OCEAN Challenge

The Challenger Society for Marine Science

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OCEAN Challenge

The Challenger Society for Marine Science

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

NB *Ocean Challenge* can be downloaded from the Challenger Society website free of charge, but members can opt to receive printed copies.

For more information about the Society, or for queries concerning individual or library subscriptions to *Ocean Challenge*, please see the Challenger Society website (**www.challenger-society.org.uk**)

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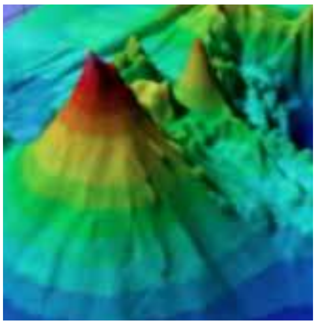
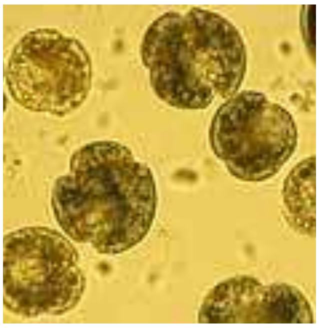




CONTENTS

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

The cover and heading graphics were designed by Ann Aldred.

Cover photo: A seaweed meadow in the Inner Hebrides, Scotland

Challenger Society Conference 2020/21

As most Challenger Society members will be aware by now, the local organising committee at Oban have regretfully decided to recommend cancelling the Challenger Society Conference that was planned for September 2021. They feel that any physical meeting would be hugely diminished compared with what it could have been, and that social and other events would be negatively impacted. It is very likely that social distancing will still be in place in September and that given the venues available, numbers of attendees would probably need to be reduced by around 50%. At least two of the parallel session venues probably couldn't be used and the scientific programme would have to be significantly curtailed. There could also be a problem with accommodation in Oban as the future of some of the hotels is still unclear. Furthermore, travel to Glasgow could still be significantly impacted in September, along with the train service to Oban.

An online event has been seriously considered, as it might have provided a forum for the presentation of fellowships and other Challenger awards and prizes. In the end, however, it was felt that a virtual Conference would not provide an environment in which the networking that forms such an important part of the usual Challenger Conference could take place very easily, and that given its relatively small size and limited resources, the Society would not be in a position to run the kind of virtual Conference that larger bodies could cope with.

Alternative virtual Challenger Society events in 2021

The Challenger Society Council feels that, nevertheless, there should be some kind of Challenger get-together in 2021 to ensure a chance to share some science, along with networking opportunities with a focus on early-career researchers (ECRs). There will therefore be a series of short events to be held at approximately monthly intervals between September and December.

- **9 September, 1.00–2.00** Awarding of Challenger Fellowships and short presentations by the new Fellows. This will be followed by a meeting of the Ocean Modelling Special Interest Group.
- **Early October** Equality, Diversity and Inclusion 'town hall' meeting, to dovetail with the MASTS 2021 Annual Science Meeting on 5–7 October.
- **18 November, 1.00–2.30** ECRs propose themes and issues to be developed as part of the Decade of the Ocean (*see opposite*), followed by discussion. An invitation for pitches will go out soon and will close mid-September. (Open to non-members)
- **9 December, 1.00–2.30** Discussion on 'Finding the voice of the UK oceanographic community' with talks from representatives of academia, industry and Government. (Open to non-members)

Challenger Society Conference 2022

Next year will be the 150th anniversary of the *Challenger* Expedition, and as a celebration the Challenger Society conference will be hosted by the Natural History Museum and some other London venues. This is intended to be a normal physical conference rather than a virtual one, and is scheduled for 5–9 September 2022. The London organising committee is currently seeking a suitable venue for the presentations as, given current restrictions, the first choice of venue cannot be guaranteed. More information about the conference will be available soon.

Challenger Society Conference 2024

This will be in Oban, and the local organising committee are looking forward to hosting a great event.

President of the Challenger Society

A decade of ocean science for sustainable development

The science we need for the ocean we want

Colin Moffat

There is an increasing awareness of the changes that are occurring to the seas and ocean as a result of human activities. Unsustainable fishing practices, the extraction of minerals and energy and the presence of contaminants are all contributing to the changes. Furthermore, the increase in greenhouse gas concentrations in the atmosphere is having a significant impact on the ocean because it is absorbing a significant proportion of both the additional CO_2 and the resulting extra heat. There is also a potential for changes in the currents that transport heat, salt and planktonic organisms, within and between ocean basins. All this presents a worrying picture for the future, but there is a plan.

A decade of collaborative science

Any plan for the future of the ocean needs to be global, which is why the United Nations has developed the UN Decade of Ocean Science for Sustainable Development (2021–2030). This will be a once-in-a-lifetime opportunity for nations to work together to generate the global ocean science needed to support the sustainable development of the ocean.

As highlighted in the Ocean Decade website https://www.oceandecade.org, one way to decide priorities is to identify the kind of ocean we want and should therefore aim for.

The 'Decade outcomes'* identified are:

- A clean ocean, where sources of pollution are identified and reduced or removed
- A healthy and resilient ocean, where marine ecosystems are understood, protected, restored and managed
- A productive ocean supporting sustainable food supply and a sustainable ocean economy
- A predicted ocean where society understands and can respond to changing ocean conditions
- A safe ocean where life and livelihoods are protected from ocean-related hazards
- An accessible ocean with open and equitable access to data, information and technology and innovation
- An inspiring and engaging ocean where society understands and values the ocean in relation to human well-being and sustainable development

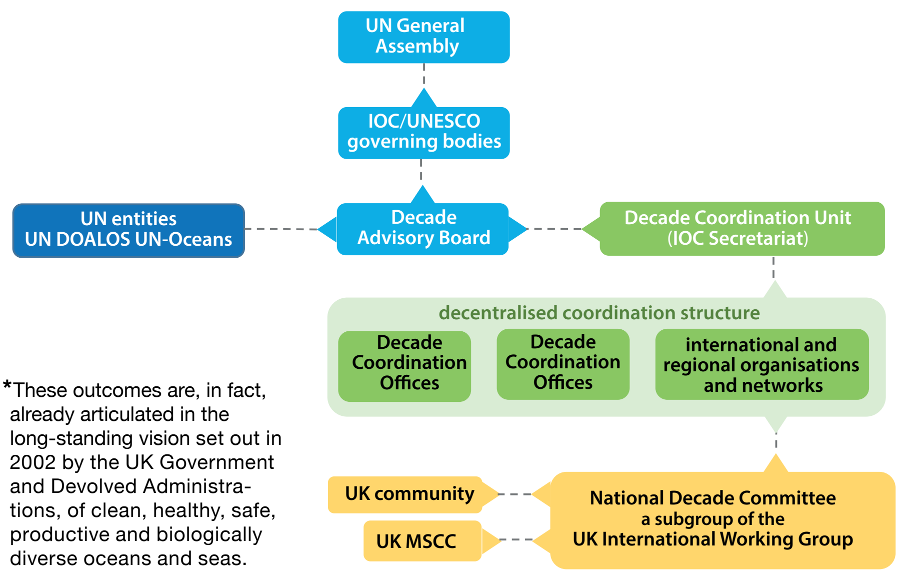
The work of the Ocean Decade will involve not only interdisciplinary marine science, but also the social sciences and economics. Success will depend on the commitment from people worldwide. There will be the widest possible diversity of participants/stakeholders in terms of gender, background and geographic coverage, as well as considerable value being placed on both local and indigenous knowledge. As a start, the two webinars on the draft implementation plan involved 600 participants from more than 80 countries.

Early Career Ocean Professionals (ECOPs) – not just early-career scientists, but also early-career decision-makers and innovators – are expected to play an important role in the Decade. ECOPs can make crucial contributions by actively participating in Decade Actions, and in governance and coordination structures, as well as being involved in the Decade's post-2030 legacy.

The approach in the UK

The UK, under the steer of the National Oceanographic Centre (as UK representative to the Intergovernmental Oceanographic Commission, IOC), has attended the global and regional planning meetings where the priorities for delivery of the various outcomes were identified. In addition, the UK Marine Science Coordination Committee (MSCC) International Working Group (IWG) has been appointed to oversee the UK's National Decade Committee (UK NDC) – a 'subgroup' of the IWG with mix of IWG members and other individuals appointed through a formal process. The UK NDC will be looking to inspire engagement in the UN Ocean Decade, will act as an information conduit from the Decade Coordination Unit to the national science and sustainable development community to promote awareness and interest (Figure 1).

The UK NDC, reporting to the IWG, will provide support for the formulation of Decade Actions – programmes, projects, activities or other contributions which will play a part in delivering 'the science we need for the ocean we want' (see Box). It will also coordinate national outreach and communication and ensure that outputs of activities implemented under the Decade are available to the wider community. It will report annually to the Decade Coordination Unit (Figure 1) on the Committee's activities as well as feeding back on stand-alone Decade Actions to the IWG and hence to the UK MSCC.



*These outcomes are, in fact, already articulated in the long-standing vision set out in 2002 by the UK Government and Devolved Administrations, of clean, healthy, safe, productive and biologically diverse oceans and seas.

Figure 1 *Governance and coordination framework for the Decade, including a structure for the UK contribution; IOC, Intergovernmental Oceanographic Commission; DOALOS, Division for Ocean Affairs and the Law of the Sea; MSCC, (UK) Marine Science Coordination Committee. (Modified from the Ocean Decade Implementation Plan Version 2)*

What does the Ocean Decade mean for you?

OCEAN POLICY & SUSTAINABLE DEVELOPMENT

Policy-makers from national and sub-national governments will connect ocean science activities with the 2030 Agenda.

UN ENTITIES & INTERGOVERNMENTAL ORGANIZATIONS

These are essential throughout the ocean science value chain: for co-design, co-delivery and use of generated knowledge, and for the provision of resources.

BUSINESS & INDUSTRY

Emerging maritime businesses and ocean information providers can contribute resources and partnerships, and as a driver of technological innovation.

DONORS & FOUNDATIONS

These will be essential to stimulating an enabling environment for the Decade that empowers communities, mobilizes partnerships and substantially increases investment in priority areas for action.

PUBLIC

Communities will engage via communication and ocean literacy activities, adapted to cultural, linguistic and geographical contexts, including access to technology.

CIVIL SOCIETY/NGO

OCEAN SCIENCE & TECHNOLOGY

EARLY CAREER OCEAN PROFESSIONALS (ECOPs)

ECOPs are the next generation of ocean scientists, decision makers and innovators. They will contribute to and lead actions throughout the Ocean Decade and continue its legacy post-2030.

MEDIA

Media partners will be essential to sharing knowledge throughout the world on how every citizen can use the results of ocean science to take action to protect our shared ocean.

LOCAL AND INDIGENOUS KNOWLEDGE HOLDERS

These communities will have the opportunity to collect and store information in innovative and accessible formats that can support its preservation and dissemination.

Taken from the Ocean Decade brochure: https://www.oceandecade.org

Descriptions of different kinds of Decade Actions

Programme A Programme will typically be global or regional in scale, and would contribute to the achievement of one or more of the Ocean Decade Challenges which represent the highest level of the Decade Action Framework and articulate the most immediate priorities for the Decade. Programmes will be long-term (multi-year) and interdisciplinary and will consist of component Projects and potentially enabling Activities.

Project A discrete and focussed undertaking. It may be regional, national or sub-national and it will typically contribute to an identified Decade Programme.

Activity A one-off stand-alone initiative (such as an awareness-raising event, a scientific workshop, or a training opportunity). It will enable a Programme or Project or directly contribute to an Ocean Decade Challenge.

Contribution Supports the Decade through provision of a necessary resource (e.g. funding or an in-kind contribution). A Contribution can support either the implementation of a Decade Action or the coordination costs of the Decade.

Some time-lines

Decade Actions require to be endorsed to be officially badged as such. Decisions on the first call for Decade Actions were announced on 8 June 2021, World Ocean Day. This followed the High-Level Launch on 1 June 2021.

You can sign up on www.oceandecade.org to be on the mailing list for updates, including information about the First International Conference of the UN Decade of Ocean Science for Sustainable Development, which began virtually on 1 June 2021 and will continue until May 2022.

Colin Moffat was until 31 March 2021 the Chief Scientific Advisor Marine, Scottish Government. He actively participated in the planning phase of the Decade.

Gaining experience through CLASS

CLASS – Climate Linked Atlantic Sector Science – is a five-year research programme, begun in April 2018, which is investigating the impacts of climate change and human activities on the Atlantic Ocean, from the surface to the sea bed. Its aim is to deliver knowledge and understanding of the Atlantic Ocean system to assist stakeholders in making evidence-based decisions relating to climate change. Research cruises contributing to CLASS have space on them for early-career researchers (ECRs) who wish to acquire training in making observations at sea, by being actively involved in collecting samples and data. Below, two early-career scientists who have benefited from going on a cruise contributing to CLASS descibe their experiences. If you would like to know more about CLASS, including how to apply for berths, see p.7.

Testing new sensors and platforms during a CLASS Fellowship *Sarah Cryer*

I'm a third-year Ph.D student at the University of Southampton and the National Oceanography Centre, and I was very grateful to be awarded a CLASS fellowship in 2019. I applied for the fellowship at the end of my first year in order to supplement work I was already undertaking in Belize, on the Caribbean coast of Central America, as part of my Ph.D. While I had some budget for fieldwork in Belize, I wanted to conduct a more thorough sampling regime than initially planned and to extend my time in Belize for additional sensor deployment.

Belize's extensive barrier reef, the significant ongoing land-use changes in the country, and the resultant effects on the chemistry of river runoff, make its coastline the

Sarah 'driving' the C-Worker 4 (visible in the distance) from the support vessel. (Photo: Millie Goddard-Dwyer)

ideal location to investigate the role played by a tropical river in coastal ocean acidification, and the potential impacts on coral-reef ecosystems. Rivers deliver nutrients and sediments to coastal seas and may also be a source of low pH water, so coral reefs, particularly those offshore major river outflows, could be experiencing a greater degree of ocean acidification than predicted by open ocean models. This could impact corals' ability to precipitate their calcium carbonate skeletons, as in order to do this corals raise their internal pH. To investigate the influence of river outflow on coastal waters we used a combination of discrete water samples and sensor deployments. Sensors mounted on the autonomous surface vehicle *C-Worker 4* were deployed to look at spatial variations in seawater properties, and sensors mounted on Ocean Acidification (OA) monitoring platforms at fixed points on the barrier reef were used to monitor temporal variations.

The *C-Worker 4* was developed by L3 Harris as part of the Containerised Autonomous Marine Environmental Laboratory (CAMEL) facility, to allow mapping and monitoring of local marine environments in small developing island states. It was deployed in Belize as part of a wider study under the Commonwealth Marine Economies Programme (CMEP)*. The *C-Worker 4* was

Left *Bottom view of the* C-Worker 4 *showing the location of the instrument payload which is retracted into the hull for protection during transportation and when not in use.* ***Right*** *OA Platform deployed on the fore-reef site near Goff's Caye on the Belize Barrier Reef. (Photos: Sarah Cryer)*

*CMEP aims to ensure that marine resources belonging to small developing Commonwealth states are better understood and managed, with the aim of enabling sustainable and growing marine economies. CMEP is a partnership between the UK National Oceanography Centre, the UK Hydrographic Office and the Centre for Environment, Fisheries and Aquatic Science (Cefas).

designed to carry 'off-the-shelf' sensors, and for this deployment we mounted quite a few, including sensors measuring conductivity, temperature, pH, pCO_2*, dissolved oxygen concentration, chlorophyll concentration, optical backscatter, nitrate and current velocity. To fully evaluate the *C-Worker 4's* capabilities I wanted to collect a number of calibration samples for these parameters, and the CLASS fellowship allowed me to do this and to conduct a more rigorous assessment of the vehicle.

As part of CMEP in Belize, an OA monitoring platform has been deployed to monitor long-term changes in pH, dissolved O_2 concentration, temperature and salinity. The CLASS fellowship allowed me to undertake a high-resolution short-term deployment of the platform, looking at how changes in pH and dissolved O_2 concentration vary on a fore-reef and back-reef site on Belize's barrier reef. There have been few *in situ* pH measurements on Caribbean reefs and, globally, a limited number of studies where both pH and O_2 have been measured. Collecting high-resolution datasets is key to understanding natural changes on reefs so we can identify when changes from the norm occur.

The CLASS fellowship gave me the opportunity to both gain hands-on experience in the deployment of OA platforms and collect validation samples for the pH sensor. As a result, I have a high-quality, high-resolution dataset with which I am preparing a manuscript focussing on the impact of changes in seawater pH and oxygen level on the Belize coral reef (*see below*). This dataset will now form a significant part of my thesis.

* pCO_2 = partial pressure of CO_2, a measure of the concentration of dissolved CO_2.

Cryer, S., F. Carvalho, T. Wood, J.A. Strong, P. Brown, S. Loucaides, A. Young, R. Sanders and C. Evans (2020) Evaluating the sensor-equipped Autonomous Surface Vehicle *C-Worker 4* as a tool for identifying coastal ocean acidification and changes in carbonate chemistry. *J. Mar. Sci. Eng.* **8**, 939. doi:10.3390/jmse8110939

Sarah is a third-year Ph.D student at the National Oceanography Centre, Southampton. She is currently working on a paper looking at changes in pH and dissolved O_2 at different reef sites measured using the OA platform, and supplementing data from Belize with data from Fiji and Dominica. A second manuscript on data collected by the C-worker 4 in Belize is also in the pipeline. S.E.Cryer@soton.ac.uk

Investigating the fate of nutrients in the North Atlantic though CLASS Lukas Marx

After successfully completing an international Master´s degree in marine sciences, I started my Ph.D at the University of Portsmouth in October 2019. My main research interest lies in biogeochemical cycling of nutrients and their fate in the marine environment. During my Ph.D project, which focusses on nutrient resources in future oceans, I am investigating how anthropogenic stressors alter the nutrient reservoirs in the ocean and what effects this has on the planktonic community and therefore on the dynamics and cycling of vital nutrients within the marine realm.

Starting a Ph.D was a big decision for me, as it involves much more than just being a student. At this stage, one fully commits to research and the life of a researcher. The nature of my project meant that I needed to join a research cruise, so I applied for a CLASS early-career researcher fellowship, to allow me to join a research cruise on board the RRS *James Cook* in January and February 2020 (JC191). The ship set sail from Fort Lauderdale, Florida, and crossed the North Atlantic along the 26°N GO-SHIP* transect to Tenerife, off west Africa.

Lukas on the rescue boat off the coast of Morocco, with the RSS James Cook *in the background. (Photo: Vanessa Romero-Kutzner)*

Thanks to the CLASS fellowship, I could collect seawater samples from six different water depths within the photic zone, for 38 of the total 135 CTD stations occupied during JC191. I wanted to assess and document the microbial and planktonic community structures, and how nutrients end up in different pools (dissolved and particulate, organic and inorganic) in the contemporary North Atlantic. Also, at pre-selected sites along the transect, on the deck of the RRS *James Cook* I conducted eight bioassay incubations in seawater adjusted to mimic possible future nutrient availability in the open ocean. Besides these, I also conducted two bioassay incubations to assess the effects of increased alkalinity on the biogeochemistry, for work in collaboration with the Woods Hole Oceanographic Institution (WHOI).

*GO-SHIP = Global Ocean Ship-based Hydrographic Investigations Program, which coordinates a network of hydrographic sections as part of the global ocean–climate observing system.

Lukas taking a sample of seawater collected at one of the 135 CTD stations. (Photo: Jessica Newman)

Looking back at the time I spent on the RRS *James Cook*, I can only be thankful for the opportunity to join the cruise. Time on a research vessel is very intense, as there are no such things as weekends or days off. It is very demanding, both physically and mentally, but I experienced a very helpful, professional and productive atmosphere. And it wasn't all work: I was lucky to see a lot of wildlife and of course many breathtaking sunrises and sunsets.

Now, being back in the UK (even though in times of Covid-19), I still remember the cruise and keep in contact with the people from the ship. I was granted readmission to the laboratory facilities at the University of Portsmouth and could start analysing the samples taken during JC191. Meanwhile, I am producing nutrient and chlorophyll maps with the data I collected, and the results look promising. However, I am very eager to analyse the remaining samples, especially from the bioassay incubations. The analyses of samples and data will form a substantial part of my Ph.D and I am planning at least one publication from this extensive and high-resolution set of samples.

On-deck incubators for bioassay experiments, where Lukas exposed the planktonic and microbial communities to an altered nutrient regime to mimic future conditions. To maintain a stable temperature, a continuous flow of seawater was supplied to the incubators, pumped up as the vessel was underway. (Photo: Lukas Marx)

To finish off, I would like to thank the CLASS programme for awarding me the ECR fellowship and making it possible for me to join the cruise, experience an amazing time on the ship, and especially for enabling me to get so much work done. Forming life-long friendships and beginning to build a professional network will be of huge benefit for my future career, and working alongside experienced researchers and people of various ages was a unique and valuable personal experience. The international group on board reflected the increasing diversity of people doing marine science, and public outreach (including live broadcasts from the female scientists onboard on the International Day of Women and Girls in Science) showcased this even more. I can only encourage other ECRs to apply for this fellowship, as it is a great opportunity to boost your career and make personal and professional contacts for life.

Lukas is now in the second year of his Ph.D and is finalising the analyses of the samples he collected during JC191. He will present his first results at the ASLO virtual meeting (22-27 June 2021) and is confident of publishing a paper on the basis of his research cruise early in 2022.

Lukas.Marx@myport.ac.uk

How to gain research experience through CLASS

CLASS is supporting the UK science community by providing opportunities for early-career researchers (ECRs), i.e. graduate students and postdocs, to work with us. CLASS also offers funded ECR Fellowships to support extended visits to the National Oceanography Centre and the Scottish Association for Marine Science, which could include joining a cruise. Find out how to apply for berths on cruises and CLASS ECR Fellowships, by signing up to our email bulletins on the website: proj.noc.ac.uk/class. You can also contact us by email (class@noc.ac.uk) or Twitter (@CLASS_URI). As well as delivering world-leading research, datasets, facilities and advice, CLASS activities will form the basis of new research projects. We encourage you to get in touch if you have ideas you would like to develop into proposals with CLASS researchers.

If you would like to know more, see:

https://projects.noc.ac.uk/class-project/academic-engagement

Blog of activity https://projects.noc.ac.uk/class-project/blog

CLASS Report 2021: Mid-term report highlighting some of the exciting research and outcomes from the first half of the project https://projects.noc.ac.uk/class-project/blog/class-report-2021

Stop Press: Although schemes are suspended due to Covid-19 restrictions, please keep an eye on the website and email bulletins for news of when they will be back up and running.

Powering the shipping world by wind

Gavin Allwright

Most people probably think of 'decarbonisation' in terms of the race to generate renewable electricity at scale, and while that is a key aspect, it is not even half the story. A huge amount of energy from solid fossil fuels is used to produce steel, and drive other industrial and chemical processes, while large amounts of liquid fuels are used for heavy transportation. At this nexus lies the world of commercial shipping – a huge consumer and transporter of energy, using the largest commercial machines ever deployed. The sector is responsible for 2–3% of global greenhouse gas emissions – the same amount of CO_2 as produced by Germany or by the entire continent of South America – along with large quantities of other pollutants. But we are all dependent on shipping as it transports up to 90% of world trade, moves hundreds of millions of passengers each year, is essential in fisheries, and so on. The global fleet is expanding and the associated pollution levels are forecast to rise significantly if nothing is done.

The shipping sector was excluded from the *Paris Agreement* on climate change, but in April 2018 set its own initial strategy of at least 50% reduction in emissions by 2050.But the question remains: how can this be achieved? Much of the debate has focussed on alternative fuels: from liquid natural gas (LNG) as a transitional fossil fuel then onto sustainably sourced ammonia, hydrogen, methanol etc. along with various biofuels and the use of batteries. However, shipping is uniquely placed to harness another energy source – wind. An energy source that fuelled shipping for millennia is now being seen by commercial shipping as a truly zero-emission, affordable option for decarbonising sea-going transport in the near term.

Modern shipping companies are looking again at vessels that use wind as an auxiliary source of power (known as 'wind-assisted') as well as ships primarily driven by the wind. The key attributes of wind energy are attractive: it is abundant, available worldwide, delivered to the point of use without the need for storage, and the cost of the energy is fixed at zero for the lifetime of the ship. The energy can be harnessed effectively with existing technologies, some of which are already on the market. These technological solutions utilise state-of-the-art materials and sophisticated automation systems and, when in operation, wind power is integrated into the vessels' energy management systems. And all the while there is the option to maximise energy delivery through modern weather routing and forecasting systems.

These advances put to bed suggestions that wind is an unpredictable and unreliable energy source, and that wind-driven vessels should be consigned to history. Many people imagine wind-driven ships as having cloth sails like those on a pirate ship, but that is not what we are talking about here. There are modern, automated soft sail options available of course, but there are six other kinds of wind-propulsion systems: rigid sails, suction wings, rotors, turbines and kites, as well as hull forms, all of which harvest the wind to generate thrust (see Box below).

Each one of these systems has its own characteristics that make it suited for particular ship types, sizes, trades and operations across the heterogenous global fleet. Large, heavy rig systems may lend themselves to tankers and bulkers (which carry non-liquid cargo) where deck space is available. Articulated and retractable systems are desirable on vessels that will encounter restricted air draft (when passing under bridges etc.) or need certain port operations (crane access etc.), and existing container vessels need retrofittable options that leave valuable deck space for cargo (e.g. kites).

Retrofitting wind propulsion systems can deliver 5–20% of propulsive energy (averaged over a year and without operational adjustments, explained below), with the potential to reach 30%. However, when wind propulsion systems are fully integrated into new-build designs, then for all types of vessel, wind could become the primary energy source, being backed by auxiliary engines using zero-emission fuel, to become 100% zero emission. When you Include operational adjustments such as routing vessels to maximise wind, regulated speed reductions (speed limits) and limitations on engine power, or optimising arrival times at port to manage energy consumption across the whole journey, then it becomes clear that the sector isn't quite so 'hard-to-decarbonise'.

At the time of writing, twelve large ocean-going vessels (some newly built) are outfitted with wind propulsion systems, with three more installations pending in the first half of 2021, and one 'wind-ready' vessel in operation which has all of

Methods of wind propulsion

Soft sails Both traditional sail and new square-rig designs such as DynaRig (a modern version of the square-rigged form of rigging, used in 19th-century clippers) (Figure 1).

Rigid sails These are various kinds of wingsails, i.e. double-skin sails analogous to airplane wings, but designed to provide lift on either side depending on the tack (Figure 2). Some rigs have solar panels for ancillary power generation.

Suction wings Non-rotating wings with vents and an internal fan (or other device) that use boundary-layer suction for maximum effect (e.g. Ventifoil and Turbosail) (Figure 3).

