OCEAN Challenge

Challenger Expedition
150th Anniversary

Tara Oceans : a window into the world of plankton • The birth of shelf-sea oceanography • The challenges of siting wind turbines offshore • Using 19th century data in climate science • Engaging with policy-makers

Vol.27, No.1

OCEAN Challenge

The Challenger Society for Marine Science

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

SCOPE AND AIMS

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

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**)

INDUSTRIAL CORPORATE MEMBERSHIP

For information about corporate membership, please contact Terry Sloane Terry@planet-ocean.co.uk

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OCEAN Challenge

The Challenger Society for Marine Science

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of marine science through research and education

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

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

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

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

Holding regular scientific meetings covering all aspects of marine science

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

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

Membership provides the following benefits:

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

Receipt of *Ocean Challenge* and 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 and retired members in the UK only). Corporate Membership is £150, and Library membership £40. If you would like to join the Society or obtain further information, see the website (above).

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 please contact the Editor: Angela Colling, Aurora Lodge, The Level, Dittisham, Dartmouth, Devon, TQ6 0ES, UK.

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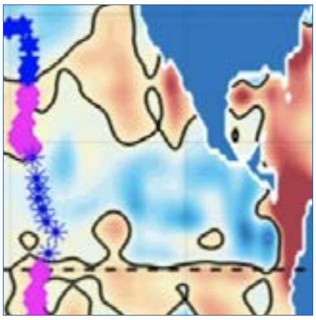

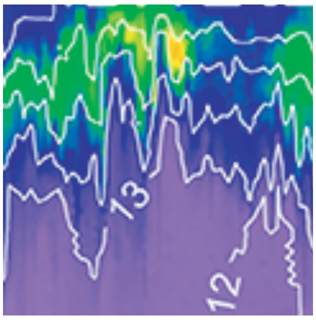

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Most of the maps and diagrams were drawn by The ArtWorks.

The cover and heading graphics were designed by Ann Aldred.

Cover photo:
School of fish off Australia
Matt Curn/
Ocean Image Bank

Message from the Editor

Sharp-eyed readers will have noticed that we are again using the *Challenger* Expedition 150th Anniversary logo on our front cover. This is because *Challenger* did not arrive home until May 1976, and was collecting data for three-and-a-half years, and in this and forthcoming issues you will find articles showing how present-day research is making good use of observations collected by HMS *Challenger*. The *Tara* Oceans project – the subject of the feature article in this issue – was inspired by the *Challenger* expedition and other early explorations of the ocean.

Challenger enthusiasts might enjoy the *Challenger*-related resources on the website of the Scottish Association for Marine Science (SAMS), https://www.sams.ac.uk/. Here you can follow the journey of HMS *Challenger* and use the interactive tool to explore the species discovered during the Expedition, along with ocean temperatures at *Challenger* stations.

SAMS is also the location for the 2024 Challenger Society Conference – so do consider making a date to visit Oban in September 2024!

Angela Colling

Atlantic overturning: new observations and challenges

A Royal Society Discussion meeting on this theme was held in December 2022 and articles arising from the event have been published in a special issue of *Philosophical Transactions of the Royal Society A* edited by M.A. Srokosz, N.P. Holliday and H.L. Bryden FRS

Overview The Atlantic meridional overturning circulation (AMOC) is projected to slow down or stop under global warming, with major climatic impacts. To determine the likelihood of this happening, and to understand its present state requires observations of the AMOC, which have only been available since 2004. Despite recent suggestions that the shutdown will happen soon, observations suggest a more complex picture of the AMOC's behaviour and point to the need to continue observing to improve future projections and to provide robust advice to policy-makers. The new observations have led to a paradigm shift in how the AMOC is conceptualised – from simple conveyor belt to more complex flows – and further observations will no doubt continue to raise new research challenges.

The articles (mostly open access) are available at https://www.bit.ly/TransA2262

You can watch recordings of the talks at
https://www.youtube.com/playlist?list=PLg7f-TkW11iWJsq-JpD9iHqWzlZ8mWbg4

The 2024 Challenger Society Conference will be held at the Scottish Association for Marine Science, Oban, 2–6 September

2024 CHALLENGER SOCIETY CONFERENCE

SAMS Scottish Association for Marine Science

The rewards of engaging with policy-makers

Matt Frost

Dr Matt Frost is Head of the International Office at Plymouth Marine Laboratory (PML). Matt chairs numerous science policy committees including the UK's National Decade Committee, the Marine Climate Impacts Partnership and the World Association of Marine Stations. Here, he shares his thoughts on why working with policy-makers is both important and rewarding.

Over the last two decades I have had the immense privilege of working at what is commonly referred to as the 'science–policy interface'. From attending meetings for PML as a registered observer for the Convention of Biological Diversity at the United Nations Office in Nairobi, giving evidence to numerous UK parliamentary committees, and working on issues of global diplomacy and human rights, it has been, and continues to be, an immensely rewarding career path.

Despite the fact that engagement between scientists and policy-makers is a useful and valuable activity, I still sometimes come across 'concerns' raised by scientists, and by students I am lecturing on engaging with policy-makers. These concerns usually fall into two categories. First, there is a fear that scientists working with policy-makers might compromise their scientific integrity by being drawn into advocacy and lobbying. Secondly, it is often difficult for scientists to identify 'impact' when engaging in policy, and it can be hard to see what such engagement achieves.

Let's look first at the issue of scientific integrity, the fear that the 'trusted' scientist interested only in 'hard facts' can become biassed or compromised (politically or commercially) through political engagement. This has been a hot topic for many years in conservation science where some say that the 'triple planetary crisis' of climate change, pollution and biodiversity loss means scientists must 'get off the fence' and speak out, even if this becomes advocacy rather than just providing evidence. I completely understand the dilemma some find themselves in here. Some years ago I was leading a major report on the state of marine ecosystems and found myself in the middle of two groups who wanted to emphasise different messages. The more government-related group were keen to promote improvements in sectors due to new policies and conservation measures, while NGOs were more keen to use older baselines to show that despite some improvements, the situation was still dire for many habitats and species. I decided all I could do was present the evidence and provide the context in terms of what we knew about baseline conditions – it was not for me to spin up a message either way.

One of my science–policy roles is to chair the Marine Climate Change Impacts Partnership (MCCIP), the primary independent source of information about evidence for the impacts of marine climate change and of advice about adaptation in the UK. We have been working with government for many years, seeing much of the evidence and advice feed into policy and legislation. We have had to work hard to ensure all the many scientists who contribute know their work is translated and communicated in such a way that MCCIP retains its reputation for independence and scientific integrity. We have even developed and published our own model for science–policy engagement where we deal with issues such as how to communicate science, and scientific concepts such as uncertainty, to an audience made up primarily of non-scientists.* In doing this we have found, as have many other scientists engaging in policy, that it is possible to work as an independent non-biassed source of scientific information for policy-makers.

Secondly, impact. A recent interview with Professor Richard Thompson OBE drew a clear line from early research findings on microplastics in 2004, through growing media and government interest, to today where the Intergovernmental Negotiating Committee has recently held its third session on developing an international legally binding instrument on plastic pollution. The problem is that a clear line from research to policy development is rarely this clear or obvious. Many of us working in the science–policy arena can point to years of attending meetings, writing policy briefs and providing evidence, but change, if it does occur, can appear slow (and sometimes non-existent). Researchers are accustomed to clear metrics of career 'success' like publishing output, an H-index or grant success. Speaking to a room full of decision-makers rarely results in such obvious and immediate measures of achievement, with the hoped-for changes more likely to come years later due to an incremental build-up of evidence feeding into discussions, consultations, policy development and legislation.

I would argue, though, that recent success stories like seeing the ocean play a bigger role in the United Nations Framework Convention on Climate Change discussions, the 2023 agreement on Biodiversity Beyond National Jurisdiction and the 2023 World Trade Organization Agreement on banning harmful fisheries subsidies are all positive developments that show the value of long-term engagement by the marine science community. It's clear that scientists should be embracing the chance to influence change in policy, industry and other sectors. Furthermore, research councils and other funders increasingly look for and reward valuable scientific contributions beyond traditional academic outputs.

Yes, it can be harder to show where your particular scientific contribution has led directly to a new policy or law but I am increasingly seeing a desire from scientists to see their work have relevance and impact beyond the academic community. Many scientists are finding that the concerns discussed in this article can be overcome and that engaging at the science–policy interface can be truly rewarding.

Matt Frost
Plymouth Marine Laboratory
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*Frost *et al.* (2017) Reporting marine climate change impacts: lessons from the science–policy interface. *Environmental Science and Policy* **78**, 114–120. doi: 10.1016/j.envsci.2017.10.003

If you would like to know more about engaging with policy-makers, one of the best opportunities is provided by the Royal Society Pairing Scheme: https://royalsociety.org/grants-schemes-awards/pairing-scheme/.
For other advice, please contact Matt.

Challenger Special Interest Groups get together

The Challenger Society supports ten Special Interest Groups (SIGs) covering a wide variety of disciplines. To learn more, go to 'Special Interest Groups' on the Challenger Society website, challenger-society.org.uk, and click on the relevant photo. Here are reports from recent meetings of two of the SIGs.

Advances in Marine Biogeochemistry (AMBIO)

Molly Phillips

This year marked the tenth biennial meeting of AMBIO, the SIG devoted to Advances in Marine Biogeochemistry. Academic and industry organisations met at Plymouth Marine Laboratory to share talks and posters on the theme of Marine Biogeochemistry for the Future. Four sessions covered: (1) Biogeochemistry and Marine Autonomy; (2) The Cutting Edge of Biogeochemical Observations and Modelling; (3) The Future of GEOTRACES; and (4) Marine Biogeochemistry at the Sediment–Water Interface.

The three-day conference had keynote speakers for each session, followed by session talks from both established and Early Career Researchers (ECRs). Each session was extensively live-tweeted by Sarah Cryer (@SarahECryer), so her posts from 6–8 September are worth looking at, along with posts about the research that went into her highly commended talk on carbonate chemistry in coral reefs.

This was my first experience at a conference, and Kate Hendry (Chair) and Sarah Reynolds (Co-Chair) made sure to make the event welcoming to all attendees, particularly with the lunchtime networking event where senior scientists joined for a Q&A session on Research Fellowships. Rhiannon Jones felt the Q&A was 'like an open discussion, that was really beneficial to my understanding of the fellowship process'. The networking event was also a great opportunity for ECRs to meet, and formed a good foundation for further discussion at the conference dinner on the second evening.

ECRs who had produced a poster were invited to give a one-minute 'Flash Talk', to introduce their research before the poster session began. The poster session was a great opportunity for all attendees to network, or catch up since the AMBIO meeting at the Challenger Conference last year. I definitely would have liked more time to get around to all the great posters being presented, and as far as my own poster was concerned, I thoroughly enjoyed receiving questions from scientists with different perspectives, challenging what I understand about my research. The presentation also allowed me to tailor how I explain my work, as AMBIO members come from a range of different research backgrounds.

In the ECR poster competition Isabelle Cooper and Ben Fisher were highly commended for their posters on nutrient influxes to sediments and the future pressures on Antarctic marine phytoplankton, respectively. My poster on a new alkalinity sensor technology, designed to measure over large concentration ranges, won overall.

Undergraduate student Stephanie Hodnett, whose talk was also highly commended, 'learnt an awful lot from the conference' and felt that the welcoming and relaxed environment of the conference 'made presenting and answering questions really enjoyable'. Her work, like many of the other talks, used data from the CUSTARD project. This project looks at seasonal nutrient availability for phytoplankton, and how the availability influences the long-term storage of carbon in the ocean.

Of particular interest to me were the many talks focussed on measuring marine carbonate chemistry *in situ*, particularly Allison Schaap's talk on autonomous total alkalinity sensors in the first session, and Ben Cala's talk on carbonate mineral dissolution experiments in the second session. Both of these talks showed the exciting future for those of us making measurements to help improve understanding of the marine CO_2 system; such measurements are becoming increasingly important, as the change in ocean pH becomes more significant due to ocean acidification.

The author standing by her prize-winning poster on the development of an innovative in situ sensor for alkalinity

'Blue carbon', carbon captured by marine systems, was also featured throughout talks in sessions 2 and 4, with Hugo Woodward-Rowe's research around blue carbon at decommissioned oil and gas platforms winning the ECR Best Talk. Hannah Muir shared her research on blue carbon in sediment around the Isle of Man, and Claire Powell used a case study in the North Sea to illustrate how Cefas is monitoring blue carbon in shelf seas.

Overall, AMBIO's conference definitely hit the brief of Marine Biogeochemistry for the Future. There was a real emphasis on supporting and celebrating ECRs: the next generation of marine biogeochemists.

