (shown in green on Figure 1), often referred to as 'the nine-dash line'. The following year, the US Seventh Fleet, charged with maintaining peace and stability in the region, positioned itself in the Pacific near Japan and Guam; the US has concerned itself with the defence of Japan, South Korea and the Philippines ever since.

In 2009, Malaysia and Vietnam filed a joint submission to the UN Commission on the Limits of the Continental Shelf, to extend their continental shelves beyond the standard 200 n.m. China objected, on the grounds that this would seriously infringe its sovereignty over islands in the region, and presented a map showing the U-shaped boundary as supporting evidence.

In January 2013, in a case known as the South China Sea Arbitration, the Philippines made a submission under Annex VII to *UNCLOS*, challenging the legality of China's 'nine-dash line' and other aspects of China's behaviour in the South China Sea. In 2015, the arbitral tribunal took up seven of the 15 submissions made by the Philippines. On 12 July 2016, the tribunal ruled in favour of the Philippines, but said that it would not '... rule on any question of sovereignty over land territory and would not delimit any maritime boundary between the Parties'. The tribunal also ruled that China has no historical rights based on the nine-dash line map. China, which had refused to participate in the arbitration, rejected the ruling, as did Taiwan.

The Spratlys and Paracels

Much of the trouble in the South China Sea has been centred on the Spratly and Paracel island groups (Figure 1). In recent decades, the most serious conflict has been between China and Vietnam, which claims to have actively ruled over both the Paracels and the Spratlys since the 17th century. In 1974, in a military engagement between the naval forces of the People's Republic of China and the Republic of Vietnam (South Vietnam), the Chinese seized the Paracels, killing more than 20 vietnamese troops. In 2012, China formally created Sansha 'city', actually an administrative body with its headquarters in the Paracels, whose role is to oversee Chinese territory in the South China Sea.

The Spratlys are scattered over nearly 410 000 km^2 of the central South China Sea and are tiny (only a few square km^2). The Philippines supports its claim to some of the Spratlys mainly on the basis of geographical proximity, and indeed part of the island group lies within its EEZ according to *UNCLOS*. However, China has a significant military naval presence, and is now militarising the islands.

Both the Philippines and China lay claim to the Scarborough Shoal (known as Huangyan Island in China) (see Figure 1). This resulted in a protracted maritime stand-off in 2012.

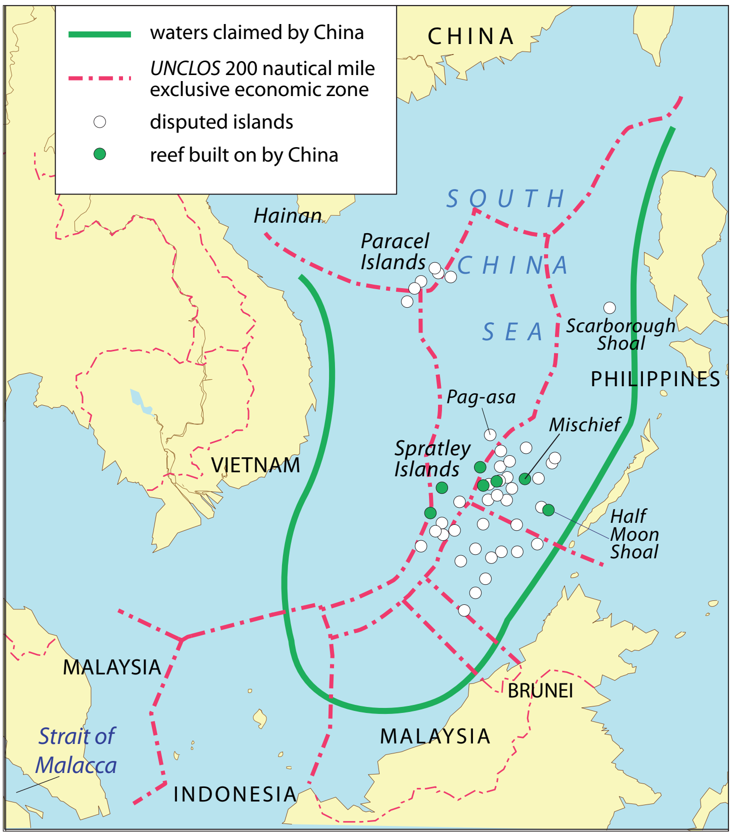


Figure 1 *The South China Sea, showing the area claimed by China, EEZs and the islands at the heart of the claim. Taiwan also has a large claim, following the same logic as China. Brunei does not claim any of the disputed islands, but Malaysia claims a small number of islands in the Spratlys*

Turning reefs into islands – whatever the environmental cost

Scattered across the South China Sea are hundreds of rocky outcrops, atolls, sandbanks and reefs. Together, these have a total land area of only about 16 km^2 – at least, that was the area until 2014.

China had been at a disadvantage in the Spratly Islands as it was the only claimant that did not have an airfield. However, it did have a Fiery Cross Reef, which it had occupied in 1988 (though it was also claimed by the Philippines, Taiwan and Vietnam). In 2014, it built a UNESCO marine observation station (leading to armed conflict with Vietnam), and began converting the reef into an artificial island of 2.74 km^2. There is a new airbase, with a ~3000 m-long runway suitable for heavy military aircraft, anti-aircraft weapons and a missile-defence system, two helipads and satellite communications antennas; there are also two lighthouses and a cement plant.

China states that it is 'aiming to provide shelter, aid in navigation, weather forecasts and fishery assistance to ships of various countries passing through the sea,' but defence analysts IHS Janes believe that the new island is part of a 'methodical, well planned campaign to create a chain of air- and sea-capable fortresses'. The fact that China now has airstrips on seven of the Spratly Islands suggsts that IHS Janes' assessment is correct.

Other coral reefs that have been similarly destroyed include Mischief Reef, Subi Reef, Johnson South Reef (which was originally completely submerged), Gavan, Hughes and Cuarteron Reef. And things can only get worse as Vietnam, Malaysia, the Philippines and Taiwan are now following China's example.

When a reef is converted into an island, it is not just the concreted-over coral which is destroyed. Coral sand from the adjacent area is dredged onto the reef to create a platform which is then concreted to make a permanent structure. The dredging not only destroys benthic organisms, but stirs up sand and silt that smothers corals and other organisms over a wide area, and clogs up the gills of fish. When the sediment eventually settles, it is full of decaying organic material, which means that it becomes anoxic, preventing recolonisation by organisms. Much of this damage is permanent.

The reason for turning reefs into islands might seem to be purely military, especially as the waters around the Spratlys are sufficiently deep (> 4000 m) to shelter nuclear submarines. However, there are other incentives. Article 121 of *UNCLOS* states that an island is 'a naturally formed area of land, surrounded by water, which is above water at high tide' and under *UNCLOS* islands have associated EEZs and continental shelves. However, 'rocks that cannot sustain human habitation or economic life of their own shall have no exclusive economic zone or continental shelf', though they can have a territorial sea and a contiguous zone (with maximum total width of 24 n.m.). If a reef or shoal beomes an island, it will automatically acquire a 200 n.m. EEZ and continental shelf, giving the relevant state rights to the resources in the water column and on/in the sea bed.

The South China Sea is known to have reserves of oil and gas, but these are nearly all along continental margins, not amongst the islands and reefs in mid ocean. A much more significant resource is found in the major fisheries – for example, it has been estimated that this area of ocean contains 40% of the world's tuna.

Fisheries under threat

The South China Sea is the main food source for the people living around it, including the 1.3 billion citizens of China. The states surrounding the Sea are expanding their fleets, but fish stocks in the area are badly depleted, and countries are using fishing bans as a means of asserting their sovereignty.

China declared in May 2017 that it is implementing a fishing ban north of 12°N (i.e. north of the Spratlys), applicable to all nations (including China), even within the EEZs of other states. This concern for fish stocks seems at odds with the drive to undertake activities that destroy reefs, which are known to support larval fish.

The work that demonstrated the significance of the reefs for fish stocks was undertaken by John McManus (University of Miami). McManus spent seven years in the northern Philippines monitoring seasonal fluctuations in coastal fish populations, and observed that devastated fish stocks would periodically recover as a result of larval fish from mid-ocean reefs dispersing throughout the South China Sea.

Another depressing aspect of the situation in the South China Sea is that (as recorded by journalist Rupert Wingfield Hayes) China has been protecting fishermen from Hainan who have been using the propellors of their vessels to destroy large areas of reef around islands/reefs in both the Paracels and the Spratlys, including reefs controlled by the Philippines, such as Half Moon Shoal (inside the Philippines EEZ) and Pag-asa (outside, but inhabited by Philippinos). The primary motive for the destruction, which is similar to that caused by island creation, appears to be to greed, as it allows the fishermen to obtain giant clam shells which, along with the endangered and protected hawksbill turtles that they are also collecting, sell for enormous prices. However, suspiciously, the reefs in question have shortly afterwards been turned into islands.

Is there any hope for the future?

John McManus, amongst others, has long argued for a 'Peace Park' in the Spratly Islands, brought about by an agreement modelled on the *Antarctic Treaty*, which has been relatively successful in preventing conflict and environmental degradation in the Antarctic since it was signed in 1959. The new treaty would be time-limited and renewable, and would impose a freeze on territorial claims (and associated activity) and involve a plan for joint resource management (including fisheries). In contrast to the situation in Antarctica, tourism (reef-diving etc.) would be encouraged, as long as it was ecologically sustainable, providing employment and a reason to protect an area of ocean with exceptionally high levels of biodiversity.

Meanwhile, the geopolitical situation gets ever more unclear. Turning away from the US, the President of the Philippines, Rodrigo Duterte, seems to desire rapprochment with China and has also declared that he wants Russia to be his country's ally and protector; he has invited Russian warships to the Philippines, and joint military exercises are planned. While US President Donald Trump's attitude to China is hard to read, Vice President Mike Pence recently stressed that 'The United States will uphold the fundamental freedoms of navigation and overflight in the South China Sea and throughout the Asia Pacific', ensuring flow of trade in the region.