Rotor sails (also known as **Flettner rotors**) Rotating cylinders operated by low-power motors that use the Magnus effect (difference in air pressure on opposite sides of a spinning object) to generate thrust (Figure 4).

Turbines Marine-adapted wind turbines to generate either electrical energy or a combination of electrical energy and thrust.

Kites These are deployed off the bow of the vessel to assist propulsion or generate a mixture of thrust and electrical energy (Figure 5(a)). They may be either dynamic (i.e. constantly moving so as to maximise thrust) or passive (adjustable to a limited extent).

Hull form Ships' hulls designed to capture the power of the wind to generate thrust (Figure 5(b)).

All these technologies are fully automated for ease of use, safety and efficiency.

the modifications and foundations in place, but currently doesn't have rotor sails fitted. These large, 21st century vessels range from a 330 m, 300 000 dwt supertanker down to 90 m, 3000 dwt general cargo vessels, and include another large tanker, bulk carriers and roll-on/roll-off ferries. These modern ships are complemented by over 20 traditionally rigged small cruise vessels, sail cargo and fishing vessels. Other traditional vessels are in operation under sail in some areas of the Indian and Pacific Oceans.

The market forecasts are conservative. In the near term there are a number of retrofitted and new-build installations in the pipeline and additional R&D underway to back up further developments. The number of vessels with wind propulsion installed is expected to double each year to 2023, with over 40 vessels in operation in 2023 and additional new-build vessels coming online in 2024/25. While these may be conservative estimates, and do not come close to addressing the climate emergency, this projected growth is in line with wind propulsion market analysis commissioned by the EU in 2016 (Figure 6, overleaf). This concluded that, depending on various market factors, if the relevant technologies entered the market in 2020 there would be up to 10 700 installations by 2030 – around 50% of all bulk carriers and 65% of all tankers in the world fleet. The UK government's research for its *Clean Maritime Plan*,

Figure 1 ***Three wind-driven/ wind-assisted vessels with soft sails, currently in development.***

Above left *136 m roll-on/roll-off car ferry, NEOLINE, France.*

Above right *DynaRig-outfitted carbon neutral vessel, Smart Green Shipping, UK.*

Right *Kamsarmax bulk carrier, with retrofitted FastRig systems, Smart Green Shipping, UK.*

(Images: © Mauric and © SGS)

Figure 2 ***Examples of rigid wingsail vessels under development.***

Right Oceanbird *car-carrier with a capacity of 7000 vehicles, being developed by Wallenius Marine in collaboration with KTH Royal Institute of Technology and the Swedish company SSPA.*

(Image: © Wallenius Marine)

Left UT Wind Challenger*, from Mitsui OSK Lines (MOL), Japan: a large bulk carrier, at sea and* ***(below)*** *in port with sails lowered.*

(Images: © MOL)

Left *The expedition cruise vessel Silenseas+ uses both sails and dual-fuel engines. The Solid Sail® system was invented and developed by Chantiers de l'Atlantique, France.*

(Image: © Chantiers de l'Atlantique)

Right *Design for a carbon neutral bulk carrier, by Windship Technology, UK.*

(Image: © Windship Technology)

NB All images on this page are simulations.

***Figure 3** Two examples of vessels with retrofitted suction wings. **Left** The general cargo vessel, MV* Ankie*, with two retractable Econowind Ventifoils installed (Netherlands). **Right** The MV* Frisian Sea *general cargo vessel with movable Flatrack system (Netherlands). (Photos: © Econowind)*

released in 2019 (Figure 7) pushed that prediction horizon out to the 2050s, estimating a 40–45% market penetration for wind systems, equivalent to 37 000–40 000 vessels. Thus, the technology take-off period is fast approaching, and we have seen indications of this with recent announcements of testing and build projects underway for delivery in 2022/23, from big ship owners Oldendorff, Mitsui OSK Lines (MOL) and 'K' Line, shipyard Chantiers de l'Atlantique, commodities conglomerate Cargill, and the space sector Ariane Group, among others.

This level of installation of wind propulsion supports the uptake of new, zero-emission fuels. These fuels are likely to be up to five times more expensive than today's fuel, and are less energy dense, so occupy relatively more space. However, wind substantially lowers the total fuel requirement meaning more cargo space available with smaller storage tanks needed on board, lower fuel costs for shipping companies, less investment in shore-based infrastructure, and potentially lower installed power requirements. This scenario will accelerate the uptake of zero-emission fuels, speed the industry's response to the climate emergency and ultimately could make the transition more viable and cheaper for all.

It is true that the new land-based infrastructure needed will take trillions of dollars of investment and decades to roll out worldwide. Furthermore, there are sceptics in the industry who point to the need for safety, certification and training, the costs, and other technical and business issues, as reasons why wind will remain peripheral. One by one these arguments are falling by the wayside. The serious issues of safety and technical considerations are handled in the main by classification bodies such as Bureau Veritas, ABS, Class NK etc. which certify all new systems and new builds. As the pioneer technologies get certified, the way is opened for more wind installations. All of the main classification bodies have upgraded and published their comprehensive wind-assist guidelines and are increasingly experienced in swiftly certifying these technologies and installations.

Training is available via 'virtual reality' systems to give crew the capability to reduce fuel use by deploying wind and so reduce operational costs. New wind systems are

***Figure 4** Examples of rotor sails. **Top left** Norsepower retrofitted rotor sails on the MV* Estraden *(Finland). The photo shows how the sails and operating system form one unit. (Photo: © Norsepower) **Top right** The movable Anemoi system installed on the bulk carrier MV* Afros. *(Photo: © Anemoi) **Bottom Left** Pioneering new-build E-ship 1 (UK) (Photo: © JöP). **Bottom Right** MV* Fehn Pollux *with bow-mounted EcoFlettner system (Germany). (Photo: © EcoFlettner)*

Figure 5 ***More unconventional approaches.*** ***Left*** *An Airseas (France) kite being used to assist a Louis Dreyfus Armateur vessel carrying Airbus parts. (Image: © Airseas)* ***Right*** *The Vindskip with a hull designed as a wing (Norway). (Image: © LADE AS) Both images are simulations, but the kite system will be installed later this year.*

highly automated and increasingly integrated into the vessel systems, so operation is designed to be hands-off. The systems can be monitored from shore, adding another layer of protection and service for customers, making it possible to deal early with any technical issues etc., while identifying further opportunities for improvements.

When we look at the bottom-line issues, the cost of these systems is not insignificant. However, from a standard capital purchase perspective, a price of around US$600 per ton of fuel starts to make most standard retrofittable systems attractive with a Return on Investment in the 3–4-year area, which many shipping companies will consider. Currently, fuel costs are lower than that, but are likely to rise as carbon levies are introduced, which will go some way to enhancing the financial attractiveness of the new systems. For example, the EU will soon include shipping in its Emissions Trading Scheme, with a carbon levy of €50 per ton (€155 per ton of fuel). One challenge is that the ship-owner often has to pay to install the system, but the charterer who leases the ship pays for the fuel, so would get the benefit from fuel-saving devices, much like a renter putting solar panels on their rented house to lower energy bills, while expecting the landlord to pay for the installation. To tackle this issue, some maritime wind-assist organisations take a different approach, offering 'wind-as-a-service, pay-as-you-save' finance models or leasing. The hardware is paid for by the savings made, and in the case of this shipowner/charterer situation the two parties can split the costs and the benefits. This financial model exists in the airline industry so it's a case of adapting and adopting it for maritime operations.

These developments are all starting to align, putting the case for wind propulsion at the very heart of shipping's decarbonisation plans. Wind propulsion opens up the potential for a paradigm shift in the industry. What if vessels could harvest and use excess wind energy onboard to generate alternative fuels such as hydrogen, and thus become truly operationally 'fuel independent' and carbon neutral? There are projects underway that are addressing that challenge, and looking at the possibility of taking that next step and developing a vessel that can produce enough energy to become a zero-emission fuel producer and tanker all in one.

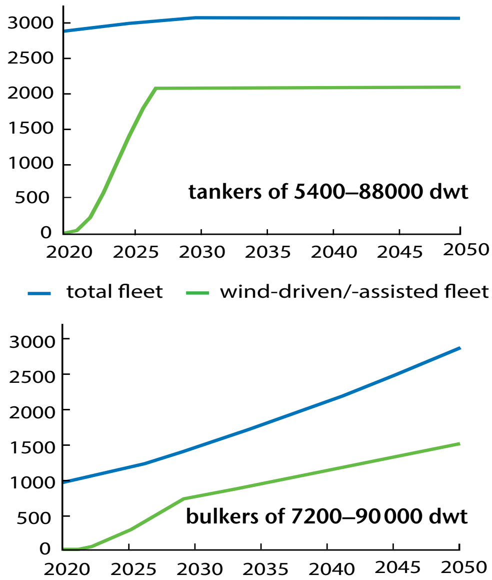


Figure 6 *Predicted increases in the numbers of tankers* ***(top)*** *and bulkers* ***(bottom)*** *making use of wind. The actual take-up of wind power will depend on the bunker fuel price, the speed of the vessels, and the discount rate applied. dwt = deadweight tonnage, a measure of the total weight a ship can carry. (From a study prepared for the EU by CE Delft 2016)*

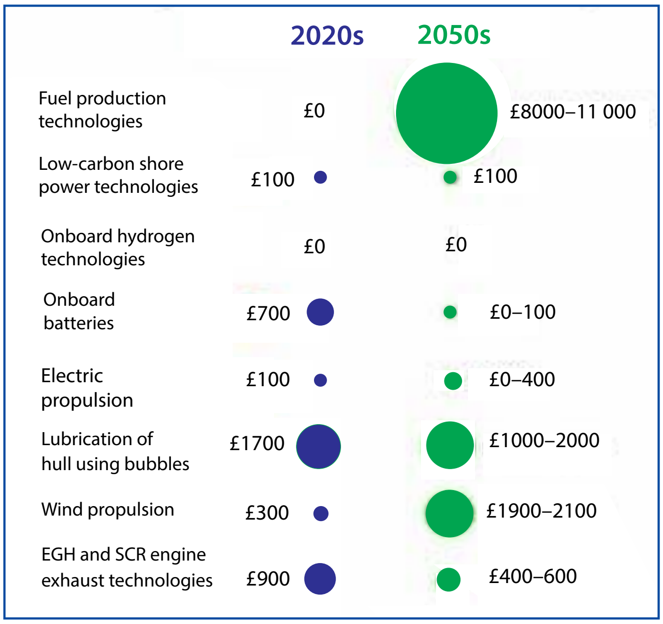


Figure 7 *Potential annual global market in GBP milllion yr^{-1} for the 2020s and the 2050s for low-carbon technologies associated with shipping (2016 prices). The wind propulsion values assume that by 2050 there would be 37 000–40 000 vessels with wind propulsion systems installed, equating to ~ 40–45% of the global fleet.*

EHR = exhaust gas recirculation
SCR = selective catalytic reduction

Taken from the UK Government Clean Maritime Plan *(July 2019)*

Extensively retrofitting today's fossil-fuelled fleet with wind-harnessing devices helps to reduce emissions and fuel use. That means that far less of the carbon budget allocated to shipping will be used up, and the fuel-savings generated can be invested in the new, primarily wind-powered vessels of the future, along with the zero-emission fuels that we need. Once wind is brought to the centre of decarbonisation efforts for shipping, there is a real possibility of a transformation in the industry.

Gavin Allwright is Secretary General of the International Windship Association (IWSA). secretary@wind-ship.org

Sentinel-3 *monitors ocean health*

Stephanie Allen and Gavin Tilstone

Due to their small size (2–250 µm) and rapid growth and reproduction rates, phytoplankton have the ability to adapt quickly to changing environmental conditions, including increased light and nutrient levels, allowing populations to rapidly form blooms so large that they can be seen from space. In the North Atlantic region, these blooms are a seasonal characteristic of temperate, subpolar and coastal waters, typically occurring in early spring. Phytoplankton blooms provide vital food sources to higher trophic levels and as such are important events in coastal waters where shellfish and fish are commercially exploited.

Though phytoplankton and bloom events are fundamental to a healthy marine ecosystem, under certain conditions, some of the species that form blooms may produce harmful toxins. These toxins accumulate in the water column and can cause shellfish poisoning; if the toxins are ingested by humans, they are dangerous to health, and may even be lethal.

These harmful algal bloom (HAB) events are associated with higher than average sea temperatures and high nutrient run-off from rivers, and are predicted to continue to increase under the pressures of global climate change and changes in land-use. The frequency and extent of harmful algal blooms are already increasing in some regions around the world.

HABs can have an extremely damaging effect on tourism, fishing and other maritime industries. In the EU, the annual cost of HABs to these industries is estimated to be in excess of €918M. Unfortunately, the current methods of tracking HABs are expensive, costing €2M annually to monitor just 6% of the Channel area. To extend the monitoring coverage of HABs over space and time, an innovative web-alert system has been created by scientists at Plymouth Marine Laboratory (PML) to both detect HABs and monitor water quality using the latest satellite technology. The alert system is the first web-portal to monitor HABs and water quality in Europe, and to do so using the new *Sentinel-3* satellite, operated by the European Space Agency programme Copernicus.

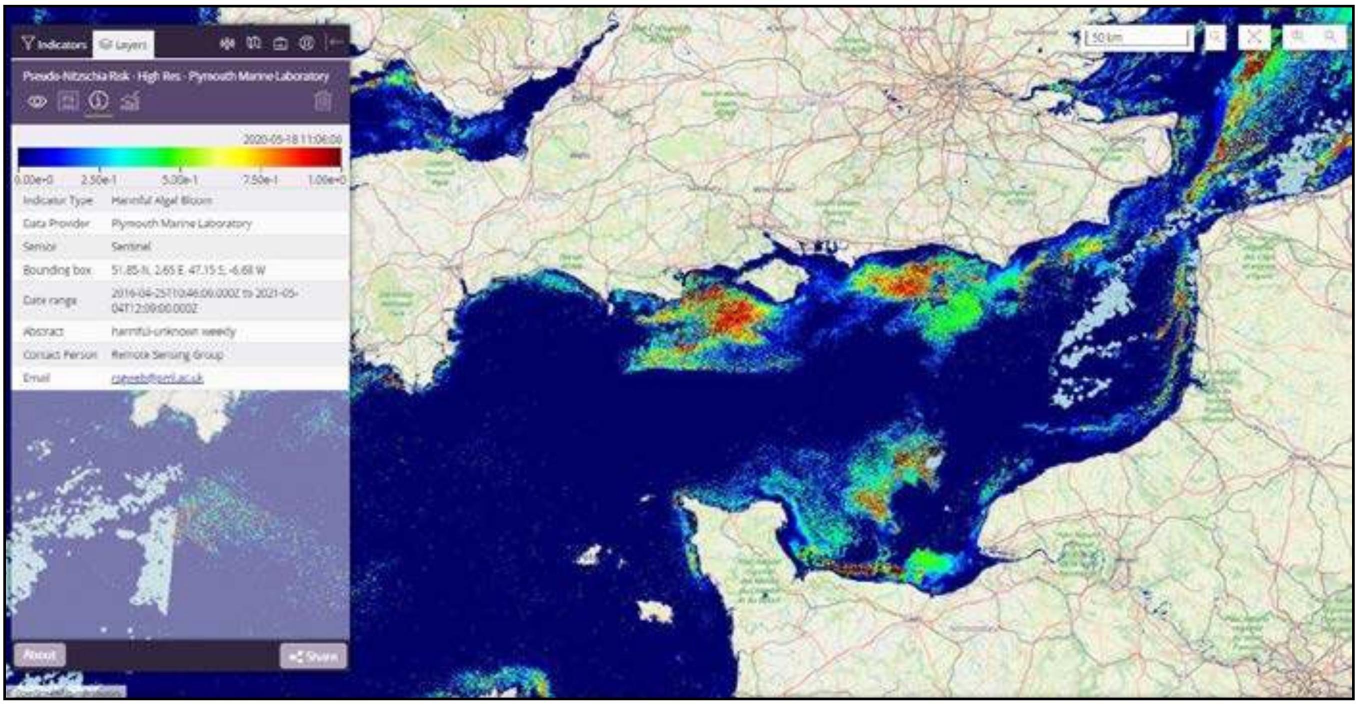
The project, known as S-3 EUROHAB, is funded for four years, involves scientists from three English and five French organisations, and is led by PML. It forms part of the larger EU INTERREG France (Channel) England (FCE) Programme which aims to foster economic development in the south of the UK and the north of France through funding innovative joint projects.

By utilising ocean colour data from the *Sentinel* mission, S-3 EUROHAB allows the entire Channel area to be monitored for HABs simultaneously, and the information to be provided in near real time. The detection of HABs in satellite images is accomplished by identifying 'optical fingerprints' which are unique to each HAB species, and the likely risk of HAB species being present is calculated and displayed on the web-portal in terms of a colour scale (*see below*).

The web-based alert system has been designed using feedback obtained through dedicated workshops with a diverse range of stakeholders, including managers of shellfisheries, monitoring organisations, conservation groups, marine management bodies and academia in the UK and France. A wide range of end-users can therefore benefit from the web-alert system, particularly stakeholders in the shellfish industry who are able to react quicker to a HAB event, by either harvesting earlier or taking stock from an unaffected area. This could save stakeholders on both sides of the Channel both money and effort.

Currently, the S-3 EUROHAB portal can provide an indication of the risk of harmful blooms of *Karenia mikimotoi*, *Phaeocystis globosa* and *Pseudo-nitzschia* spp., as well as displaying other ocean characteristics, such as sea-surface temperature, turbidity, mixing and rainfall. The system

S-3 EUROHAB web-portal image displaying the risk of harmful blooms of Pseudo-nitzschia *spp. in the Channel, produced using high-resolution (300 m) data from Copernicus* Sentinel-3 *(OLCI sensor).*



Small but mighty
From top to bottom: Karenia mikimotoi, Phaeocystis globosa, Pseudo-nitzschia *spp.*

(Top: Elisabeth Nezan, © Ifremer. Middle: Jolanda van Iperen, © NIOZ. Bottom: Adrian Marchetti, NASA, via Wikimedia Commons)

therefore allows us to assess the environmental conditions that lead to HABs, the origins of the blooms, and where they are transported to in the Channel.

Over the course of the four-year project, in addition to designing the HAB monitoring network and the web-based alert system, S-3 EUROHAB has conducted a socio-economic analysis of the impact of harmful algal blooms in the Channel. Interviews with shellfish producers, processors and food businesses were conducted across south Devon and Cornwall to assess the impact of HABs and associated closures of shellfish beds. HABs present a significant threat to shellfish farms, where the resulting weekly loss in sales could be as much as £100 000. By continuing to monitor the socio-economic impacts the S-3 EUROHAB project can also assess the long-term benefits of a region-wide HAB monitoring programme.

In the near future, the S-3 EUROHAB team will be expanding the number of species that can be detected from space and will also combine together multi-parameter satellite data to improve the detection of certain species. It will also expand the scope of the system so that it can use environmental parameters as proxies for HAB species that occur at very low density.

To find out more about S-3 EUROHAB, go to www.s3eurohab.eu/portal/.
For more about HABs in general see a new IOC report: https://ioc.unesco.org/news/unprecedented-analysis-global-harmful-algal-blooms-launched-ioc

Stephanie Allen is an Earth Observation Scientist at Plymouth Marine Laboratory sall@pml.ac.uk and **Gavin Tilstone** is the S-3 EUROHAB Lead at Plymouth Marine Laboratory. GHTI@pml.ac.uk

Results of the Covid-19 Working Group UK Marine Science Survey

In October 2020, representatives of the UK marine science community conducted a survey to assess the impact of Covid-19. The 193 respondents were based at marine research institutes from across the UK; about half were from universities and other institutes of higher eduction, and the rest were from research institutes, the public sector and industry. The Covid-19 Working Group was led by Kate Hendry of the University of Bristol and supported by Jackie Pearson of the NOC Association of Marine Science National Capability Beneficiaries (NOCA). There will be a detailed article on the implications of the survey results in the next issue of *Ocean Challenge*, including recommendations for science leaders, particularly with respect to Early Career Researchers (ECRs) and staff on fixed-term appointments (FTAs), which may help to enhance the working environment for scientists in a post-pandemic world. The full report and a summary of those recommendations can be found at https://naqbase.noc.ac.uk/content/covid-19-survey-working-group-impact-survey. Here is a summary of the responses to the survey.

Fieldwork 84% of planned marine fieldwork in UK has been cancelled or postponed since March 2020

Labwork > 90% of marine science labwork was impacted either moderately or severely
Most strongly impacted ECRs and FTAs and their supervisors • Researchers in the university sector • Researchers with caring duties • Researchers with a disability

Grants > 50% of those planning on writing a grant proposal were negatively impacted.
Most strongly impacted Mid-career scientists • Researchers in the university sector • Researchers with caring duties, and/or pastoral care duties for postgraduate students

National capability ~ 33% of end-users found access to facilities negatively impacted

Conferences and networking > 50% of respondents attended fewer conferences

Teaching and education > 35% of those involved in education reported cancelled/postponed field teaching
> 50% reported that face-to-face teaching was cancelled/postponed

Mentoring ~ 50% of ECRs reported a drop in mentoring and supervision • 17% of ECRs don't feel they have a mentoring and supervising programme

Career progression > 33% feel their career progression will be negatively impacted • ~ 33% don't know if career progression and promotion has been cancelled or postponed

Other > 50% find it hard to work from home • 25% have suffered a decline in mental health • > 50% feel more isolated • 40% have an increased administrative workload

Overall, negative impacts were felt most strongly by: ECRs and FTAs • Women • Scientists with disabilities
Scientists in full-time employment

Sharing scientific skills and expertise

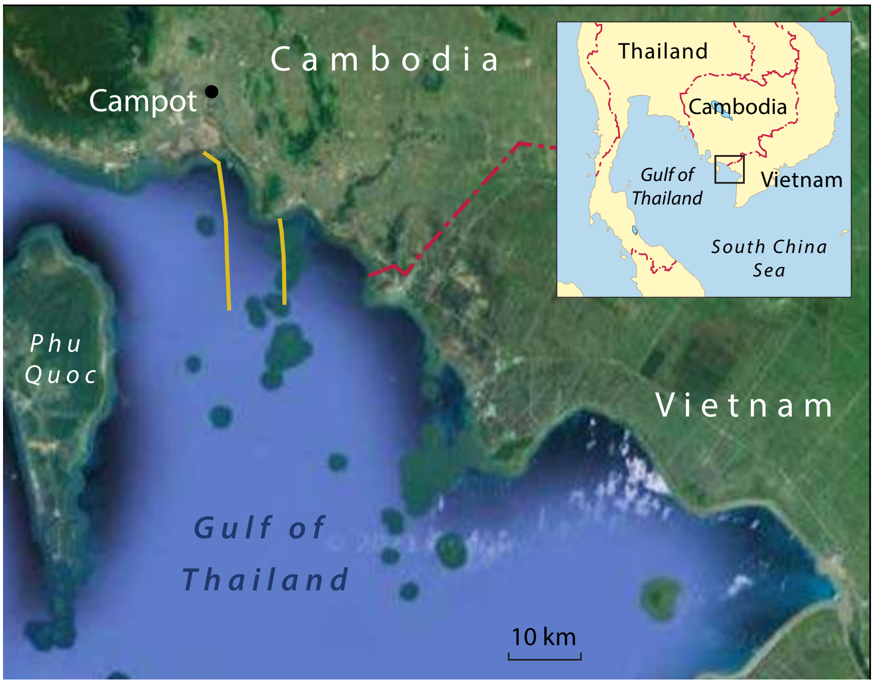
Equipping Cambodian scientists to better manage their own marine resources

Kelvin Boot

The coastal seas of South East Asia are among the most biodiverse on Earth, and provide a wide range of goods and services to local communities. Yet despite their obvious ecological, economic and social value they are threatened by increasing human populations and accompanying developments, global economic markets and local desires for economic growth, set against a backdrop of shifting ocean conditions, as sea temperatures rise and pH drops inexorably as atmospheric CO_2 concentrations increase.

Coastal ecosystems have supported communities for millennia, enhancing the lives of people living in proximity to the marine environment. Today, however, coastal and island communities face an uncertain future when the resources upon which they rely deteriorate. This is not to say that coastal resources cannot be exploited and provide opportunities for further development of mineral extraction, tourism, aquaculture and fisheries, not to mention 'blue carbon' initiatives, i.e. enhancing the ability of certain marine habitats to become long-term reservoirs of carbon.

On a wider scale, coastal states may also wish to exploit ocean resources and seek new products and markets to grow their economies and attract inward investment. However, in order to protect these local, national and often globally important assets – their 'natural capital' – they need to balance exploitation against preserving habitats and the resources they provide.



Satellite image of the coast in the vicinity of the Cambodia–Vietnam border, showing the positions of the ACCORD transects through islands off Cambodia; the longer transect starts within the outflow of the river that flows through Campot. Measurements undertaken during the transects included sea-surface temperature and Secchi depth (for water clarity) and other optical properties, and seawater samples were collected for measurement of salinity, concentrations of inorganic and organic nutrients, particulate organic carbon and nitrogen. Note that maritime jurisdiction in the area is complicated, particularly as the island of Phu Quoc is Vietnamese.

Around the Gulf of Thailand, mangroves are essential habitat for a wide range of species, above and below the water, and provide buffers against rising seas, but even they are not immune from plastic pollution. (Photo: ACCORD)

This balancing act requires political will and local buy in, which in turn rely upon sound science and reliable interpretation of data.

In many developing countries expertise and the infrastructure needed to support marine science investigations may be at best low priority and at worst almost non-existent. By comparison, the UK has been at the forefront of marine research for centuries and benefits from an active and comprehensive marine science community, a community that has always been happy to share expertise, experience and enthusiasm. Now the Foreign and Commonwealth Office's Official Development Assistance (ODA) programme is enabling Plymouth Marine Laboratory (PML) and the National Oceanography Centre to work together to share their experience and expertise in South-East Asia through the ACCORD project (ACCORD = Addressing Challenges of Coastal Communities through Ocean Research for Developing Economies).

A first for Cambodia

Gathering data is the starting point for any proposed enterprise involving management, sustainable exploitation or conservation initiatives. Work has begun with fieldwork, among the first by any scientific institution in Cambodia, a country with sparse data about its marine environment. What data do exist have largely been generated by Marine Conservation Cambodia, the NGO that is the local partner for the UK-based scientists. As might be expected, the local studies had targeted particular 'high profile' aspects including seahorse and seagrass distributions, and dolphin-spotting in coastal waters. There are some existing conservation areas but they are few and, despite the best efforts of local organisations, are not underpinned by much scientific information. When it comes to the foundations of understanding the marine environment in an academic way – the physical, biological and chemical oceanography – there is practically nothing. So ACCORD is really the first serious attempt at establishing a scientific baseline for coastal Cambodia and its ecosystems, and indeed the region as a whole.