At the townhall, Katy Hill from the FMRI* had raised a call for ideas on what marine biogeochemical measurements should be improved or developed in the future, and Sarah Reynolds brought together the feedback on this topic. The AMBIO community had some great suggestions for tackling the limitations on currently available *in situ* measurements, and for the parameters we would prioritise in developing measurement techniques. However, the general feeling was that we can't immediately replace traditional methods, used on research cruises, with state-of-the-art autonomous underwater vehicles, as we don't yet know their *in situ* performance, or long-term capabilities.

Kate and Sarah will continue in their roles for the next year, until AMBIO meets again next September in Oban, during the Challenger Society Conference at the Scottish Association for Marine Science campus.

Molly Phillips is developing a high-frequency, wide concentration range, alkalinity sensor at the at the University of Southampton. Her work is funded by Southampton Marine and Maritime Institute. Molly.Phillips@soton.ac.uk

*The FMRI is the Future Marine Infrastructure Programme.

Deep-Sea Ecosystems

James Bell

The Deep-Sea Ecosystems Special Interest Group has been meeting annually since around 2015 and comprises about 40 academics and civil servant scientists across a range of career stages working in deep-sea science in the UK. The group's members focus on a range of deep-sea research topics spanning biochemistry, community ecology and genomics. We work extensively in the north-east Atlantic, as well as further afield including the UK Overseas Territories and the Southern Ocean. Members are also active participants in a range of fora, including the UK Marine Facilities Advisory Board, the Deep-Ocean Stewardship Initiative, and regional fisheries management organisations. The annual meetings are a welcome chance for the group to catch up and invite colleagues to share their work, in particular students and early career researchers.

This year the meeting, convened by Kerry Howell and myself, was held on 13–14 September at the Centre for Environment, Fisheries and Aquaculture Science (Cefas) in Lowestoft. We welcomed around 25 people to the physical meeting, as well as a number who attended online, and there was an engaging mixture of presentations and discussion groups.

There were four sessions with presentations, as follows:

- Clarion–Clipperton Zone: Ecology and Biogeochemistry*,* with presentations from Herriot-Watt University, the University of Leeds, and Cefas. The Clarion–Clipperton Zone is the principal area of research into the potential impacts of deep-sea mining. This area, spanning most of the region between Mexico and Hawaii, and larger than western Europe, plays host to vast quantities of polymetallic nodules, and scientists from our SIG are working closely with international partners to understand the likely impacts of the proposed mining activities.

- Biodiversity and Functional Ecology of Deep-Sea Ecosystems, with presentations from the universities of Plymouth and Oxford, Herriot-Watt University and Ocean Census/Nekton Foundation. Efforts to understand the deep sea suffer from a chronic lack of data but we know that life here underpins a range of important ecological functions and services. In this session, we heard about efforts to expand knowledge of biodiversity in the deep ocean and to alert society to the value of ecosystem services provided by the deep sea.

- Deep(-sea) Engagement*,* with presentations from the Deep-Ocean Stewardship Initiative, Armatus Oceanic and the Sustainable Ocean Alliance (Costa Rica group). The deep sea is home to many enigmatic and fascinating species and environments, and increasingly faces threats from human activities. This session saw talks from experts spanning a range of public and policy engagement relating to deep-sea research, all the way from grassroots organisations in Latin America up to international policy work at the UN.

- Methods Development for Deep-Sea Ecology, with contributions from the University of Plymouth and Cefas. Members of our SIG are actively engaged in developing new methods for improving deep-sea research, ranging from improving image data acquisition through to innovative machine learning tools to communicate with managers and policy-makers.

The first discussion session, on Cross-Governmental Policy and Science Network for Deep-Sea Mining Evidence*,* was led by Defra. Negotiations on regulations for the exploitation regulations for deep-sea mining continue to progress at the International Seabed Authority. Through our SIG, Defra are leading the creation of a science and evidence network to ensure that relevant academic research can be most effectively utilised in the design of regulations to minimise ecological damage and to identify the most pressing outstanding data gaps hindering the creation of such regulations.

*Bubblegum coral (*Paragorgia *sp.) on the Grattan Seamount, in the Ascension Island Marine Protected Area.*

(Photo: Ascension Island Government and UK Blue Belt Programme)

The second discussion session, on UK Science Developments*, was* led by the universities of Plymouth and Essex. This is a regular feature of our meetings and several of our members serve on various national boards and committees relating to marine research and infrastructure. Those representatives fed back on recent developments and we held a discussion on what the deep-sea research community will need in terms of equipment infrastructure in the future.

After serving as the meeting Chair since 2019, Kerry decided it was time to move on and I (James) have stepped up to lead our SIG over the next few years. I've been a member since 2015 and, moving forward, my priorities for the deep-sea research network are: to grow and reach out to people not currently involved; to strengthen the links between academics and policy counterparts in the UK Government through organisations like the Joint Nature Conservation Committee (JNCC) and Cefas; and to address equality and inclusion within the UK deep-sea community, building on my role as co-lead of Tackling Racism at Cefas.

Thanks to everyone who participated in the meeting and made it such an enjoyable event. Our next meeting will be tied into the Challenger Society Conference in September 2024 at the Scottish Association for Marine Science in Oban, and we hope to see you there. In the meantime, for more information, and for instructions for how to join the mailing list, see the Deep-Sea Ecosystems webpage at challenger-society.org.uk.

James Bell works at Cefas, principally on the UK Government Blue Belt Programme with the UK Overseas Territories.
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The other Challenger Society SIGS are: Ocean Wind Waves, Sea Ice, Sea Level, Coastal and Shelf Seas, Ocean Modelling, Marine Science and Policy, Marine Data Science, and History of Marine Science.
challenger-society.org.uk

EuroGOOS holds its 10th Conference in Galway

A Global Ocean Observing System (GOOS) was established by the Intergovernmental Oceanographic Commission of UNESCO in the early 1990s with the aim of coordinating ocean observations around the world to support real-time services, support life in the oceans and address climate change. GOOS is organised in thirteen regional alliances around the globe and EuroGOOS – the European Global Ocean Observing System – is one such regional alliance. Member organisations are in thirteen European countries; those in the UK are the Centre for Environment, Fisheries and Aquaculture Science (Cefas), the National Oceanography Centre (NOC) and the UK Met Office.

In October 2023, Ireland's member organisation, the Marine Institute in Galway, hosted the 10th EuroGOOS Conference. Through the Marine Institute, Ireland has been a member of EuroGOOS since c. 2005 and Irish scientists participate in EuroGOOS regional systems, task teams and working groups.

This conference was entitled 'European Operational Oceanography for the Ocean We Want: Addressing the UN Ocean Decade Challenges'. Operational oceanography is the timely provision of oceanographic information to a range of end-users: commercial (maritime traffic, fishers, aquaculture producers), government agencies and regulatory authorities, people involved in search and rescue; also those working in longer term monitoring of climate and in satisfying European obligations such as the Marine Strategy Framework and Marine Spatial Planning Directives.

Operational oceanography encompasses the systematic collection of routine and long-term measurements of the ocean and atmosphere, and their rapid interpretation and dissemination to users. It usually involves the swift transmission of observational data to data assimilation centres where numerical forecasting models process the data to allow the generation of data products, often through intermediary organisations.

Important products derived from operational oceanography, relied upon by users in Europe and worldwide, are: accurate description of the present state of the sea including living resources; continuous forecasts of the future condition of the sea for as far ahead as possible; and hindcasts assembling long-term datasets which provide data for description of past states, and time series showing trends and changes.

Examples of products include warnings of coastal floods, ice and storm damage, harmful algal blooms and distributions of contaminants, etc., along with electronic charts, optimum routes for ships, prediction of seasonal or annual primary productivity, ocean currents and ocean climate variability.

The 10th EuroGOOS conference brought together more than 160 experts – oceanographers, ocean forecasters, technology developers, policy-makers, providers of data services and their recipients. They exchanged ideas and shared recent developments, and discussed priorities in the context of the UN Decade of Ocean Science for Sustainable Development 2021–2030.

A Conference Statement (to be found at https://marineinstitute.clr.events) summarised the conference presentations and discussions, and provided a signspost for EuroGOOS activity in coming years. The statement began by acknowledging that while the diversity of Europe and the European operational oceanography community is a great strength, it can also lead to fragmentation and associated challenges.

Here is a condensed summary of the 'Key priorities and messages' arising from the conference, and set out in the Conference Statement.

- Operational oceanography in Europe must develop with a holistic Earth system approach, and be better connected to other environmental domains (terrestrial, hydrological, atmospheric, cryospheric, climatic, etc.) as well as socio-economic information systems.

Operational oceanography helps mariners avoid accidents at sea, which can lead to loss of life, loss of goods and pollution.


(Photo: NASA)

- Ocean observations must be sustainable, cost-effective and with sufficient coverage. The continued development of the European Ocean Observing System (EOOS) is of the highest priority.
- EuroGOOS activities are an important asset contributing to the UN Ocean Decade Challenges. Alignment with Decade activities and objectives will further reinforce the impact of EuroGOOS, helping to realise its vision at a global level.
- For operational oceanography to truly meet societal needs, stakeholder engagement and co-design of the system with users, must become the standard practice from the outset. Only through properly planned and resourced engagement and co-design activities, including iterative review as needed, can operational oceanography fully deliver its benefits. Ocean Literacy is key if co-design and stakeholder engagement are to reach their full potential.
- Enhanced training and education are needed, along with opportunities to ensure operational oceanography is an attractive career path, whether in scientific, technical, managerial or other domains.
- Appreciation of the value of ocean observing and operational oceanography should not be taken for granted. Their importance needs to be highlighted through communication, awareness-raising, and demonstration of economic value.

Beyond these overarching priorities, several specific recommendations emerged regarding improving/enhancing ocean observations, modelling, forecasting, Digital Twins of the Ocean and data, as well as engagement and ocean literacy. See the conference website for more details: https://marineinstitute.clr.events

If you are interested in becoming involved in the work of EuroGOOS, see https://eurogoos.eu/about-eurogoos/list-of-eurogoos-member-agencies-and-contact-persons/.

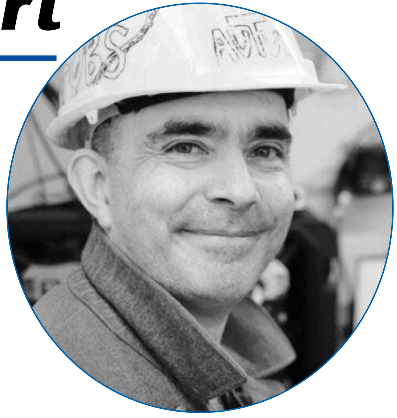
Ed

Information about conference outcomes was taken from the conference website. Thanks also go to Glenn Nolan, Marine Institute, Galway, for his assistance.

An interview with a deep-sea ecologist who loves tech, sci-fi and art

Dr Autun Purser, of the Deep Sea Ecology and Technology Group in the Alfred Wegener Institute (AWI) in Germany, carries out deep-sea ecological studies, overseeing the underwater imaging systems for the group. He usually works with remote AUVs or towed camera systems, often on the RV *Polarstern* in ice-covered waters. He is usually at the forefront of exploration of these areas, using the latest generation of equipment. After a recent cruise to Arctic waters he discussed his work, and thoughts about science, with Kelvin Boot.

Ed



(Photo: Mario Hoppmann)

You've just stepped ashore from your latest research cruise on the* Polarstern*. What were you doing?

We were collecting a great set of data to add to a 20-year time series in the Fram Strait. We often set out from the Norwegian island of Spitsbergen and go across to eastern Greenland, stopping at various fixed points or reference stations which we visit every year. My job is to look at the sea-floor communities at these locations so I video and photograph the megafauna – the larger animals – and we can see that those communities across the Fram Strait are changing quite a lot. This is really interesting and important data to collect as we think the Gulf Stream may be slowing down against a background of general warming and reduction of ice. Ice-loss causes many ecological problems. An example is the effect on the algae that grows on the bottom of the ice – if there's no ice we will lose the algal flux to the sea floor, which is likely to affect the community there.

How deep do you go?

We cover the whole Arctic depth range in this transect, from the shallows, several hundred metres depth off Spitsbergen, across to the Molloy Deep, in the middle of the Fram Strait, which at 5500 m deep is the deepest part of the Arctic. All of our equipment is depth-rated, so we can even investigate the flanks of trenches down to 6000 m, but most of my work is at 2000–5000 m.

How did you arrive at the job that you are now doing?

I grew up in Tintagel on the Cornish coast, and I've always liked the ocean. I did an oceanography course in my thirties, then I was offered a Master's Degree, in Germany, on cold-water coral reefs, and it just carried on from there. I like to explore new areas and I do like being involved in the hands-on development of the technology, so what I do now seems ideal and is very stimulating.