Acknowledgments/Further reading

This article is based on a large number of sources, notably:

Asia Focus No.16 – Asia Programme (Feb. 2017) http://www.iris-france.org/wp-content/uploads/2017/02/Asia-Focus-16-South-China-Sea-Elie-Khoury-feb-2017.pdf

Rupert Wingfield-Hayes (15 December 2015 Why are Chinese fishermen destroying coral reefs in the South China Sea? *BBC News Online Magazine* http://www.bbc.co.uk/news/magazine-35106631

ISRS (2016) *Coral Reefs of the South China Sea – A need for action.* Briefing Document prepared for the International Society for Reef Studies (IRS) by J. McManus, E. Gomez, S. Wells, S. Norman and S. Jupiter. http://coral-reefs.org/wp-content/uploads/2017/03/SCS_Briefing_ISRS_20161711_revised_v3.pdf

Ed.

The Great British Beach Clean 2016

Recent progress seen from the perspective of an MCS Conservation Officer

Catherine Gemmell

For four days in September 2016 thousands of Beachwatch volunteers headed out to beaches across the UK to take part in the Marine Conservation Society's (MCS) Great British Beach Clean. The annual Great British Beach Clean report is now out, and the results can be found at www.mcsuk.org/greatbritishbeachclean.

The great success story in 2016 was about plastic bags. The number of single-use carrier bags we found on our beaches has almost halved in one year. Wales put a carrier bag charge in place in 2011, followed by Northern Ireland in 2012, Scotland in 2014 and England in 2015. Since 2011 we have seen a 22% overall decrease in carrier bags on the beaches we've surveyed. This is the first year that we have seen a drop in plastic bag levels in a decade, vindicating the carrier bag charge now in place across the whole of the UK. However, in England we want to see the exemption for small businesses lifted, as do the small stores themselves, as this would create a single UK-wide system which would be simpler for customers and retailers. We are also asking for no exemptions for biodegradable bags and paper bags in England.

On the down-side we have seen increasing numbers of wetwipes and drinks containers, and a huge jump in balloon litter, which has doubled from 2014. Balloons have been steadily increasing over the last couple of years but showed a steep increase in 2016. Why this has happened is not clear, so we will continue to monitor balloon litter to see if this trend continues. We will also continue our work on our 'Don't Let Go' campaign which encourages local authorities to ban balloon and lantern releases within their jurisdiction. 50 have authorities already signed up.

So what is Beachwatch?

Beachwatch is the MCS's UK-wide beach clean and litter survey programme and the Great British Beach Clean is the flagship event. This citizen science project has been running for over 22 years and we have used the beach litter data collected by our volunteers to shape campaigns and influence policy. We now have over 600 active volunteer Beachwatch organisers, who arrange surveys on more than 1400 beaches. In 22 years, over 100 000 members of the public have been recruited to take part.

Beachwatch volunteers come together after a busy session. This group have been cleaning the beach at St Andrews, Fife, in Scotland.

The methodology

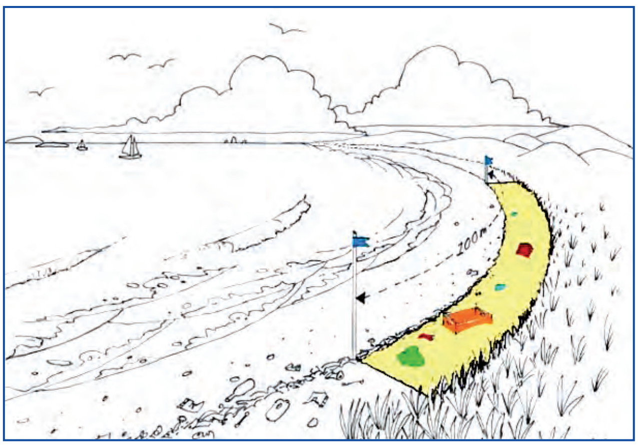
Through the Beachwatch project, local people/groups/companies volunteer to undertake beach cleans and litter surveys of their chosen beach. Each beach has a designated organiser who is provided with a detailed pack containing information on how to organise and carry out a beach clean, for example: how to gain permission to carry out a clean, how to give a safety briefing, and how to fill in the various forms. We also provide training workshops around the country for new and existing organisers.

We ask the organiser to pick a representative 100 m stretch of the beach in question and to always use this section for surveying purposes. For reasons of safety, we advise starting the survey about an hour or two after high tide. Volunteers are asked to pick up every item of litter in the 100 m stretch and, using the survey sheets provided, categorise litter items according to material type (e.g. plastics, metal, sanitary) and object (e.g. bottle, crisp packet, cotton bud stick). There is also space on the sheet for unusual items, dead/stranded animals etc. The total number of litter items in each material category, the total number of bags, weight of litter and width of beach surveyed, weather conditions on the day, and the number of volunteers, are also recorded. Finally, the results are uploaded to the MCS Litter Database.

What happens to the data?

The data are analysed by MCS to identify the quantities, types and sources of litter affecting the UK coastline and the impacts of litter on marine life, human health and local economies, providing evidence that can be used to target specific polluters and pollutants at local, national and international levels.

Beachwatch also provides and shares data with a number of organisations, from other NGOs to water companies and academic institutions. We also provide data for the UK's Marine Strategy Framework Directive beach litter monitoring programme, the International Coastal Cleanup, co-ordinated by the Ocean



Beach Clean survey areas extend for 100 m along the beach, and from the last high-tide mark/strandline up to the back of the beach (e.g. grass, dunes or a seawall)

Conservancy, as well as the OSPAR Commission on marine litter and the UK Government.

Internally, the data are used to shape our pollution campaigns such as our successful call for a carrier bag charge and the recent microbead ban, all of which aim to stop different types of litter from ever reaching the sea in the first place.

Wetwipes turn nasty!

One of our pollution campaigns running on the back of Beachwatch is 'Wet Wipes Turn Nasty (when you flush them)'. Beachwatch data show that there has been a near seven-fold increase in wet wipes on our beaches over the last decade. Beachwatch has therefore made a two-pronged atttack: a public awareness campaign and a focussed engagement with retailers. Our Beachwatch organisers will often highlight the wet wipe problem in their briefing, and people are also being alerted to it via our website, social media channels and outreach work.

As well as raising public awareness, our Pollution Team has joined forces with water companies to do something about wet wipes. Some retailers and producers are confusing the situation by advertising 'flushable' wipes, which has led to our petition calling for clearer labelling – you can join the fight and sign our petition at www.wetwipesturnnasty.com.

Has Scotland got the bottle?

A *Zero Waste Scotland* report estimated that single-use drinks containers constitute 17% of Scotland's total litter by weight. As a result, taxpayers pay an estimated £7.28m each year to clean up this litter in Scotland. Two years ago in Scotland we found almost 80 bottles per kilometre, marking a 21% increase on 2014. In 2016 plastic and glass bottles, cans and lids increased another 10% in Scotland, contributing to a 4% increase in drinks containers UK-wide. In Scotland, MCS, together with the Association for the Protection of Rural Scotland (APRS) and others, have been supporting the 'Have You Got The Bottle' campaign which is using our Beachwatch data to try try to persuade the Scottish Government to establish a deposit return system which will increase recycling rates and reduce the number of plastic and glass bottles and cans on our beaches and in our seas.

In a deposit return system for single-use drinks containers (e.g. plastic and glass bottles and aluminium cans), consumers are charged a small deposit on each can or bottle, which is fully refunded when the containers are returned. Deposit return systems operate in around 40 other countries and regions around the world, from Croatia to Australia, and Canada to Fiji.

There are a number of different systems which we might learn from. To work well, any system would need to be designed with local conditions in mind. One of the key issues is to establish how such a system could work most effectively with local authorities' existing services, as it already does in places like Lithuania, Norway and Canada. Deposit return systems have been shown to reduce litter, especially as littered cans and bottles tend to increase the incidence of other litter – the 'litter breeds litter' effect. They also increase recycling, and create a reliable supply of affordable, high-quality recycled materials for manufacturers to use.

In 2014, data from the Ocean Conservancy, which runs the International Coastal Cleanup, showed that along 23 km of beach in Germany, which has a deposit return system, 552 drinks containers were found (160 plastic bottles, 304 glass bottles, 88 cans), compared with 8295 along 25 km of coastline in Spain, which does not have a deposit return system (2940 plastic bottles, 1468 glass bottles and 3887 cans). There is fast growing support for the deposit return system in Scotland, where MCS's 2016 Beachwatch volunteers found an item of drinks-related litter every 3 m of Scottish coastline surveyed – that's about 8000 items every 25 km.

Successful events were held at the Scottish Parliament in January and December 2016. At the January event, every MSP received a plastic bottle that had been picked up from a Scottish beach by an MCS volunteer. Each bottle contained an invitation to use it in a reverse vending machine. At the December event, pupils from a local school that MCS has been working with, created a giant jellyfish made of bottles collected from a beach. MCS has launched a new social media campaign called #wildbottlesighting where we are asking everyone to put pictures of discarded bottles with the above hashtag on their social media to use at our next Parliamentary event.

Recently, Sky News launched their new 'Ocean Rescue'campaign which is aimed at tackling the issue of single-use plastic items. An MCS Beach Clean at Arrochar in Scotland featured in their hour-long documentary called 'A Plastic Tide', which is now available online along with videos in support of deposit return systems by MCS President, His Royal Highness The Prince of Wales, and other well known figures including Sir Richard Branson. With the issue now being brought to the global table we are hoping to move forward quickly in securing a commitment not just from the Scottish Government but from all UK governments to put in place deposit return systems, for the benefit of people and the environment.

Citizen science success in Scotland

As the MCS Scotland Conservation Officer I was tasked, when I started in May 2015, with boosting the number of citizen scientists taking part in the Great British Beach Clean. Responding to a huge amount of partnership working, promotion, education and outreach, the Scottish people rose to the challenge spectacularly: in 2014 we had 45 Great British Beach Clean events in Scotland, in 2015 there were 75! I then set Scotland quite a challenge for 2016, but again through some new partnerships and ongoing training and communications with our Beachwatch organisers we managed to break the record for Scotland in 2016 with 121 datasets being returned for this year's Great British Beach Clean.