Blooming stimulus

The local spur for this Cambodia–UK collaboration was a couple of large harmful algal blooms around the islands off Cambodia (Figure 1), the first such blooms to be recorded and a cause for concern for the Cambodian administration. Two benefits the local marine environment provides are fishing and tourism. Tourism along the 40 km coastline has been earmarked for expansion, so the occurrence of masses of decaying algae thrown up on beaches, while maybe not toxic, certainly created a negative aesthetic impact. Harmful algal blooms can cause discomfort, distress and death to fish and other marine life with the knock-on effect to human health from consuming affected fish and shellfish. The unprecedented and unexpected harmful algal blooms dramatically highlighted the obvious lack of understanding about the marine environment, prompting questions such as: 'Where did the bloom come from? What caused it and will it happen again? What can be done to prevent a recurrence?'

But harmful algal blooms are only part of the story. At the most fundamental level there is a need to know what is actually there and how the coastal ecosystem works, what the relationships are between the oceanography, the productivity and the sustainability of the existing fisheries, and how the ecosystems maintain the water quality. Massive port developments are being planned to encourage increased tourism. Many thousands of people are going to be arriving on the doorstep, putting a lot of pressure on the resources of the local area and perhaps modifying the composition of the water being delivered into the archipelago. The development of the port and maintenance of the access in a pretty restricted area (especially given the proximity of Vietnamese waters) will likely have a massive impact. Alongside that there is a lot of development planned in nearby Campot, from where a river spills out into the archipelago, a potential source of run-off chemicals and nutrients.

Pencil urchins and colourful starfish are amongst the more obvious benthic fauna sampled around the coast to provide a baseline against which future change could be measured. (Photos: ACCORD)

The ACCORD project

Timing is everything and it was quite fortuitous that an opportunity for this ODA project was brought to the attention of the Cambodian national administration and NGOs. It provided the perfect opportunity to gather data to develop understanding of the marine environment, which in turn would inform a desire to develop policy to protect Cambodia's ecologically, economically and socially valuable marine environment. Projects like ACCORD are essential, not least because they have a very real potential for genuine, on-the-ground impact. The ACCORD project is designed to provide partner countries (in this case, Cambodia and Vietnam) with an improved capability for integrated and sustainable management of marine activities. This increased capability should enable them to build a resilient marine and coastal socio-ecological system, alongside economic growth, and so support their developing blue economy.

As in many projects, desk-work occupied the first phase of ACCORD. Bringing together existing information about the marine environment from freely accessible sources, it entailed literature searches, modelling and remote sensing studies. This phase provided a better understanding of how water bodies move through

Basic measurements, such as sea-surface temperature, were almost completely lacking, but by providing easy-to-use equipment, like hand-held infrared thermometers, and a modicum of training, the gap could be plugged. (Photo: ACCORD)

the region, the seasonality of temperature, salinity and other parameters, and, through the use of satellite sensors, the variability of chlorophyll and hence phytoplankton. But ultimately to gain a much better understanding and contextualise the data, in some cases very limited, there was a need to get feet on the ground.

Fieldwork

As a country with little tradition of marine science investigation, Cambodia is a difficult place to carry out fieldwork. Coming from the relatively well funded west, the lack of facilities, which are taken for granted in any laboratory in the UK, was an eye-opener for the ACCORD scientists. There was no laboratory, just a series of huts, with no continuous electricity or running water. There were no containment facilities for holding seawater and live samples, chemicals could not be used, and there were no chillers. On the positive side, there was a boat available, and there was plenty of local enthusiasm, with NGO and Ministry of the Environment scientists joining in with the research. ACCORD project scientist Dr Darren Clark from PML summed it up:

This was 'science on the edge' – I have never experienced anything like the working conditions we were dropped into. However, the enthusiasm of Marine Conservation Cambodia and their volunteers was an inspiration. They really wanted to understand how their environment worked, but the lack of facilities, even on the mainland, really limited what could be done. It gave me a much greater appreciation for the systems, institutions, facilities and skills we have in the UK.

Sharing experience and expertise

While the visiting scientists were monitoring and measuring, observing and recording, they were also training and encouraging local scientists and volunteers, who joined in with the fieldwork. The experience the local people gained will carry on under the aegis of Marine Conservation Cambodia. But they will not be left adrift – the UK scientists hope to be on the ground a few more times to gain a picture across the seasons. In the meantime the newly trained local scientists will be making headway, filling in gaps between those visits. They will continue recording salinity, temperature and optical measurements, standard observations for UK scientists but novel, though essential, in Cambodia. Salinities, in particular, are very relevant to understanding bloom formation and timing, because the freshwater input from rivers brings with it elevated levels of nutrients which can lead to proliferation of algal cells to bloom proportions.

'Laboratory' facilities are primitive and challenged the ingenuity of the enthusiastic local scientists and the team working on the ACCORD project. (Photo: ACCORD)

At the time of the first ACCORD visit there were two theories for the cause of the harmful algal blooms: intensification of trawling or an increase in nutrients from aquaculture and terrestrial run-off. The project looked for evidence to see if these theories could be dispelled. So, making observations and checking against data became crucial. No-one had been there to do this before. Furthermore, this was the first time that the broad overview provided by *in situ* observations, remote sensing satellite sweeps and modelling had been available in Cambodia. Bringing all of this together, the evidence points to unintentional consequences of land-use changes in Vietnam since 2000 which favour increased agriculture and especially land-based aquaculture. These changes result in high nutrient levels from land run-off into rivers and hence out to sea. The scientists suspect that these changes have resulted in the plankton blooms, but they retain open minds and are helping Cambodia to look at all possibilities including the increase in trawling.

While working in Cambodia, Clark and his colleagues were very aware of the challenges that will face the local workers as a result of the paucity of skills and facilities:

While we can offer training and the understanding and theoretical knowledge, this needs to go hand-in-hand with support through sufficient resources to build and furnish and maintain laboratories in a country which is not yet mature in marine science. The Cambodian administration recognised that the link between PML and the Ministry for the Environment could be useful in helping to build their own capacity in the environment and marine science.

Next steps

A start has been made and Cambodia–UK scientific links have been established but there is always the danger that such projects fade away once the initial funding has come to a close. Clark hopes the connections and groundwork will bear fruit and that understanding of these rich seas, on a regional scale, will continue to grow:

We have laid the foundations, we have at least some facilities for use as a base; we have close links with NGOs and government, so there is now a network, but Cambodia is a difficult place to work in because of the logistical, transport, communications and resources challenges.

The experience made me wonder if we in developed countries are over-reliant on 'tech'. While there is no denying the great advances we can make with technology, I wonder how much 'average' science is pumped-up by the use of high tech approaches? Good science starts with a well thought-out question, and a tractable strategy to test/deliver a solution. In Cambodia we used, and provided training for, relatively basic equipment. However we were able to develop some very useful understanding about the Cambodian islands, the sort of understanding that can only be generated with 'feet on the floor' complementing models and satellite-derived data.

Clark and the rest of the ACCORD team are also working in neighbouring Vietnam, so there is an opportunity to spread understanding and concern between the countries bounding the shared seas. But although ACCORD still has some way to go as a project they hope that having done important groundwork other research institutes in the UK and elsewhere will be concerned enough to take up the baton, perhaps instigating a series of coordinated research projects, maybe a swarm of Ph.D studies engaging local people, but above all to continue gathering the knowledge and sharing expertise and experience to encourage a regional approach to managing the Gulf of Thailand and the South China Sea as a whole.

Making a difference?

As Clark points out, the job of the visiting scientists is to help and encourage the local researchers and provide impartial information.

> *It's not our job to tell them how to manage their environment, but if they are informed, at least they can make informed decisions.*

> *Fortunately there are people within the administration that do want information so they can pass it on to decision-makers. The big decisions for them surround the port development. It will certainly bring in tourist dollars but will inevitably impact the local environment and other sectors, perhaps killing the goose that laid the golden egg.*

But it is not simply about local management challenges, there is also a much bigger driver than what is happening in this relatively small region. Sharing the Gulf of Thailand and its oceanography with other countries means that whatever happens locally can have international implications. Clark believes that the recent occurrence of harmful algal blooms was indeed connected to land-use changes and the increase in aquaculture in the region, which are feeding nutrients offshore and into the complex current systems, transporting them to other jurisdictions where they can cause problems from afar. He points to Cambodia, Thailand, Malayasia and even China as potential recipients of enhanced algal blooms resulting from these inputs. But it is not about singling out any particular country as being at fault, it is recognising that any state can impact on a shared resource – in this case the South China Sea.

Kelvin Boot is a freelance Science Communicator who works with a number of organisations. kelvinboot@yahoo.co.uk

For more about harmful algal blooms see pp.12–13.

Matters arising ...

Naval nomenclature and the gendering of ships

While reading p.21 of the previous *Ocean Challenge* I was puzzled to notice a reference to an unfamiliar addition to the NERC fleet: '*Discovery III*'.* The context reveals that the vessel intended was RRS *Discovery* (1962), the third '*Discovery*' to have been a British research vessel and the replacement for RRS *Discovery II* (1929). The reason for this apparent reversal was explained by the late Sir Anthony Laughton on pp.272–3 in *Of Seas and Ships and Scientists*, the history of the National Institute of Oceanography published in 2010: 'The name given to her by Viscountess Hailsham when she was launched in July 1962 was RRS *Discovery*. Many have since asked why not *Discovery III*? By now the original RRS *Discovery*† of Scott fame lay alongside the Embankment in London and had been acquired by the Navy and renamed HMS *Discovery*. So in keeping with naval tradition the name RRS *Discovery* was once more available.' As Daniel Behrman wrote in his overview of the International Indian Ocean Expedition, published by Unesco in 1981: '[O]nly the British can explain why *Discovery II* came before *Discovery*'.**

*The Editor is happy to take responsibility for any mis-numbered '*Discovery*'s in the article in question.

† Now a tourist attraction in Dundee.

***Assault on the Largest Unknown* (p.72).

It may be worth mentioning that there have been seven HMS *Challenger*s since 1800; the most recent, an advanced diving support vessel (K07), was decommissioned in 1990 and sold in 1993. (She has been converted to mine offshore diamonds and is now working in Namibian waters under the name of *Ya Toivo*.) The title is vacant again – perhaps the Society should drop a word in some Admiralty ears?

On a related but more contentious matter – ships' gender – I was glad to see that throughout his article about RRS *Sir David Attenborough* on pp.14–15 Michael Gloistein of BAS adhered to tradition by consistently referring to the ship as 'she' (despite the meteorologists' priapic instrument platform mounted in her bows!). This convention has deep roots in English culture, going back to Chaucer and beyond. In Nelson's day the 'man-o'-war', armed with three decks of cannon, was considered feminine by her officers and crew.

Today the Royal Navy is still on the side of history, but maritime museums are tending toward the use of neutral pronouns. The choice is not a simple one because its implications are personal to each individual mariner. Does the attribution of femininity suggest that a ship is reliable or capricious, wilful or cooperative, unfortunate or lucky? That depends! On the other hand, 'it' and 'its' can seem inadequate as replacements for something more personal. Relationship with the inanimate objects we rely on is often expressed by the pronouns applied to them. I suspect that even *Boaty McBoatface* has a gendered image in the mind of its human colleagues.

No doubt the usage of third-person pronouns will continue to evolve in the same direction until a new balance is achieved. I must accept the inevitable, while lamenting the loss of another dash of colour from an increasingly ungendered vocabulary. One thing is certain: it was *men* who were responsible for setting this trap for themseves so many centuries ago, although fortunately there's been no counter-claim on behalf of the masculine pronouns – at least not yet!

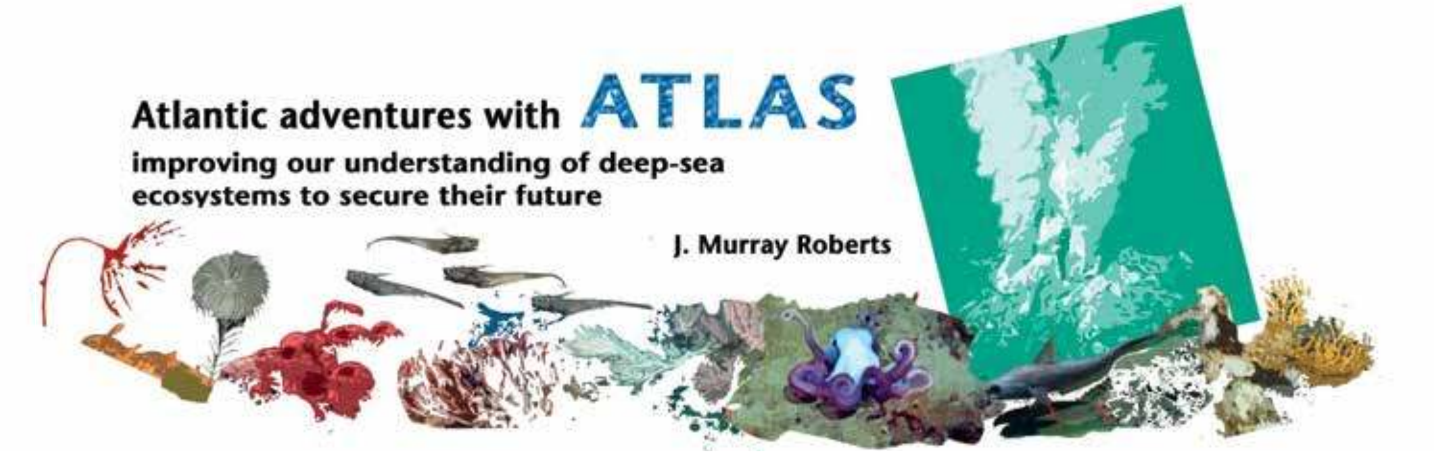
John Phillips

Cartoon of *Boaty McBoatface* by courtesy of the National Oceanography Centre/NERC.

Atlantic adventures with ATLAS

improving our understanding of deep-sea ecosystems to secure their future

J. Murray Roberts



The deep sea is the last frontier on Earth. Yet for over 30 years this frontier has been under increasing pressure from human activities, and we are now reaching the point when new industrial activities like deep-sea mining may move from phases of exploration to exploitation. And all this is happening at a time when we are seeing unprecedented rates of seawater warming, acidification and deoxygenation, including in the vast and typically rather stable environment of the deep ocean.

With expanding human activities and the pressures of global change very much in mind, the 4.5 year ATLAS* project (2016–20) created a team from across Europe, Canada and the USA to better understand deep North Atlantic ecosystems. ATLAS assembled interdisciplinary expertise – spanning social and natural sciences, environmental economics, policy and governance – not only to acquire new knowledge but to bring this straight to those shaping ocean policies at national, regional and international levels (Figure 1). This made ATLAS a big, complex multi-million European project with 72 researchers and 10 Ph.D students working across 10 work-packages and on 45 offshore expeditions. Like the HMS *Challenger* expedition 150 years ago, ATLAS had four overall objectives.

Figure 1 *The ATLAS projects came together as one jigsaw where each piece had its unique part to play. Communication, networking and policy were all developed alongside research activities spanning the socio-economic and natural sciences.*

(Image: ATLAS project; AquaTT)

*ATLAS = A trans-Atlantic assessment and ecosystem-based spatial management plan for Europe.

†'Blue Growth' is the term used by the EU to describe its long term strategy to support sustainable growth in the marine and maritime sectors as a whole.

For ATLAS, these objectives were:

- Improve understanding of deep Atlantic marine ecosystems and populations by collecting and integrating high-resolution measurements of ocean circulation with functioning, biological diversity, genetic connectivity and socio-economic values.
- Improve the capacity to monitor, model and predict shifts in deep-water ecosystems and populations in response to future change through better understanding of the connections between physical parameters and biological characteristics to support sustainable exploitation in the North Atlantic.
- Transform new data, tools and understanding into robust ocean governance in line with an adaptive ecosystem-based maritime spatial planning (MSP) approach to achieve ecosystem preservation, sustainable exploitation and Blue Growth.†
- Scenario-test and develop science-led, cost-effective adaptive management strategies for sustainable use of living and non-living resources that stimulate Blue Growth.

The North Atlantic has a long history of deep-sea research. This heritage extends back before HMS *Challenger* to the pioneering dredging studies of Michael Sars in Norway, the voyages of HMS *Porcupine* and *Lightning* in the north-east Atlantic and of the US Coast Guard Steamers *Corwin*, *Bibb*, *Hassler* and *Blake* in the north-west Atlantic. Although the picture is far from complete, we know more about the ecology and biogeography of the North Atlantic than any other ocean basin. Thanks to trans-Atlantic monitoring through programmes like RAPID (Figure 2) and OSNAP the North Atlantic's oceanography is uniquely well understood – and a tight integration of marine physics and ecology formed the foundation of the ATLAS approach.

The ATLAS approach

ATLAS was designed so that the latest understanding of Atlantic oceanography and of the strength of the overturning circulation informed four research themes tackling ecosystem function, biodiversity and biogeography, connectivity, and economic valuation. These four ecosystem themes became the engine room of the project, powering the development of new spatial plans to manage human activities and bringing newly acquired knowledge and understanding straight to policy discussions.

This closely integrated approach was fundamental to ATLAS. It relied not only on good internal communication but on co-design and continual discussion with government agencies and multinational industries active in the deep Atlantic. ATLAS was one of the first projects to be funded following the European Union's 2015 'Blue Growth' call under the Horizon 2020 programme. This request from the EU sought ideas and plans to improve the preservation and sustainable exploitation of Atlantic marine ecosystems. It also had a mandate to implement the 2013 *Galway Statement on Atlantic Ocean Cooperation* – something our team took to heart.

ATLAS built its research plans informed not only by the vast value of the global oceans to the world's economies but the potential for certain sectors like aquaculture, marine renewable energy, tourism, biotechnology and sea-bed mineral mining to grow in the future. We grasped the opportunity to create a unified ocean-basin-scale research programme on deep-sea ecosystems and we wove social science, environmental economics and public engagement throughout the project plan.

One of our biggest challenges was how to assess deep-sea ecosystem function, biodiversity and biogeography, connectivity and economic value at the scale of the North Atlantic. We tackled this by selecting 12 Case Study areas where our focal ecosystems included cold-water coral reefs and carbonate mounds,* sponge grounds, canyons, seamounts, and chemosynthetic and hydrothermal communities; *see map overleaf*). Our Case Studies varied from areas within national jurisdiction, to areas managed under EU legislation to areas in international waters beyond national jurisdiction. Some Case Studies included heavily fished areas, sites used by the oil industry, and areas designated as Marine Protected Areas or sites that might be designated as Ecologically or Biologically Significant marine Areas (EBSAs) – a mix that gave us an exciting range of governance and policy regimes to work with.

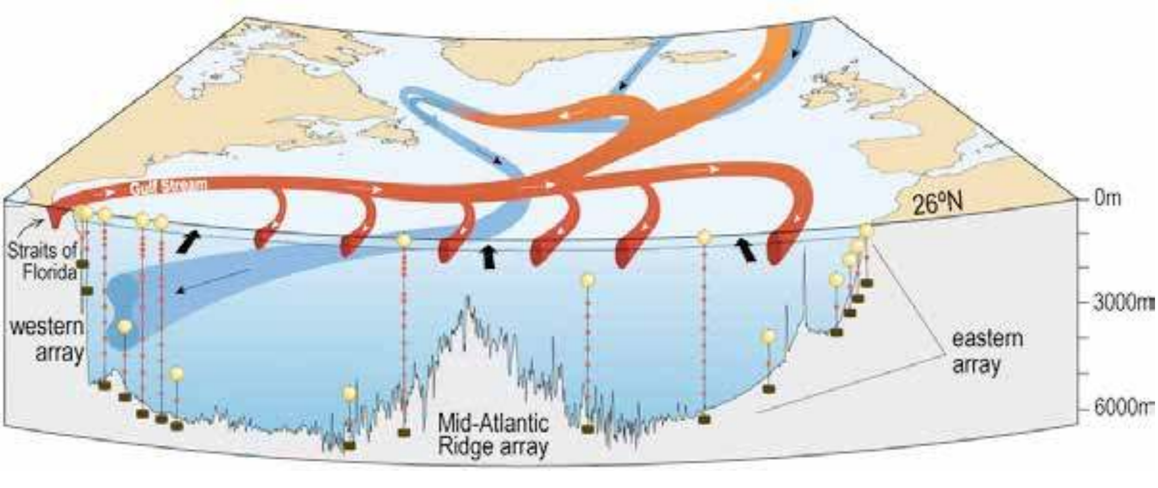
We also brought together a team of advisors including people from the offshore energy industry, the biotechnology sector, government agencies and academics expert in spatial ocean management to challenge the ATLAS consortium to revise and improve its work throughout the project. Our advisors were led by Jake Rice, Scientist Emeritus from Canada's Department of Fisheries and Oceans. Known to many as the godfather of the EBSA process, Jake became the critical friend every project needs.

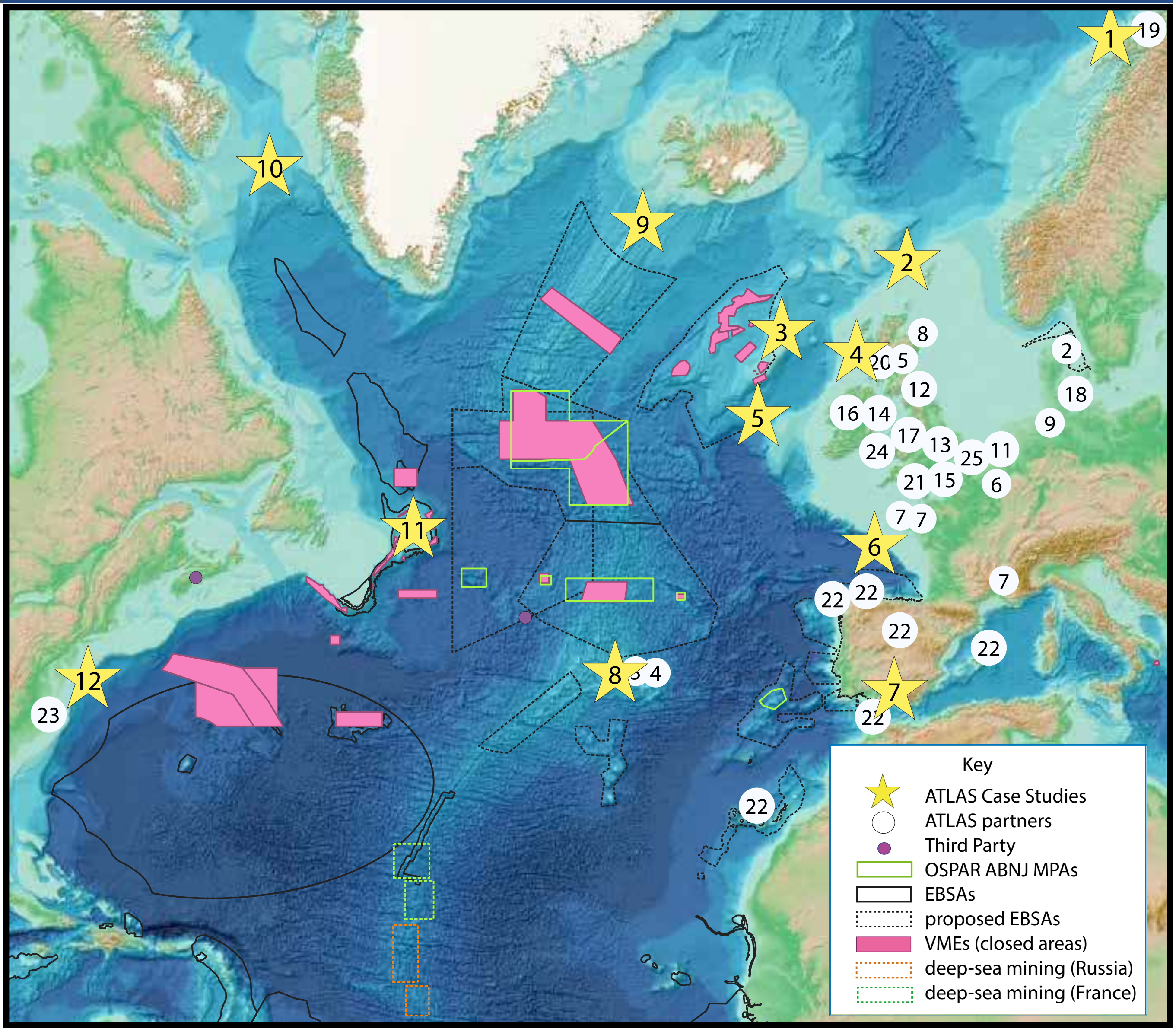
A changing Atlantic

Look at a map showing the major ocean currents of the Atlantic and your eye is immediately drawn to the dominant flows of the Gulf Stream and its extension, the North Atlantic Current, which transport vast quantities of heat and energy towards Europe. As these warm waters flow northwards they cool, become denser and sink, transporting oxygen, CO_2 and nutrients into currents that flow back into the Atlantic deep sea. This Atlantic Meridional Overturning Circulation (AMOC; Figure 2) is responsible for over 20% of global atmospheric and oceanic heat transport as it moves warm salty waters from the Equator to the subpolar Atlantic and Arctic Ocean. The intensity of the air–sea interactions created above this

*Carbonate mounds form over long periods of time from layers of debris from cold-water coral reefs and sea floor sediment; they may support diverse biological communities.

Figure 2 *Schematic representation of the Atlantic Meridional Overturning Circulation (AMOC) in the North Atlantic, consisting of (red) flow in the Gulf Stream/North Atlantic Current and the subpolar and subtropical gyres, (blue) the deep return flow concentrated along the western boundary, and (broad black arrows) near-surface wind-driven Ekman transport arising from the zonal wind stress. Also shown are the RAPID mooring arrays along ~26° N. (Modified from an original figure by Neil White and Lisa Bell, CSIRO)*





The ATLAS Consortium: partners and Third Party

1 The University of Edinburgh (UEDIN)
2 Aarhus University (AU)
3 IMAR – Instituto do Mar (IMAR–UAz)
4 Secretária Regional do Mar, Ciência e Tecnologia (DRAM)
5 British Geological Survey (BGS/NERC)
6 Gianni Consultancy (GC)
7 Institut Français de Recherche pour l'Exploitation de la Mer Ifremer)
8 Marine Scotland Science (MSS)
9 University of Bremen (UniHB)
10 Iodine (Iodine)
11 Royal Netherlands Institute for Sea Research (NIOZ)
12 Dynamic Earth (DE)
13 Oxford University (UOX)
14 University College Dublin (UCD)
15 University College London (UCL)
16 National University of Ireland, Galway (NUIG)
17 University of Liverpool (ULIV)
18 University of Southern Denmark (USD)
19 The Arctic University of Norway (UiT)
20 The Scottish Association for Marine Science (SAMS)
21 Seascape Consultants (SC)
22 Instituto Español de Oceanografía (IEO)
23 University of North Carolina, Wilmington (UNCW)
24 AquaTT UETP CLG (AquaTT)
25 Seascape Belgium (SBE)
● Fisheries and Oceans Canada (DFO)

Figure 3 ***Left*** *Map showing the positions of the ATLAS Case Studies (stars) and the locations of ATLAS partners (white circles) who are identified below the map, and sea-bed areas considered to be particularly in need of protection. (Based on the the map in the ATLAS Brochure; see http://www.eu-atlas.org)*

OSPAR ABNJ MPAs are Marine Protected Areas beyond national jurisdiction, as identified by OSPAR. ABNJ = Area Beyond National Jurisdiction; OSPAR is the body set up as a result of the 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic. *EBSA = Ecologically or Biologically Significant Area. VME = Vulnerable Marine Ecosystem.*

The 'Blue Growth Sectors' above the map are those areas the EU sees as contributing to the long-term strategy to support sustainable growth in the marine and maritime sectors as a whole. The map shows areas marked out for sea-bed mining by France and Russia.