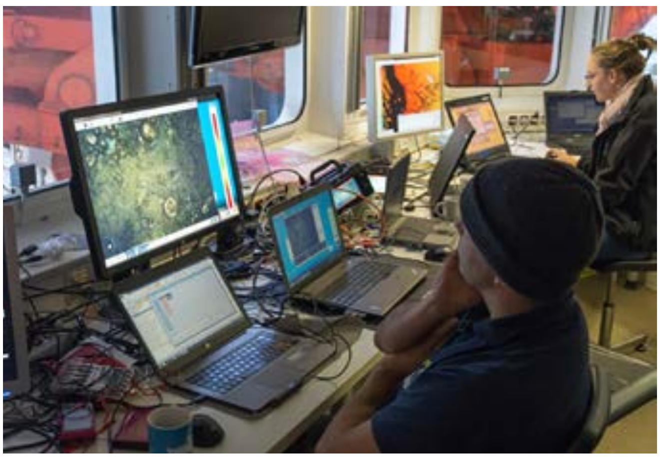
You work alongside the technicians and engineers to develop the devices. It must be so gratifying for you all when you get it to the sea floor and everything works perfectly

Absolutely, it's teamwork. The technicians are as crucial as the scientists in deep-sea work because every ship is different and the software keeps being improved, which always brings challenges for some of our legacy equipment.

We've been using our latest towed camera sled for four or five years now and it's almost past the protype stage. We began just photographing the sea floor but what has really helped the recent work, and publications on the crawling sponges and the fish nests (see photos), is the fact that we've bolted side-scan sonar onto the camera sled. We're flying at 1.5 m above the sea floor and photographing an area of about 5 m^2, which is a very small area of the deep sea, but at the same time we're now taking a 100 m swathe with sonar, and we can see anything bigger than a few centimetres in the sonar image. So we are now exploring quite large areas of the sea floor in fantastic detail.*

The technology has certainly come a long way since HMS* Challenger*!

Challenger *would have just one small sample from a point location whereas in three hours travelling at 1 knot, we will take 600 photographs at 24 megapixel resolution, and we'll take HD video, so we get a great idea of what's there and how creatures are moving, as well as detailed information about the rise and fall of the sea-bed topography. It's giving us far more spatial information than we've had in the past, and we see the animals alive. We can even see tracks and trails, signs of life, in the sea-floor mud, which you would never get with physical sampling.*



Scientists in the winch room on RV Polarstern *looking with amazement at images of the large sponge field on seamounts under the Arctic ice, in the video feed from the PS101 AWI OFOS camera system.*

*See: Giant sponges discovered on Arctic seamounts, *Ocean Challenge* **26** (2), 20–26.

We've also deployed fixed sea-bed cameras for the past five years. On this last trip we retrieved a camera that's been on the sea bed for the last year taking an image with flash every 6 hours, so we really see the ways the animals are behaving in the absence of our towed, potentially noisy equipment.

The cameras capture the pulses of organic debris that occur through the year, sometimes lasting just a few days but having a large impact on sea-bed life. We've known about these for quite a while, but the cameras are now providing much more information, even in the Arctic. Of course ships can only go to these areas in calmer conditions, and if our time-lapse cameras weren't there when events like this occur, we would completely miss them.

This new technology reveals another world. What have you seen that has amazed you the most?

The ice fish nursery was strange – it looked like a poorly programmed computer game from the early 2000s (photo, right), because every nest was identical, and they were arranged grid-like for kilometre after kilometre. That was amazing. Thanks to our side-scan system, after surveying the site and consulting our data, we estimated that there were 60 million nests across the colony, representing 60 000 tonnes of fish. In the past any camera had only occasionally seen one or two nests. So, it's great that in one deployment we could understand the sheer size of some of these things.

But perhaps the most surprising for me was the sponge community on top of seamounts in the central Arctic. It's a long way under permanent ice and the entire tops of these seamounts were covered by living sponges that we now know were crawling! To me as a real science fiction fan it's like visiting a planet by Polish writer Stanislav Lem where ecosystems are obviously working, but humans cannot understand how. I like trying to understand the un-understandable – life down there is doing stuff completely different to what we are used to – it's working on a different temporal scale and we still don't understand it.

You talk about science fiction worlds. Do you think that what you are seeing is giving us hints about life elsewhere?

Well, I am a very big fan of the idea that life is going to be anywhere where there's an extreme gradient, be it chemical, pressure, temperature, whatever. Where there's a sudden differentiation in an environment, life can establish itself. Bacteria are a great example – they exist in every single location and they change so quickly. On this recent cruise we visited an area where gas hydrates are breaking through the mud. We've been going to this area every year for the last 20 years, and when you approach the methane area the community changes completely. You've got worms, totally different fish, mobile and sessile animals just a few metres away from the background community; life finds niches everywhere and I'm sure there is life elsewhere in the Solar System.

Are you tempted to knock on NASA's door and become an astrobiologist?

Well, we do have projects with NASA, ESA and the German Space Agency about developing underwater robots for sensing life in other environments. We have one project to make small AUVs to go through the ice of Europa and Enceladus, moons of Jupiter and Saturn, to look for traces of life, and we'll test them in the ice of the Weddell Sea. We're developing techniques to find life, not necessarily in the obvious way of seeking DNA but perhaps those extreme gradients I mentioned, if we can get to them.

The deep sea is so remote from our environment. Is the deep so deep as to be safe from the threats our seas face?

It's definitely not safe because we already have changes in the algal communities in the upper waters. Even under the ice we are seeing changes in the photosynthetic communities and the things that feed on them; we're seeing an increase in gelatinous organisms, which in turn feed different communities, so the ecosystem is changing and that's bad for biodiversity, and ultimately for us.

We're beginning to exploit minerals such as manganese nodules. Does your work help to inform how, or indeed whether, we should go forward with these operations?

Yes, some of our work will do that. We filmed benthic octopuses that spend all their lives on the sea floor, among the manganese nodules in the South Pacific. They lay eggs on

Right *Just a few of the 60 million fish nests covering an area of 240 km^2 beneath the ice of the Weddell Sea. The small fish are known as Jonah's ice fish. Area shown = 4 m x 7 m.*

Below *An ice fish using its pectoral fin to clear away sand and gravel to make a nest about 15 cm deep.*

(Images taken using the PS101 AWI OFOS camera system)

stalks on the nodules, so if we lose the nodules we lose the octopuses. Most exploitation is in the North Pacific, but we now know what lives on the nodules further south so we are armed with information we didn't have before, so at least we can now advise governments about what may be threatened by nodule removal. I do think our work does have impacts.

When it comes to extracting nodules I'm a proponent of the 'drunkard's walk', with the mining device going forward 100 m then choosing a random compass direction, and going another 200 m, so zig-zagging rather than strip mining. It may cost a bit more for the ship but it will leave islands of untouched communities, rather like in the terrestrial rainforest where such islands are shown to maintain biodiversity.

I think we have a duty to give good advice. We shouldn't stay on our scientific clouds and not get our hands dirty with policy. We get a lot of money from taxpayers and industry and we have an obligation to advise in a sensible way. It is often difficult for scientists – many are contract scientists and simply don't have the time to be involved in policy when their futures are reliant on the number and quality of publications. We must make time and space for opinions.

Do you see a future for an Environmental Impact Assessment approach, in much the same way as happens on land?

I think it will go forward in that direction. There's interest in establishing a similar approach to what we do with our monitoring regime in the Fram Strait, in Antarctica. People are interested in the natural community, seals and the wild community down there, so I think there should be wide support for long-term monitoring, especially in the more picturesque, charismatic or important environments. It could get expensive quite quickly if we cover large areas and great depths, but sensible, cost-effective monitoring in the face of climate change and other threats will be necessary over the next decade or so.

Are you optimistic about the future of the oceans?

Ah! That's a great question! There will be huge change, but life will find a way even though some species will have a tough time of it. Back in the Weddell Sea, if the ice goes the fish nests will probably no longer be viable, because the juvenile fish feed on the algae under the ice. If there's no ice to protect them, they'll come up only to be eaten by something else, or remains of dead algae might rain down from the surface and smother any nests. We don't know what will happen, but we will see changes.

Long-term monitoring stations, like in the Fram Strait or the Porcupine Abyssal Plain, already indicate that changes are happening. We now know that far from being remote and unconnected, the deep sea is closely linked to the upper ocean. What will happen in the future, how fluxes from the surface to the deep sea bed will be affected, is totally unpredictable. We know that event timings are crucial – some species are broadcast spawners that produce eggs and sperm once a year based on a single lunar cycle. If that doesn't fit with any change in algal cycles, then they are all likely to die. Some animals, on the other hand, are more opportunistic and they may increase in abundance. We can't yet say who the winners and losers might be, but entire ecosystems will be unbalanced.

You're a huge sci-fi fan and an illustrator. Does your science feed the fiction, or fiction feed the science?

They feed each other. I'm greatly influenced by science fiction that describes life forms and worlds so different from our own, the unknown and alien, so I started doing illustrations for some of these old books, using my scientific experience to create the images. When I do my illustrations, I am influenced by the things I see. I was asked to illustrate a science fiction book based on the premise that trilobites were the dominant animals on Earth, so it was great to bring them alive through my illustrations using photographs of environments from my scientific work. I also make drawings of the cruises I go on. This makes me look at the animals and other features more closely, and that gives me a much better understanding of what I am looking at. It's too easy to get the wrong end of the stick in science and I think science fiction has made me look at things in a different way and keep conclusions tentative. Some scientists cling to their ideas through thick and thin. I'm quite flexible, and look at things with slightly 'broader eyes'.

What's next for Autun Purser?

Well, for years I have been a post-doc, but this year I am starting a permanent position at AWI and that will give me opportunities to apply for more grants myself and drive my own projects so I can really think about what I want to revisit and look at in more detail. For example, there is the methane area I mentioned, which I want to go back to. We've also got the fish nests; I want to learn more about how that community works. And I would really, really like to drop the camera down to other previously unexplored polar seamounts, to see whether the sponges are exclusive to where we found them; there are about 600 seamounts in the Arctic and the only good camera work is on the seamount we visited!

Do you have any advice for the next crop of scientists, just starting out?

Don't try and change the world with all your papers, remember not everything should or can be aimed at the top journals. 4000 words, six figures and a succinct story highlighting small observations are super important. Keep the stories focussed, concentrate on addressing one particular question, with a useful outcome but perhaps also hinting at larger possibilities. On a more practical level, get some coding skills and a grasp of technology – it's no longer just about pure biology.

Further reading

'World's largest fish breeding grounds found under the Antarctic ice' by Erik Stokstad. *Science,* News 13 Jan 2022. doi: 10.1126/science.ada0112

To see some of Autun's art, go to https://www.apillustration.co.uk/ (Autun's work includes the cover art for the SF Masterworks series of books, published by Orion Gollanz.)

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Using 19th century data to study climate-induced changes in the hydrological cycle

Many of the environmental challenges arising from global warming – excessive rainfall and flooding, desertification, and stronger tropical cyclones – are a manifestation of an increase in the intensity of the hydrological cycle. As far as the oceans are concerned, patterns of evaporation and precipitation, as determined by the global wind system, are reflected in the distribution of sea-surface salinity, with areas where evaporation exceeds precipitation having higher salinity and those where precipitation exceeds evaporation having lower salinity (see Figure 1).

We think of climate change studies as relying on new data collected using new techniques, but collection of data from the oceans on a global scale began in the 1870s with the expeditions of HMS *Challenger* (1872–76) and the German vessel SMS *Gazelle* (1874–76), about a century after concentrations of greenhouse gases began to rise as a result of increasing steam-driven industrialisation.

Oceanographers today take for granted that seawater salinity will be measured using conductivity, but up until the mid 1960s it was necessary to determine the concentration of dissolved salts by weight. In the 1870s this could be done using a hydrometer, which determined specific gravity (numerically equal to density) (Figure 2) using Archimedes' Principle: the extent to which a hydrometer sinks into a liquid such as seawater depends on the weight of liquid displaced, and hence on the density/specific gravity of the liquid.

Challenger's chemist, John Young Buchanan, was meticulous in measuring the specific gravity of the many seawater samples collected during the expedition, including surface samples collected with a bucket, under his supervision. Buchanan used a hydrometer of his own design (Figure 2); he wote *'... I considered that the specific gravity of the water of the ocean, and its variations, would be one of the most important matters for continuous observation. ... I chose the hydrometer ... because it appeared to me to be the only type of instrument which furnished directly the information demanded, namely, the specific gravity of the water, and that with the exactness required ... indirect methods are, in the nature of things, affected with at least a double quantity of errors ...'*. For consistency of measurement Buchanan used the same hydrometer and weights throughout the expedition.