Great British Beach Clean events are fantastic ways to get everyone out onto the beach, not only to tackle the problem that they can see at their feet, but also to contribute to tackling litter at its source by collecting valuable data. Schools, community councils, boat clubs, rangers, scouts and guides take part, and in 2016 MSPs up and down the country headed out to their local beaches too. By the end of the long weekend, three parliamentary motions had

Anything flushed down the toilet could end up in our seas or on our beaches, so MCS is encouraging everyone to only flush the three p's – pee, poo and paper! Or, as one schoolboy suggested, four p's if you include puke!

been tabled by attending MSPs recognising the work MCS volunteers were doing, and the importance of the data they were collecting for future legislation.

So from the beach to Parliament I want to thank everyone who took part in this year's Great British Beach Clean – let's see what we can achieve together in 2017!

Further information

For more information, and to sign up to take part, go to www.mcsuk.org/beachwatch

See also:

http://www.oceanconservancy.org/our-work/international-coastal-cleanup/2015-ocean-trash-index.html

www.mcsuk.org/greatbritishbeachclean

www.wetwipesturnnasty.com

www.haveyougotthebottle.org.uk

www.skyoceanrescue.com

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Putting MCS Beach Clean data to good use

The scale of the problem of litter on UK beaches can be gauged by the fact that local authorities spend around £15 million on its removal every year. Tackling the litter problem, both locally and globally, has been hampered by a lack of detailed knowledge about where it comes from, and its pathway through the environment. However, knowledge is power, and it is hoped that data collected through the Marine Conservation Society (MCS) Beach Clean events (*see previous article*) will provide some answers as far as litter around the UK is concerned.

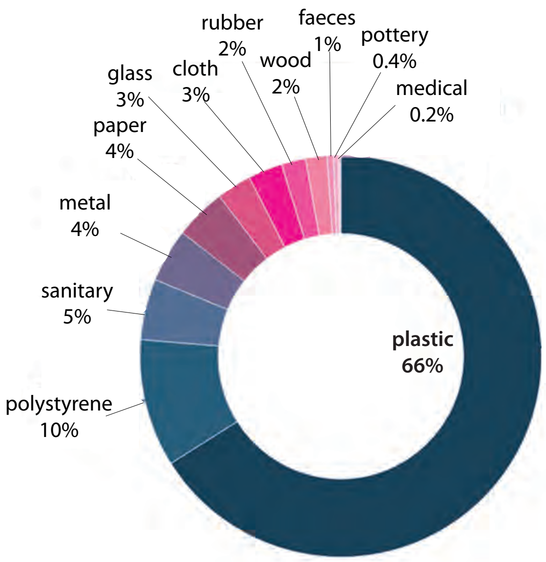
An article* first published online in the journal *Science of the total environment* in November 2016 presents the results of analysing data from ten years' worth of Beach Clean events on 736 beaches in England, Scotland and Wales, from 2005 to 2014 inclusive (*see map*). Working with the MCS, the authors investigated the composition, distribution, abundance and origin of marine litter around the British coastline.

*Nelms *et al.* (2017) Marine litter on British beaches: a 10-year nationwide assessment using citizen science data. *Science of the total environment*, 597, 1399–1409. doi: 10.1016/j.scitotenv.2016.11.137 http://www.sciencedirect.com/science/article/pii/S0048969716325918

The ubiquity of plastic

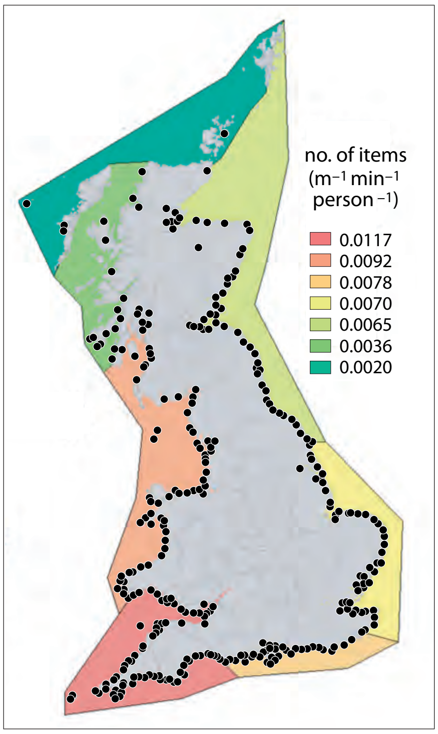
During Beach Clean events items collected were recorded and assigned to one of 101 categories (e.g. cotton bud, cigarette stub, fragment of glass ...) and one of 12 types of material. As shown in the figure below, about three-quarters of the items collected were identified as being made of plastic (66%) or polystyrene (10%), itself a kind of plastic. Plastics are made from a wide range of organic polymers (polyethylene, PVC, nylon, etc.) that can be moulded into shape while soft. Being cheap and durable, plastic items are becoming ever more popular with consumers worldwide, and it is unsurprising that a large proportion of litter in the marine environment, incuding litter on beaches, is made of plastic.

The most common identifiable objects were plastic caps and crisp packets, but the most common items overall were fragments of plastic, which made up 23% of all items; about half of these fragments were less than 2.5 mm across.



Litter collected during MCS Beach Clean events over the period 2005–14, categorised according to material. Percentages are of numbers of items in each category. Note that polystyrene is more expensive to recycle than other plastics.

(By courtesy of the MCS)



Mean litter abundance on beaches (•) surveyed during Beach Clean events during 2005–14. The coastline was broken down into seven segments corresponding to the Regional Seas designated by the UK Joint Nature Conservation Committee on the basis of biogeographical characteristics: clockwise from top right: Northern North Sea, Southern North Sea, Eastern English Channel, Western English Channel and Celtic Sea, Irish Sea, Minches and West Scotland, Scottish Continental Shelf.

(By courtesy of the MCS)

The researchers looked into whether most beach litter was coming from the land (e.g. as a result of public littering or fly-tipping, or in sewage) or from the sea (e.g. from fishing and shipping). They found that of items that could be attributed an origin, 42% came from land-based sources, and 18% from marine-based activities. Overall, 36% of the items were a result of public littering, 15% were associated wth fishing, 5% came from sewage, 0.7% came from fly-tipping, and 0.2% were medical in origin. The source of ~40% of the items could not be identified, either because they were fragments of an unidentifiable larger item (e.g. small pieces of plastic) or because they could have come from a variety of different sources (e.g. buttons of various kinds).

Regional variations

The highest levels of overall litter were recorded on beaches along coastlines of south-west England and south Wales (*see map*). Interpreting the map isn't straightforward, however: different coastlines will be affected to different extents by urbanisation (or holiday visitors), and by litter carried in rivers and sewage; some adjacent waters may have busy sea lanes (the Channel is the third busiest waterway in the world) or support a large amount of fishing activity. The distribution of litter will also be affected by the morphology of the coastline, and the extent to which the adjacent waters are enclosed. Because much of it is buoyant, the distribution of plastic in particular is affected by winds and currents.

Trends

The researchers investigated long-term changes for overall litter and did not find a trend in the overall abundance of litter on beaches over the 10-year study period. The reason for this is unclear – it could be that litter removal by local councils and volunteers between Beach Clean events has been keeping pace with any increase in litter deposition. However, there was a change in the composition of the litter. Abundances of plastic food packaging, wet wipes, polystyrene foam, balloons and large fishing nets increased during 2005–14. Significantly, the abundance of small plastic fragments also increased, and indeed it will continue to do so as plastic already in the ocean breaks down, eventually becoming microplastics (*see the following article*).

It is hoped that the results of the study will go some way to help in tackling the scourge of marine litter around the UK, both by shedding light on the sources of litter and its pathways in the environment, and by identifying ways in which valuable MCS Beach Clean data can be made even more useful in the future.

Ed.

Impacts of plastic in the marine environment

A study published in *Science* in 2015 by Jambeck *et al.* (http://science.sciencemag.org) presented an estimate of the amount of plastic entering the ocean globally in 2010 as between 4.8 and 12.7 million metric tonnes, with a projection to ~40–110 million metric tonnes in 2017, and double this by 2025. The graphs presented in the paper are cumulative because although plastic degrades to some extent under ultraviolet light, to all intents and purposes every bit of plastic ever produced still exists in some form or other, and nearly every piece of plastic that has entered the ocean is still there. Two important aspects of the growing problem of plastics in the marine environment are discussed below. *Ed.*

Microplastics – what are they and why are they a problem?

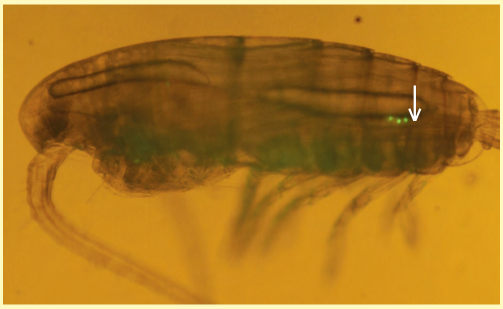
Rachel Coppock, University of Exeter and Plymouth Marine Laboratory

Microplastics are pieces of plastic that are less than 5 mm in size. They are ubiquitous in the marine environment, from surface waters to the deep sea, from equatorial waters to polar seas, in the open ocean and on shorelines worldwide. Microplastics have three main sources: (1) purposeful manufacture, as in the case of 'microbeads' that are found in many exfoliating cosmetic products and industrial pre-production pellets; (2) fragmentation of larger plastics such as bottles and bags, broken down via processes such as UV radiation and wave action; (3) shedding from textiles – a single 6 kg load of washing can release as many as 700 000 microscopic fibres into a waterway.

Unlike larger plastics, microplastics are not easily visible to the naked eye. Because they are so small, waste water treatment plants are unable to wholly prevent microbeads and fibres that have been washed down the drains from being released into the marine environment, where they are picked up by a wide range of organisms, from the smallest animals in the sea to the largest. Container spills at sea and loss from production plants release billions of pre-production pellets, also known as nurdles, which can be seen washed up all around the coastline.