Right *Information about Case Studies 1–4; for the other Case Studies see the following pages. The principle partners are underlined (partners' names are given in full under the map).*

warmer water, combined with the strength of the AMOC, make the subpolar North Atlantic a global hotspot of carbon storage – in fact it's estimated that around 40% of CO_2 drawn into the ocean from the atmosphere is in the northern North Atlantic.

Climate models have predicted that anthropogenic climate change could reduce AMOC strength by a quarter or more by the late 21st century. The RAPID array at 26° N recorded an AMOC decline of about 15% from 2004 to 2018. Surface circulation data collected over longer time periods have shown how quickly boundaries between warmer, more saline waters from the south and cooler, fresher subpolar waters can shift – changes driven by natural variability in atmospheric circulation have led to waters around Iceland becoming warmer by 1–2 °C, leading to declines in the capelin fishery but increasing populations of mackerel and monkfish.

Recognising the critical importance of the subpolar North Atlantic in understanding overturning variability, the international oceanographic community created the Overturning in the Subpolar North Atlantic Program (OSNAP) in 2014. In 2017 ATLAS contributed to OSNAP's new evidence, published in *Science*,* showing how processes east of Greenland have a greater impact on AMOC variability than changes in deep-water formation in the Labrador Sea. The same year, ATLAS also supplied biogeochemical sensors to OSNAP's Eastern Boundary Array moorings in the Rockall Trough to measure oxygen, pH and CO_2, and an automated sampler to collect seawater for nutrient analysis.

As well as working on present-day AMOC strength from instrumental records, ATLAS used forensic

*See https://science.sciencemag.org/content/363/6426/516.editor-summary

1

LOVE OBSERVATORY
(NORWAY)

COLLABORATORS
NIOZ, Equinor, UEDIN

FOCUS ECOSYSTEMS
Cold-water coral reefs, sponges

Due to its narrow continental shelf, this area is described as the gateway to the Barents Sea. It is an important habitat and spawning ground for key species such as North-East Atlantic cod and the reef-building cold-water coral Lophelia pertusa *which forms substantial framework reefs in this area. (Photo of* L. pertusa*: Dick van Ovelen, © Solvin Zankl, GEOMAR)*

2

FAROE–SHETLAND CHANNEL (UK)

COLLABORATORS
UEDIN, BP, OGUK, MSS

FOCUS ECOSYSTEMS
Sponge grounds

This area's sea-floor morphology leads to a variety of different benthic communities: stalked sponges occupy deep-water sandy sediments, brittlestar beds are found on gravel, sponges and soft corals colonise mixed gravel–cobble–boulder bottoms, and well developed communities inhabit coarse sediments. A distinct sponge belt occurs between 400 m and 600 m depth. OGUK = Oil & Gas UK. (Photo of giant carnivorous club sponge, Chondrocladia *sp.: © SERPENT project)*

3

ROCKALL BANK
(UK–IRELAND)

COLLABORATORS
MSS, IEO, UOX

FOCUS ECOSYSTEMS
Cold-water coral reefs, coral gardens, carbonate mounds, sponge grounds, cold seeps

Enhanced oceanographic circulation around the Rockall Bank may give rise to highly localised and specialised biological communities such as sponge aggregations, coral reefs and coral gardens. Large and productive fish stocks, some perhaps endemic, are supported. It has been proposed as an Ecologically or Biologically Significant Area (EBSA) under the Convention on Biological Diversity. *(Photo of blackbelly rosefish,* Helicolenus dactylopterus*: © J Murray Roberts)*

4

MINGULAY REEF COMPLEX
(UK)

COLLABORATORS
UEDIN, MSS

FOCUS ECOSYSTEMS
Cold-water coral reefs

This rare inshore ecosystem at 100–200 m depth has distinctive mounds formed by L. pertusa *over the last 7000 years. It is an ideal site to study the vulnerability of cold-water corals to ocean warming and acidification. Sharks use the reefs for egg-laying and resting. It is part of a Special Area of Conservation under the European Commission's* Birds and Habitats Directive. *(Photo of pandalid shrimp,* Pandalina brevirostris*: © Henry* et al. *2013; doi:10.5194/bg-10-2737-2013)*

5

PORCUPINE SEABIGHT
(IRELAND)
COLLABORATORS
NUIG, Woodside

FOCUS ECOSYSTEMS
Cold-water coral reefs, coral gardens, carbonate mounds, sponge grounds

The intensely researched cold-water corals in this area form part of the Belgica Mound province, a Special Area of Conservation. With different stakeholders involved in fishing, telecommunications, oil and gas exploration, research and conservation, this area is ideal for developing Maritime Spatial Planning approaches. (Photo of deep-sea corals: © AWI and Ifremer)

6

BAY OF BISCAY
(FRANCE)

COLLABORATOR
Ifremer

FOCUS ECOSYSTEMS
Cold-water corals on slope and in canyon settings

Recent studies have confirmed the occurrence of cold-water coral habitats in the Bay of Biscay and told us more about how these coral populations are structured in the NE Atlantic. Lophelia pertusa *has a relatively genetically homogeneous population between Iceland and the Mediterranean Sea, whereas* Madrepora oculata *populations are genetically distinct. A Natura 2000 network has been proposed for reefs in the area. (Photo of small coral reefs at 1545 m deep in the Lampaul Canyon: ©Ifremer, BobEco 2011)*

7

GULF OF CÁDIZ, STRAIT OF GIBRALTAR, ALBORÁN SEA
(SPAIN – PORTUGAL)

COLLABORATORS
IEO, Ifremer, IMAR-UAz

FOCUS ECOSYSTEMS
Cold-water coral reefs, coral gardens, sponge grounds

The degree of interconnectedness and interdependency of many deep-sea species found in both the Atlantic Ocean and the Mediterranean is unknown. Work focussed on on Atlantic–Mediterranean biodiversity and connectivity will address the fact that intensive human activity occurs in these waters. (Photo of sponges of the species Pheronema carpenteri*: © IEO-MEDWAVES/ATLAS)*

8

AZORES
(PORTUGAL)

COLLABORATORS
IMAR-UAz, IEO

FOCUS ECOSYSTEMS
Hydrothermal vents, seamounts, coral gardens, sponge grounds

The sea floor of this volcanic archipelago comprises various open-ocean deep-sea habitats, from seamounts to hydrothermal vents and abyssal plains. Prominent cold-water corals support commercially important fishes, while little is known about the extensive sponge aggregations. These Vulnerable Marine Ecosystems (VMEs) are included in the OSPAR network of Marine Protected Areas. (Photo of dense coral garden, Condor Seamount, Azores, © University of the Azores)

approaches to reconstruct how AMOC strength varied further back in time. This relied on analysing sediment cores to see how the populations of fossil plankton varied from those that would have preferred warmer waters to those associated with cooler conditions. When combined with sediment grain-size proxies for near-sea-bed current strength (larger grains mean faster currents) these cores gave compelling new evidence, published in *Nature*, that AMOC weakened significantly at the end of the Little Ice Age around 1850, and has remained weaker ever since. This weakening was most probably caused by increased freshwater input from melting glaciers and sea ice, possibly related to early anthropogenic warming.

The role of the Atlantic's circulation is central to understanding the distribution and functioning of its deep-sea ecosystems in many important respects. The overturning of surface waters transports oxygen to the deep sea so any changes could have dramatic consequences for deep-sea ecosystems. Cold-water corals, sponges and other animals that live fixed in place also rely on currents not only to bring them food particles but also to disperse their larvae. There's now good evidence showing how their dispersive potential allowed reef framework-forming cold-water corals to rapidly recolonise areas of the continental shelf scraped bare by ice sheets during glacial periods. This recolonisation was powered by the increased strength of the Atlantic's overturning circulation as the Earth's climate moved from glacial to interglacial conditions. So what would happen to Atlantic deep-sea ecosystems if the major circulation patterns of the Atlantic changed? And do we have enough biologically relevant information about Atlantic circulation to answer such questions?

ATLAS looked at these issues in several ways including by running simulations of how deep-sea species might disperse from our Case Study areas. Since so little was known about the larval biology of these species, we used a range of possible biologically realistic behaviours. Fortunately, just as ATLAS began, important discoveries on the larval biology of the cold-water coral *Lophelia pertusa* were made at the Tjärnö Marine Station in Sweden, so some of our simulations were grounded in reality. Larvae of *Lophelia pertusa* are positively buoyant and so rise upwards, allowing them to disperse for several weeks in fast-flowing surface currents – very important information for the ATLAS connectivity models. Dealing with a complex area the size of the North Atlantic required vast computing power, and simulations on the University of Edinburgh's supercomputer cluster took two weeks to run. But when the modellers working on dispersal of larvae teamed up with Parallel Works in Chicago, Google Cloud computing power reduced model run times to just an hour.

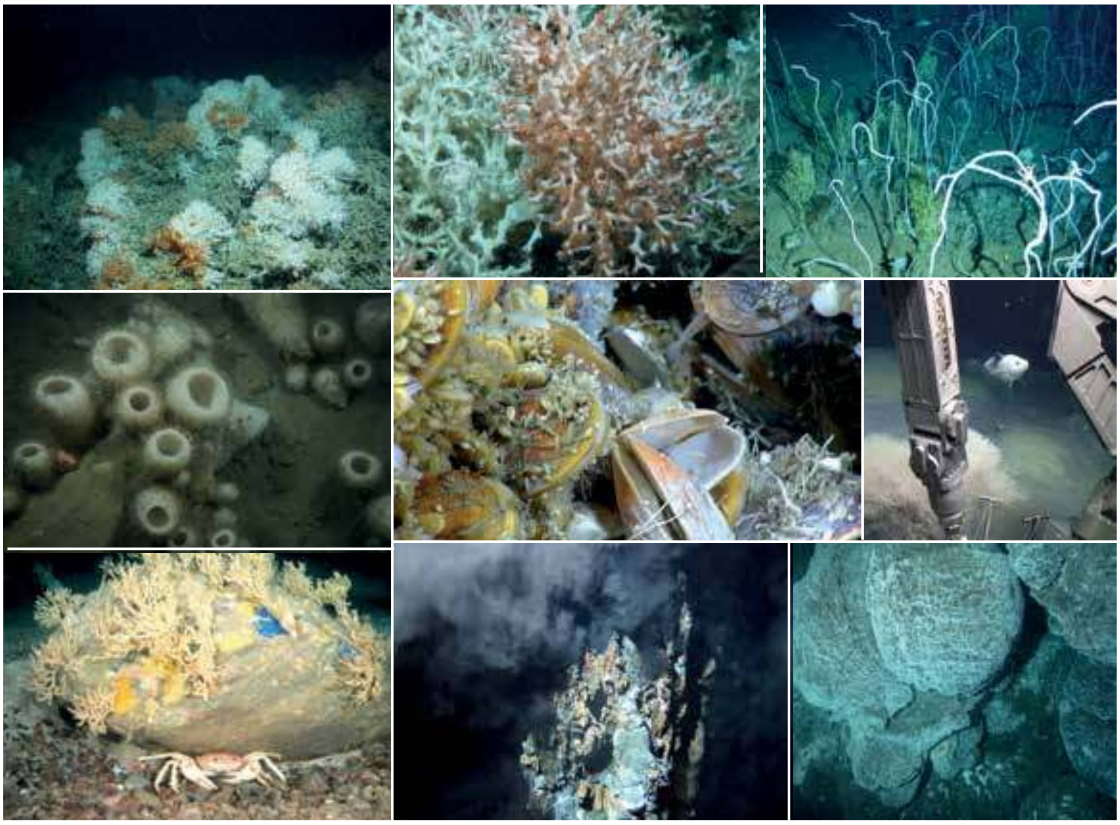


Figure 4
ATLAS studied structurally complex deep sea-bed habitats including cold-water scleractinian coral reefs, coral gardens on seamounts, sponge grounds and chemosynthetic communities.

(Photos: J. Murray Roberts, Gavin Newman (Greenpeace), Department of Fisheries & Oceans (Canada), BP, Jens Carlsson

These simulations gave us many new insights into deep-sea ecosystem connectivity. For example, we found that the connectivity of Marine Protected Areas off Scotland will be very different depending on the prevailing weather conditions with the westerly winds associated with positive North Atlantic Oscillation (NAO)* states enhancing larval supply from offshore to onshore areas.

This work has highlighted how important it is to understand the larval biology of deep-sea species. Without this basic knowledge, models will remain poor representations of reality, hugely limiting our ability to design ecologically coherent networks of spatially managed areas. And it's vital we have strong science informing decisions about these networks. Many of the species ATLAS focussed upon create habitat for other species – they are the engineers of the deep sea, with sponges building cities of silica and corals gradually building deep-sea reef and carbonate mound structures lasting many millennia.

Vulnerable ecosystems

These structural habitats are inherently vulnerable to being damaged by bottom fishing and nearly 20 years ago concerns related to this damage had escalated as far as the United Nations General Assembly. Through a series of subsequent resolutions the UN called upon states to protect such vulnerable marine ecosystems (VMEs) from destructive fishing practices where they are known to occur *or* are *likely* to occur, and the UN's Food and Agriculture Organisation developed five overarching VME indicator criteria related to the ecosystems' rarity, functionality, fragility, life-history and structural complexity. ATLAS compiled a new database of species that met these criteria. This VME indicator database pulled together 455 000 records spanning the North Atlantic, including over 38 000 new records from ATLAS partners. ATLAS then worked with the International Council for the Exploration of the Sea's Working Group on Deep-water Ecology to assign areas a VME index score depending on the species present and their abundance. The VME index has been used by ICES since 2018 in their advice to regional fishery management organisations and the European Union.

As well as improving our understanding of where vulnerable marine ecosystems occur, ATLAS examined how these places work (Figure 4). One of the most amazing contrasts in the natural world is the difference between the deep sea bed in general and what you see as you approach a cold-water coral reef. Away from the reef the sea bed is flat and relatively featureless. Animals here live burrowed in the sea bed or clinging to isolated pebbles and boulders. But as you move to the fringes of the reef itself, the diversity of life explodes in front of your eyes. Every nook and cranny of dead coral skeletons is colonised by a bewildering array of sponges, byrozoans, soft corals, hydroids and other invertebrates adapted to snag food from passing currents. We've known for a while that the diversity of life on such coral habitats was roughly three times greater than that from the surrounding sea bed, but we understood very little about how these species interacted or how deep reef and sponge ground ecosystems functioned.

*A positive NAO phase represents a stronger than usual difference in pressure between the subtropical high (also known as the Azores High) and the subpolar low (Iceland Low), resulting in stronger westerlies over the northern Atlantic.

9 **REYKJANES RIDGE**
(ICELAND)

COLLABORATOR
UCD

FOCUS ECOSYSTEMS
Hydrothermal vents, cold-water coral reefs, coral gardens, sponge grounds

Our understanding of the effects of ridges on the composition and distribution of pelagic and benthic fauna is limited. Ridge communities may be endemic to that area and may also influence the processes affecting the slope and shelf biota. Coral and sponge gardens are associated with V-shaped ridges in the Mid-Atlantic Ocean and can be found on both sides of the Reykjanes Ridge. (Photo of coral garden: © MARUM, Center for Marine Environmental Sciences, University of Bremen)

10 **DAVIS STRAIT**
(CANADA AND GREENLAND),
LABRADOR SEA

COLLABORATOR
DFO

FOCUS ECOSYSTEMS
Cold-water coral reefs reefs, coral gardens, sponge grounds

The Davis Strait is known for its complex hydrography. A ridge along the Labrador Sea slopes to 2500 m, supporting corals and sponges, including the only known L. pertusa *reef in Greenlandic waters. These waters support high phytoplankton biomass and copepod grazers, a valuable food source in the pelagic and the benthic environment. (Photo of diverse assemblage of corals, sponges and other benthic fauna in Davis Strait off Greenland: © DFO)*

11 **FLEMISH CAP**
(CANADA)

COLLABORATORS
IEO, DFO, UOX, NAFO[2]

FOCUS ECOSYSTEMS
Coral gardens, sponge grounds

Flemish Cap is an offshore Bank located in an Area Beyond National Jurisdiction within the North-west Atlantic Fisheries Organisation (NAFO) regulatory area. The main ecosystems are sponge grounds and cold-water corals, and include important international fishing grounds. (Photo of deep-sea starfish: © NEREIDA Project)

12 **MID-ATLANTIC CANYONS**

COLLABORATORS
UNCW, TU, NOAA

FOCUS ECOSYSTEMS
Cold-water coral reefs on slope and in canyon settings

The oceanography and geology of the submarine Baltimore and Norfolk Canyons greatly influence the benthic community. Methane seeps support chemosynthetic communities and many diverse organisms. Vulnerable habitats in mid-Atlantic canyons and surroundings have been given protected area status. TU = Temple University, Pennsylvania; NOAA = National Oceanic & Atmospheric Administration. (Photo of bubblegum coral, Paragorgia arborea*: © Steve Ross)*

Cities beneath the sea

In its first year, ATLAS used a modelling approach to see how the presence of the huge coral carbonate mounds found on the Rockall Bank (Case Study 3) might alter the transfer of food-rich surface waters to the sea bed. These models strongly suggested that the coral mounds interact with tidal currents creating downwelling events capable of bringing food to depths of 600 m – where today we find abundant live reef frameworks in places like the Logachev Mounds. As well as helping to confirm that cold-water corals are fed from surface productivity via a topographically enhanced carbon pump, this work also brought home just how significant these corals are as ecosystem engineers – the mounds are now so large that food supply is focussed to them to the detriment of surrounding areas.

This pattern was confirmed by measuring overall biological activity in these habitats. To do this we needed to measure community respiration rates by recording how fast a defined area of reef respired. For years, making this measurement proved problematic – as well as difficulties caused by their remoteness, it's impossible to seal a portion of a cold-water coral reef in an incubation chamber and measure its respiration. ATLAS solved this problem by using the aquatic eddy covariance approach to estimate oxygen uptake in structurally complex coral and sponge habitats. We discovered that these habitats indeed consume more oxygen than areas at the same depth without coral or sponge habitat. For example, the cold-water coral reef areas in the Logachev Mounds have respiration rates roughly five times those of sea-bed environments from comparable depths, with even greater enhanced turnover of carbon of up to 10-fold in the coral garden habitats of Condor Seamount in the Azores.

These findings were a wonderful reinforcement of the existing evidence for the ecological importance of these structurally complex biogenic habitats. And as well as identifying deep coral and sponge habitats as important centres of carbon turnover, ATLAS reported several new lines of evidence showing how closely they recycle nutrients, all helping to explain the paradox of how these diverse communities develop and flourish in relatively food-limited deep-sea environments. These are truly the cities of the deep-sea – packed, productive places that need to retain and recycle precious nutrients.

An uncertain future

But just as we start to appreciate the true significance of these habitats, their future looks increasingly uncertain. The ocean has already absorbed over 90% of global heating and 25% of anthropogenic CO_2 emissions. The framework-forming scleractinian (i.e. hard) cold-water corals which build the large deep-sea reefs and carbonate mounds secrete their skeletons from aragonite, one of the more soluble mineral forms of calcium carbonate. This makes them vulnerable to ocean acidification. Over the last decade several studies have examined this and found that these corals have rather remarkable ways of dealing with progressively lower pH conditions. Where coral tissue covers the skeleton they continue to grow. But ATLAS research has revealed an Achilles heel. Places like the Logachev Mounds and other cold-water coral habitats grow in waters close to the depth at which aragonite naturally dissolves in seawater – a depth known as the aragonite saturation horizon. As more CO_2 dissolves in the global ocean this saturation horizon is getting shallower and shallower, to the point that most Atlantic cold-water coral habitats will be surrounded by seawater corrosive to any exposed aragonite skeletons by the late 21st century.

ATLAS used material science approaches to compare *Lophelia pertusa* coral skeletons from long-term experimental exposures to high CO_2 conditions with skeletons of *L. pertusa* from the North Pacific that grow in waters naturally richer in CO_2. The results were fascinating. Coral skeletons from both the long-term exposure study and the Pacific were far more porous than coral skeletons from the North Atlantic, and showed all the symptoms of osteoporosis. This 'coralporosis' goes a long way to explaining why the scleractinian coral habitats of the Pacific fail to develop into the vast reef frameworks and coral carbonate mounds we see in the Atlantic. It's also a worrying glimpse into the likely future of the Atlantic's deep coral reefs.

Looking at these issues from an ecological perspective, ATLAS used environmental niche modelling approaches to assess habitat suitability for cold-water scleractinians, octocorals (soft corals), and a suite of commercially important fish. We compared the distributions of particular marine environmental conditions for 1951–2000 with those predicted under the International Panel for Climate Change's RCP 8.5 scenario* for 2081–2100. These models, published in *Global Change Biology*, projected a decline of between 28% and 100% in habitat suitability for cold-water corals and a marked northward shift for the fish species.

Science to policy

These stark findings once again emphasise the overriding importance of reducing CO_2 emissions as the single biggest priority for humanity in the 21st century. But while the world grapples with this challenge, we must do all we can to understand how best to manage human activities to limit additional pressures on ecosystems. In the ocean this means understanding how well any management measures will work in years to come.

*The high-emissions RCP 8.5 scenario (often referred to as 'Business as Usual') would result in a temperature rise of ~ 4.3°C by 2100, relative to pre-industrial temperatures. RCP = Representative Concentration Pathway and RCP 8.5 refers to the concentration of carbon that delivers global warming at an average of 8.5 W m^{-2} across the planet.

As things stand there's a lot to be done. Habitat suitability modelling can help to identify potential climate refugia, where threatened species might survive, and, as summarised above, we need to bring real understanding of ecological connectivity into the designs of networks of Marine Protected Areas. We also need to understand how well areas recognised as being ecologically significant may fare in a future ocean. ATLAS examined all the 'area-based management tools' (ABMTs), including Marine Protected Areas, that have been designated in areas beyond national jurisdiction in the North Atlantic (*see map*) to see how they would be likely to meet their management objectives over the next 20–50 years. Of the 30 ABMTs examined, all but one were found highly likely to be negatively impacted by changing environmental conditions.

At all stages throughout the project, the ATLAS consortium worked hard to bring findings like these directly into relevant policy processes. ATLAS overlapped with the first intergovernmental conference negotiations at the United Nations (including the preparatory meetings) to formulate a new internationally legally binding instrument for the conservation and sustainable use of marine biodiversity beyond national jurisdiction. *The Marine Biodiversity of Areas Beyond National Jurisdiction Treaty*, known for short as the BBNJ treaty, is the single biggest development for a generation in how humanity might manage the largest biome on the planet – the deep and open ocean. The BBNJ negotiations focus around four central elements of a package agreed by the UN General Assembly in 2011: (1) marine genetic resources, including questions on the sharing of benefits; (2) measures such as area-based management tools, including Marine Protected Areas; (3) environmental impact assessments; and (4) capacity-building and the transfer of marine technology.

Clearly marine science has a major role to play in all four elements of the BBNJ package. But how important is science to those negotiating the treaty? ATLAS used semi-structured interviews at the second intergovernmental conference of the BBNJ negotiation to explore the opinions of delegates and other stakeholders on how ideas about science-based management could be used in the BBNJ treaty. We found areas of consensus and conflict in the perceptions of those interviewed. For example, viewpoints converged around the benefits of integrative, participatory management and the use of precautionary approaches. People found science to be trustworthy and credible. In contrast we found divergent opinions regarding the definition, function and authority of science within current and future BBNJ governance processes. For instance, some people felt that science had been well represented during the negotiations while others felt science hadn't had sufficient prominence and that it wasn't clear how scientific evidence could be used during the BBNJ negotiations and any subsequent agreement.

Through our interviews, we found that there was general agreement that maritime spatial planning could be one route through which strong science-led decisions on how we use ocean spaces could be implemented. This was great news for ATLAS as our final work included testing maritime spatial planning approaches in some of our case study areas, including those extending into areas beyond national jurisdiction. ATLAS ran these test spatial plans in the Rockall Bank, Porcupine Seabight and Flemish Cap (Case Studies 3, 5 and 12). As well as collating all the necessary spatial information on ecosystem distribution, human activities and institutional arrangements from which to plan, ATLAS advanced the concept of maritime spatial planning in the deep sea, notably in sites including areas beyond national jurisdiction such as Flemish Cap.

As a research project, ATLAS clearly had no authority to enact spatial planning measures but, as well as running these test exercises, we used systematic conservation planning approaches to identify priority management areas at both North Atlantic scale and local scale, targeting specific ecosystems. For example, ATLAS worked closely with the Regional Government of the Azores to produce detailed systematic conservation planning scenarios for the deep sea around the Azores and to examine the potential impacts of fisheries closures over seamounts.

*Submarine mud volcanoes are large structures resulting from the eruption of mud due to escape of hydrothermal fluids and/or methane from deep within the sea-bed sediments.

But while such conservation planning approaches hold huge promise they can only ever be as good as the information that feeds into them – and of course the deep sea remains the least well studied place on Earth. During the course of its work ATLAS discovered new habitats (including a hydrothermal vent field – the Luso Field – on the Gigante Seamount west of the Azores), reported 35 new records of species in areas where they were previously unknown, and described three molluscs, four bryozoans and five zoantharians that were new to science. We're particularly proud of the bivalve mollusc *Myonera atlasiana*, a member of the family Cuspidariidae, named in honour of ATLAS (Figure 5, top). This species was discovered during the ATLAS MEDWAVES expedition that sailed from southern Spain to the Azores in 2017 to study the influence of Mediterranean Outflow Water on the biodiversity and biogeography of mud volcanoes* and seamounts.