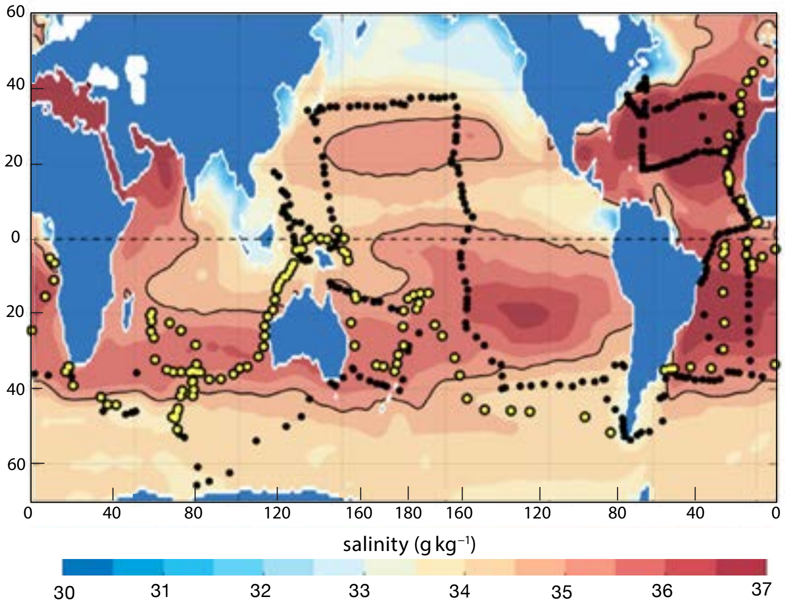

Figure 1 Challenger *(black) and* Gazelle *(yellow) stations superimposed on the mean modern salinity field.* The bold contour corresponds to 35 g kg^{-1} (approx. mean sea-surface salinity). Relatively high sea-surface salinities are found in the subtropical gyres beneath anticyclonic wind systems, and relatively low salinities are found in subpolar regions below cyclonic wind systems, along with areas affected by fresh water from ice-melt and rivers.*

Figure 1 and the plots in Figure 3 are taken from a 2021 article by John Gould and Stuart Cunningham (Further Reading), which makes use of Buchanan's specific gravity data (converted to salinity in g kg^{-1}) to look at how the strength of the hydrological cycle changed between the 1870s and the early 21st century. (The article also used measurements collected by *Gazelle*, but here we will concentrate mainly on *Challenger*.)

Challenger's track was quite complex and it crossed itself in places, but the salinity data collected by *Challenger* (and indeed by *Gazelle*) are consistent with the global pattern of salinity that we know from modern measurements. In Figure 3, salinity values derived from Buchanan's measurements (red), plotted 'along track' in the order of *Challenger* station numbers, are

*In this article, modern values are 5 m depth values from the EN4 dataset (1950–2019).

Figure 2 Right *An artist's impression of Buchanan employing the hydrometer in his laboratory, where he would lock the door to avoid being disturbed. To isolate it from the motion of the ship, the hydrometer rested on a hanging shelf.* ***Far right*** *A drawing of the hydrometer, taken from the Challenger Reports. It was ballasted by mercury in the bottom bulb, and to enable it to be used in seawater of a wide range of salinity, its weight could be altered by adding or removing small weights at the very top.*

'I decided that, in the values of the specific gravity obtained ..., units in the fourth place of decimals must be exact, and that exactness should be pushed as far as possible into the fifth place.'

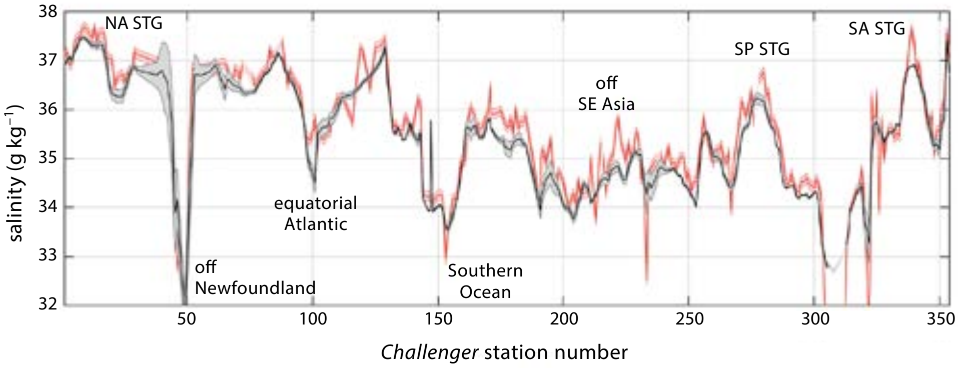

Figure 3 *Salinities derived from Buchanan's measurements along Challenger's track (Figure 1) (red) compared with modern-day values (black). Some locations characterised by relatively high or relatively low sea-surface salinity are highlighted. STG = subtropical gyre; NA = North Atlantic; SA = South Atlantic, SP = South Pacific. (A similar plot for Gazelle is almost as impressive, although there is a greater vertical offset between the two plots.)*

compared with with modern-day values from the same positions (black). The similarity between the two plots pays tribute to Buchanan's meticulous work.

To investigate the changing strength of the hydrological cycle, Gould and Cunningham identified regions whose surface salinity had increased or decreased between the 1950s (1950–1959) and the 2010s (2010–2019), and the *Challenger* and *Gazelle* stations for each of the regions. Figure 4(a) shows the *Challenger* stations superimposed on areas of freshening (blue) and salinification (red and pink).

For each of regions 1–12 on the map the authors worked out the annual rate of change in salinity between the 1870s and the 1950s ($g\,kg^{-1}\,yr^{-1}$) and plotted it against the annual rate of change in salinity between the 1950s and the 2010s. The ratios of the two rates of change (Figure 4(b)) are measures of the rates of change of salinification or freshening, and hence of changes in the strength of the hydrological cycle. This plot (and a similar one based on *Gazelle* data) show that the area of strongest and most consistent freshening since the 1870s is the Pacific warm pool. The areas of strongest and most consistent salinification are the North and South Atlantic subtropical gyres, along with the equatorial Atlantic (*Gazelle* only). Taking all the *Challenger* points together, the gradient of the regression line in Figure 4(b) indicates that between the 1870s and the 2010s the average rate of salinity change (salinification and freshening) increased by a factor of about 0.6.

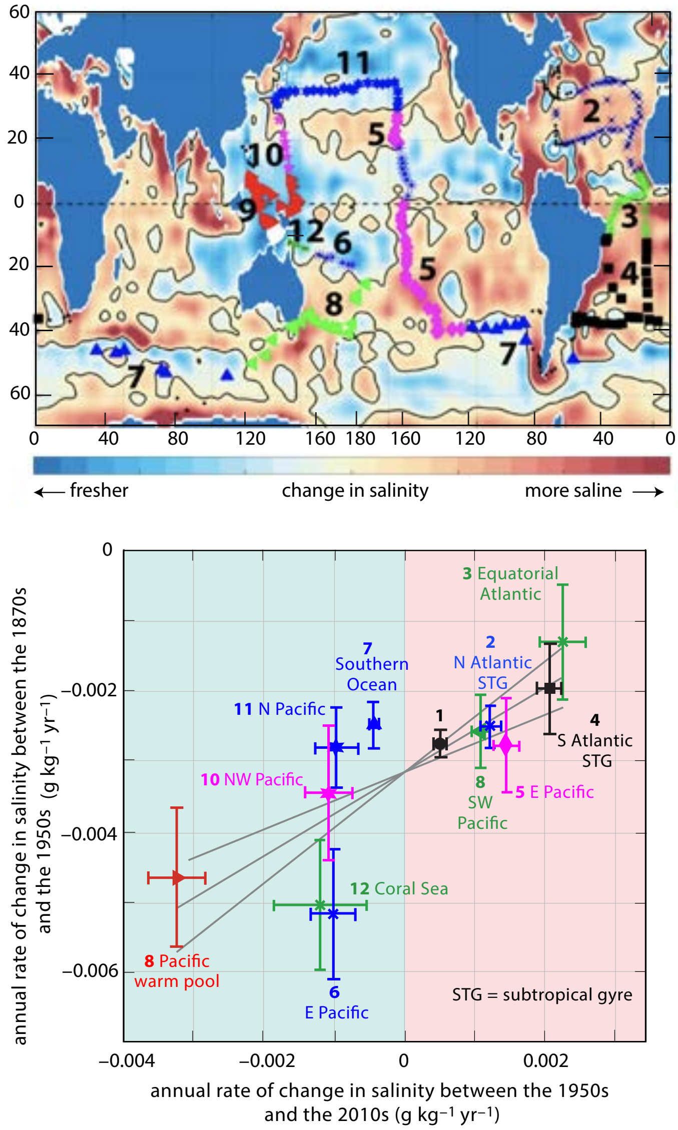

Figure 4(a) *Map showing areas of freshening (blue) and salinification (pink/red) between the 1950s and the 2010s. Superimposed are Challenger stations, with different colours/symbols acccording to the area of freshening/salinification they fall in. Colours and symbols tie up with those in (b).*

(b) *Annual rates of salinity change between the 1870s and the 1950s plotted against annual rates of salinity change between the 1950s and the 2010s. Each salinity change is scaled by the time span (81 years for 1873 to 1954, and 60 years for 1955 to 2015). The error bars for the 1870s reflect the variations within each region. The black dot (no. 1) is the global average.*

Using modern global sea-surface salinity data, and further analysis, the authors deduced a *mean global* salinity change between the 1870s and 1950s equivalent to $0.166\,g\,kg^{-1}\,century^{-1}$ (for both freshening and salinification). They also found that since the 1950s the intensification of the hydrological cycle has been increasing more than twice as fast as before.

Furthermore, *Challenger* and *Gazelle* measurements of sea-surface and air temperature, along with modern data, suggest that these changes in salinity were associated more with increases in sea-surface temperature than increases in air temperature.

Buchanan might have assumed that his careful measurements would stand the test of time, but he may well have been amazed to know how valuable they would be a century and a half into the future.

Further reading

Durack, P.J., S.E. Wijffels and T.P. Boyer (2013) in *Ocean Circulation and Climate: A 21st Century Perspective*, International Geophysics Series Vol. 103 (eds Siedler *et al.*), Academic Press, Elsevier, 727–57.

Gould, W.J and S.A. Cunningham (2021) Global-scale patterns of observed sea surface salinity intensified since the 1870s. *Nature Coms; Earth and Environment* **76**. doi: 10.1038/s43247-021-00161-3

Gould, J. (2022) Preparations for the *Challenger* voyage and for a parallel German venture, *Ocean Challenge* **26** (2), 19–25.

To see the global distribution of sea-surface density, compiled largely from *Challenger*'s observations, go to wikipedia.org/wiki/Challenger_expedition#/and click on the map.

Ed

With thanks to John Gould and John Phillips.

A seminal paper on shelf-sea fronts

Insights that led to a new branch of physical oceanography

Tom Rippeth

In August 1974 John Simpson and John Hunter of the (then) Department of Physical Oceanography at Bangor University published a paper which arguably set the agenda for the development of a new branch of oceanography: the physical oceanography of the shallow continental shelf seas which separate the continents from the oceans. The paper also provided the first quantitative link between dissipation of tidal energy and ocean mixing. Here we investigate the background to the paper and look at its impact in the development of our understanding of the continental shelf seas.

The focus of this research was the Irish Sea and was, at least in part, facilitated by the proximity of the Irish Sea to Bangor and Liverpool universities (Figure 1), and the fact that it was in range of the Bangor University research vessel, the *Prince Madog*. A consequence is that today the Irish Sea has become the 'model' shelf sea for oceanography students globally, despite only accounting for 0.009% of the surface of the Earth!

Early oceanographic measurements in the Irish Sea

The Simpson and Hunter paper built on previous research going back to the early years of the 20th century. Unusually extensive systematic (for the time) hydrographic surveys of the Irish Sea had been carried out between 1907 and 1912 by Donald Matthews of the Department of Agriculture and Technical Instruction for Ireland. The surveys consisted of quarterly visits to 68 stations across the western Irish Sea and Celtic Sea and were undertaken in February, May, August and November of each year. These early measurements were taken from the Dublin-based purpose-built research and fishery protection vessel, the *Helga*.

Water samples were taken at several depths using Ekman reversing water bottles, each of which carried two reversing thermometers. In consequence, only a few samples were collected over the entire water column, so the vertical resolution of the measurements was very low. The water samples were recovered and then preserved in 6 oz milk bottles with porcelain stoppers, rubber washers and spring catches, before titration against International Standard Seawater to calculate the salinity.

The surveys revealed that there were two areas in which temperature stratification was observed, but only during the August surveys. Matthews noted that these areas were places 'where the [tidal] stream is almost imperceptible and where the power of the tide to cause vertical mixing of the water is almost nil'. These areas were the western Irish Sea and the Celtic Sea.