Right *Microplastics on an area of sand about 6 cm across, including pre-production pellets, also known as nurdles (or mermaids' tears) – the purple, green and black roundish/cylindrical objects in the middle of the image – and fragments of larger plastics.* ***Inset top right*** *An individual weathered nurdle, about 4 mm in diameter.*

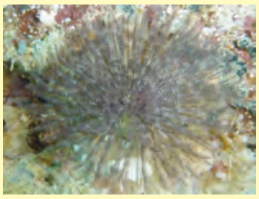
Marine organisms can mistake small plastic pieces for food, with the result that they can cause internal injury, starvation and death. Ingestion by zooplankton, near the base of the food chain, has been shown to negatively affect their food intake, reducing their ability to grow and reproduce. Whether this has negative impacts on predatory animals further up the food chain is still unknown.



The copepod, Calanus helgolandicus, *viewed under fluorescent light, with three 10 μm fluorescently labelled polystyrene beads in its gut (the copepod is ~ 2 mm long)*

(Lugworm photo: © Nick Veitch)

Organisms like lugworms (left) that feed by processing mud will inevitably be exposed to microplastics in the sediment, and suspension-feeding marine worms (below) collect plastic particles from the water column.



It's not only in the water column that microplastics are abundant. Fouling of the microplastic by tiny algae and microbes can cause the once buoyant particles to sink to the sea bed, making the plastics readily available to sediment-dwelling organisms (e.g. worms and bivalve molluscs) in shallow-water environments like estuaries, and the deep sea. The deep ocean floor has been suggested as a sink for microplastics, even for those that would normally be buoyant in seawater. There are estimates of around 4 billion plastic fibres per km^2 littering the sediments of Indian Ocean seamounts. Plastics are therefore readily available to important nutrient-recycling organisms living in shallow and deep-water sediments alike.

Solutions

As a result of consultation and lobbying, based on rigorous scientific evidence, a plastic bag levy is now in place in all parts of the UK (see p.34). Furthermore, legislation will come into effect in 2017 banning the use of plastic microbeads in cosmetic products, stopping the release of billions of microplastics into the marine environment around the UK every year. These are both fantastic starts to reducing the rate at which microplastics and larger plastic items (which break down to become microplastics) are added to the marine environment, but they are only a drop in the ocean. However, as consumers we can all play our part: we can help to slow the rate at which plastics are manufactured by thinking carefully when choosing which products to buy, and we can take care when disposing of them.

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Plastic ingestion by marine turtles: macro to micro

Emily Duncan, University of Exeter and Plymouth Marine Laboratory

Plastics threaten many forms of marine wildlife through being ingested, causing entanglement, and contributing to degradation of habitats and ecosystems. Sea turtles are of particular concern because their complex life histories, and their highly mobile lifestyle – swimming across oceans, and using numerous marine habitats – expose them to harm from plastic pollutants through many different pathways.

Macroplastics

Ingestion of plastic by sea turtles is now a global phenomenon affecting all seven species. Researchers studying turtles inhabiting highly polluted areas such as Brazil have reported that, on average, 70% of dead sea turtles examined have ingested plastics. Plastic ingestion can be lethal through causing blockages and internal injuries, and if not lethal, can cause adverse sub-lethal effects, such as reducing the amount of real food of nutritional value that they can take in ('dietary dilution'), potentially producing malnutrition/starvation and impaired immunity.

Sea turtles may ingest plastic items accidentally and/or because they mistake them for food. As turtles are primarily visual feeders, the colour and shape of plastic items are likely to be important in determining how likely turtles are to selectively target them. What is not known is the extent to which different species of turtles may also ingest plastics because they are mixed in with food items.

Above *A dead juvenile green turtle found washed up on Cyprus. It may have died from starvation, as its stomach contained an extremely large proportion of plastic and very little of nutritional value.*

How much plastic a sea turtle ingests is likely to vary dramatically according to its species and life stage. Hatchlings of six out of the world's seven sea turtle species undergo a period of pelagic drifting, when currents transport them to highly productive foraging hotspots. These are sometimes the same currents that concentrate floating anthropogenic debris, thus creating a spatial overlap between plastics and young turtles at a critical stage of their development. As sea turtles mature, each species develops a more specialist diet, resulting in different species having varying likelihoods of exposure to plastic, and hence varying consequences of plastic ingestion; for example, green and leatherback turtles both selectively ingest clear soft plastics whose structure, and behaviour in water, resemble those of of sea grasses or gelatinous prey. Similarly, the large number of plastic bottle lids discovered inside loggerhead turtles is thought to be due to the lids' shape resembling that of organisms normally preyed upon (e.g. bivalves).

Right *The contents of the turtle's stomach. The plastic debris includes a fragment of a balloon, some pieces of hard plastic, and some sheet-like plastic as used in plastic bags*

Microplastics

Even less is known about the potential ingestion of microplastics by sea turtles, and potential ingestion pathways are currently unclear. Carnivorous species such as the loggerhead, Kemp's ridley, olive ridley and flatback turtles may be at risk indirectly, ingesting microplastics by consuming contaminated prey items, whereas the herbivorous green turtle may be exposed to microplastics adhering to the surfaces of seagrass. All species might also ingest microplastics through swallowing polluted seawater or sediments along with food items.

Ingestion of microplastics by sea turtles directly or via their prey is of concern as it could result in bio-accumulation of pollutants, a problem that has been inferred for other marine vertebrates but has not yet been investigated in turtles. Plastics contain plasticisers such as bisphenol A and phthalates, and attract to their surfaces harmful hydrophobic contaminants such as polychlorinated biphenyls (PCBs). The tiny plastic particles have very large surface area : volume ratios, and so carry disproportionately large amounts of contaminants. Due to long gut residency times these may be released into the animals' tissues and can act as endocrine disrupters, causing interference to hormonal pathways important in both development and reproduction. Abnormalities caused by such pollutants include egg-shell thinning and delayed ovulation in birds, as well as hepatic stress in fish. However, to date, knowledge of levels of these pollutants in sea turtles, and the connection to plastic ingestion, is limited.

Ingesting plastics may impact a sea turtle's health and physical condition, and so impair its ability to avoid and/or survive predators or anthropogenic threats. Other long term consequences of ingestion could include reduced rates of growth and reproduction, which could have ramifications for the stability of vulnerable sea turtle populations. In summary, the potential effects of plastic ingestion on marine turtles are diverse and often not obvious, making it difficult to identify a clear causal link.

Future research

Urgent action is required to better understand the issue of plastic pollution and its effects on marine turtles. Future research projects should employ comparable classification systems when analysing the types and properties of plastics ingested. More data must be collected over wider geographic areas (including ocean gyres), and with good coverage of all life stages of all species, ideally culminating in a global meta-database. Collaborative application of oceanographic modelling could aid in highlighting hotspots of plastic accumulation and hence the vulnerability of turtles to debris ingestion. Investigations into the possible impact of microplastics need to further consider the potential for bioaccumulation of chemicals from plastic and the resulting contaminant burdens in associated food webs.

This whole field has recently been reviewed in the *ICES Journal of Marine Sciences*. It is freely available in an open access format at http://icesjms.oxfordjournals.org/content/early/2015/09/26/icesjms.fsv165.full

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From persistant pollutant to valuable human habitat?

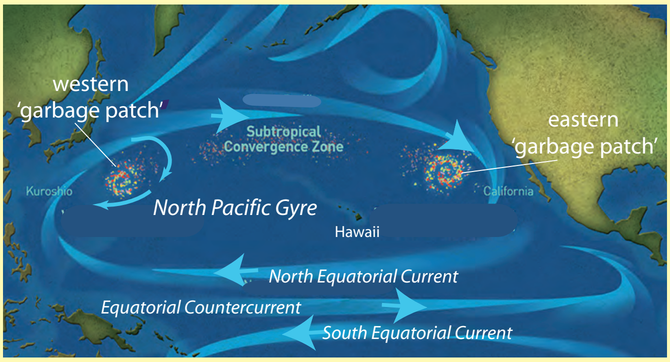
Ramon Knoester

In 2006 I read a short article in the Dutch newspaper *de Volkskrant*. I discovered that in the eastern North Pacific there is a huge quantity of floating plastic debris, occupying an area the size of France and Spain together (*see Box for more information*). These plastics are caught in the North Pacific Gyre. Some of that litter might have been there for a decade and might never ever reach a coast.

As an architect living below sea level in the Netherlands, I grew up with the risk of flooding. Water management is a big issue in my country and climate change is making flood prevention an even bigger priority. We've prevented big floods in the last fifty years, but we need to take extra measures for the coming fifty years. Sea level is rising and we need to create more space for water. In one of the most densely populated countries in the world, the creation of more watery areas demands innovative thinking and expansion of floating habitats. Living on the water is already a tradition in the Netherlands, with many small vessels transformed into houseboats. We're currently expanding this tradition by producing new types of floating housing on our many canals, rivers and lakes.

'Garbage patches' in the North Pacific

Oceanic areas with higher concentrations of plastic than elsewhere are sometimes referred to as 'garbage patches', a term which brings to mind acres of bobbing plastic bottles and yoghurt pots. However, most of the plastic in these areas is in the form of microplastics (see pp.37–9) which are suspended throughout the water column. In fact, there are a number of 'garbage patches' in the North Pacific, and in other parts of the ocean too. In the North Pacific, the eastern garbage patch, referred to in this article, is the result of the convergence of currents at the surface and upper ocean that occurs in the centres of anticyclonic gyres (see diagram on p.25). The western garbage patch consists of debris caught within a recirculatory current system within the larger gyre.