Figure 5 *Two of the twelve new species found during ATLAS.*
Upper *The bivalve* Myonera atlasiana.
Lower *The zoantharian* Epizoanthus martinsae, *which lives on dead black coral skeletons.*
(Photos Upper: Utrilla et al. *(2020)* Scientia Marina ***84****, 273–95. http://scimar.icm.csic.es/scimar/index.php/secId/6/IdArt/4593/ Lower: Carreiro-Silva et al. (2017)* Frontiers in Marine Science **4**, *88 doi: 10.3389/fmars.2017.00088)*

Given the relatively sparse understanding of the deep sea it's particularly important that new discoveries can be rapidly fed into to relevant policy processes. ATLAS fed its findings into many such processes, including determining the measures to be employed in conservation areas for deep-water sponges in the Faroe–Shetland Channel, Gulf of Cadiz and Davis Strait (Case Studies 2, 7 and 10). In several instances we went from discovery at sea through scientific analysis and straight to policy processes. For example, when ATLAS reviewed sea-bed surveys from Tropic Seamount off the Canary Islands we identified diverse communities of coral gardens, fields of crinoids (featherstars) and unusual sponge grounds dominated by the stalked glass sponge *Poliopogon amadou*. We included the Tropic Seamount among our submissions to the UN *Convention on Biological Diversity*'s North-East Atlantic EBSA workshop in late 2019. The new EBSAs proposed by this workshop will be considered at the 15th CBD Conference of the Parties in October 2021. ATLAS contributed to the description of five other potential new EBSAs in the North Atlantic – the Gulf of Cádiz, North Azores Plateau, Charlie Gibbs Fracture Zone, the Southern Reykjanes Ridge, and nearer the UK, an area encompassing the Hatton Bank and Basin, and the Rockall Bank and Trough (see map and Case Studies 3, 7, 8 and 9).

The human dimension

But it will always remain the case that even if the very best science is taken straight to policy-makers we won't see action to better manage human activities in the deep sea unless there's societal engagement driving political will. I'm particularly proud of the way ATLAS worked with children and members of the public to share the wonder of the deep sea and its importance. Our partners at Dynamic Earth in Edinburgh created a fantastic range of materials from high tech remotely operated vehicle simulators and immersive 3D videos from ATLAS expeditions, through to low tech cold-water coral floor mats that parents and teachers can explore with their children. In 2020, as the Covid-19 pandemic spread and lockdowns closed schools, we were able to share these materials with home schoolers across the world (Figure 6). I'm also delighted to say that ATLAS work will live on through Dynamic Earth's new permanent 'Discovering the Deep' exhibition that traces deep ocean research from HMS *Challenger* to the present day.

As we witness the inexorable rise of atmospheric CO_2 concentrations, the rapid loss of polar ice, thawing tundra, increased wildfires and extreme weather, all happening at the same time as habitats are lost and species extinction rates spiral, it can be hard to find reasons for optimism. But there are reasons to be hopeful. As part of our socio-economic work we asked completely independently selected cross-sections of the public in Norway and Scotland what they knew about the deep sea off their coasts, and what value they placed on deep-sea ecosystems. We found that people in Norway were far better informed about deep-sea ecosystems than those in Scotland: for example, 60% of Norwegians had heard of cold-water coral reefs in their marine environment but only 16% of Scots. But despite this we were genuinely surprised to find that people still placed considerable value on leaving the deep sea in a good state for future generations, over and above short-term economic gains.

While the published papers, policy engagements and news reports from an ecological project are all important, the real legacy is through the people who move forward in their careers with the expertise and international networks to tackle the challenges of climate change, habitat loss and species extinction. As we look forward to the pivotal negotiations at the Climate COP26 in Glasgow, and celebrate the launch of the UN's Decade of Ocean Science for Sustainable Development, it's vital we remember that, and do all we can to sustain and build opportunities for people across all societies to get involved.

iAtlantic

Although ATLAS has now finished, we have reinvented our work and are applying a similar approach through the new 'iAtlantic' project (2019–23). Again funded through the EU's Horizon 2020 programme, iAtlantic is completing an integrated assessment of deep and open ocean ecosystems in space and time. This work takes place across the entire Atlantic, with a team including

Figure 6 *Deep Atlantic ecosystem educational resources were developed early and used throughout the ATLAS project. They remain in use at Dynamic Earth in Edinburgh and are all available on the project's website.*
(Photo: Dynamic Earth)

35 partners from Argentina, Brazil, South Africa, Canada and the USA joining eleven European nations. In addition to its research objectives iAtlantic is dedicating a lot of effort to building human and technical capacities on both sides of the Atlantic. Please visit the iAtlantic project's website (https://www.iatlantic.eu/) or contact the Project Office for more information.

Further reading

ATLAS website: http://www.eu-atlas.org/

ATLAS Results Highlights Report: https://zenodo.org/record/3925096#.xwdbfchkhpy

Policy implications of the ATLAS project: https://zenodo.org/record/4063323#.YFHQkWT7RGw

Henry, L.-A., O. Covadonga, G. Kazanidis, L. Durán Suja, U. Witte and J. Murray Roberts (2016) Coral cities of the deep: Species–habitat associations on the Mingulay Reef Complex. *Ocean Challenge* **21**(2), 17–19.

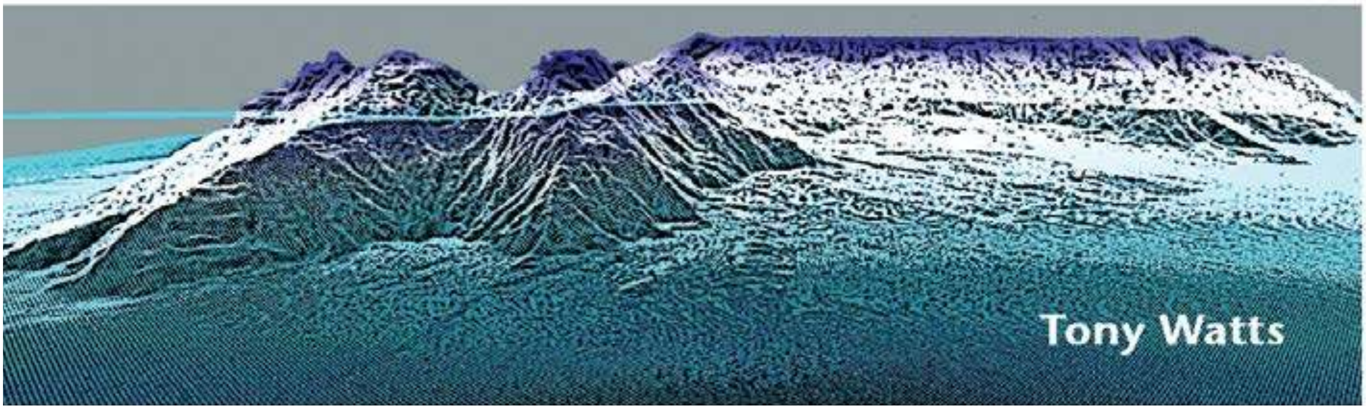
Smeed, D. (2017) The RAPID challenge: Observational oceanographers challenge their modelling colleagues. *Ocean Challenge* **22**(1), 16–18.

J. Murray Roberts is the ATLAS and iAtlantic Coordinator, and Head of the Changing Oceans Research Group, School of GeoSciences, University of Edinburgh. Murray.Roberts@ed.ac.uk

The ATLAS team taking a break from the 2018 General Assembly meeting

(Photo: Laurence de Clippele)

Science, seamounts and society



It has been more than one hundred years since the publication of Sir John Murray's 'bathymetrical chart' of the Atlantic Ocean (Figure 1). Compiled from lead-line surveys during expeditions such as those of *Challenger* and *Michael Sars*, the coloured contour map revealed for the first time the nature of Earth's surface beneath the oceans and the outline of the continental margins, the Mid-Atlantic Ridge and the intervening abyssal plains (labelled 'Deeps'). Seafloor profiles showed, however, that apart from the prominence of a few scattered islands such as the Azores, the seafloor of the oceans was smooth and featureless, a view that persisted for about the next four decades. The development of new technologies during World War II dramatically altered this view.

Arguably the most important new piece of equipment was the Precision Depth Recorder (PDR), which used a hull-mounted acoustic transducer/receiver to continuously measure two-way reflection time and hence, knowing the velocity of sound in seawater, depth. For example, the

Figure 1 *Sir John Murray and part of his 'bathymetrical chart'. Published in 1912, it was constructed from approximately 3200 lead-line soundings made with pre-stressed hemp rope and lead weights on British and other survey ships. 'Deeps' (in red type) correspond to seafloor depths >3000 fathoms (5486 m). The chart was produced by John G. Bartholomew, cartographer to the King.*

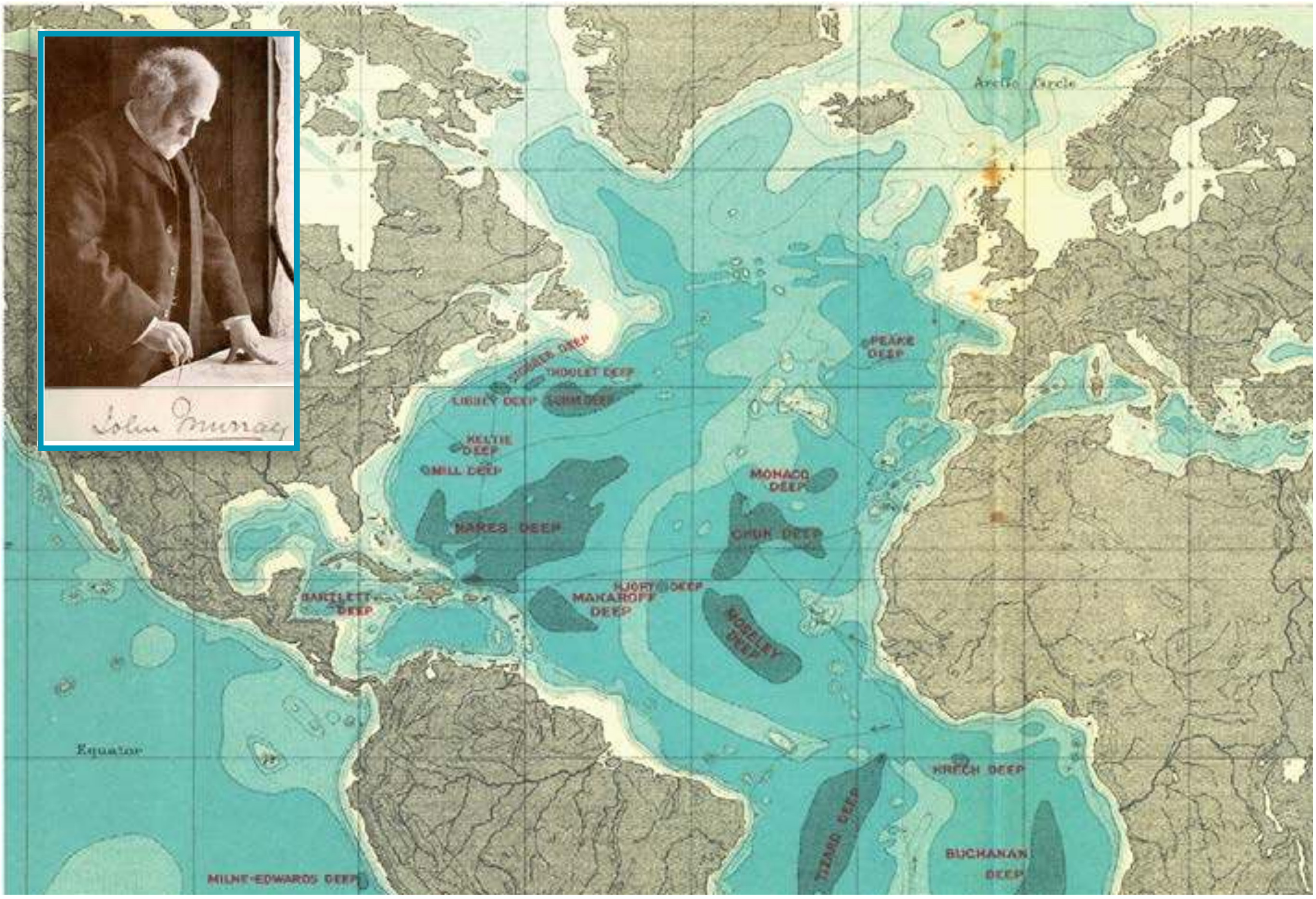
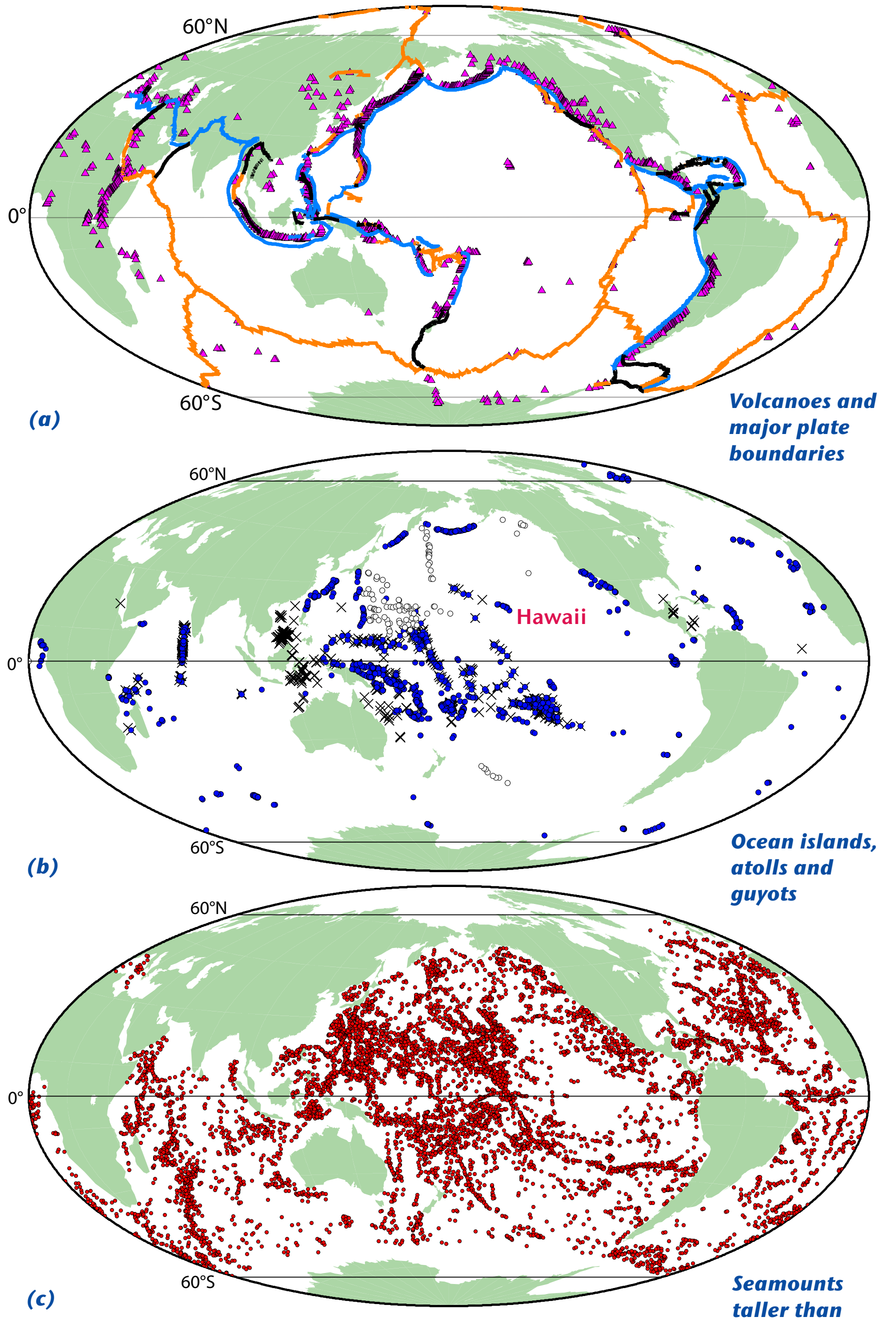


__Figure 2__ Global distribution of volcanoes, ocean islands and seamounts. __(a)__ Volcanoes less than ~ 12000 years old, according to the Smithsonian Global Volcanism Program (triangles) compared with major plate boundaries (blue, subduction zones; orange, mid-ocean ridges; black, transform/strike-slip faults). __(b)__ Ocean islands (blue circles), atolls (×), guyots (open circles). Note: Distribution is incomplete and probably more extensive than shown. __(c)__ Seamounts (red circles) with height above surrounding seafloor that is the same or greater than the height above sea-level of Ben Nevis, the mountain with the highest prominence in the UK (1344 m).



Volcanoes and major plate boundaries

Ocean islands, atolls and guyots

Seamounts taller than Ben Nevis

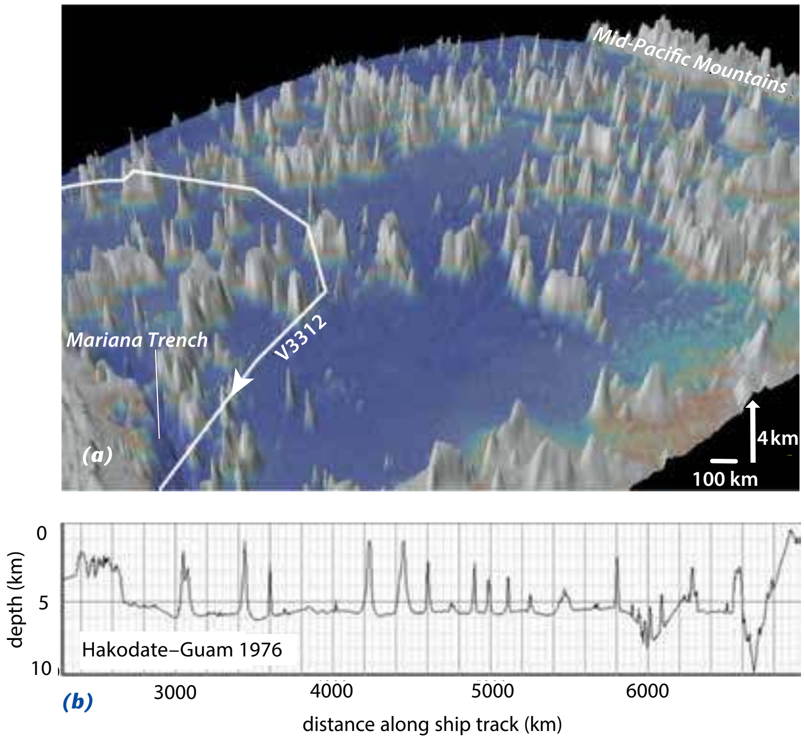
Princeton academic, Harry Hess, who had been given command of the troop-carrying ship USS *Cape Johnston*, used a PDR in the Pacific Ocean to chart 160 flat-topped bathymetric features that rose up to 4.5 km above the seafloor. He named them guyots, in honour of the Swiss-born geographer and Princeton Professor, Arnold H. Guyot. Hess considered guyots ancient volcanic oceanic islands that had been trimmed by the waves prior to subsiding below sea level.

After more than three centuries of discovering ocean islands, we know there are 1770 (all but one discovered by 1840), 47 of which are active volcanoes. Approximately 439 are atolls, which Darwin hypothesised in 1842 are coral reefs that had grown upwards on the summit of volcanoes as they subsided below sea level. While we now generally attribute the subsidence of guyots and atolls to sinking of an oceanic plate as it ages and cools, their spatial distribution still raises questions about the origin of volcanic activity on Earth.

The Smithsonian Global Volcano Program, for example, lists 1535 volcanoes that have been active during the past 12 000 years, the large majority of which are associated with compressional plate boundaries, where one plate is underthrust by another (e.g. the circum-Pacific subduction zones), and extensional plate boundaries, where the plates are moving apart (e.g. the rift valley in East Africa). Yet, the large majority of guyots and atolls are located in the interior of plates, far from plate boundaries (Figure 2(b)).

__Figure 3__ Rocks dredged from the submarine flanks of intra-plate oceanic islands and seamounts in the Atlantic and Pacific oceans. They comprise mainly basaltic rocks that are geochemically distinct from basalts sampled at extensional (e.g. Mid-Atlantic Ridge) and compressional (e.g. island arc) plate boundaries. The bottom row shows examples of the reaction of seawater with iron and magnesium in the basalts, the products of which provide an important source of energy for microbial life in the ocean.

Rock samples collected from seamounts are typically volcanic in origin



Many of the tallest seamounts are found in the western Pacific

Figure 4 *Bathymetry of the western Pacific Ocean between the Mariana Trench and the Mid-Pacific Mountains.* ***(a)*** *Perspective view (looking towards the north-east) based on a gridded dataset from GeoMapApp. Vertical exaggeration × 25. Scale is approximate. The white line illustrates the track of RV* Vema *during cruise V3312.* ***(b)*** *PDR bathymetry profile along the* Vema *ship track.*

Swath mapping has revealed features resulting from debris being carried down the slopes of ocean volcanoes

Figure 5 *Perspective views of the bathymetry and topography of the Hawaiian Islands.* ***(a)*** *South-east flank of Hawaii showing Loihi, the newest submarine volcano added to the island chain.* ***(b)*** *North flank of Maui, Molokai and Oahu showing incised canyons, large-scale slope failures and debris flow deposits with large blocks that overfill the 'moat' flanking the islands. Vertical exaggeration ×4. Scales are approximate.*

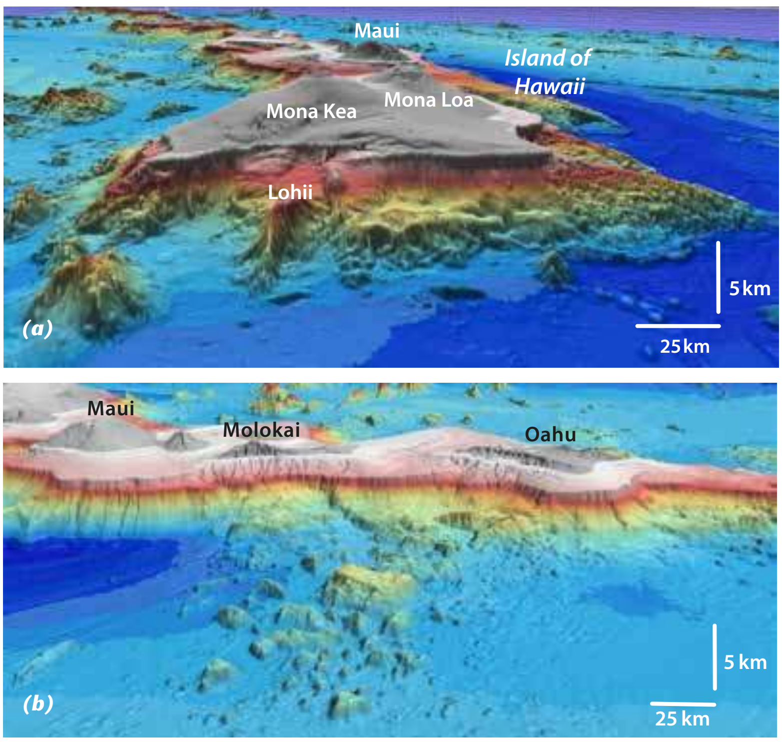


Figure 2(c) shows that when 'seamounts' (most of which are also volcanic in origin; Figure 3) are added into the mix, the spatial extent of known magmatic activity on Earth changes even more dramatically. Indeed, the distribution raises important scientific questions about Earth's 'magmatic pulse' and the origin of intra-plate volcanism, as well as societal questions about the role that volcanoes on the ocean floor play in navigation, in fisheries and as geohazards.

What is a seamount?

Bill Menard in his 1964 book entitled *Marine Geology of the Pacific* defined a seamount as: 'a more or less isolated elevation of the seafloor with a circular or elliptical plan, at least 1 km of relief, comparatively steep slopes and relatively small summit area'. Menard estimated there were about 2000 seamounts greater than 1 km high in the ocean basins. Satellite-derived gravity and ship PDR data, however, show there are >14 500 seamounts higher than 1 km. A large concentration of these seamounts is found in the western Pacific Ocean (Figures 2 and 4). Some are growing up on the seafloor and may become islands, while others that were once islands are now sinking.

An important technological development in the late 1980s was the introduction of multibeam swath bathymetry systems. These had an advantage over PDRs in that rather than determining water depth immediately beneath a ship's hull, they insonified a broad swath of the seafloor, up to about 2.5 times the water depth. Such systems have revealed the morphology of seamounts, guyots, atolls and ocean islands in unprecedented detail, for example those along the Hawaiian–Emperor chain* in the central Pacific Ocean (Figure 5). Other islands to have had their submarine slopes swath mapped include the Cape Verde and Canary Islands in the Atlantic Ocean, and La Réunion and Kerguelen in the Indian Ocean. However, the number of swath surveys carried out to date is limited and only about 12% of the seafloor has been swath mapped.

Dynamics

While we still do not know how many seamounts are growing and sinking, field observations suggest they are important if we are to fully understand Earth history and environmental change. Data from oceanic rock samples and drill cores suggest that there have been bursts of volcanism, for example the 90 to 100-million-year 'event' that created many of the seamounts and oceanic plateaus in the central Pacific Ocean (e.g. Shatsky Rise, Hess Rise and the Mid-Pacific Mountains (Figure 4)). There may have been other such volcanic events in the Pacific Ocean, peaking in the Late Jurassic (163–145 Ma) and the Eocene (56–33.9 Ma). Once formed, seamounts are sus-

*The Hawaiian–Emperor chain can be seen in Figure 2(b) extending from the intersection of the Kuril and Aleutian trenches to Hawaii.

ceptible to modification by large-scale collapse, as manifest by scalloped coastlines, submarine debris flows and the emplacement of large blocks on the seafloor (Figure 5(b)). Such processes operate intermittently over time scales on the order of hundreds of thousands of years as seen, for example, on the north flank of Tenerife, in the Icod and Orotava submarine landslides (which occurred about 150 and 450 thousand years ago respectively).

In historical times, seamounts show surprising spatial variability on scales that greatly exceed their terrestrial counterparts. The number of historically active volcanoes in the Smithsonian Global Volcano Program dataset is 538, about 35% of the total number of volcanoes younger than ~12 000 years. If a similar percentage of seamounts higher than 1 km are active then we might expect upwards of about 5100 historically active volcanoes on the seafloor. We know, however, only a few (~12) from floating pumice and discoloured water, Remotely Operated Vehicle (ROV) observations, and repeat swath bathymetry surveys.

One of the best surveyed active submarine volcanoes is Monowai in the Tonga–Kermadec arc, south-west Pacific Ocean. The volcanic centre (Figure 6) was swath surveyed in 1998, 2004, 2007, 2011 and 2013. Large changes in seafloor depth, up to several tens of metres, were measured between the surveys. During the 32-day-long cruise of MV *Sonne* in 2011, the centre was surveyed twice. Seismic data recorded on Rarotonga (Cook Islands) revealed that Monowai erupted during 17–22 May 2011, and pre- and post-eruption surveys with swath bathymetry showed that after the eruption the seafloor depth on the cone summit shallowed by up to 70 m in one area and deepened by up to 18 m in another.