The mean salinity measurements showed that the salinity values of the water in the North Channel, at 34 g kg^{-1}, were lower than those observed in St George's Channel, at the southern entrance of the Irish Sea, where mean salinity was ~ 34.9 g kg^{-1} (Figure 1(a)). By assuming that this drop in salinity was due to diilution by river water, Ken Bowden of Liverpool University used a salt budget to deduce a northward residual (i.e. net) flow through the Irish Sea of a couple of cm s^{-1}. Whilst his calculation revealed a weak net flow through the Irish Sea it did not explain the flow and so it was not possible to use this information to make predictions as to how it might change over long time scales.

In a 1920 paper, G.I. Taylor used tidal information collected around the Irish Sea to consider the fate of energy dissipated by the ocean tide. In doing so he expressed the local rate of dissipation of tidal energy as the sum of the direct rate of working by the tide-generating force across the Irish Sea and the net flux of tidal energy into the Irish Sea. The latter was estimated from the difference between high water times, and the timing of the maximum tidal flow through St George's Channel. He then equated the net rate of input of energy by the tide with the tidal dissipation through bottom friction, which is proportional to the cube of the maximum current speed, u^3.

Through this calculation Taylor was able to show that whilst the direct impact of the tide-generating force on the Irish Sea tides is minimal the Irish Sea is a significant sink for tidal energy. The astronomer and geophysicist Harold Jeffreys extended this calculation globally and compared his

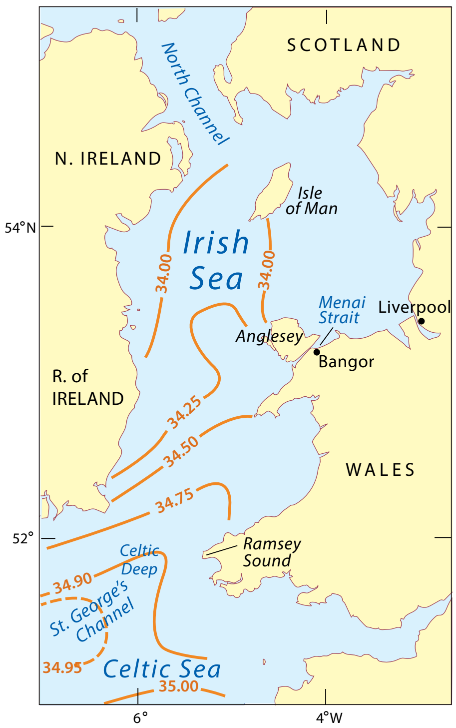

Figure 1 *Annual mean sea-surface salinity in the Irish Sea derived from water bottle samples taken quarterly between 1907 and 1912; contours are from Matthews (1913). Locations mentioned in the article are also shown.*

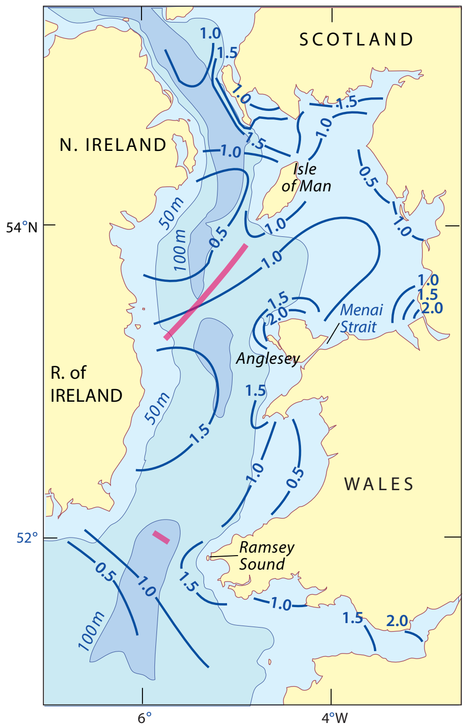

Figure 2 *Contours of tidal current speed (m s^{-1}) in the Irish Sea at mean spring tides, superimposed on the bathymetry. The positions of the shelf-sea fronts according to Simpson and Hunter are shown in red. (Current speeds are taken from Bowden (1955))*

result to estimates of global tidal dissipation based on the rate at which the Moon was recessing from the Earth. He estimated that, despite their small area (7% of the global ocean total), the shelf seas accounted for over half of total global tidal energy dissipation.

There is a large variation in tidal current speed across the Irish Sea, with tidal flows exceeding 4 m s^{-1} in coastal areas such as Ramsey Sound off Pembrokeshore and the Menai Strait (Figure 2), whilst in other areas, such as the western Irish Sea and the Celtic Deep, tidal currents peak at around 10–20 cm s^{-1}.

By the 1950s a number of oceanographers, including Walter Munk at the Scripps Oceanographic Institution and Günter Dietrich of the German Hydrographic Institute, Hamburg, were speculating on the role of the turbulence generated by the dissipation of tidal energy in driving water column mixing.

Advances in the 1960s and 1970s

In 1968 Bangor University took delivery of a new purpose-built research ship, the RV *Prince Madog.* The new vessel, fitted out with state-of-the-art Bathysonde (an early CTD), provided easy access to observations in the Irish Sea from its base in Menai Bridge on the Isle of Anglesey. Surveys in 1968 and 1969 had confirmed the presence of seasonally stratified water in the western Irish Sea, with a region of strong surface gradients (a front) separating the well mixed waters of the eastern Irish Sea from the seasonally stratified water of the western Irish Sea. Thermograph measurements from the ship as it crossed the front revealed a sharp gradient in sea-surface temperature, with higher temperatures on the western side of the front (Figure 3). In June 1973 an airborne Infrared survey was undertaken, coincidently following several weeks of calm weather. The survey revealed the geographic extent of the front with the aircrew noting that 'the line of the front was clearly visible because of an accumulation of surface material in the vicinity of the maximum temperature gradient'.

Informed by these new measurements Simpson and Hunter developed a one-dimensional model of 'buoyancy input' by surface heating (lowering the density of surface water) versus tidal stirring in controlling water column stratification. To quantify the degree of stratification, and how much kinetic energy input would be required to overcome the stratification, they used a quantity called the potential energy anomaly ϕ. In doing so they

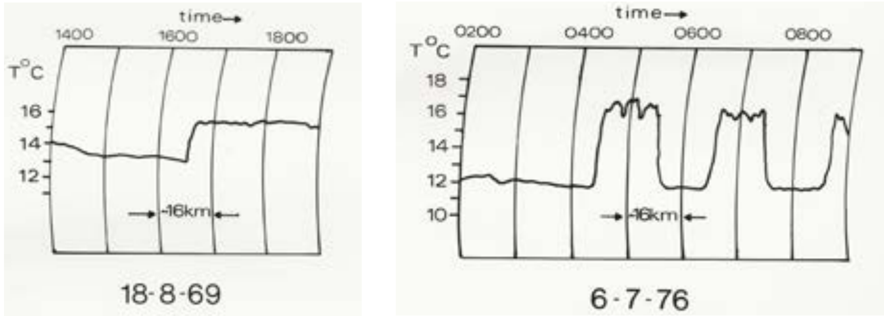

Figure 3 *Thermograph records of sea-surface temperature crossing the Irish Sea front.* ***(a)*** *is for a single crossing from east to west in August 1969 and* ***(b)*** *is for multiple crossings in July 1976.*

derived the Simpson–Hunter parameter (h/u^3), where h is the water depth and u the maximum tidal current speed:

$$\frac{h}{u^3} = \frac{8c\rho k\varepsilon}{3\pi\alpha g Q}$$

with k a constant relating to friction, c the specific heat capacity of seawater, α its thermal expansion coefficient, Q the rate of heat input at the surface, ρ seawater density and g acceleration due to gravity. Assuming Q and the mixing efficiency ε are constants, the position of the shelf-sea front will be determined by a critical value of h/u^3. Figure 2 shows positions of fronts in the Irish Sea estimated using the h/u^3 relationship. The model was then applied to all available data for a large section of the European shelf to provide confirmation.

By this stage the first infrared satellite images (from NOAA 4) were becoming available and were able to resolve temperature sufficiently to show the 2–3°C difference across the shelf-sea fronts (Figure 4). Although the first images came from NASA, more soon followed from the newly established Dundee Satellite receiving station courtesy of Peter Bayliss and John Brush.

Independent confirmation of the significance of h/u^3 came from Robin Pingree and David Griffiths at the Plymouth Marine Laboratory who used a two-dimensional depth-averaged numerical model of the tides to derive the Simpson–Hunter parameter for the shelf seas surrounding the British Isles, with the estimated frontal locations matching those observed. Globally other researchers showed that the parameter accurately predicted the location of shelf-sea fronts in, for example, the Gulf of Maine, the Bering Sea and the Patagonian Shelf. Accordingly, the model provided the first quantitative evidence for the role of dissipation of tidal energy in driving ocean mixing.

Figure 4 *The first satellite image to show the presence of shelf-sea fronts in the north-west European shelf seas. The image is an infrared satellite image and the shading corresponds to sea-surface temperature – the darker the shade the higher the sea-surface temperature. The image, for 20 August 1976, was provided by Wayne Esaias at NOAA. It was so heavily rasterised that at the time John Simpson thought it had been created by some students as a joke!*

Biological and biogeochemical significance of shelf-sea fronts

On the original 1973 flight the aircrew noted changes in colour either side of the front, put down to changes in the standing crop of phytoplankton. The front separates two very different ecological regimes. The well mixed water is nutrient-rich as phytoplankton growth is light-limited, whilst following the spring bloom, on the seasonally stratified side of the front the surface mixed layer is nutrient-limited, and so any primary productivity is limited to the subsurface chlorophyll maximum. Recent DNA analysis has revealed that the community structure and diversity of bacterioplankton communities on either side of the shelf-sea front are very different. A consequence is that the front separates two very different biogeochemical regimes, with the seasonally stratified region acting as an important CO_2 sink and the area that remains well mixed tending to be a net source.

The frontal region benefits from both the high-light regime of the stratified side and the good supply of nutrients of the mixed side, and so supports a rich and diverse ecosystem. On the basis of this knowledge, maps of shelf-sea frontal positions derived from satellite images, compiled by Peter Miller and his team at the Plymouth Marine Laboratory (PML), were used by Defra as a proxy for the abundance and diversity of mobile species in the planning of Marine Protected Areas around the UK (Figure 4).

The accumulation of floating material along the front as noted by aircrew on the original 1973 overflight provides evidence of circulation patterns associated with the front. The front results in a significant lateral density gradient which supports an along-front residual flow (a frontal jet) and a convergence. A decade-long programme of satellite-tracked drifting buoy measurements integrated with numerical modelling, led by Ed Hill (at Bangor, then the National Oceanography Centre), revealed a highly organised 'thermohaline' circulation consisting of narrow, fast-flowing frontal jets. These jets provide a highway through the Irish Sea carrying and dispersing a wide range of marine organisms. At the time, they also provided a mechanistic explanation of Bowden's original residual flow estimate.

Shelf-sea fronts and changing climate

The predictability of the position of shelf-sea fronts has provided insights into the evolution of the shelf seas since the last glacial maximum. Analysis of sea-bed sediment cores, including identifying microfossils from which to infer plankton community structure at different points in the past, allows an estimation of the timing of the movement of shelf-sea fronts over the sediment core location as sea level rose following the last glacial period. As the shelf seas expanded, both the magnitude and geographical distribution of tidal dissipation changed, which could have had global implications, for example in impacting the rate of tidal mixing which supports the Atlantic Meridional Overturning Circulation and the uptake of CO_2 by the ocean (see the Wider Implications section of the Further Reading).

As sea levels continue to rise into the future, and new shelf seas form as ice sheets disappear around Antarctica, shelf-sea fronts will move in response to changes in the global distribution of tidal dissipation. Despite the key role of the shelf seas in the global carbon cycle, and as a major sink for tidal energy, plus their changing geography as sea level has varied over glacial cycles, shelf-sea processes are poorly represented in global climate models. Nevertheless the predictability of the positions of tidal mixing fronts coupled with our ability to time the transgression of those fronts at particular points as sea level changes, provide useful tools in the validation of shelf-sea parameterisations in global climate models.