Schematic representation of so-called 'garbage patches' in the North Pacific

(Adapted from a map on https://marinedebris.noaa.gov/info/patch.html)

Recycled Island

Reading about plastics polluting our oceans, and thinking about innovation in floating housing, I started to wonder if we can bring these ideas together. Can we use plastics that are already floating in the ocean as a new building material for floating habitats? One of the main problems of our ocean junkyard is the cost of cleaning it. How can we remove plastic particles from an area of ocean surface the size of an entire state in an effective and environmentally friendly way? Giving value to the plastic will help: new flood-proof land would be valuable. Retrieving, recycling and building where the concentration of plastic debris is greatest would limit the otherwise expensive transport costs. In the eastern North Pacific, between Hawaii and San Francisco, a new island could be constructed from marine litter. Because I take plastic pollution very seriously and think we should consider all options to fight this threat, I studied the topic for a year and looked for ideas along the same lines. I couldn't find a proposal in the way I imagined it, so I started to visualise it myself. I imagined 'Recycled Island' – a new floating island built entirely from marine litter in mid Pacific. Recycled Island could be 10 000 km^2 in area, about the size of the main island of Hawaii. This area is based on estimates of the amount of plastic floating around in the North Pacific Gyre nine years ago, and the likely further increase in the following decades.

Recycled Island would tackle plastic debris effectively and create a new flood-proof habitat resistant to climate change. It would be an entirely new habitat supporting approximately 400 000 people. The island would be completely self-sufficient: local resources would be exploited to their full potential and all waste would be recycled; seaweed, composting and compost toilets could be used to create new soil and to fertilise the new land. It wouldn't make sense if an island constructed from pollution then created new pollution. Because we can build this new living environment from scratch, we have the opportunity to do it right – start by creating the infrastructure and facilities that would allow a zero-waste environment. Wave and solar energy could create sufficient power supply. Seaweed cultivation, hydroponics and agriculture could feed its population. In addition, the presence of a floating landscape could improve the ecosystem in the ocean, with newly created habitats for fish and other marine life beneath it, so a sustainable fishery might be created to help feed the population.

With like-minded colleagues, I set up the Recycled Island Foundation in 2014, but given the challenges of plastic retrieval in mid ocean, and the complexities of plastic recycling, we are not yet able to begin realising our dream. Luckily, other organisations, like the Ocean Cleanup Foundation (https://www.theoceancleanup.com), have already started to study and test the possibility of retrieving plastic pollution from the ocean.

Recycled Villa

However, still frustrated about increasing plastic pollution, we continued to look at the problem of recycling marine litter as a building material for new floating habitats. A large part of what ends up in our oceans washes up on shorelines, where the plastics are much easier to collect. If we could prove that marine litter can be recycled to make building materials for new floating housing structures, we would already be taking a huge step forward. Together with a naval architect, Alexey Shifman, we designed a floating villa constructed mainly from coastal pollution.

Recycled Villa

Recycled Villa would be a prototype for Recycled Island. It would be the proof of concept for how we can recycle waste into a beautiful and valuable new habitat. Together we looked at ship and house construction to find innovation and design suiting the material characteristics. The floating villa would be constructed using techniques similar to those used in yacht building. Triangular segments like pieces of a pie would fit together to form a circular island. Recycled Villa would have all the environment friendly characteristics of the larger Recycled Island. Wave and solar energy would be harvested and new fertile soil for the garden would be created by composting and fertilised by seaweed.

Both Recycled Island and Recycled Villa received international interest – well, from the press, at least – but so far we have not found the investors to start the realisation of our dream. But of course, publicity will help to get these projects off the ground.

In 2012 I was giving a lecture on these ideas at a festival close to my home town, the port of Rotterdam, and I met Joep van Leeuwen, a senior advisor from the Rotterdam Municipal Council. We shared ideas and the question arose as to how we can address plastic pollution locally. Two large European rivers, the Rhine and the Meuse, eventually end up in the Rotterdam Canal, and Rotterdam is the last big city these rivers pass through before reaching the North Sea. Recreational areas, industries and cities along the rivers cause plastic pollution, and plastics are also blown into them by the wind. The rivers carry the plastics to the sea where it becomes part of the increasing plastic soup. 60 to 80% of marine litter comes from land. What if we could stop this?

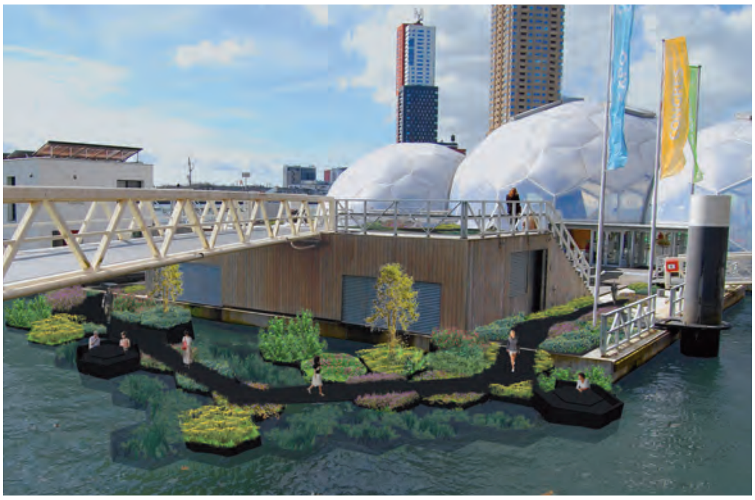


Image to show the completed Recycled Park attached to the Floating Pavilion in Rotterdam harbour

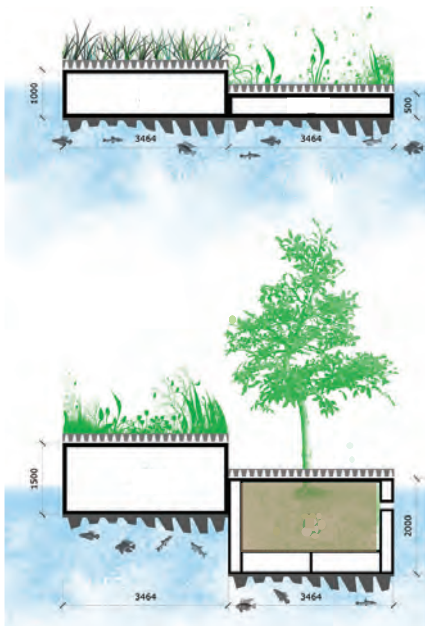
Recycled Park

Recycled Park, our latest project, involves retrieving plastic pollution from rivers and ports and preventing it from entering the sea. We began in Rotterdam, where our office is and where we can easily collaborate with our partners, and the first 15 m^2 Recycled Park is already floating in Rotterdam harbour. We aim to complete a 190 m^2 prototype before the summer.

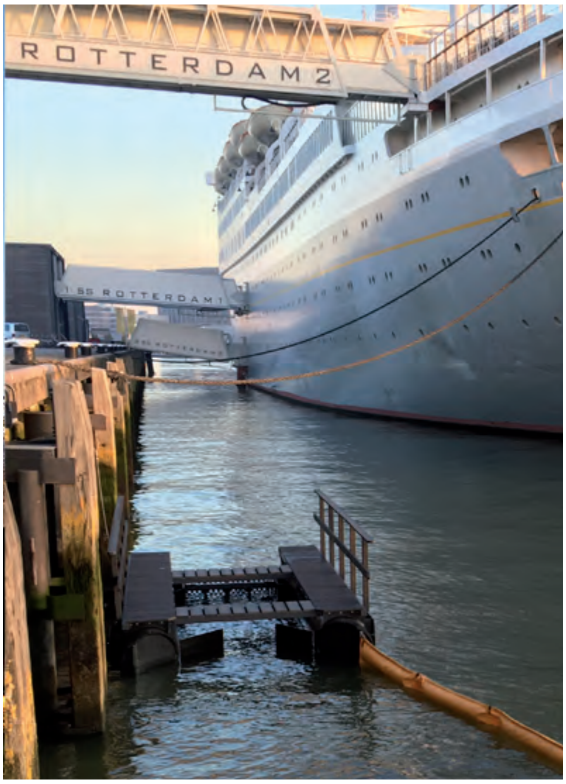
Before we could find the necessary collaborators and funding we had to prove the feasibility of all the different aspects of the project. For a start, we even had to prove that there is indeed plastic pollution in Rotterdam harbour. Then we had to find ways of effectively retrieving the litter without disturbing the ship traffic (*see overleaf*).

We tested the potential of effective plastic retrieval by using floating litter traps. We set up a retrieval, sorting, recycling and production line We analysed the litter to determine what it is made up of, and we now know what types of plastics are polluting our river and the percentages in which they are present. We recycled the first river litter to produce samples, and these samples are tested for UV and water resistance, and of course for strength. The results told us the characteristics of the recycled materials, and hence provided design guidelines. With the help of Rotterdam University, we developed a modular

Connecting modules of different heights can produce varied floating landscapes, or sloping shorelines. As well as supporting a variety of plants, from moss to small trees, above water, the modules also have a bottom surface where algae and aquatic plants can attach, and where fish and other marine life can deposit their eggs, so enhancing the ecosystem of the river.



A Recycled Park: By connecting hexagonal modules together, floating platforms can be created, providing accessible green spaces. Rotterdam Municipal Council are also interested in softening hard shorelines of canalised rivers. Demolition of existing shores and replacing them by natural slopes would be expensive, but using floating modules of different heights (see right) effectively provides new sloping land, and new habitats for birds and animals. See recycledpark.com



Upper left and right We are using passive litter traps to retrieve plastic waste from the rivers flowing into Rotterdam harbour. The trap shown was developed by WHIM Architecture and HEBO Maritiemservice for the Recycled Island Foundation. Together we are further developing passive litter traps which will be permanently installed in strategic positions. ***Lower left*** 98% of all plastic waste turns out to be in the uppermost 0.5 m of the water column. The litter consists of organic and inorganic waste – plastic packaging, foil, bottles, cans, spray cans, bags, etc. (All photos by courtesy of WHIM architecture; www.whim.nl)

system to build large floating platforms from recycled plastics (*see right*).

Together with the Municipality of Rotterdam and the Dutch Ministry of Infrastructure and Environment we see great potential for recycled parks. So yes, we're taking the plastics from the river and then putting them back again, but the plastics are recycled and should last for decades as a public amenity that will improve the quality of life in the city and support the ecosystem in the river and harbour. It is difficult to reclaim land used by building and infrastructure – the harbour, for example, is an area of concrete, brick and steel; but with the floating platforms we can create new areas of landscape, within which we can even have new shallow-water environments – small canals of about 0.5 m deep, where aquatic life could thrive.