The seismic events recorded on Rarotonga were generated by the displacement of seawater that accompanied the rapid emplacement of volcanic rock onto the seafloor at Monowai. The resulting hydroacoustic waves became trapped in the SOund Fixing And Ranging (SOFAR) channel, a layer at the bottom of the thermocline where sound velocity is at a minimum, along which whale calls are transmitted. When these waves, known as *T*-waves, impact an ocean island they convert to seismic body waves and, depending on background noise levels, may be recorded at a seismic station on an ocean island.

Other recorders of *T*-waves are the hydrophone stations maintained by the Consortium for Test-Ban Treaty Organization (CTBTO) throughout the ocean basins. Hydrophones are deployed on tethers in groups of three in the SOFAR channel, so a *T*-wave generated by an active submarine volcano will, if it is not obstructed, have a unique back azimuth when it arrives at a station. Explosive volcanic activity at Monowai, for example, has a back azimuth of 243.8° at a station south of Juan Fernandez Island in the eastern Pacific Ocean (Figure 7).

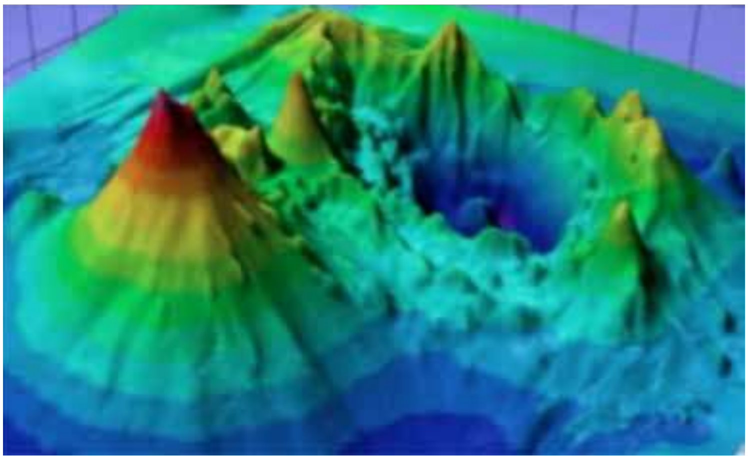
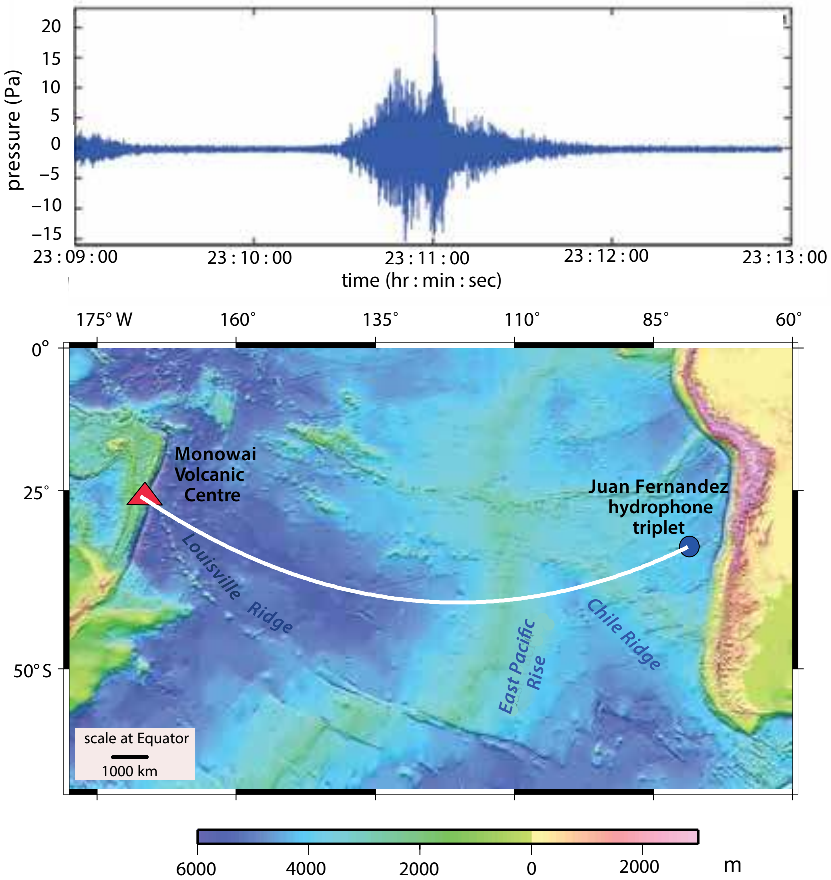


Figure 6 *Perspective view (looking towards the north-west) of the Monowai volcanic centre in the Tonga–Kermadec island arc, south-west Pacific Ocean. The centre comprises a ~1000 m high, 10 to 12 km wide strato-volcanic cone (i.e. one built up of layers of lava and other volcanic products) with parasitic cones and a flanking ~500 m deep and 7–10 km wide caldera with ring faults and a central mound.*

Monowai is one of the best surveyed active submarine volcanoes

Figure 7 Top *Typical* T-wave *generated by volcanic activity at Monowai and recorded at a hydrophone triplet maintained by the CTBTO south of Juan Fernandez Island, eastern Pacific Ocean.*
Bottom T-waves *recorded at Juan Fernandez have a back azimuth unique to Monowai (243.8°) and provide a means to continually monitor the submarine volcanic centre. Note* T-waves *generated at the volcano were able to transmit across the South Pacific Ocean, despite possible bathymetric obstructions on the Louisville Ridge, East Pacific Rise and Chile Ridge. (Based on Metz* et al. *(2018); see Further Reading)*

T-wave signals travelling in the SOFAR channel reveal locations of volcanic activity at the seafloor



A recent study of these data by Dirk Metz at Oxford University reveals that Monowai has erupted some 82 times over a 3.5 year period, making it arguably the most active volcano on Earth.

Origins

Away from island arcs, many seamounts form distinct lines that progressively increase in age away from an active volcano and can be explained by absolute motion of a tectonic plate over a fixed mantle hotspot. The 7000 km long Hawaiian–Emperor chain in the central Pacific Ocean (Figure 2(b)) is arguably the best known example of such a hotspot track. Seamounts increase in age from ~20 ka at the young end of the chain, through ~50 Ma at the Hawaiian–Emperor 'bend', to ~80 Ma at the old end of the chain. The young end comprises ocean islands which are superimposed on a broad topographic swell ~1.5 km in height, which gravity and seismic data suggest is supported by a deep mantle plume, while the old end is characterised by guyots and an absence of a swell.

A fixed hotspot origin for the Hawaiian–Emperor chain is supported by palaeomagnetic data that show that up to the 'bend', volcanism occurred at or near the present-day latitude of the Hawaiian hotspot. But the Emperor Seamounts (which are mostly guyots; Figure 2(b)), beyond the 'bend', formed at a latitude up to 15° north of the current location of the hotspot beneath Hawaii. John Tarduno at the University of Rochester and colleagues have interpreted this as evidence that during 50 to 80 Ma, the Hawaiian hotspot was not fixed with respect to the deep mantle and had migrated south while the plate moved north.

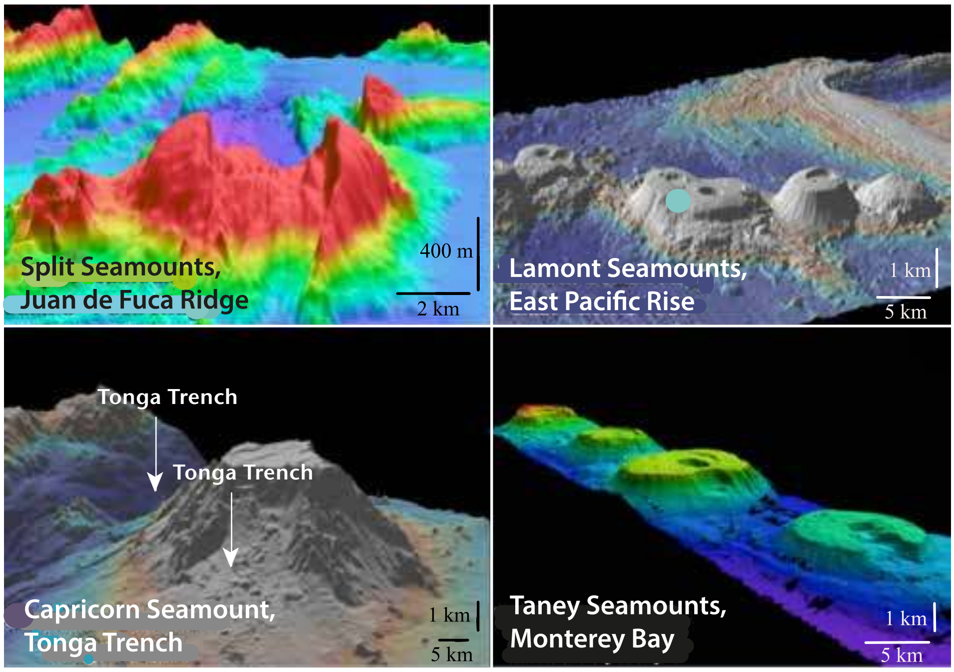
While palaeomagnetic data suggest the Louisville Ridge, a seamount chain with a 'bend' in the south-west Pacific Ocean (cf. Figure 7), may also have formed at a fixed mantle hotspot, other volcanic lines are more difficult to explain. Some show an age progression, but form close to a mid-ocean ridge (e.g. the Lamont Seamounts close to the East Pacific Rise; Figure 8) and have been attributed to a melt source that is fixed with respect to relative, rather than absolute, plate motion. Other lines of seamounts (e.g. Puka Puka, south-central Pacific) form narrow ridges that show neither an age progression nor an alignment in the direction of relative or absolute plate motion and have been attributed to melts that migrate through cracks formed in response to intra-plate stresses generated by forces such as a 'slab pull' towards a trench and a 'ridge push' away from a mid-ocean ridge, convective instabilities and mantle dynamics.

Most difficult to explain are the numerous isolated seamounts that litter the seafloor. Some occur in regions of plate flexure at trench–outer rises (e.g. the 'petit spot' volcanoes* in the western Pacific), submarine volcanic loads (e.g. the North and South Arch volcanics of the Hawaiian Islands) and along transform faults and 'leaky' fracture zones, where the plate-bending stresses may be high enough to cause faulting. Others are too widely scattered and show no obvious link to regions of loading and flexure. The occurrence of so many scattered seamounts (e.g. Figure 8) implies an extensive melt source in or below the

Figure 8 *Perspective views of isolated seamounts and short seamount chains in the Pacific Ocean. Note the tilt down towards the Tonga Trench of Capricorn's flat top and the large-scale collapses on Capricorn and the Lamont and Taney seamounts. Summit craters are visible on the Lamont and Taney seamounts. Vertical exaggeration ranges from ×2 (Taney) to ×5 (Split). Scales are approximate.*

(Image of Split Seamount from data in Carbotte et al. *(Geology 2006) and is courtesy of W.B.F. Ryan. Images of the Lamont Seamounts and Capricorn Seamount constructed using GeoMapApp. Image of Taney Seamounts from data in Coumans* (J. of Petrology 2015)*.)*

Seamounts are of different shapes and sizes and the extent of collapse of their flanks varies widely



*A petit spot volcano is a small young volcano formed from magma that has risen up through a fissure from the base of an oceanic tectonic plate.

oceanic crust and lithosphere. The observation by Nicholas Schmerr and colleagues of seismic precursors to reflections from the underside of the crust between an earthquake and a receiver suggesting an age-independent discontinuity at 55–75 km depth is therefore an exciting development, especially as it might reflect an ocean-wide thin zone of partial melt.

Seamounts and society

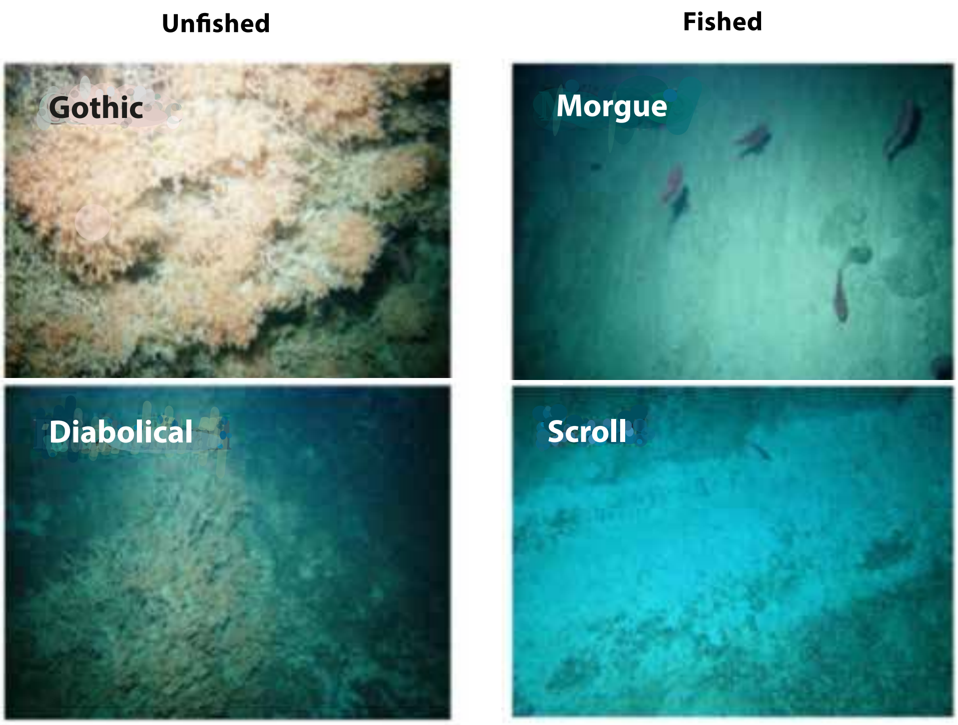
While the origin of seamounts, especially the isolated ones, remains a scientific enigma, they are significant in a number of ways that impact society. Seamounts have steep slopes (up to ~25°) and rise abruptly above regional seafloor depth, so are potential hazards for navigation. This was illustrated by a tragic accident in 2005. The USS *San Francisco*, a nuclear attack submarine at 160 m depth, collided with an uncharted seamount between the Pikelot and Lamotrek atolls in the western Pacific Ocean (Figure 9). Four minutes prior to the collision the seafloor depth was measured at 2000 m.

Figure 9 *USS* San Francisco *in Guam in January 2005. The submarine was in collision with an uncharted seamount while travelling at 33 knots between Guam and Brisbane. One sailor was killed and 115 others were injured. (Image source: https://en.wikipedia.org/wiki/USS_San_Francisco_(SSN-711).)*

The fact that seamounts rise so steeply from the seafloor makes them a hazard to submarines

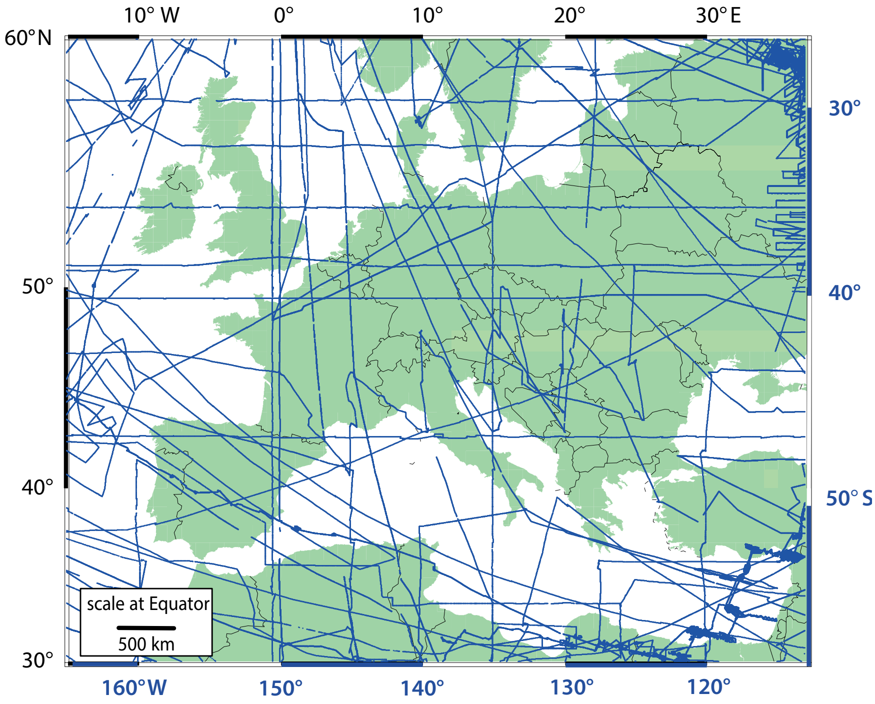
Other significant roles played by seamounts are as seismicity moderators, tsunami wave scatterers, oceanographic ‘stirrers’ and biodiversity ‘hotspots’. Seamounts carried by plate motions towards a trench, for example, are potential asperities on a subduction zone megathrust and may either inhibit or promote seismic activity. Futhermore, if intact when subducted into a trench, seamounts may disrupt the fore-arc (on the landward side of the trench) and cause submarine landslides. Groups of seamounts may also diffract earthquake-generated tsunami waves, so that they may constructively interfere and have higher amplitudes along a particular segment of coastline. Finally, seamounts may be sites of tidally induced ocean turbulence, which aids in bringing nutrients from the flank of a seamount to its summit. Indeed, some of our favourite fish and their predators are found over the summits of seamounts, and seamounts have been targeted by the fishing industry, although not always with a positive outcome for their coral habitats, as for example in the Graveyard Seamounts, east of New Zealand (Figure 10).

Figure 10 *Unfished and fished seamounts in the Graveyard Seamounts, east of New Zealand. Unfished seamounts have extensive areas of cold-water corals which support a diverse array of invertebrates. Fished seamounts have had their coral removed by bottom trawlers that leave their marks in the pelagic sediment drape on their summits.*



The nutrient-rich water above seamounts means they can support abundant life, but that can easily be destroyed by unsustainable fishing practices

(Images based on the work of Malcolm Clark and colleagues at the National Institute of Water and Atmospheric Research, Wellington, New Zealand)

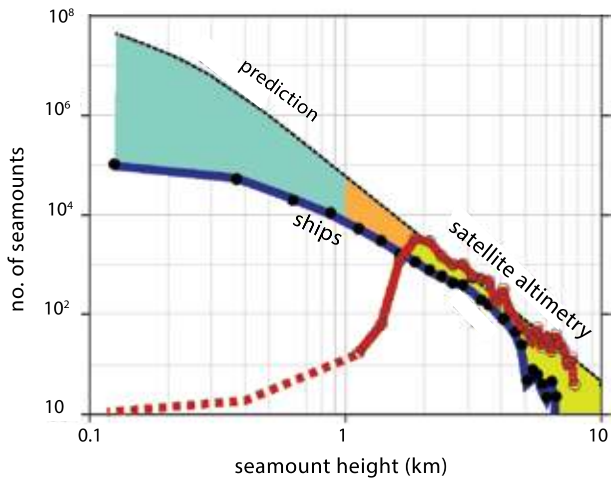


Most of the deep seafloor has yet to be mapped

Figure 11 *Plot showing all available single-beam bathymetry, gravity and magnetic ship-track data in part of the central Pacific Ocean (bounded by 113°–165°W and 26°–56°S, in blue on map) superimposed at the same scale on a map of Europe (blue lines, ship tracks; grey lines, national boundaries). Areas of seafloor equivalent in size to UK, Germany and France have been sampled by the equivalent of just 8, 8 and 5 ship tracks respectively. Areas of seafloor equivalent to entire countries (e.g. Greece, Bulgaria and Poland) have barely been sampled at all.*

Comparing the no. of seamounts predicted by satellite measurements and the no. found by ships suggests that thousands of large seamounts still remain to be discovered

Figure 12 *Number of seamounts vs seamount height above the regional seafloor depth (note logarithmic scales). Satellite data (thick brown line) reveal nearly all the large seamounts, while surface ship data reveal most of the small seamounts (thick dark blue line). The areas of the orange and turquoise regions suggest many more seamounts remain to be discovered, a few tens of thousands of which may have heights up to 1–2 km. (Modified from data in Hillier and Watts (2007); see Further Reading)*



Exploration limits

The lack of field data limits our exploration of seamounts. The number of scientific research cruises with PDRs on board increased rapidly following World War II, but has been in a steady decline since the early 1970s. Single-beam bathymetry ship-track coverage is therefore limited, especially in the South Pacific Ocean, south of latitude 26° S (Figure 11). Multibeam swath bathymetry coverage is even sparser. Imagine the difficulty in determining the geology of a country the size of France from just a few transects of geophysical data!

The challenge becomes even clearer when we consider the number of undiscovered seamounts that might exist in the world's oceans. Satellite-derived gravity data have found most, if not all, large seamounts, but few of the small ones, while ship PDRs have found some large seamounts (ships tend to avoid the largest seamounts!) and many of the small ones (Figure 12). If we assume that satellites have found *all* the seamounts with heights between, say, 2 and 9 km, then the relationship between the number and height of seamounts in this height range can be extrapolated into the domain of the smaller, yet still significant, seamounts (dashed line in Figure 12). If we then compare this with the seamount number–height relationship obtained from ship data (blue line) we find that there may be upwards of ~30 000 seamounts in the height range of 1 to 2 km (orange area in Figure 12) that remain to be discovered!

So, what might Sir John Murray and the other great bathymetric chart makers of the last century, such as Heezen and Tharp, Uchipi and Emery, and Fisher and Mammerickx, have made of this challenge? Surely, they would have wanted the ocean floor to be mapped in its entirety. Walter Smith and Karen Marks of the Laboratory for Satellite Altimetry, National Oceanic and Atmospheric Administration, have estimated that it will take about 200 ship-years (e.g. 20 ships for 10 years) to completely swath map the world's ocean basins and their margins. Incidents such as the loss of flight MH370 and the 2004 and 2005 Java–Sumatra megathrust earthquakes suggest that we should start soon in order to build a global database that can be used as a reference to compare with new data, so enabling large objects, or changes in seafloor depth, to be detected.

The challenge has been recognised by the committee for the General Bathymetric Chart of the Oceans (GEBCO) who, with the help of the late Sir Anthony Laughton, brought the organisation together with the Nippon Foundation on a project called 'Seabed 2030'. The aim of the project is to map the bathymetry of the world's oceans to a vertical and horizontal accuracy of 100 m, with extensive use of ROVs which offer the prospect of even higher accuracies over small areas.

In the meantime, we should encourage academic research ships with on-board swath bathymetry systems to record data not only in their survey regions but also during transits to and from a focus site. Such efforts would be enhanced by public engagement using 'ships of opportunity', for example cruise ships, Navy vessels and 'mega yachts'. Only then might we be able to put to rest the well known cliché that we know the surfaces of the Moon, Mars and Venus better than we know the surface of our own planet.

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Tony Watts is a Professor of Marine Geology and Geophysics at Oxford University. He has had a career-long interest in exploring seamounts in the world's main ocean basins, and discovering what they tell us about the motions and rigidity of Earth's tectonic plates and the volcanism and dynamics of the plate interiors.
tony.watts@earth.ox.ac.uk

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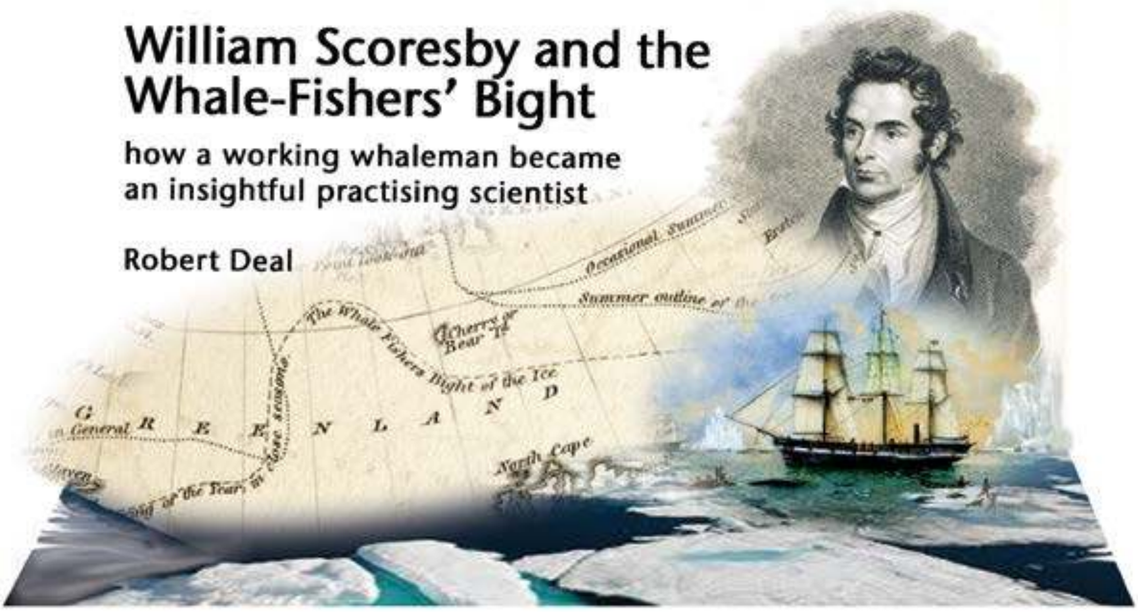
William Scoresby and the Whale-Fishers' Bight

how a working whaleman became an insightful practising scientist

Robert Deal



Novelist Herman Melville's knowledge of whaling was personal. He had sailed aboard a Massachusetts vessel hunting sperm whales in the Pacific Ocean during the early 1840s. Yet, when he began work on *Moby-Dick*, Melville turned for guidance about whales, whaling and oceanography to the work of William Scoresby. Melville's reliance on Scoresby was neither unique nor misplaced. A pioneering observer of the marine environment, experienced whaling captain, and gifted writer, Scoresby was ideally suited for his task of explaining the Arctic environment and whaling. His 1823 *Journal of a Voyage to the Northern Whale Fishery* and other writings met the growing public appetite for natural history and tales of adventure in an exotic environment. Scoresby remains an indispensable guide to whaling in the early 19th century.

While scholars have long looked to Scoresby to understand the history of British whaling and Arctic conditions, his recognition and rudimentary understanding of the mechanism by which warm Atlantic water reaches the west coast of Spitsbergen have been largely overlooked. That a captain whaling in Arctic waters should above all mariners have such a keen interest in ocean currents and the formation and distribution of sea ice is logical. Successful whaling and even survival in the Greenland whale fishery required constant attention to the environment. A whaleman who did not understand where whales could be located and how to get to the most profitable areas of sea was unlikely to return to port with a full hold of blubber and whalebone. A captain who failed to monitor conditions in the water placed the lives of his crew at great risk.