The significance of the partitioning of shelf seas by seasonal shelf-sea fronts was evident during the Category 4 heat wave which hit the UK shelf seas in June 2023. A sea-surface temperature anomaly map (Figure 6) clearly shows that over the continental shelf, seasonally stratified regions (e.g. the northern half of the North Sea and the western Irish Sea) have sea-surface temperatures up to 5 °C above normal, while in the well mixed regions the anomalies are generally < 1 °C. The predictability of the positions of shelf-sea fronts implies that water column structure in shelf-sea regions is controlled to the first order by vertical exchange processes. The distribu-

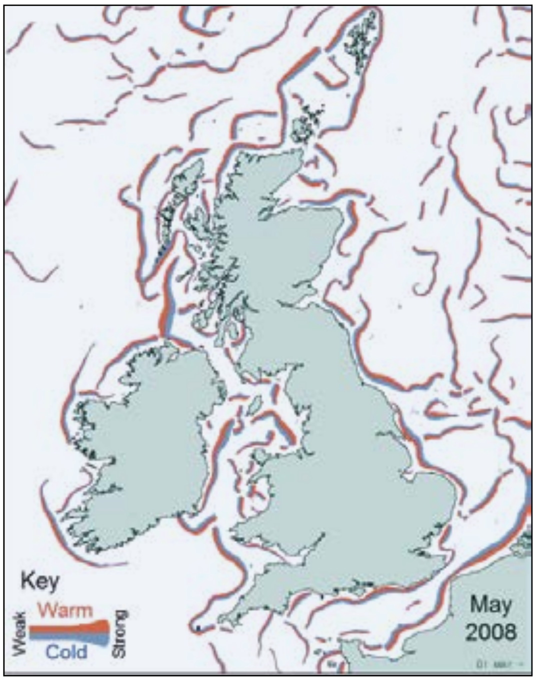

Figure 5 Location of shelf-sea fronts in May 2008, illustrating typical summer locations of persistent fronts around the UK, which influence feeding areas for basking sharks, cetaceans and other marine life. (Red/blue indicate the warm/cold side of each front, and the width indicates the strength of the front.)

(Simplified front map derived by Peter Miller at PML from Miller, Xu and Carruthers (2015); see Further Reading)

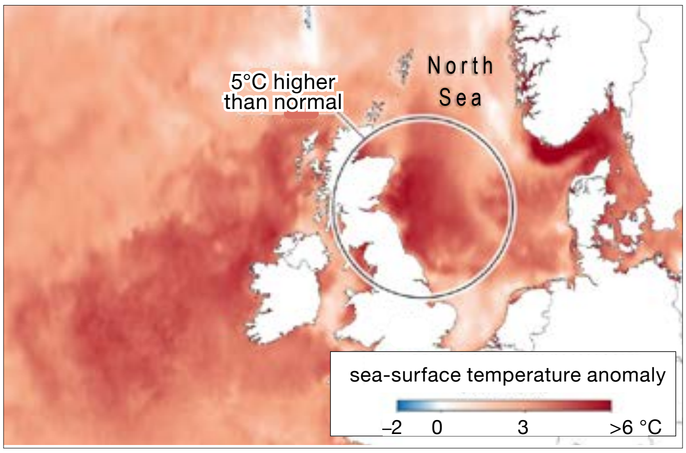

Figure 6 Sea-surface temperature anomaly during the severe marine heat wave off the UK in June 2023.

(Taken from ESA for 18 June 2023; https://www.esa.int/ESA_Multimedia/Images/2023/06/UK_suffers_marine_heatwave) tion of sea-surface temperature during the heat wave can therefore be explained as resulting largely from changes in stratification in the seasonally stratified regions, and in particular, unusually shallow surface mixed layers concentrating the seasonal heat input.

Early research on the Irish Sea

Bowden, K.F. (1955) *The Physical Oceanography of the Irish Sea Fisheries Investigations, Series 2,* XVIII, No.8.

Jeffreys, H. (1921) Tidal friction in shallow seas. *Phil Trans Roy Soc.* A, **221**, Issue 582–93, 239–64.

Matthews, D.J. (1913) The salinity and temperature of the Irish Channel and the waters south of Ireland. *Fisheries Ireland Scientific Investigations (Fish Branch)* **4**, 26pp.

Taylor, G.I. (1920) Tidal friction in the Irish Sea. *Phil. Trans. Roy. Soc.* A, 220, Issue 571–81, 1–33. doi: 10.1098/rsta.1920.0001

Irish Sea shelf-sea front

Simpson, J.H. (1971) Density stratification and microstructure in the western Irish sea. *Deep Sea Research* **18** (3), 309–19.

Simpson, J.H. and J Hunter (1974) Fronts in the Irish Sea. *Nature* **250**, 404–406.

Simpson, J.H., C.M. Allen and N.C.G. Morris (1978) Fronts on the continental shelf. *Journal of Geophysical Research* **83**, 4607–14.

Shelf sea fronts globally

Dietrich, G. (1951) Influences of tidal streams on oceanographic and climatic conditions in the sea as exemplified by the English Channel. *Nature* **168**, 8–11.

Garrett, C.J.R., J.R. Keely and D.A. Greenberg (1978) Tidal mixing versus thermal stratification in the Gulf of Maine. *Atmosphere–Ocean* **16**, 403–23.

Glorioso, P.D. and R. Flather (1995) A barotropic model of the currents off SE South America. *Journal of Geophysical Research* **100**, 13427–40.

Pingree, R.D. and D.K. Griffiths (1978) Tidal fronts on the shelf seas around the British Isles. *Journal of Geophysical Research* **83**, 4615–22.

Schumacher, J.D., T.H. Kinder, D.J. Pashinski and R.L. Charnell (1979) A frontal structure over the continental shelf of the eastern Bering Sea. *Journal of Physical Oceanography* **9**, 79–87.

Biological Implications

Hill, A.E., J. Brown, L. Fernand, J. Holt, K.J. Horsburgh, R. Proctor, R. Raine and W.R. Turrell (2005) Thermohaline circulation of shallow tidal seas. *Geophysical Research Letters* **35**, L11605.

King, N.G, S.-B. Wilmes and 9 others (2023) Seasonal development of a tidal mixing front drives shifts in community structure and diversity of bacterioplankton. *Molecular Ecology*. doi: 10.1111/mec.17097

Miller, P.I., W. Xu, and M. Carruthers (2015) Seasonal shelf-sea front mapping using satellite ocean colour and temperature to support development of a marine protected area network. *Deep Sea Research Part II: Topical Studies in Oceanography*, **119**, 3–19. doi: 10.1016/j.dsr2.2014.05.013

Wider implications

Green, J.A.M., C.L. Green, G.R. Biggs, T.P. Rippeth, J.D. Scourse and K. Uehara (2009) Tidal mixing and the meridional overturning circulation from the last glacial maximum. *Geophysical Research Letters* **36**, L15603.

Scourse, J.D., W.E.N. Austin, B.T. Long, D.A. Assinder and D. Huws (2002) Holocene evolution of seasonal stratification in the Celtic Sea: Refined age model, mixing depths and foraminiferal stratigraphy. *Marine Geology* **191**, 119-45.

Thomas, H., Y. Borac, K. Elkalay and H.J.W. Baar (2004) Enhanced open ocean storage of CO_2 from shelf sea pumping. *Science* **304**, 1005–8.

Wilmes, S.-B., J.A.M Greem, N. Gomez, T.P. Rippeth and H. Lau (2017) Global tidal impacts of large-scale ice sheet collapse. *Journal of Geophysical Research* **122**, doi: 10.1002/2017JC013109.

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Developments in offshore renewable energy

At Cop28 at least 117 governments have agreed to triple the world's renewable energy capacity by 2030. At the time of writing, the draft Cop28 agreement refers to 'reducing both consumption and production of fossil fuels ... so as to achieve net zero by, before, or around 2050 in keeping with the science'.

As part of its plan to reduce carbon emissions by 68% (from 1990 levels) by 2030, the UK goverment aims to have 25 GW of offshore wind generation operational by 2031. However, despite the growth in UK offshore wind in recent years (see p.16), in September 2022, Round 5 of the government's 'sustainable energy auction' saw no new applications for offshore wind farms.

This was the result of a 30–40% increase in supply chain costs, higher interest rates and competition for international capital, and the fact that the maximum price companies could charge the goverment for the energy was set at too low a rate of £44 per MWh – bidders compete in a reverse auction to offer electricity at the lowest cost. The 15-year contracts guarantee top-ups from bill payers if the wholesale electricity price falls below a certain level.

However, Round 5 was not all bad news for offshore energy production, because as a result of there being no bids for floating wind projects – which the industry refers to as FLOW – the allocation was available for tidal stream projects, and bids were accepted for 11 projects in Scottish and Welsh waters, adding to four accepted in Round 4.

After urgent talks with windfarm developers Ministers agreed that for Round 6, in 2024, the starting price in the offshore wind auction would be raised to £73 per MWh to help more offshore projects to move ahead. The starting price for floating offshore wind projects was raised from £116 per MWh to £176 per MWh. FLOW will also have ring-fenced funding in recognition of the large number of projects ready to participate. Developers welcomed this news but time has nevertheless been lost in the UK's struggle towards net zero.

Happily, the general public should be benefitting from the Round 4 auction. For the 2022–23 financial year, the Crown Estate reported a record net revenue profit of £442.6 million thanks to receipt of option fees from developers of offshore wind farms. Some of the profits from the option fees will be directed into the public pot as King Charles III has asked that the share of the offshore wind earnings to which the Royal Family is entitled 'be directed for wider public good'. Option fees are payable for 3–10 years, depending on when a project will be ready for signing a lease.

Ed.

Wind turbines in temperate shelf seas

In the first quarter of 2023, nearly half of the energy generated in the UK came from renewable sources, and 40% of that renewable energy came from offshore wind turbines. More offshore wind farms are planned and the UK's 'pipeline' of offshore wind projects (operational, under construction, consented or planned; Figure 1) is approaching 100 GW.

Until now, most offshore wind turbines have been located near to the shore, in water < 50 m deep, because of ease of installation and access, and easier connection to the grid. This includes the three-part Dogger Bank Wind Farm (pink areas at 55° N on Figure 1), the first turbine of which was connected to the UK national grid in October 2023. With 277 turbines and a final generation capacity of 3.6 GW, Dogger Bank may become the world's largest wind farm.

As the offshore wind sector grows, turbines will increasingly be situated further out on the continental shelf, and in temperate waters this may well mean waters that are stratified in the summer (e.g. the northern part of the North Sea; cf. Figure 1). Shallow water close to the shore is well mixed by storms and because strong tidal currents (metres per second) interact with the sea floor, generating turbulence. The strength of tidal currents decreases with increasing distance from the shore, so while deeper shelf waters are well mixed in winter, in spring and summer, increased insolation means that they become thermally stratified, with a warm surface layer above a seasonal thermocline (Figure 2). The sea-bed depth at which waters become stratified – i.e. the position of the seasonal shelf-sea front – depends on where the stratifying effect of surface waters becoming warmer exceeds the effect of turbulence generated at the sea bed by relatively weak tidal currents. The depth at which this occurs varies; in the North Sea it is in the region of 50 m (Figure 1).