Recycled Park will be somewhere between an urban park and natural landscape. While demonstrating the quantity of plastic pollution normally floating towards the sea, and creating awareness of its environmental impact, it will show what we can do when we handle waste carefully and turn litter into something valuable and enjoyable.

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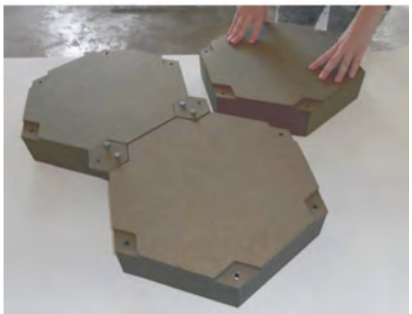
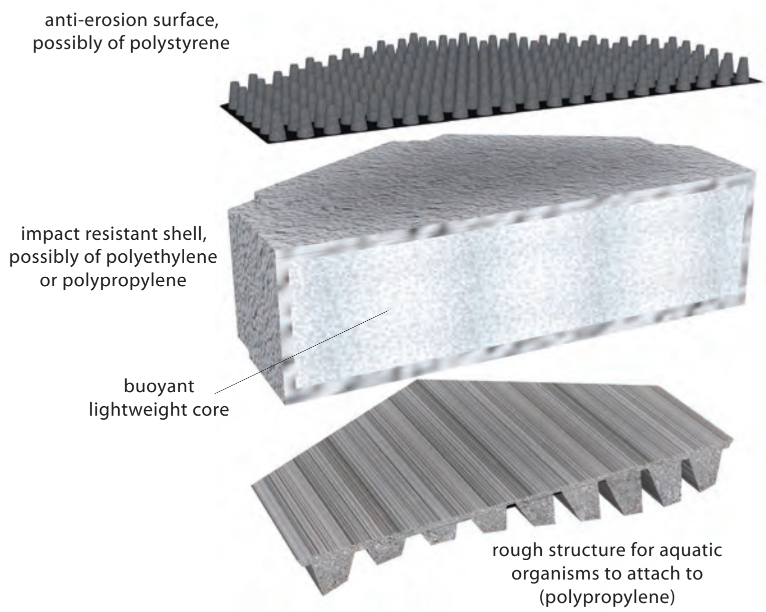


Right *Students of Rotterdam University have designed hexagonal blocks that fit together by means of pins to support the floating landscape. This block design will be used as a starting point for further development.*

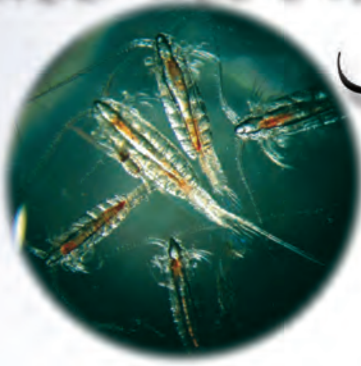
Below *Students of the Delft University of Technology (TU Delft) are currently working on which plastics can be used for various components of the blocks; it's important to try to make use of as many kinds of recycled plastic as possible*



Dancing in the moonlight

zooplankton activity during the polar night in the high Arctic

Laura Hobbs



During the Arctic winter, temperatures plummet, sea-ice covers much of the ocean and for a number of weeks the Sun remains below the horizon for 24 hours a day, resulting in constant darkness. This period of darkness, known as the 'polar night', can last from just three weeks at 67° N through to a full six months at the North Pole. The marine ecosystem during this time has often been referred to as a 'black box', with little of what happens being understood. Up until recently, it was assumed that ecological activity ceased during this time of continual darkness, and that zooplankton populations entered a period of hibernation, but over the past seven years marine ecologists have started to question this assumption. Several research programmes have focussed on investigating the Arctic Ocean during the winter with intense sampling campaigns off the coast of Svalbard in particular. Collectively, these have greatly increased our knowledge of this 'black box', especially concerning the behaviour of the zooplankton.

A vertically migrating population

It is well known that, across the globe, zooplankton such as *Calanus* spp. undergo diel* vertical migration (DVM). This mass migration – the largest by biomass on the planet – involves zooplankton in both marine and freshwater ecosystems migrating to depth during daylight hours to avoid the threat presented by visual predators in the illuminated surface waters, and as the Sun sets, returning to the surface to feed on phytoplankton. This response continues, cycling every 24 hours. DVM affects predator–prey relationships and also influences the transport of organic carbon to depth so as to cause an increase in carbon sequestration (long-term removal of atmospheric carbon into ocean sedments). Until recently, DVM was thought to cease during the polar night, with individuals entering a state of hibernation known as diapause† for winter (perhaps sinking to depth), and becoming active again in the spring. However, this has now been shown to be only partially correct.

Mid-winter activity of zooplankton was first observed in a fjord on the west coast of Svalbard in 2006 (see Berge *et al*. 2009 in Further Reading). Even though there were no consistent diel migrations, the population was also not consistently in a state of diapause, as originally expected. It was argued that an external cue was probably causing the synchronised migrations, and it was boldly suggested that in the absence of sunlight, it might instead be the Moon that was driving zooplankton to migrate. This suggestion formed the basis of my doctorate, and led to the aim of actually quantifying a 'lunar migratory response', not just in one fjord in Svalbard, but across the entire Arctic Ocean.

Observing zooplankton on an oceanic scale

But how did we observe zooplankton over an entire ocean? Data from Acoustic Doppler Current Profilers (ADCPs) moored in numerous sites across the Arctic, by a variety of research labs, had already been collated. The amount of backscatter – sound reflected by particles in the water column – is a convenient proxy for zooplankton biomass. The ADCPs recorded backscatter data at a time resolution of between 20 minutes and one hour, at 4–8 m depth resolution, and were deployed for up to a year at a time. The vast array of ADCP moorings around the Canadian Arctic Archipelago, off west Greenland, in

The photo of **Calanus** *in the title gaphic is by courtesy of Kim Last, SAMS.* **Calanus** *spp. are one of the one of the most abundant group of zooplankton in the Arctic Ocean.*

*Diel = having a cycle that takes place over 24 hours.

†Diapause = period of hibernation in response to regularly recurring periods of adverse environmental conditions.

Svalbard fjords, in the Laptev Sea and the Bering Strait, and over the North Pole, yielded nearly 10 million data points from 58 winters and provided the foundations for my Ph.D.

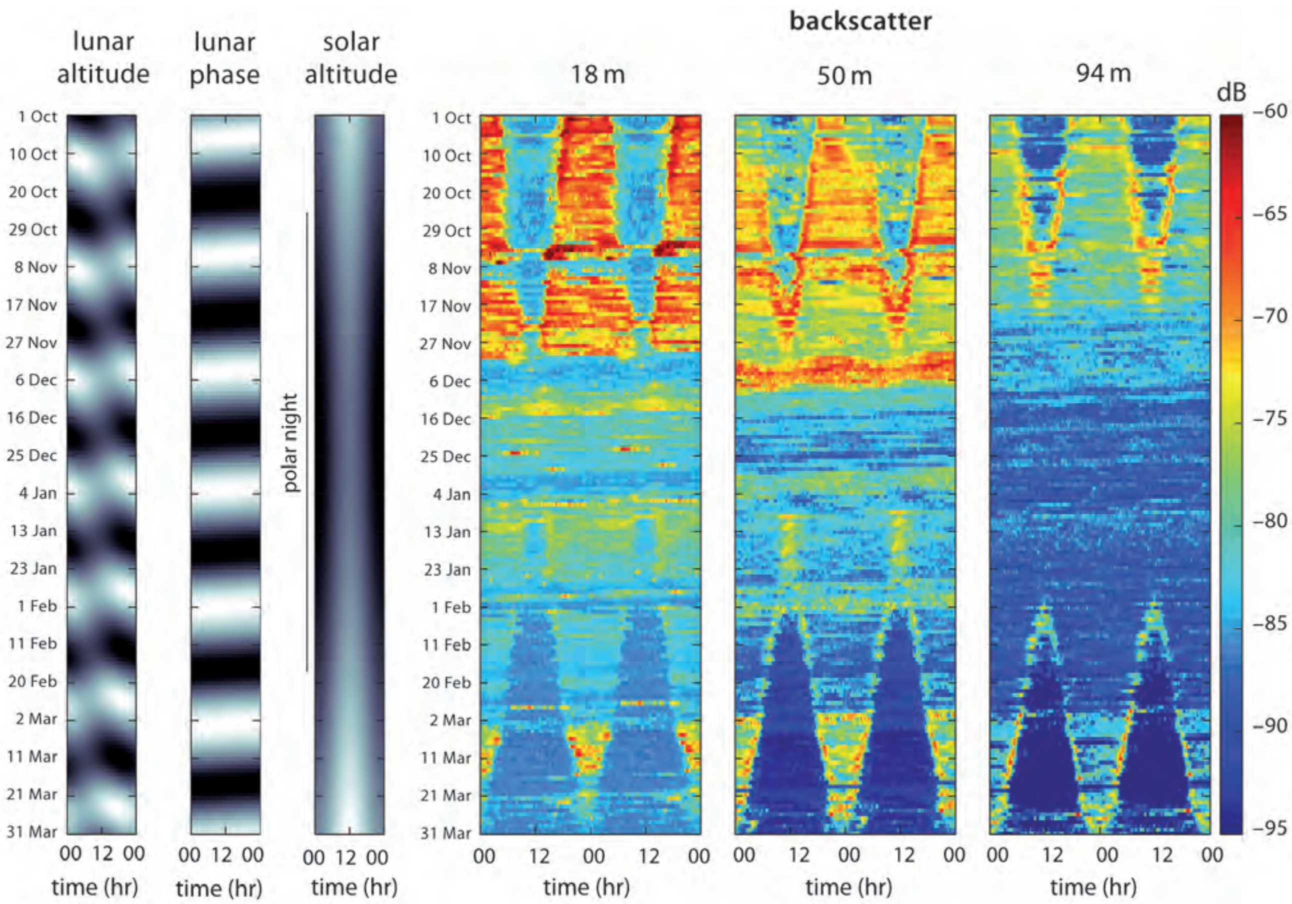
The main intention when analysing this acoustic data was to investigate how the DVM cycle progresses through the polar night, and to this end, methods commonly used by researchers working in the fields of biological clocks and circadian rhythms were applied. For the first time, acoustic data were plotted in the form of actograms – graphical displays of time-series which use two time axes in order to highlight cyclical behaviour. In the case of the DVM studies, the actograms showed the ~24 hour DVM cycle along the *x*-axis and the progression of DVM behaviour over a period of six months along the *y*-axis. In other words, 6 months' worth of 24-hour periods of data were stacked one above the other.