Becoming a gentleman and a scientist

William Scoresby was born in 1789 in Pickering – a small village in Yorkshire – and named after his father who was a celebrated English whaling captain. It was on his father's 1800 trip to the Greenland whale fishery that the young Scoresby first experienced the pursuit of bowhead whales in Arctic waters; he was only ten, and had stowed away. By the age of sixteen Scoresby was working as first mate for his father and, more remarkably, beginning studies at the University of Edinburgh. While serving as an officer on a whaling vessel could be lucrative and was certainly respectable, few – if any – students attending British universities could claim such experience. Scoresby, in fact, speculated that he was the lone mariner enrolled at Edinburgh. It was at Edinburgh that Scoresby began his ascent from mariner to the ranks of the gentleman scientists expanding the limits of what was in the period often termed 'useful knowledge'.

After attending a boys' school in the coastal town of Whitby, Scoresby received more rigorous instruction in London when his family relocated to the capital in 1802. Of the six months spent at Mr Stock's school, Scoresby wrote in his unpublished autobiography* that 'the advantage I gained was incalculable. In grammar I obtained an uncommon proficiency; in calculation much facility; in writing much improvement'. Back in Whitby, Scoresby found his teachers wanting by comparison. In mathematics and the study of navigation, he discovered that once his instructors had reached the limits of the normal course of study provided for generations of boys destined for a life at sea 'their explanations of any difficulties that occurred [were] neither satisfactory nor intelligible'.

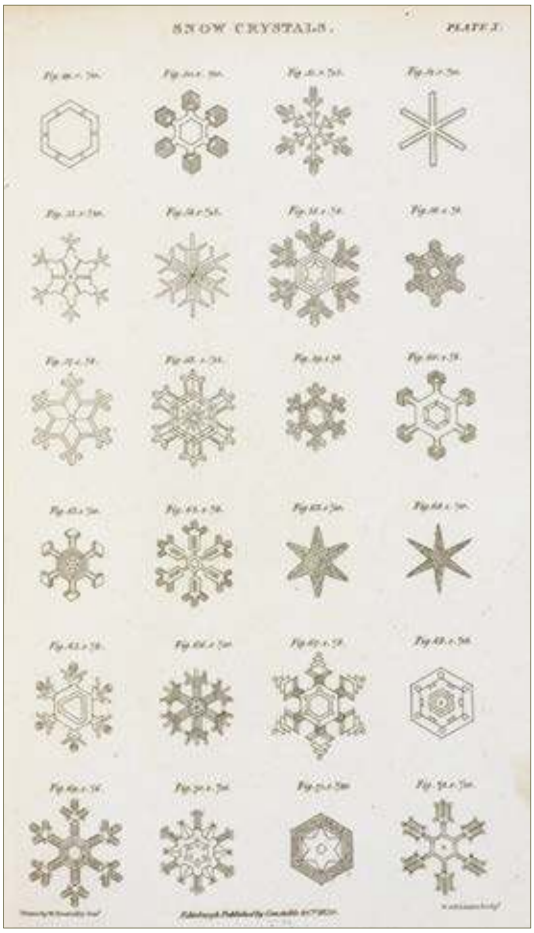
*Scoresby's account was liberally quoted in the biography written by his nephew, Robert Scoresby-Jackson (see Further Reading).

Despite having left school at the age of nine, William Scoresby senior was a firm proponent of education and supported his son's determination to attend the University of Edinburgh in the autumn of 1806. At Edinburgh, Scoresby attended classes in chemistry and natural philosophy. Taught by John Playfair, the course in natural philosophy proved particularly important in Scoresby's intellectual development. Playfair, whose expertise included mathematics, physics, and astronomy, was a leading proponent at Edinburgh of 'Plutonism' or 'volcanism' which later evolved into what came to be called the uniformitarian view of geology. Following the theories of his mentor James Hutton, Playfair argued that the Earth was formed over an inconceivably long period of time, partly through the solidification of magma into igneous rocks, and that the processes that shaped the Earth's surface have remained the same over time. Playfair, like a number of his teachers at Edinburgh, was intrigued by Scoresby's Arctic experiences and encouraged the young whaleman to share his observations of the polar environment. Scoresby's time at Edinburgh was brief, however. In March 1807, with Professor Playfair's lectures turning to astronomy, Scoresby departed Edinburgh two months before the end of term, to ply his trade in the Greenland whalefishery.

Scoresby's return to Edinburgh and his studies were delayed until November 1809. It was during his second stint at Edinburgh that Scoresby came under the tutelage of natural historian Robert Jameson. Jameson, much like Playfair, was excited when he learned that Scoresby not only made regular visits to the waters off the coast of Spitsbergen but that he had kept meteorological records over several summer whaling seasons. While Playfair and Jameson were both impressed by Scoresby and recognised that his knowledge of the Arctic would advance their own understanding of that environment, they were on opposite sides of the great debate on the age and geological origins of Earth then agitating the University of Edinburgh and other European seats of learning. Rather than embracing Plutonism, Jameson was a proponent of the 'Neptunist' position of Abraham Gottlob Werner under whom he had studied at Freiburg. Werner posited that the solid Earth formed largely through minerals crystallising out ot the primeval ocean and sinking and accumulating to form rocks like granite. Thus, Neptunists believed that the processes which formed the early Earth were no longer occurring. Like many scientific disputes of the period, this controversy was also enmeshed in religious and political arguments. While Neptunists did not necessarily cite the Flood recounted in Genesis as supporting evidence, the implication was clearly that their position was more in line with the Biblical account of Creation and Christian ideas about the age of the Earth.

The nature of this dispute about the formation of the Earth is instructive as to how the scientific community into which Scoresby was entering operated in the opening decades of the 19th century. Neither Playfair nor Jameson were what we would think of as geologists with an exclusive expertise in the field of study central to the dispute. Both men had wide-ranging interests in all manner of scientific and philosophical questions spanning what today would be considered discrete scientific and academic fields. Science, and indeed the knowledge conferred on students at places like Edinburgh, was not divided into rigid subject areas because all branches of learning were seen as inter–related and interconnected. To understand one field often required some understanding of all of the other courses of study. It was indeed possible for a learned individual to have a solid grasp of several branches of science.

Scoresby's formal education at Edinburgh ended in late February with preparations for the start of the 1810 whaling season, but his relationship with Professor Jameson continued to shape his entry into the highest circles of Edinburgh's intellectual and scientific communities and ultimately those of Europe. Upon meeting Jameson in November 1809, Scoresby had provided his professor with journals of his meteorological observations including drawings of snow crystals compiled during his 1807, 1808 and 1809 voyages. Jameson was so impressed by the young mariner's work that he arranged for its presentation at the January 1810



Twenty-four of the 96 snow crystals drawn by Scoresby, and included in his An Account of the Arctic Regions

meeting of the Wernerian Natural History Society, an organisation Jameson had founded in 1808 for the advancement of scientific knowledge. The following month, Scoresby's accounts of bowhead whales and his journal of his 1806 voyage with his father to 81° 30' N – the highest latitude yet reached by European seafarers – were read to the Society's members. The rules for membership in the Wernerian Society were thereafter suspended and Scoresby was elected by acclamation. Portions of the material presented at the January and February meetings were published the following year in the first volume of the Society's *Wernerian Memoirs*. Scoresby's writings became a regular feature in the *Wernerian Memoirs* with his 1811 and 1812 Greenland meteorological journals appearing in 1814 and his observations on polar ice published in 1818.

In 1811, at the age of twenty-one, Scoresby was given command of the *Resolution*, a whaler from Whitby bound for the Greenland whale fishery. Scoresby's obvious abilities as a mariner aside, his status as son of Whitby's most prominent captain likely hastened his promotion. As captain, Scoresby was able to combine the economic imperative of catching whales with scientific experiments. Over the course of the next dozen years, Scoresby's wide-ranging observations and experiments were published and he became recognised by the European community of scientists as perhaps the leading authority on the Arctic environment. Admittance into some of the leading European societies dedicated to the advancement of scientific knowledge evidenced Scoresby's progression from whaleman to gentleman. In 1819, with the support of rivals Jameson and Playfair, Scoresby was selected to join the Royal Society of Edinburgh and in 1827 he was awarded a Corresponding Membership of the Institute of France.

Sir Joseph Banks as President of the Royal Society in 1812 *(Painted by Thomas Phillips; © The Royal Society)*

It was, however, his association with Sir Joseph Banks that solidified Scoresby's status as a gentleman. Banks was a natural historian and botanist who rose to prominence after James Cook's 1768–1771 voyage to the Pacific, which resulted in the European discovery of Australia.

Banks was elected President of the Royal Society in 1778 and held the position until his death in 1820. Founded in 1662 to promote what was termed 'natural knowledge', the Royal Society had by the early 19th century a long history of advancing scientific experimentation. Yet, as historian C. Ian Jackson has noted, the Royal Society during Banks' presidency operated also as a sort of gentleman's club. Membership was conferred more on social position than on scientific accomplishments. Members of the Royal Society were often gentlemen with a keen interest in all matters scientific who enjoyed the lectures of leading scientists, but Royal Society meetings did not include the often vigorous give and take of challenging and pointed questions that typify debate at modern academic conferences. Under Banks, the Royal Society remained an organisation that considered all fields of scientific study to be interconnected and was attempting to forestall the already inevitable fragmentation of science into a myriad of distinct fields each with its own professional organisations.

Scoresby's personal introduction to Banks came in 1808. In London after a couple of months of volunteer service to the Navy in bringing captured Danish ships to England, Scoresby received a letter from his father directing that he present to Banks the meteorological observations taken during the 1808 season in the Greenland whale fishery. Banks, an acquaintance of the elder Scoresby, proved to be a cordial host and put the eighteen-year-old mariner with but a few months of university experience at ease. Their discussion of the Arctic environment clearly impressed Banks to the degree that he invited Scoresby to attend his weekly 'breakfast'. Famous throughout the scientific community, Banks' Thursday breakfasts brought together distinguished gentlemen and scientists and for Scoresby provided entry into a world very different from that he experienced on a whaler in the Greenland Sea. It was, however, a community of gentlemen who recognised a bright mind and respected the contributions Scoresby could make to the advancement of knowledge about a part of the world that was increasingly being viewed as important to English commercial prospects and national interests. Banks and Scoresby thereafter remained in regular correspondence, with Banks providing the younger man with scientific equipment to advance his experiments. The multiple attempts of Banks to advance Scoresby's cause by securing funding and a position commanding a vessel on a Navy research mission to the Arctic, however, ultimately proved unsuccessful.

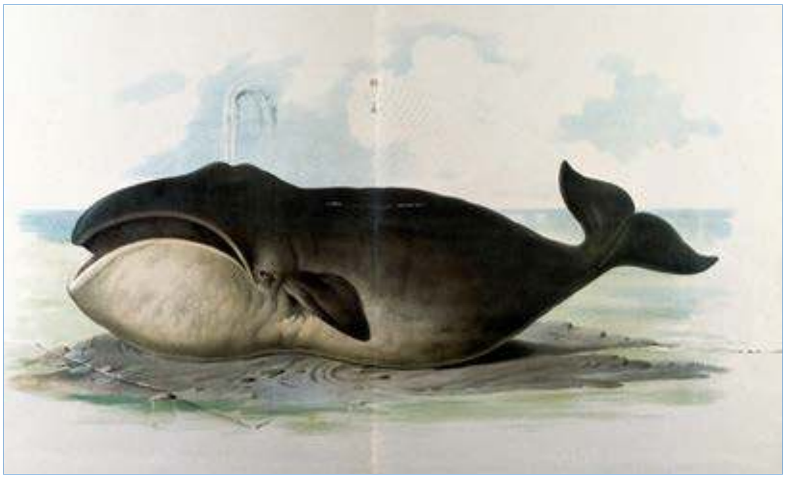
Working whaleman

In the opening decades of the 19th century, the port of Whitby grew busy each January as captains began preparing their vessels for the upcoming season in the whale fishery in the Greenland Sea. For the past sixty or so years, Whitby's ships had headed north in search of bowhead whales (*Balaena mysticetus*).

Bowheads are the only baleen whales to stay in Arctic and sub-Arctic waters all year long. Likely as an adaptation to life in such cold water, bowheads are protected by an extraordinarily thick layer of blubber. Despite the dangers and difficulties of the hunt, bowheads were rich sources of oil and thus appealing targets for whalemen. They mostly live in shallow coastal water amongst the pack ice, and their movements are therefore influenced by the melting and freezing of the ice. As the ice breaks up during spring, they mate and calve while migrating northwards, and they spend the summer feeding and raising their young.

Passage out of Whitby's harbour in March into the North Sea was, at best, difficult. The inner and outer harbours were separated by a two-leaf drawbridge with stone abutments that left a mere 10 m for passage. The shallowness of the channel provided additional challenges, effectively limiting the harbour to vessels of no more than 350 tons. The rigours of leaving Whitby were probably a welcome relief from the tedium of stocking the ship, acquiring a suitable crew, and securing the certificates, bonds and oaths required to gain permission to depart from the local customs agent. English law dictated that every ship bound for the Greenland fishery be adequately provisioned and manned by the requisite number of Englishmen possessing specified levels of experience and skill.

Once Scoresby assumed command of the *Resolution* in 1811, his decision as to when to leave Whitby was – like that of all similarly situated captains – the product of multiple factors. Weather, ice formation, available maritime technology including ship construction, bowhead migration patterns, and – perhaps most importantly – personal experience in the Greenland Sea, all played into a captain's calculations. Despite possible advantages of reaching bowheads prior to competitors, a departure before the middle of March was not generally practical. The ice and darkness encountered in the targeted latitudes north of 75° N until after mid April presented extremely dangerous conditions. Scoresby explained in his 1820 *An Account of the Arctic Regions* that this combination of ice and darkness 'probably produce as high a degree of horror in the mind of the navigator ... as any combination of circumstances which the imagination can present'. Yet a captain always feared that too much caution in timing his ship's arrival in the Greenland fishery would give other vessels a precious head start to the season's work.



A bowhead whale on a sandbank
Bowheads are very long-lived and attain a length of 20 m. Like other baleen whales they take large volumes of water into their mouths and use baleen plates to strain out zooplankton and fish. With their thick-skulled heads and powerful bodies, they can break through sea ice ~ 0.5 m thick. (Chromolithograph: F. Gerasch after A. Gerasch (1860/1880?); Wellcome Collection; Attribution 4.0 International CC BY 4.0)

The constant gamesmanship between captains as to their date of departure and progress to the prime hunting grounds masked the collegial nature of whaling. As intensely competitive as whalemen were, they also recognised the degree to which they depended upon one another in the harsh and dangerous conditions of the Greenland Sea. Information was shared as to ice conditions and even the location of whales. Should a ship become trapped in the ice, as Scoresby's *Esk* would be in 1816, competitors could be counted on to come to the rescue.

A week or so after leaving their home port, Whitby whalers arrived in the Shetland Islands about 60 km north the Scottish mainland (*see map on p.40*)
A visit to the Shetland port of Lerwick was generally the last opportunity for whalers bound for the Greenland fishery to take on fresh supplies and make any needed repairs before the long trip north. Sails were trimmed, casks were filled with water to serve as additional ballast, and the crow's nest was affixed to the main-top-mast; this elevated, protected space, from which whales could be spotted and paths through the ice discerned, was an innovation often credited to the elder Scoresby. From Lerwick, captains plotted their strategies, considered the weather, and determined the most propitious time to embark. The exact date of departure was largely dependent upon the weather and varied from season to season. The decision of a single captain to set sail could lead, on occasion, to a mass movement of the fleet. On 9 April 1812, Scoresby noted with disdain in his journal that despite an unfavourable wind a dozen ships followed a single vessel out of port 'like as one sheep followeth another to a Waterpool'. Scoresby opted to leave the following day in company with nine other ships.

70°N

Left *Part of a map which accompanied Scoresby's paper 'On the Greenland or polar ice', which was published in Vol.2 of* Memoirs of the Wernerian Natural History Society***.*** *'East Greenland' is what today we call Svalbard. Jan Mayen is at about 8°W and the Shetland Islands are near the bottom of the map.* ***Inset above*** *The shape of the Whale-Fishers' Bight in open and closed seasons. It was the configuration of the ice in spring that determined whether a season would be 'open' or 'closed'.*

This map accompanied Scoresby's article in Vol.2 of Memoirs of the Wernerian Natural History Society.

Basic whaling decisions such as where to hunt and how to get there were the product of individual experience and the received wisdom from generations of earlier captains. Whalemen kept ships' logs recording latitude and longitude along with detailed records of weather, ice, and whales encountered. From this information they were able to determine the favoured haunts of bowheads. Yet, captains were painfully aware that no two seasons were exactly alike: at best, the past provided a framework for making decisions.

The 1812 whaling season was a typically challenging one. As in other years, when Scoresby left Lerwick, he knew that his probable destination was an area of sea to the west of Spitsbergen, the largest island of the Svalbard Archipelago, somewhere between 78° and 81° N. He also understood that the precise path to his expected destination could not be charted in advance. Ice and weather would determine the way to the desired latitude.

Each spring the limit of the pack ice in the Greenland Sea assumed roughly the same shape, with the particulars the result, in Scoresby's estimation, of year-to year-variations in the weather. As shown in the map above, at the start of some whaling seasons, known as 'closed' or 'close', the pack ice reached Iceland and surrounded the volcanic island of Jan Mayen; in others, known as 'open', the ice edge was north of both Iceland and Jan Mayen.

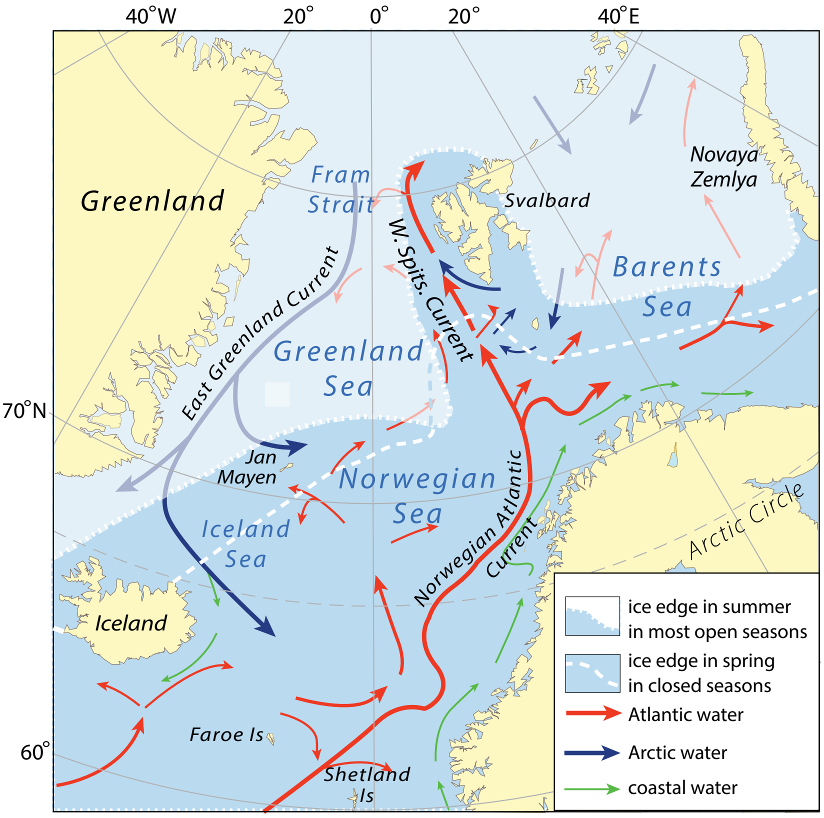
While Scoresby was certainly atypical in his attention to and understanding of the formation of sea ice, all experienced Greenland captains recognised that in order to reach their quarry they must find and sail through an extensive area of open water they called the Whale-Fishers' Bight. As shown in the inset map, on closed seasons, this open water did not extend as far as Svalbard, while in open seasons it could extend to the north of it. Either way, at the northern terminus of the Whale-Fishers' Bight was an expanse of ice-infested water that must be passed through before the business of hunting whales could commence in earnest.

The *Resolution's* departure from Lerwick on 10 April 1812 was, in comparison with past seasons, late. Given ideal weather conditions, the fleet generally set sail from the Shetlands before the end of March, but that year conditions were far from ideal. A hard gale had commenced on the evening of the second day out, forcing Scoresby to seek refuge in Balta Sound on the east coast of the Shetland Island of Unst. The *Resolution* remained at anchor until the wind changed on 19 April. Had the *Resolution* taken leave of the Shetland Islands a few weeks earlier, Scoresby would have likely headed to the southern Greenland Sea between 70° and 72° N. There they would have hunted seals, waiting for conditions to the north to improve. The previous generation of British captains remained at sealing until the start of May when they finally deemed the path to 78° N sufficiently clear of ice to attempt passage to the bowheads' summering grounds. The fortification of British whalers such as the *Resolution* with additional planks and iron plates on the exterior and interior beams and stanchions permitted captains like Scoresby to push through the ice toward the desired latitudes weeks earlier than previously judged prudent. The season being late, Scoresby opted to head directly for the Whale-fishers' Bight.

The beginning of May in 1812 found the *Resolution* in open water within the Whale-fishers' Bight at a latitude of around 74° N. While remaining on watch for ice, the crew indulged in the traditional revels that marked 1 May on a British whaler. The banging of pots and pans accompanied a 'ridiculous dance' of 'fantastically dressed' crew members 'with blackened faces'. Scoresby's brief description of the hour-long festivities concluded with the terse observation, 'No ice seen this Day'.

The long anticipated first encounter with ice came the next day. At around 75° N, 14° E, the *Resolution* spied what Scoresby years later termed 'ponderous field-ice'. In the parlance of the Greenland fishery, it was a 'closed season'. In such a year the ice at the northern terminus of the Whale-Fishers' Bight was so closely packed that passage beyond 75°–76° N was extremely difficult and fraught with danger. An open season, by contrast, permitted whalers to proceed directly to the hunting grounds early in the year, sometimes sailing poleward of 80° N without encountering significant amounts of ice. In closed seasons, an overly cautious captain could wait until the end of May when the ice would have broken up sufficiently, and thereafter safely reach the desired latitude, but such a captain would lose the respect of his crew and soon his command. Instead, captains sought paths through narrow openings in the ice that could quickly close with a shift in the wind. Navigating through the ice in a closed season was like seeking passage through a challenging maze that frequently changed its form. A promising patch of open water might lead, instead, into a lethal trap of constricting floes of ice. Whalemen persevered, however, because the rewards of quickly reaching the hunting grounds were substantial. In a whaling season that lasted only a couple of months, captains had little time to spare.

In most closed years, passage to the north – while challenging – was made possible by the composition of the ice. The ice at the edge of the Whale-Fishers' Bight in closed years generally



Generalised current flow pattern in the subpolar seas between Greenland and Norway, with the edge of the Whale-Fishers'Bight shown for both 'open' and closed' seasons. The Norwegian Atlantic Current is an extension of the North Atlantic Current.

consisted of drift ice, pieces up to a kilometre or so across, which were often fused together by areas of thin, newly formed ice. Although pack ice might appear to form a continuous front impervious to penetration, captains constantly probed its edges for passages to the open water that beckoned, in a typical closed season, at a distance of 100–200 km. In addition to a captain's ability to read the ice and the sky at the horizon,* and willingness to take chances, a way forward was offered by the thin ice between the floes – also known as 'bay ice' – which could be broken up by the employment of saws or the concussive force of dropped whaleboats. The conditions that faced *Resolution* in 1812 were, however, far from typical. Scoresby termed the ice formation blocking his passage 'one of the most formidable that had ever been encountered'.

By the middle of May 1812, still struggling to find his way through the ice, Scoresby faced a significant decision. On 12 May, Scoresby had written in his journal that he had two options. The first was for the *Resolution* to retreat to the south and hunt bowheads between the edge of the ice and the open sea. While whales in these waters tended to be large and provide impressive yields of oil, they were relatively scarce and, in open water, difficult to catch. This 'southward' fishery was also subject to severe gales and difficult conditions. Scoresby's other option was to continue to seek 'passage thro' this Ice into an opening of water which is

*Of the phenomenon known as 'ice-blink' (a white glare on the underside of low clouds on the horizon) Scoresby wrote '... it affords to the eye a beautiful and perfect map of the ice, twenty or thirty miles beyond the limit of direct vision ... [It] not only shows the figure of the ice, but enables the experienced observer to judge whether the ice thus pictured be field or packed ice: if the latter, whether it be compact or open, bay or heavy ice.' By contrast, dark streaks on the underside of low clouds indicated the presence of open water in the vicinity of sea ice.

almost universally found between the Land [Spitsbergen] and the Ice about this Season'. As was often the case with Greenland captains considering their options, Scoresby was able to draw on intelligence from other masters as to the status of the rest of the fleet. Two captains boarded the *Resolution* on the afternoon of 12 May and informed Scoresby that most of the other British ships were to the south-east. Captain Shields of the *Euretta* related how in a recent storm his ship had been blown upon the ice and nearly 'stoved'. Scoresby assessed his situation and confessed "[t]he Prospect at present does not seem exceedingly favourable' for reaching the desired latitudes above 78° N. Yet, like most similarly situated masters, Scoresby chose to push northward. The *Resolution's* passage would prove difficult and within the week almost turned catastrophic.

On 19 May, the *Resolution* was in a 'dreadful situation'. The previous day had been quite successful as the *Resolution* found an opening in the ice and managed to travel nearly 100 km to the north-east in the company of three other whalers. Still working this passage to the north-east on 19 May, Scoresby spied at about 7:00 p.m. a path between two ice floes. Although narrow and apparently closing, the corridor appeared wide enough to proceed safely. Having entered into the opening, 'a blackness was observed on the water and showers at a small distance [,] the sails shook [,] the vane whirled round and in less than 15 seconds of time a heavy gale of wind right a head at NbW* fell upon the Sails'. The *Resolution* was driven for a distance of 100 m and crashed against one of the floes, breaking the wheel ropes. On its side and temporarily disabled, the *Resolution* awaited being crushed as the gap between the two floes closed rapidly. When it came, the collision was powerful, but the ship was spared its full force. Changing winds and the use of a hawser attached to an ice hummock freed the *Resolution*, but did not eliminate the danger of being crushed by the shifting floes. Scoresby therefore took advantage of an opportunity to sail the vessel into a large patch of bay ice. Firmly attached to the western floe, the freshly formed bay ice provided protection by equalising the pressure on the *Resolution* and absorbing the impact of further collisions. At 3:00 a.m. on the following day, the wind separated the floes and the *Resolution* sailed free.