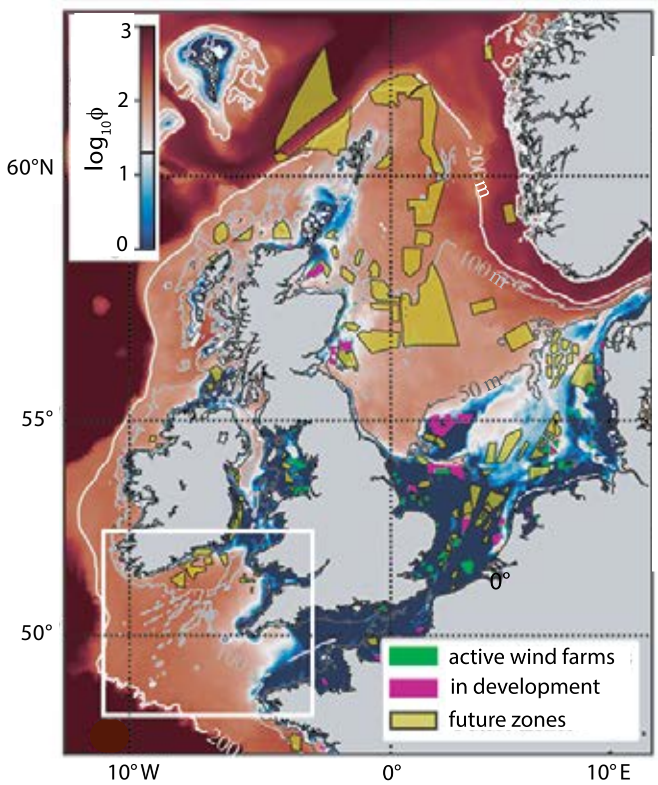


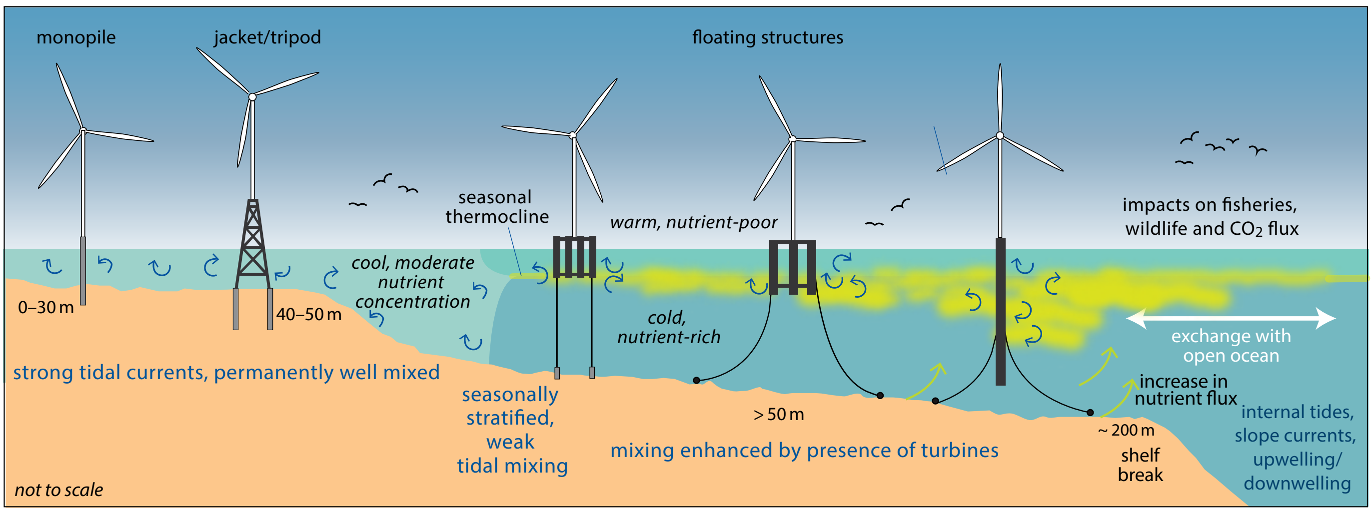
Figure 1 *Positions of actual and planned wind farms (2018 data) in relation to the summer distribution of mixed (blue) and stratified (red) waters off north-west Europe. The degree of stratification is given by the potential energy anomaly ϕ, i.e. the energy required to fully mix the water column. The boundary between mixed and stratified is taken as $\phi = 20$, or $\log_{10}\phi = \sim 1.3$ (cf. key top left). The white box is the area covered by Figure 3.*

(Degree of mixing is taken from the NEMO model; Guihou et al., 2018; doi: 10.1002/2017JC012960*)*

Turbines in deeper stratified water

In deeper water, wind turbines require floating foundations which, to cope with the enormous stresses upon them above and below the waves, need a large cross-sectional area horizontally, or a large draft (Figure 2). Their presence is highly likely to affect stratification in the water column. Existing floating foundations have drafts of about 20 m or more, and so extend down

Figure 2 *Schematic diagram showing how an offshore current flowing past wind turbines could generate mixing which could weaken seasonal stratification and result in a much thicker subsurface chlorophyll maximum (yellow), and generate plumes downstream of the turbines. Turbulence could also result in nutrients from organic debris at the sea bed being mixed back up into the water column and supporting higher primary productivity. The diagram shows examples of different designs of turbines used in different depths, each of which will produce different mixing effects.*



into seasonal thermoclines. Mixing occurs because, like their shallow-water equivalents, floating foundations exert drag on water flowing past them.

In the future, turbines in deeper water will have bigger rotors and will need larger floating foundations. At present little is known for sure about the effect these larger foundations will have on the stratification, but it is anticipated that their presence will generate sufficient turbulence to significantly weaken the thermocline, and change the character of the subsurface chlorophyll maximum – a layer of high chlorophyll concentration 10–30 m thick, often associated with the thermocline in strongly stratified waters (Figures 2 and 4), discussed below.

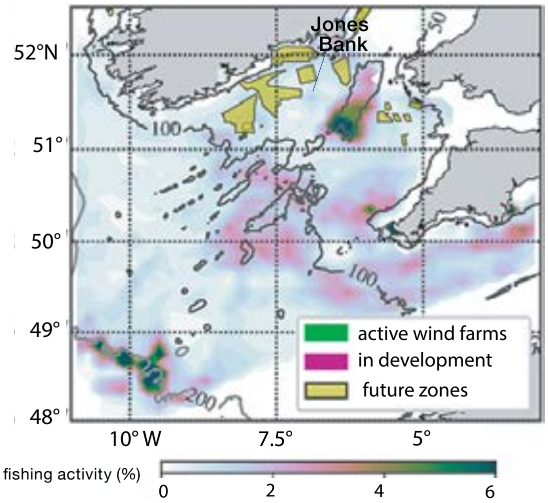
Primary productivity in shelf seas

In well mixed regions close to shore primary production occurs mainly during summer when sunlight is strong. However production is limited by the fact that phytoplankton are continually being carried up and down through the water column by turbulence, so for much of the time are at depths where light levels are insufficient for them to grow.

In the case of stratified shelf waters, the ideal conditions for phytoplankton growth occur in spring; the thermocline acts as a barrier to mixing, and phytoplankton trapped in the well-lit surface layer grow rapidly and multiply, giving rise to the annual spring bloom. The spring bloom eventually exhausts the supply of nutrients in the surface layer, but a significant level of primary production is sustained at depth throughout the period of seasonal stratification (Figure 4). This persistent phytoplankton layer is the subsurface chlorophyll maximum.

The high seasonal primary productivity of temperate stratified shelf seas makes them important areas for marine ecosystems, so we need to learn more about how wind farms will affect them with some urgency.

__Figure 3__ To the south-west of the British Isles, fishing activity, concentrated in areas of high primary productivity, is most intense in regions of mixing such as over the shelf break at ~ 200 m depth, and over rough topography/topographic highs, such as Jones Bank (cf. Figure 4). Enhanced mixing is also expected to occur in the vicinity of wind farms.



Modelling and observations

The dimensions of many existing and proposed wind farms are such that the complex flow patterns associated with the interaction of tidal currents with wind farm infrastructure are not accurately resolved in current state-of-the-art predictive ocean models.

There have been very few modelling studies of flows past tubines in stratified waters, let alone through groups of turbines. However, we can gain some insight into possible effects by looking at the features that result when currents interact with sea-bed topography. For example, to the south-west of the British Isles (Figure 3), the intensity of fishing activity – a proxy for high primary production resulting from a good supply of nutrients associated with mixing – is highest at the southern end of the Jones Bank and over the shelf break (cf. Figure 4).

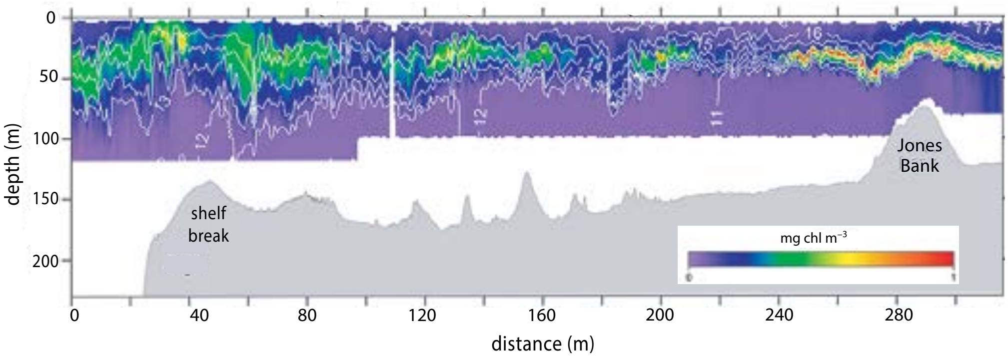
Another analogous natural phenomenon is the 'island wake effect', where flow past an island results in eddies spinning off in the lee of the island. Modelling studies of flow past vertical cylinders representing 'monopile' turbines (Figure 2) have demonstrated similar effects. Wakes have been observed in coastal wind farms (albeit not in deeper stratified water) where levels of turbulence are high. The wakes, at least 1 km in length, were in the form of plumes of sediment trapped in vortices, and were observed to spread and interact as they passed through the wind farm. In deep-water sites, with lower background turbulence, the wakes could be even larger.

Wind farms can also affect shelf seas through their effect on the atmosphere. A group of turbines can cause wind shear, leading to local areas of upwelling and downwelling around the edges of the wind farm – an effect observed both around shallow-water wind farms and islands in stratified water, and reproduced in modelling of flow around monopiles in shallow-water conditions.

Potential effects on ecosystems and biogeochemical cycling

The subsurface chlorophyll maximum plays a key role in supporting the pelagic food web during the summer months. Stronger mixing in the thermocline, associated with wind turbine foundations, could have both positive and negative effects. By carrying more nutrients from the bottom up into the subsurface chlorophyll maximum – and, if the mixing is strong enough, up into the surface layer

__Figure 4__ Section of temperature (white contours) and chlorophyll concentration (colours) along a transect that goes more or less south-westwards from Jones Bank at ~ 50° N, 8° W to the shelf break at 48° N, 10° W (cf. Figure 3). High chlorophyll concentrations in the subsurface chlorophyll maximum can be seen extending hundreds of km across the shelf. Enhancements in chlorophyll concentration over rough topography, such as Jones Bank, are a result of nutrients being brought up from below through increased turbulent mixing.



Observational Scanfish CTD towed data from the Celtic Sea collected in summer 2008, supported by NERC's Oceans2025 Programme

Figures 3 and 4 are by courtesy of Jonathan Sharples. See Sharples, et al. (2013) Fishing and the oceanography of a stratified shelf sea. *Progr. Oceanogr.* **117**, 130–39.
doi: 10.1016/j.pocean.2013.06.014

– it could support additional phytoplankton growth and hence higher trophic levels. However, mixing also alters the light regime surrounding phytoplankton, with stronger mixing potentially disrupting light sufficiently to hinder photosynthesis. Whether or not the extra mixing increases net phytoplankton production will depend on the balance between the nutrient and light effects.

Increased mixing caused by the presence of turbines could also affect not only the location of the transitions from well mixed waters to stratified waters, and *vice versa*, but also *when* they occur. Increased mixing could delay the onset of stratified conditions in the spring and hasten the breakdown of stratification in the autumn. Changes in the timing of the spring bloom may have serious implications for zooplankton and fish larvae whose life cycles have evolved to exploit it. This could have implications for animals higher up the food web; seabirds, for example, might have reduced breeding success.

Such changes will have an effect on biogeochemical cycling in the vicinity of wind farms. Changes in the sizes and timing of phytoplankton blooms will affect associated fluxes of CO_2 across the sea-surface, and cycles of nutrients will also be affected directly and indirectly. For example, high primary productivity in surface and near-surface waters results in a rain of debris to the sea floor. This provides food for benthic animals, but if the supply of organic debris is excessive, decomposition by bacteria can result in low dissolved oxygen concentrations at depth, already increasingly found in stratified coastal waters as the ocean warms. However, turbulence caused by turbines results in oxygen being mixed downward, so there is a need to understand the net effect on bottom water of enhanced mixing in near-surface waters.

Assessment of impacts and attempts to mitigate them

All proposals for offshore wind farms are required to be supported by Environmental Impact Assessments (EIAs) to enable decision-makers to consider likely effects on the environment of construction, operation (over ~20 years) and decommissioning, and enable them to plan to avoid, reduce or offset those effects likely to be negative. The responsibility for seeing a wind project through the EIA falls to the developers, who have been contracted by the project owner to plan and develop a project. This could involve reviewing existing research and commissioning new research.

In the case of turbines sited in shallow water, one of the largest concerns about environmental disturbance during construction relates to the noise produced by pile-driving, which can be heard tens of kilometres away. The foundations of some more recently installed wind turbines (not shown in Figure 2) are large concrete structures that rest on the sea bed and rely on their weight to provide stability for the wind turbine. For these 'gravity foundations', no noisy pile-driving is needed, and there is less disturbance of the sea-bed. Of course, installation of floating wind turbines also does not involve pile-driving although, as for shallow-water sites, assessments of sea-bed composition and bottom currents are needed, as there may be the potential for sea-bed scour around anchors and cables.

Two of the six turbines forming the Kincardine floating wind farm 15 km off the coast of Aberdeen, in water depths ranging from 60 m to 80 m. The floating foundations are ~31 m top to bottom, of which ~19 m are below the sea surface. (Photo: R. Wakefield/ Flotationenergy)

Developers are expected to determine ways to mitigate any expected negative effects of wind turbines, and perhaps to undertake long-term monitoring. In the case of noise-generation, it's long been known that loud noise can have a negative impact on marine mammals which use sound to communicate, and it's now known that fish and other animals may also be affected, though, problematically, different marine animals are affected by different frequencies of sound. The damaging effect of noise is now often ameliorated by the use of 'bubble curtains' – barriers of bubbles around the area where noise is being produced. Using bubble curtains is relatively inexpensive, and they can absorb sound by up to 95%.