Figure 1 shows actograms for data collected from Kongsfjorden, a fjord on the west coast of Svalbard. On the right are actograms for backscatter data from three different depths (18 m, 50 m and 94 m), and on the left are actograms for data relating to the light regime at the relevant latitude: lunar altitude, lunar phase, and solar altitude. Actograms for the lunar/solar data are single-plotted, whilst acoustic data are double-plotted (i.e. duplicated so that the *x*-axis is 48 hours long) so that the change in behaviour around midnight can be distinguished clearly.

The actograms in Figure 1 are most easily interpreted by going down the months in a step-wise fashion. The top third of the backscatter actograms show that DVM was occurring during October and November because for those months they show high levels of backscatter (red/orange) during hours of darkness (00 = midnight) and low levels of backscatter (blue/green) in the hours surrounding mid-day. As autumn progresses into winter, and hours of daylight decrease, the amount of time spent migrating also decreases, which results in the V-shaped patterns in the actograms for all three depths. Eventually, each of these V's come to a point, indicating that the solar driven behaviour has ceased, presumably because light levels fell below a detectable threshold throughout the

The decibel (dB) is used to express sound intensity relative to a standard reference value. The dB scale is logarithmic and goes up in powers of ten: every 10 dB increase is equivalent to a 10-fold increase in sound intensity. A dB value of –90 is 10^{30} smaller than one of –60.

Figure 1 *Actograms of lunar/solar and backscatter data collected during 2006–07 from Kongsfjorden, western Spitsbergen (~79°N). Figures are created by stacking 24-hour periods of data vertically to create a matrix that is 24 hours long in the* x*-axis (00 = midnight) but sometimes double plotted, and six months long in the* y*-axis. From left to right: lunar altitude (white = highest, black = lowest); lunar phase (white = Full Moon, black = New Moon); solar altitude (white = highest, black = lowest); double-plotted actograms (copied in the x-axis) of backscatter (dB) from Acoustic Doppler Current Profilers at three different depths. A colour scale indicates the strength of backscatter, a proxy for zooplankton biomass (dark red = highest, dark blue = lowest). (Adapted from Last* et al. *2016; see Further Reading)*



daily solar cycle. In January, the DVM response reappears, with the amount of time that backscatter is low (blue), because zooplankton have migrated down to depth, increasing with increasing day-length, resulting in an inverted V. The non-inverted and inverted Vs correspond to the parts of the solar altitude actogram which show greater day-length (Figure 1).

Werewolves of the polar night

In addition to this change in the DVM response with day-length, the actograms also tell us something about the behaviour of zooplankton during mid-winter. If the polar night were, as once assumed, a time of total inactivity, all three backscatter actograms in Figure 1 should look like the one at 94 m, with an unchanging level of backscatter between the V shapes that correspond to the diel activity. Instead, the 18 m and 50 m actograms show evidence of activity during this period, with discrete changes in backscatter for a number of days each month showing up as horizontal bands. This is seen as a band of lower backscatter (blue) at 18 m accompanied by a band of higher backscatter (red/yellow) at 50 m: examples of this can be seen around 8 November, 6 December, 3 January and 1 February.

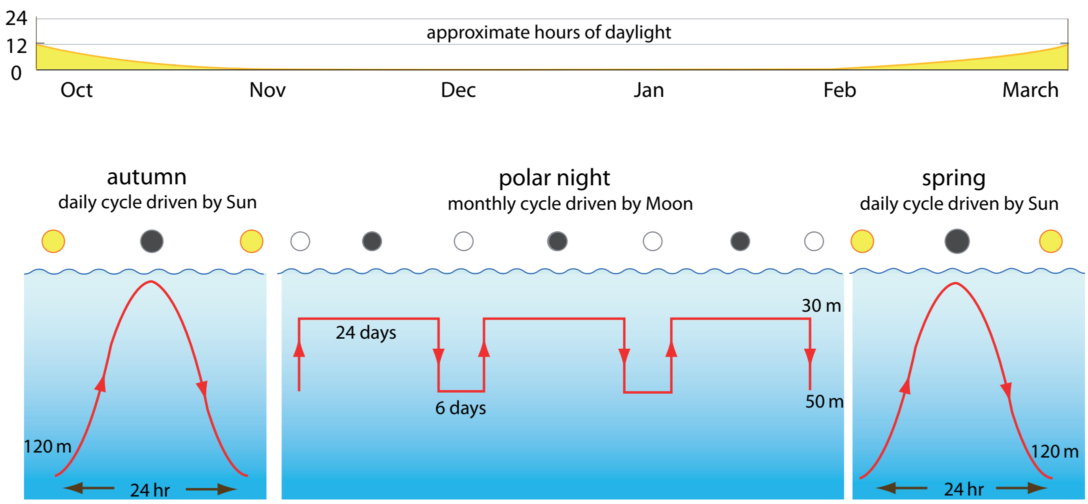
Comparison of the backscatter actograms with the actogram created from lunar phase data reveals that these bands are appearing when the Moon becomes full each month, suggesting that it is moonlight that is driving the zooplankton population to aggregate at ~ 50 m each month. The Full Moon brightly illuminates surface waters (cf. Figure 2), making them perfect hunting grounds for Arctic werewolves – in this case not the mythical version but real life predatory zooplankton. As the Moon rises, *Calanus* populations are actively moving to depth to avoid this threat. Figure 3 summarises how, with the onset of the polar night, zooplankton migrations in response to the 24-hour cycle of the Sun are replaced by lunar driven migrations, so that migrations take place monthly rather than daily. In reality, there is some overlap between the solar and lunar driven cycles, as can be seen in Figure 1 where the ‘Full Moon’ band around 8 November cuts across the Vs caused by diel migration.

Figure 2 *The Full Moon rises above Adventfjorden, Svalbard, brightly illuminating the surface waters.*

(Photo: Lewis Drysdale, SAMS)

The backscatter signals of these lunar migrations vary in strength – for example, the band around 6 December is weaker than that around 3 January. This can be explained by variations in cloud cover. Recordings of cloud data taken at a nearby airport show that extensive cloud cover masked the effect of the Full Moon in January, whereas

Figure 3 *A schematic diagram illustrating the seasonal shift in migrating behaviour displayed by Arctic zooplankton. In the autumn and spring, the daily solar cycle drives diel vertical migration. During the polar nght, monthly migrations take place in response to the changing phases of the Moon; during the winter, the Full Moon is never below the horizon. (As discussed in the text, in reality there is some overlap between the solar and lunar driven cycles.)*



During autumn and spring, zooplankton respond to the 24-hour cycle of the Sun, but during the polar night, migrations are driven by the Moon

clear skies resulted in a stronger migratory response in December.

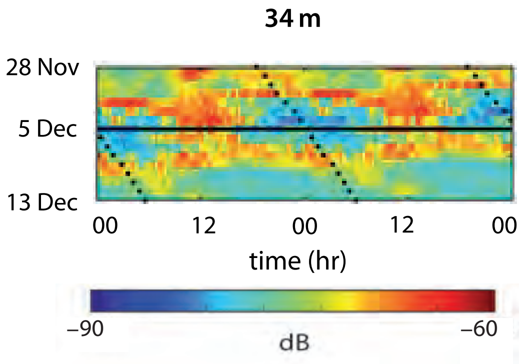
It is not entirely clear what the lunar driven migrations mean for the polar marine ecosystem. Whilst surface avoidance during the Full Moon is thought to be a behaviour intended to reduce predation risk, the dense aggregations of populations at depth seen in the actograms might actually increase the predation risk from non-visual predators such as chaetognaths (arrow worms) through a higher likelihood of chance encounters.

A shift in the daily routine

The actograms revealed further surprises. Zooplankton also appear to show evidence of responding to the lunar altitude cycle, which takes place over 24.8 hours (rather than 24 hours, as in the case of the solar altitude cycle). This response is not visible at the three depths shown in Figure 1, and so a 'mini-actogram' has been produced for a depth of 34 m to highlight this behaviour (Figure 4).

Figure 4 *14-day backscatter actogram centered around the Full Moon of 5 December 2006. Black dots show the timing of highest lunar altitude each day, and the black horizontal line shows the date of the Full Moon. Dark red = highest backscatter, dark blue = lowest backscatter.*

The varying height of the Moon in the sky drives a 24.8-hr zooplankton migration cycle



In this actogram, the lowest levels of backscatter are seen around the time of the highest lunar altitude (signified by black dots), and the highest backscatter when the Moon is lower (in between the dots). This suggests that zooplankton are leaving surface waters (<40 m) during the hours of highest lunar altitude, and returning to them once the Moon goes below the horizon.

This DVM-type behaviour, but on a 24.8-hour cycle rather than a 24-hour one, was detected back in 2009, when it was first suggested that zooplankton might be responding to the Moon. This migration is not seen to occur at all depths, as in DVM, but instead is largely restricted to a narrow 30–60 m depth layer. The two lunar driven zooplankton migratory behaviours described above have been termed Lunar Vertical Migration (LVM). The sinking of zooplankton to 50 m each month (as seen in Figures 1 and 3) is termed LVM-month, and the response to the lunar altitude cycle (as seen in Figure 4) is termed LVM-day.