The immediate danger having passed, Scoresby continued to seek the open water that experience taught could be found along the western coast of Spitsbergen. If the floes prevented passage to the north-east, Scoresby reasoned, perhaps the ice could be escaped by flanking it to the south-east. A week later, the *Resolution*, about a degree of latitude to the south and a degree of longitude to the east, was still dodging floes and cutting and pulling its way through bay ice. Scoresby noted the growing anxiety of the British fleet – even the oldest captains had never experienced such challenging conditions.

Although many ships had already killed a whale or two, Scoresby and his colleagues were well aware that a successful season could not be achieved in pursuit of stragglers from the main herd which by late May was probably well to the north. When whales were sighted, the concentration of ships – thirty-seven spied by Scoresby at noon on 30 May – diminished the odds of any one ship securing a bowhead. Still hampered by ice, the *Resolution's* initial lowering of its whaleboats ended poorly on 28 May when two whaleboats belonging to a London vessel interfered with what Scoresby thought a likely catch. While Scoresby did not indicate the nature of the interference or how many other ships were in pursuit, he did relate that on the previous day he saw twenty boats chasing a single whale. In such circumstances, the necessity of returning to port with an ample supply of blubber and whalebone placed officers and crews on edge, feeling their chances of a profitable season slipping away. And then, on 1 June at 7:00 p.m, the *Resolution* was delivered by 'Almighty Providence' out of the ice and into nearly open water with Spitsbergen in view at a latitude of 77°N. In company with twenty-two other ships all set with studding sails,† the *Resolution* was finally released to, in the words of Psalm 107 in which whalemen often took comfort, 'do business in great waters'.

As a closed season, 1812 proved – as was generally the case – a successful year in the fishery. Scoresby's *Resolution* took an impressive twenty-five whales which produced over 200 tons of oil. While it is perhaps counterintuitive that a season during which whalemen struggled to make progress through the ice to the preferred hunting grounds would make for a rich harvest, Scoresby clearly believed this to be true. He explained in Vol.2 of *An Account of the Arctic Regions* that in years when the fleet was able to sail directly into the higher latitudes west and slightly north of West Spitsbergen, whales were also free to 'sport in' about 2000 square leagues (i.e. about 60 000 km^2) of open water that in a closed season would be full of ice. The absence of ice meant that bowheads could easily pass from one part of the Greenland Sea to another and were not tempted to tarry in sheltering ice where whalemen normally sought their prey. The vast area of ice-free water in an open season meant that whalemen had to guess where they would find whales. A wrong decision might waste precious days or weeks of the short summer season. In a closed season, once a ship fought its way through the ice, bowheads could predictably be found – as they were in 1812 – at the western edge of the main mass of ice between 78° and 79° N. In the restricted grounds of a closed season, bowheads could seek shelter amongst the ice, but not make their escape through it.

*****NbW is a compass direction between N and NNW.

†Studding sails or stud sails are extra sails designed to increase speed in light winds.

Practising science

Scoresby believed that the Whale-Fishers' Bight was, at least in part, a product of the Gulf Stream. Since the early 16th century it had been recognised that there was a current running from Florida up the east coast of North America. It was not, however, until the latter part of the 18th century that ocean currents received serious scientific scrutiny. The impetus for much of this research was practical. Finding the quickest and safest routes between two ports required an awareness of powerful currents that could add or subtract weeks of sailing time.

One of the earliest attempts to map the course of the Gulf Stream up the coast of North America and then eastwards towards Europe was produced by Benjamin Franklin. In 1769, Franklin, in his capacity as Deputy Postmaster General of North America, was asked why it took packet ships carrying mail from Falmouth to New York about two weeks longer to make the passage than merchant vessels bound from London to Rhode Island. Franklin recognised from his own experiments during Atlantic crossings that there was an eastward current discernable by elevated water temperature. Nantucket whaling captain Timothy Folger was enlisted by Franklin, his cousin, to sketch a map of the Gulf Stream. Folger's map (*below*) showed the Gulf Stream flowing up the American coast to just south of the Grand Banks, before turning sharply southwards as it heads towards Europe.

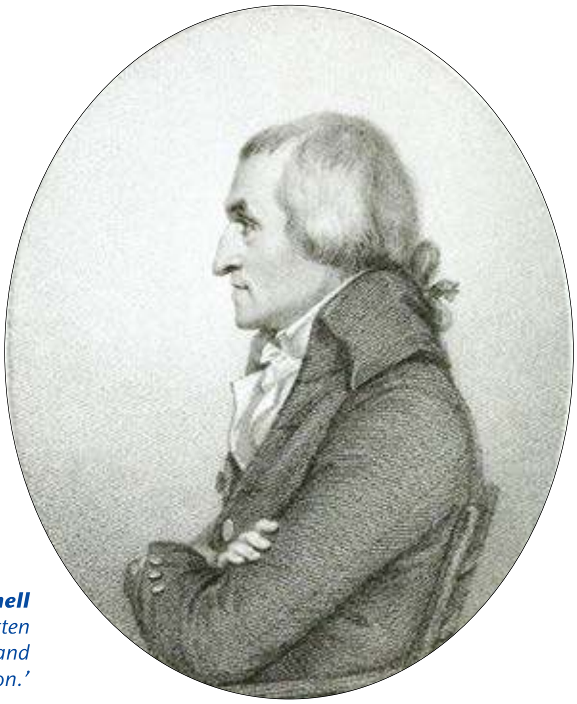
In the early 19th century, the pre-eminent student of Atlantic currents was James Rennell. Rennell, whose interest in the workings of the world's oceans began as a teenager in the British Navy, turned serious attention to currents in 1778, after serving as Surveyor General for the East India Company. Rennell's most important and influential work, *An Investigation of the Currents of the Atlantic Ocean and of Those Which Prevail Between the Indian Ocean and the Atlantic*, was published shortly after his death in 1830, and was a pioneering attempt to understand circulation in the North Atlantic. His book on the Atlantic and the accompanying current charts proved tremendously useful to mariners throughout the 19th century and beyond. As with Folger's map, Rennell's chart shows the Gulf Stream turning towards the south as it heads east. Rennell thought that the weakened remnants of the Gulf Stream ultimately terminated in the vicinity of the Azores.

While Rennell obviously recognised that the water in the Gulf Stream was warm he did not make any real use of temperature in determining its course. Rennell, like Franklin, believed that the Trade Winds piled up water against the coast of America, and that the Gulf Stream was driven by the downstream pressure gradient resulting from the difference in sea-level.

Rennell's primary sources of information about ocean currents were logbooks and reports from Royal Navy ships and other vessels that used marine chronometers, which allowed accurate

Timothy Folger's chart of the Gulf Stream drawn at the instigation of Benjamin Franklin. The Grand Banks are here referred to as the 'Great Bank of Newfoundland'

(The chart was published in 'Remarks upon the navigation from Newfoundland to New York in order to avoid the Gulph Stream' from Transactions of the American Philosophical Society, *Vol.2, published in 1786)*



Major James Rennell
Under the image is written 'Drawn by Scott,' and 'Engraved by A. Cardon.'

knowledge of londitude. Rennell's careful methods and his understanding that wind, topography and pressure gradients largely determine surface currents served him well in providing useful current charts for mariners. For Rennell, the density of seawater was not relevant to the patterns of current flow.

There were, however, other explanations for how ocean water moved that looked below the surface currents and assumed that at depth conditions were far from the stasis generally postulated. As early as the late 17th century, Luigi Ferdinando Marsigli theorised that an undercurrent flowing from the Mediterranean Sea into the Black Sea by way of the Sea of Marmara and the Bosphorus was set in motion by evaporation in the Mediterranean. Marsigli realised that the water in the Mediterranean being subject to a large degree of evaporation became, as a result, more saline. The Mediterranean water being therefore of greater density than the less salty water from the Black Sea would, Marsigli reasoned, sink and thereby cause a current of denser water to flow out of the Mediterranean into the Sea of Marmara, while a current of less dense water would flow at the surface in the opposite direction. Marsigli's theory, which ran counter to the accepted notion of ocean water being static at depth, failed to attract much attention until 1755 when Jacob von Waitz published the rationale behind his belief that more saline and denser seawater flowed out through the Strait of Gibraltar at depth, below inflowing less saline and less dense Atlantic water.

It was, in large part, the experiments of Count Rumford* into the properties of water that facilitated a clearer understanding of the behaviour and movement of ocean water at depth. Central to Rumford's theories was the discovery that – contrary to previous scientific understanding – water is an extremely poor conductor of heat and, as a result, water at depth is not the same temperature as that at the surface, which is in contact with the atmosphere, and warmed by the Sun. Rumford explained in his *Essays, Political, Economical, and Philosophical* that water with a higher specific gravity (effectively density) than surrounding water 'will immediately begin to spread on the bottom of the sea, and to flow towards the equator, and this must necessarily produce a current at the surface in an opposite direction'. This process accounts, in Rumford's telling, for the Gulf Stream which moves at the surface 'from the equator towards the north pole, modified by the trade winds and by the form of the continent of North America; and the progress of the lower current may be considered as proved directly by the cold which has been found to exist in the sea at great depths in warm latitudes ...'. While Rumford recognised that the density of water increased as its salinity rose, he did not realise that the salinity of seawater could vary significantly and so largely left that factor out his discussion of the movement of water in the ocean.

* Count Rumford was born Benjamin Thompson in America.

Rennell and other British scientists ignored or were hostile to Rumford's work on the thermal properties of water. While some British scientists (e.g. Mary Somerville in her 1849 discussion of currents) did recognise the importance of heat-driven differences in the specific gravity of ocean water, it was the young Whitby whaling captain with mere months of university science instruction who was one of the first in England to embrace the ideas and approvingly cite Rumford's theories.

It was not that Rennell was less rigorous in how he gathered data or less perceptive than Scoresby. Rather Rennell's work – like that of any researcher – was built on the evidence he pursued, the questions he sought to answer, and the information to which he had access. With a background in the Royal Navy and work with the East India Company, Rennell's concerns were often intensely practical and generally directed at the safe and swift passage of ships. It was, in fact, Rennell's insistence on the quality and precision of his data that led to his using evidence gathered by ships employing marine chromometers. That the types of ships equipped to accurately measure latitude at sea rarely ventured into the northern waters sailed by whalemen like Scoresby meant that Rennell's knowledge of the Greenland Sea and other parts of the northern North Atlantic was extremely limited. Scoresby's economic welfare and safety, on the other hand, required that he constantly pay heed to the temperature of the water and the formation, movement and state of the ice in the Greenland Sea. Given his curiosity and interest in science, Scoresby saw in the Whale-Fishers' Bight not just a passage to prime bowhead hunting grounds but a curious natural phenomenon that required an explanation.

As mentioned earlier, even before his time at the University of Edinburgh, Scoresby was honing his skills of observation and keeping meticulous records of what he saw. It was, after all, the quality of his meteorological observations that first drew the attention and interest of John Playfair and Robert Jameson. With the training he received at Edinburgh and by 1811 the degree of freedom to combine whaling with scientific discovery that command of a ship allowed, Scoresby conducted a series of experiments measuring the temperature and specific gravity* – 'the usual measure of saltiness in the sea' – of water at depth in the Greenland Sea. Determining the temperature and specific gravity of ocean water presents a number of challenges that increase with the depth of the measurement.

One must first find a way to capture seawater at the desired depth, and in 1810, his final season as first mate on his father's ship, Scoresby lowered a wooden cask into the Greenland Sea. Equipped with a conventional thermometer, the cask had valves at both ends designed to remain open allowing for a continual passage of water through the device during descent, but which would close when the cask halted, trapping the water then inside. The cask was then left at depth for half an hour allowing the wood to reach the same temperature as the water before being brought to the surface as swiftly as possible. The resulting measurements, while inevitably reflecting some change in temperature imposed by conditions encountered on the upward journey, were nevertheless useful in gaining a reasonable approximation of the characteristics of the water in the Greenland Sea at a particular location, depth and time. The problem Scoresby encountered was that his fir cask became soaked and began to swell with usage. Having developed leaks, the cask was rendered useless in capturing and preserving the characteristics of the retrieved seawater.

Scoresby's benefactor, Sir Joseph Banks, supplied the whaleman with an improved device to record seawater temperature during his 1811 visit to the Greenland whale fishery. It made use of a thermometer invented by James Six in 1780 (generally referred to as Six's thermometer) which recorded the maximum and minimum temperatures achieved during a particular submersion. Although the wooden cask provided by Banks was bound with brass to prevent leakage as the wood swelled, it failed to maintain its structural integrity when lowered to 300 fathoms (~550 m). Scoresby was now required to find a new way to measure water temperature at depth. His solution was to have a crew member whom he dubbed 'an ingenious mechanic' assist him in casting a brass instrument to hold the Six's thermometer salvaged from Banks' device. Scoresby called his creation a 'marine diver' and it served him well until it was lost when its rope broke during an attempt to take readings at a depth of 1200 fathoms (~2000 m) in June 1817.

A replica of the 'marine diver', based on Scoresby's description and drawing. The original was made in1811 and lost in 1817 when the rope broke.
(Science Museum; Attribution 4.0 International (CC BY 4.0)

Scoresby proved to be persistent and, as development of his marine diver indicated, creative in conducting experiments and gathering data. His understanding of ocean currents and the Gulf Stream and its extensions, in particular, were the product of his meticulous observation and experimentation, the available scientific literature, and the accumulated wisdom of whaling captains. As with most of his explanations of natural phenomena, Scoresby's discussion of current creation and movement was richly multi-causal. He cited the rotation of the Earth, the gravitational pulls of the Sun and Moon, temperature variation, and strong or prevailing winds. To this mix of factors, Scoresby added 'the peculiarities of form in sea-coasts, and in the bed of the ocean, with other topical circumstances'.

Scoresby knew that the Gulf Stream runs from the Gulf of Mexico north-eastwards towards Newfoundland along the coast. He believed that as it passes the Grand Banks off Newfoundland, it encounters a current flowing south from Baffin Bay along the west coast of Greenland. This deflects the Gulf Stream to the east and Scoresby speculated that the current splits into two branches as it heads towards northern Europe. The northern portion of the current (now known as the North Atlantic Current) flows north-eastwards up the western coast of the British Isles and then up the western side of Norway (cf. map on p.41). Scoresby believed that at North Cape, at the northern tip of Norway in the Barents Sea (cf. inset map on p.40), a westward current from the direction of Novaya Zemlya, on the eastern side of the Barents Sea, pushes the Gulf Stream's remnants to the north-west into the Greenland Sea off the west coast of Spitsbergen. While acknowledging his uncertainty as to the exact connection between the warm water originating in the Gulf of Mexico and the current found off Spitsbergen, Scoresby

*Specific gravity (now referred to as relative density) is the ratio of the density of a substance to the density of a given reference material, and is measured using a hydrometer. Because density is affected by temperature, Scoresby used tables to correct all his density readings to a temperature of 60°F.

speculated that it is this current, today dubbed the West Spitsbergen Current, that prevents the spread of ice and explains the Whale-Fishers' Bight. Scoresby noted that the surface water west of Spitsbergen, predominantly in longitudes of 6° to 10° E, was frequently as warm as 38°F (~3°C) even when the temperature on deck was well below freezing, allowing portions of the Greenland Sea to remain open for navigation at latitudes farther north than elsewhere in the Arctic.

In 1816 and 1817, using the marine diver in the Greenland Sea at latitudes between 78°N and 79°N, Scoresby detected the presence of unexpectedly warm water at a depth of 100–200 fathoms (~180–360 m). This water was 16–20 Fahrenheit degrees (~9–11 Centigrade degrees) warmer than the mean air temperature, which, Scoresby explained, indicated a warm Atlantic origin. Sounding much like Rumford (p.44) Scoresby wrote 'it seems not improbable that the water below is a still farther extension of the Gulf Stream, which, on meeting with water near the ice lighter than itself, sinks below the surface, and becomes a counter under-current'.

Scoresby correctly deduced that the cold Arctic water entering the Greenland Sea through the Fram Strait can lie above warmer Atlantic water because it is less dense. He was certainly aware that the density of seawater was partly determined by its salinity but, like Rumford, believed that the differences in the salinity of seawater were not significant enough to play an important role in determining current patterns. Scoresby thought (erroneously) that the relatively high density of the water in the 'undercurrent' was a result of the density of seawater being at a maximum 'a few degrees above the freezing temperature', as is the case with freshwater. He also did not associate the relatively low density of Arctic surface water with the addition of low-salinity meltwater from sea-ice.

Conclusion

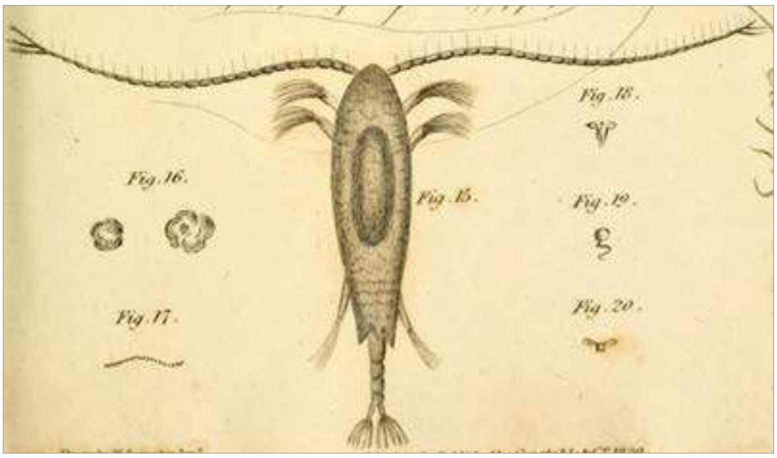
While it is certainly likely that Scoresby's success as a whaling captain (in most seasons it exceeded that of his competitors) can be attributed in large measure to his superior understanding of currents and his obvious powers of observation, it is beyond doubt that Scoresby's understanding of ocean circulation equalled that of widely recognised experts in the field.

Applying the discoveries of Rumford as to the nature of heat transfer and the importance of density differences for fluid flow to the results of his own experiments measuring the temperature of water at depth in the Greenland Sea, Scoresby surpassed Rennell in grasping the importance of Arctic waters for ocean circulation. Rennell's brusque dismissal of Scoresby's conclusion that an extension of the Gulf Stream brings Atlantic water into the Greenland Sea can be read today with some amusement. Terming Scoresby's work 'interesting and instructive', Rennell scoffed in *An Investigation of the Currents of the Atlantic Ocean and of Those Which Prevail Between the Indian Ocean and the Atlantic* that the whaling captain 'does not produce any facts, to show on what authority he grounds an opinion contrary to those which commonly prevail: and, it may be said, to facts, as far as they are known.'

Given that Scoresby was, in fact, correct about so much concerning ocean circulation it is curious that he is not given more credit by scholars studying the history of oceanography in this period. The point is not that scholars have paid too much attention to Rennell and his work. Rennell's understanding of surface currents and the charts he produced were invaluable to mariners and scientists for decades after his death. Rather, it is important to recognise Scoresby's achievements in order to gain a clearer understanding of the process by which the ocean came to be explored. While Scoresby's grasp of the basic principles of ocean circulation equalled or even surpassed that of Rennell, it has been Rennell's assessment of Scoresby that has largely endured. Scholars have – like Rennell – recognised Scoresby's writings as 'interesting and instructive', but have failed to read much deeper into the significance of his work in the story of how ocean currents came to be understood.

Scientific observation and discovery was in the early 19th century still within the province of men like William Scoresby. The ability to advance the cause of knowledge was in the power of any curious and reasonably intelligent person. A whaleman with a keen interest in the natural world – who turned clergyman in the 1820s – Scoresby saw all of creation as a whole. To understand each piece of the puzzle was essential to the goal of understanding how everything in the known, unknown, and the unknowable world fit together.

Scoreby's interests were wide and varied – as well as climatic conditions, geography, geology, meteorology, ocean currents and ice formations, they included terrestrial magnetism and how it might affect the compass in a metal ship, along with botany and zoology, particularly as it related to the diet of whales.



Scoresby's drawing of a 'beautiful little animal brought up by the marine diver' became No.15 in Plate 16 of Vol.2 of An Account of the Arctic Regions

That Scoresby was not an academic or – to use an anachronistic term – a scientist, did not prevent him from being widely respected as an expert on the Arctic. Professional jealousy perhaps and a general disdain for whalemen on the part of Rennell and those in the British Navy who controlled much of the exploration of the ocean certainly hampered Scoresby's access to funding, but during Scoresby's lifetime even a working mariner with primitive equipment could contribute much to an understanding of ocean currents. In the decades after Scoresby's death in 1857, the equipment and the level of academic training necessary to engage in the nascent field of oceanography provided a sort of death knell for the involvement of gentlemen like Scoresby in discovering the mechanisms of ocean circulation.

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With thanks to Gwyn Griffiths for his helpful comments on the article.

Robert Deal is is an Associate Professor of American history at Marshall University, Huntington, West Virginia, USA. His research focusses on the laws and customs of the American whaling industry in the 18th and 19th centuries. He became interested in William Scoresby while researching a 1812 dispute he had with his father over possession of a contested bowhead whale. (see Deal (2016) in Further Reading). dealr@marshall.edu

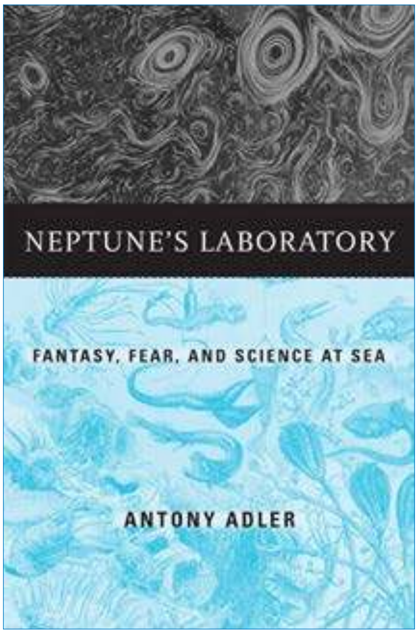
Book Review

A kaleidoscopic ocean

Neptune's laboratory: Fantasy, fear, and science at sea by Antony Adler (2019) Harvard University Press, 256pp. £32.95 (hard cover, ISBN: 978-0-67-497201-8); Also available in Kindle: £28.66.

As a subject of study, the history of oceanography has come a long way in just half a century. Since the pioneering works published in the early 1970s, which centred on the development of oceanography as a science, its syllabus has been steadily expanding to include more of the social and political context for ever-increasing scientific activity in the oceans, while the passage of time has given a clearer perspective to this growing narrative.

In this book Antony Adler takes the story forward from the middle of the 19th century to the end of the 20th, tracking the multiple images of the sea created by humanity's conflicting desires and ambitions. Highway and habitat or barrier and battlefield, playground or rubbish dump, infinite resource or doomed ecosystem, not least laboratory and museum – he shows that the sea has played all these parts in recent history. Despite this diversity of motive, there is a dominant theme running through the text, and that is the role of scientific internationalism and its fluctuating fortunes.



Prior to 1900 international co-operation in the marine sciences was largely informal, underpinned indirectly by government funding for fishery research and higher education. A significant development occurred in 1902, when national rivalries over fishing grounds led eight countries in northern Europe to form the International Council for the Exploration of the Sea (ICES), which pursued a broader, oceanographic, programme of research. Prince Albert I of Monaco had a major influence on the progress of oceanography throughout his reign (1889–1922), both as director of his own expeditions and by his patronage of marine research by other scientists. A committed internationalist, he was dismayed by the outbreak of World War I. Oceanography's advance was interrupted in both world wars, but accelerated rapidly around 1960, assisted, and to a considerable extent steered, by the military support it had received during World War II.

Perhaps the sections of the book least familiar and therefore of most interest to European readers are those concerning the Pacific Ocean. During the interwar years the USA increasingly regarded it as the arena for peaceful international collaboration. Even in the period of the Cold War, scientific programmes like the International Geophysical Year of 1957/58 continued, within limits set by national security. In the USA itself, oceanographic research was pursued for a variety of reasons – scientific, commercial, military – often in combination. Adler provides a case study: Cobb Seamount is a guyot 270 nautical miles west of Grays Harbour in Washington State. He describes its summit as 'only twenty-six feet from the surface' (p.119). [*Metres*, surely? The generally accepted figure is 34 m (112 feet).] Lying at such a shallow depth and well outside any national jurisdiction, it seemed ready for occupation. Ambitious plans were made for an underwater habitat, but funding was never adequate to develop them, probably because the USSR showed less interest in pursuing this kind of seabed technology. Nevertheless, between 1968 and 1975 there were ten diving expeditions to the seamount, during which it was thoroughly surveyed, examined and instrumented. Cobb became the largest open-water scuba project ever conducted.

To illustrate changing conceptions of the ocean in the 20th century, Adler chooses two individuals who reflect the prevailing attitudes of their times: the visionary, if eccentric, hydraulic engineer Carroll Livingston Riker (1853–1931) and Elisabeth Mann Borgese (1918–2002), the indefatigable promoter of international ocean governance. Riker, under the slogan 'Man Can Control All', proposed building a 200-mile jetty from Newfoundland across the Grand Banks to obstruct the Gulf Stream and deflect the Labrador Current, thereby warming the American seaboard at the expense of northern Europe; fortunately nothing came of it. Borgese was more successful; her influence was a key factor in the negotiations that led to the adoption of the *United Nations Convention on the Law of the Sea* in 1982. Although human relations with the natural environment are gradually moving from conquest to conservation, there's still a long way to go and not much time left. The scale of change has to be international.

By exploring the progress of humanity's relationship with the sea from around 1850, when it intensified together with rapid growth in the marine sciences, the author shows how social and political pressures have combined to produce the crisis threatening our oceans today. He covers a vast subject as comprehensively as one could hope in a relatively short book (~ 60 000 words, plus an abundance of endnotes), adding that the field is by no means exhausted. As an interdisciplinary work of consistent accuracy it will be appreciated by scientists and historians alike, while its fresh perspective should appeal to a far wider public.

John Phillips
Marine bibliophile

OCEAN Challenge

The Challenger Society for Marine Science

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of marine science through research and education

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

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

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

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

Holding regular scientific meetings covering all aspects of marine science

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

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

Membership provides the following benefits:

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

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

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

MEMBERSHIP SUBSCRIPTIONS

The annual subscription is £50 (£25 for students in the UK only). If you would like to join the Society or obtain further information, see the website (given above).

COUNCIL FOR THE CHALLENGER SOCIETY

For information about Council members see the Challenger Society website

ADVICE TO AUTHORS

Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. For further information (including our 'Guidance for Authors') please contact the Editor:

Angela Colling, Aurora Lodge, The Level, Dittisham, Dartmouth, Devon, TQ6 0ES, UK.

Tel. +44-(0)1803-722513 **AngelaMColling@gmail.com**