Responding to the Moon on an oceanic scale

Once the new migrating behaviours had been characterised for Svalbard it was time to see if they were also apparent across the Arctic Ocean. Backscatter data were taken from the six days across the Full Moon at 50 m in each of the 58 datasets. Chronobiological methods were applied to detect rhythmicity, or cyclical patterns, in the data. Whilst data from Full Moons in November and February showed zooplankton behaviour responding to a solar driven 24-hour cycle, data from the Full Moons in December and January showed cycles closer to 24.8 hours, and hence evidence of a pan-Arctic LVM-day response. As expected, this behaviour only occurred in the depths of winter, when the Sun no longer controlled the responses of zooplankton. Using similar methodology, LVM-month behaviour was found in all polar night datasets from 20 m, 40 m or 60 m.

This research shows, for the first time, an ocean-scale migratory response of zooplankton to the Full Moon, with animals migrating out of the surface for a number of days at a time, and aggregating at depth to avoid the illuminated water. In addition to this, a new behaviour of LVM-day has been defined, in which zooplankton shift their migration timings from being solar driven in autumn and spring, to being lunar driven in mid-winter. The work contributes to a suite of papers published in the past few years that show that zooplankton activity continues in the polar night even in the high Arctic, despite a previously held assumption of quiescence during this time.

Future research

So what lies in store now for the team of 'lunartics' who have been researching the polar night? Personally, I have spent the last three years looking at lunar responses in Arctic zooplankton, and the progression of the different migratory behaviours across seasons as part of my Ph.D. Further investigations will hopefully lead me to a better understanding of the trade-offs that these zooplankton make for an optimal strategy in their annual and diel vertical migrations in order to increase their overall fitness. Using behavioural models, I hope to find out what causes some individuals to hibernate and some to stay active, and to better understand not only the light-related factors that are driving these zooplankton down to depth but also what keeps them at the surface the rest of the time. When there is no visible (to the human eye) sunlight, and no primary production, there must be factor(s) that make the risky surface layers a worthwhile habitat. Many of us will continue to delve into the polar night through the Arctic ABC project – a Norwegian based research programme focussed on using novel technology to understand under-ice processes in the high Arctic (http://www.mare-incognitum.no/). Be it through models or observational data, the aim of the next few years' work will be to discover some more secrets from the ecological black box of the polar night.

This article is adapted from results presented in Last *et al.* (2016) (see Further Reading). A short documentary video in which Kim Last discusses this work (a visual abstract of the paper) is available at https://www.youtube.com/watch?annotation_id=annotation_416526281&feature=iv&src_vid=eB96vUrqX1M&v=ITI7PjpvfT

Further reading

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Book Reviews

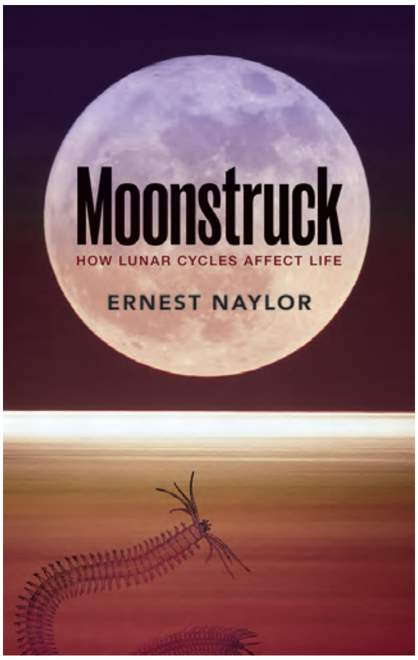
Moonstruck: how lunar cycles affect life by Ernest Naylor (2015) Oxford University Press, 256pp. £18.99 (hard cover, ISBN 13: 978-0-19-872421-6). Also available as an ebook.

It is rare indeed that I feel appropriately qualified to pass critical judgment. But sitting here on a flight into Longyearbyen, Svalbard, watching the Sun gradually set to the west for the last time in several months and with the Moon high in the sky, I feel justified to pass comment on Ernest Naylor's latest book, *Moonstruck*. As I look out the window I can see the moonlight cast a shadow on the mountains of Sptisbergen and imagine the influence of this on the biology below. I am *en route* to the latest fieldwork campaign of our pan-Arctic study, and this book, which beautifully details the Moon's influence on life on Earth, has proven a worthy choice of reading matter.

Moonstruck makes for a good read and presents a mix of folklore, scientific fact and conjecture. The author introduces our early obsession with the Moon, considered a sign of fertility with its waxing and waning symbolising the cycle of life, and describes how in many cultures the Moon was worshipped or represented a deity. Once we were able to go into space, our understanding of the satellite became based in fact rather than fiction – well mostly anyway!

The first Russian lunar images were intercepted by a British Radio telescope and relayed to the press via wire-service fax machine. Press reports relayed images of dramatically mountainous scenery, accompanied by speculations by geologists about volcanoes and rich seams of gold. Amusingly, the fax had resulted in lateral compression of the images and when the bemused Russians finally released the images they showed that the Moon is only slightly hilly.

Naylor explains how the Moon's influence on life is both direct, though moonlight, and indirect, through the influence of gravitational tidal forces. Many studies show that organisms display astonishing synchronicity between the Moon's phases and their behaviour and/or physiology; sand hoppers swim when the tide comes in, for example, and many corals undergo mass annual spawning events, all at specific phases of the Moon and usually at a particular time of the year. Laboratory observations have revealed



internal rhythms which unmask biological clockwork. Naylor presents a wealth of scientifically supported accounts relating to a wide range of organisms, which, at times, made me chuckle. For example, in the enigmatic and ancient turtles, tides and moonlight synchronise the migrations of females onto the sandy beaches where they lay their eggs. Spring tides, which extend furthest up the shore, provide a helping hand to the weighty, awkward reptiles. Naylor describes how, on some Californian beaches, humans indulge in amorous encounters, which may coincide with turtle nesting areas. Local officials have installed streetlamps, or 'morality lighting', in an attempt to dissuade such amoral behavior (that of people not turtles). Sadly, studies show that artificial lights may interfere with the turtles' navigation to and from beaches, hence curtailing reproductive activities of both turtles and humans.

The book is written in an informal yet informative style and even complex animal behaviours are coherently described. Even if you don't care for the lunar synchronised sooty tern migratory calendar and are selfishly self-centered, Naylor's book delivers. We learn that many studies trying to link moonlight to human behaviour are inconclusive, and that all too frequently and incorrectly correlation is inferred as causation. However, one finding stands out as reasonably robust. Subjective and objective measures of our sleep activity tend to vary with the phases of the Moon. So the next time you cannot sleep, it may pay to close the curtains to shut out those pesky moonbeams.

At the core of Naylor's book we see him addressing the sceptics who question Moon-related phenomena, the general public and scientists who historically may have called people like us 'lunaticks' (after members of the Lunar Society of Birmingham, 1776–1820). However, those lunaticks have now discovered that that there is a molecular basis for a tidal clock which is separate from the circadian clock, and that a molecular lunar clock probably also exists, at least in some marine polychaete worms.

My own work offers further credibility to the ideas in Naylor's book. Recent data have revealed that during the polar night of the high Arctic, when the Sun is permanently below the horizon, zooplankton respond to moonlight in quite a dramatic way. They undergo lunar driven daily and monthly migrations, activities that are probably adaptations for avoiding visually hunting predators. Like Naylor, this finding left me 'moonstruck'.

Clearly Naylor and I need no convincing that life on Earth is much influenced by our Moon, but if you are still in any doubt, go out and get a copy – you might learn something in a wholly enjoyable way.

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For more about Moon-related cyclic behaviour see the article 'Dancing in the moonlight: zooplankton activity during the polar night in the high Arctic' by Laura Hobbs, on pp.42–47. *Ed*

Marine geochemistry: ocean circulation, carbon cycle and climate change
by Matthieu Roy-Barman and Catherine Jeandel (2016) Oxford University Press 432pp. £65.00 (hard cover, ISBN 13: 978-0-19-878749-5), £32.50 (paperback, ISBN 13: 978-0-19-878750-1). Also available as an ebook.

This as an excellent toolkit (with instruction manual included!) for any budding geochemist starting out in postgraduate study or for more 'seasoned folk' who want a good text for working with a variety of elements and isotopes in marine science. It is packed full of great figures to illustrate the oceanographic concepts discussed.

It is generally well crafted with a glossary, list of notation, chapter appendices and in-text citations that can actually be found in the reference section at the end. Relevant problem exercises covering each chapter, along with worked solutions and related references to journal articles, mean this book will also double up as a resource for postgraduate teaching and indeed for final-year undergraduates on more focussed marine or geochemistry courses.

The book comes at an opportune time with the completion of many of the GEOTRACES cruises and a 'bumper crop' of available trace-element and isotope (TEI) oceanic data. I found its title to be rather broad and all-encompassing as its chapters are not fully comprehensive in terms of chemical processes for TEIs. However rather than spread themselves thinly, the authors focus on highly topical and important subject areas, which I liked and found very useful. Topics of chapters include: use of stable and radiogenic isotopes (e.g. Be, B, C, O, Si, S, Nd isotopes and U series), transport models, limitation of primary productivity, CO_2 exchanges at the ocean–atmosphere interface, and measuring particle fluxes using Th isotopes.

The order of the chapters is a little counterintuitive. For example, the final one is a very short synthesis chapter with a biogeochemical perspective on the history of the Earth and its future, which seemed a little out of place.

However, my overall impression of the book was that it would be a useful and well thumbed asset for any geochemistry collection and it comes highly recommended.

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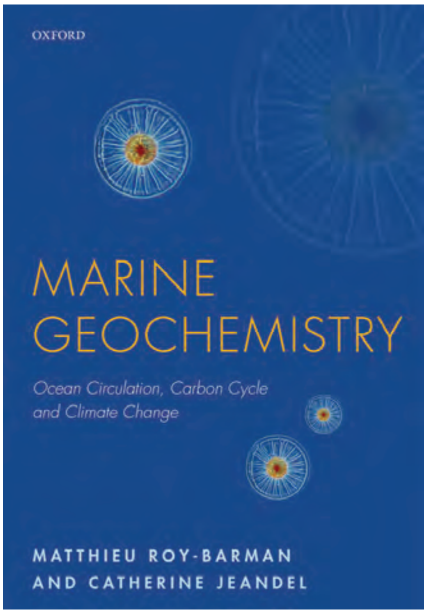

OCEAN Challenge

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