So what of the much more complicated – and relatively little studied – effect of turbines in shelf waters that could become seasonally stratified? Concerns about increased mixing in the vicinity of a front have in fact arisen during the the EIA process for the Hornsea Four windfarm, which received the go-ahead in July 2023. Hornsea Four is about 70 km off Flamborough Head; its postion is marked by the yellow rhomboid at ~ 54°N on Figure 1, just within the blue area on the map. This is in the vicinity of the seasonal Flamborough Front, whose average position corresponds to the blue/red boundary in Figure 1. This means that, depending on the actual position of the front at a given time, one or more of the Hornsea Four turbines could be within the frontal region or in the stratified waters.

In such a case, studies associated with an EIA would have to address impacts that might arise as a result of increased primary production through enhanced mixing caused by the presence of turbines, including impacts on the benthic habitat. Potential impacts on fish would be assessed fishery by fishery, and those on seabirds, colony by colony.

However, it is not straightforward to assess likely changes in primary production, biogeochemical changes in the water column and at the sea bed, and the effect on nutrient cycling and fluxes of CO_2 across the sea-surface. Accurately forecasting the interaction between the flow and infrastructure, and the effects on stratification, will require observations (including detailed baseline surveys) and models for different scenarios, including positions and spacings of turbines. Apart from these challenges, climate change will affect the distribution of seasonally stratified waters, and designs of turbine infrastructure will continue to evolve.

But turbines may bring positive effects, which might be identified through EIAs. A positive influence that is already appreciated is that biodiversity around any turbine (as around an oil rig) benefits from the 'artificial reef effect', as the submerged parts of the structure provide new hard substrate for benthic species. Furthermore, their faecal matter increases food supply and hence animal populations at the sea floor below, and higher trophic levels (predatory fish, birds, marine mammals and seabirds) also profit from locally increased food availability and/or shelter. This increased biological activity would result in a net increase in storage of carbon in sea-bed sediments over the life of a turbine. However, predicting the overall effect on the CO_2 flux across the sea-surface for an impact assessment will be complicated, especially in the case of turbines that might result in enhanced mixing in seasonally stratifed regions.

In the future, assessing environmental impacts associated with wind turbines may be even more challenging, as there are plans to develop 'multi-purpose platforms' – co-location of wind turbines with wave-power generators and aquaculture (fish, shellfish or algae). Working out the potential effects of changes in mixing combined with alterations in nutrient fluxes – for example in the water column in the vicinity of a fish farm – will be challenging.

Further reading

Benjamins, S., E. Masden and M. Collu (2020) Integrating wind turbines and fish farms: An evaluation of potential risks to marine and coastal bird species, *J. Mar. Sci. and Eng.g* **8**, 414.

Black, K. (2021) Floating offshore wind generation. *Ocean Challenge*, **25** (2) 12–13.

Heinatz, K. and M.I.E. Scheffold (2023) A first estimate of the effect of offshore wind farms on sedimentary organic carbon stocks in the Southern North Sea. *Front. Mar. Sci.* 9:1068967. doi: 10.3389/fmars.2022.1068967

Dorrell, R.M., C.J. Lloyd and 10 others (2022) Anthropogenic mixing in seasonally stratified shelf seas by offshore wind farm infrastructure. *Front. Mar. Sci.* 9:830927. doi: 10.3389/fmars.2022.830927

Potlock, K.M., A.J. Temple and P. Berggren (2023) Offshore construction using gravity-base foundations indicates no long-term impacts on dolphins and harbour porpoise. *Mar. Biol.* **170**, 92. doi: 10.1007/s00227-023-04240-1

Sharples, J., J.R. Ellis, G. Nolan and B.E. Scott (2013) Fishing and the oceanography of a stratified shelf sea. *Progr. Oceanogr.* **117**, 130–39. doi: 10.1016/j.pocean.2013.06.014

Ed.

With thanks to Tom Rippeth.

The 'Sargassum-eating' AlgaRay is evolving fast

On learning that the publication *TIME* had chosen AlgaRay as one of the best inventions of 2023, I checked seaweedgeneration.com to see how AlgaRay has been developing. As described in *Ocean Challenge,* Vol.26 (2), AlgaRay was designed to collect invasive *Sargassum* weed from the sea surface and then drop it into the depths where the carbon it contains would become part of the sea bed sediments.

Right *Early AlgaRay surface platform with PV panels for charging the robot's batteries.* ***Left*** *Artist's impression of autonomous AlgaRays working at the surface and at depth.*

In the previous issue, we described a prototype AlgaRay. In the current version, power for propulsion and sinking/resurfacing comes from photovoltaics, making the AlgaRay carbon neutral in operation. It will operate autonomously and use Artificial Intelligence and Machine Learning to ensure that interception, collection and deposition of weed is undertaken as efficiently as possible.

There are plans for a series of robots that would be used in the seaweed production industry (*see left*). The AlgaRay would be the harvesting and transportation robot, another robot would be a seaweed cultivation platform, and two other robots would monitor conditions at the surface and at depth. Such a system could automate farming of deeper-growing seaweed, to be used by both humans and livestock (see p.20). *Ed.*

All is not quite lost for the vaquita

In August 2023, the International Whaling Commission (IWC) issued its first ever Extinction Alert. It was for the smallest cetacean which, as *Ocean Challenge* readers may remember (Vol.26 (1), pp.30–32), is the vaquita, a porpoise that lives only in the northernmost part of the Sea of Cortez (also known as the Gulf of California). Vaquitas have long been dying through entanglement in gillnets, used to catch totoaba, a fish whose swimbladders are believed by many to have therapeutic value. The IWC Alert was issued to encourage wider recognition of the warning signs of impending extinctions, and noted: '*The decline of the vaquita has continued despite a very clear understanding of both the cause ... and the solution ...*'.

However, the 2023 Vaquita Survey, which took place in May (through a partnership between the conservation NGO Sea Shepherd and the Natural Protected Areas Commission of Mexico, found that the vaquita population had not declined, and that there may be 10–13 individuals, including at least one newly born calf.

In Operation Milagro, Sea Shepherd and the Mexican Government have been working to keeping gillnetting out of the Zero Tolerance Area of the Vaquita Refuge. In 2022, following the introduction of a new Sea Shepherd ship MV *Seahorse* there was a 79% reduction in hours of illegal gillnet fishing. Installation on the sea bed, in mid 2022, of concrete blocks with hooks to entangle gillnets, also seems to have had an effect, as in the months prior to the survey there was a 90% decline in the number of small boats using gillnets. There had been concern that the hooks would snag nets that could in turn entangle vaquitas, but state-of-the-art side-scan sonar indicates that this does not occur.

The leader of the survey, Barbara Tayor, said: '*This is the most encouraging news ever of human intervention to save vaquitas. The results of the May 2023 survey provide clear evidence that this type of protection needs to be expanded to cover more of the high-use areas of the remaining vaquitas.'*

In August the Mexican Navy said that it was planning to extend the area with blocks with hooks over a wider area. *Ed*

It's time for seaweed to be protected

As our appreciation of the value of macroalgae in ecosystems and the climate system is growing, the abundance and health of seaweed has been declining globally. This alarming message is highlighted in a recent Policy Brief by the United Nations University Institute on Comparative Regional Integration Studies (UNU-CRIS) (see Further Reading).

Seaweed provides habitats for an enormous number of species, including commercially valuable fish and crustaceans. It has been estimated that species richness in seaweed forests is 38% greater than in areas that have lost their seaweed. Seaweed protects vulnerable coastlines by attentuating wave energy, and benefits its immediate environment by lowering acidity levels in seawater.

Seaweeds are naturally prolific; they readily produce young and can also reproduce asexually through fragmentation or division. With their high growth rates (up to ~61 cm day, in the case of kelp), seaweeds globally are thought to take up nearly 200 x 10^6 t of CO_2 per year. Recent global estimates suggest that kelp forests export ~80% of their production (~153 x 10^6 tC yr^{-1}) for long-term burial at the sea bed.

Seaweed cultivation and harvesting

Cultivation of seaweed began in Japan in the 1670s, and today seaweeds are farmed and/or harvested from the wild in over 56 countries worldwide. China, South-East Asia and Chile are the dominant seaweed producers, with cultivation extending well over of 1000 km^2 for China alone. Seaweed may be harvested from shallow near-shore waters, and from 10s of km offshore, where it is collected by divers. Approximately 200 seaweed species are harvested from the wild and over 80 species are farmed commercially. The main cultivated species are the large brown kelp *Saccharina japonica*, and a number of red seaweeds. Commerical production has grown rapidly over the past 50 years, and at ~ 35 million tonnes currently accounts for over 50% of total global mariculture production by weight; the industry's total value was estimated at US$ 14.7 billion (2019 figures). Seaweeds are produced mainly for human consumption, and for hydrocolloids, animal feed and fertilisers. Since 2010, however, there has been growing commercial interest in higher value seaweed-derived products, such as cosmetics, pharmaceuticals, agricultural bio-stimulants and bio-packaging. Seaweed-derived products could also provide alternatives to those originating from fossil fuels, such as plastics.

The seaweed industry supports around 6 million small-scale farmers and processors, both men and women, many of whom live in low- and middle-income countries. In contrast to land-based agriculture, growing seaweed requires minimal addition of fertilizer and no freshwater, and it can be combined with other kinds of aquaculture (e.g. fish farming) or with renewable energy installations such as wind turbines.

Seaweed harvesting also has the positive side-effect that it removes excess nutrients carried from the land, which could otherwise result in eutrophication and oxygen depletion of coastal waters. Indeed, cultivating seaweed can combat existing oxygen depletion and play an important role in regenerating degraded coastal environments.

Threats to wild seaweed

Wild seaweed populations are being overharvested for food, and to provide new stock for seaweed farms. However, the most serious threat to wild seaweed comes from climate change, which has particularly affected the distribution of kelp forests. Off eastern Tasmania, for example, over the past 80 years rising ocean temperatures and acidification have wiped out 95% of kelp forests, with disastrous effects on fish stocks. The situation may be reversible because, to ecologists' surprise, off northern California there has been some regeneration of the kelp forest, most of which was lost during 2013–15, a period of warming waters combined with a population explosion of kelp-eating sea-urchins. Generally speaking, however, kelp's range seems to be shifting polewards. Furthermore, a 2022 study suggests that kelp's role in locking away carbon in sea-bed sediments will decline as warming oceans speed up the rate of decomposition of dead kelp, allowing less of it to reach the sea floor.

Interactions between cultivated and wild seaweed

Other serious threats to both wild and cultivated seaweeed populations arise from the fact that like terrestrial crops, seaweeds are susceptible to the unintentional introduction and spread of non-indigenous species, pests (including grazers), along with diseases, the severity of which may be increased by the effects of climate change. Unfortunately, biosecurity measures for seaweed farms have been largely neglected in almost all farming countries.

Reliance on a very limited number of commercially grown species and their interbreeding with wild native stocks has reduced the genetic diversity of seaweed cultivars used by the industry, and depletion of wild stocks has further reduced the potential to reinvigorate the gene pool. In some regions of the Philippines and Tanzania, only introduced varieties of certain species can be found in the wild.

Conservation challenges

There have been various localised attempts to protect seaweed habitats. For example, Bangladesh introduced a localised ban on the harvesting of wild seaweeds in 1999, sustainable harvesting practices were introduced for wild *Sargassum* in the Philippines, and there have been restrictions on mechanical harvesting of seaweeds in northern Spain. Most recently, in the US the protection and restoration of kelp forests were specifically highlighted in an 2021 Executive Order relating to climate change.

Women harvesting seaweed at low tide, near Jambiani village, Tanzania. This work gives them economic independence and enables them to support their families.

(Photo: Yann Macherez; Creative Commons Attribution-Share Alike 4.0 International)

There is no coordinated global effort to protect seaweeds. There are extremely few Marine Protected Areas (MPAs) (or equivalent) specifically for seaweeds or their habitats. Indeed, designations for MPAs etc. rarely even mention seaweeds – this is despite many of these areas overlapping with regions exploited by the seaweed industry. Unfortunately the baseline surveys that would allow declines in seaweed populations to be detected have not been undertaken. Efforts at both conservation and improving biosecurity are hindered by the fact that seaweed names are not standardised.

For more about the challenges facing wild seaweed and the seaweed farming industry, and proposals for how to tackle problems see: Cottier-Cook, E.J., P.E. Lim and 6 others (2023) *Striking a balance: wild stock protection and the future of our seaweed industries*. *UNU-CRIS Policy Brief*. ISBN 978-92-808-9143-0 See also a related *UNU-CRIS Policy Brief, Ensuring the sustainable future of the rapidly expanding global seaweed aquaculture industry – a vision*, published in 2021, ISBN 978-92-808-9135-5.

Ed.

New protected 'Swimway' for migratory species

The Galápagos Archipelago lies in the eastern tropical Pacific, an area of high biodiversity, which is intensely exploited by fishing fleets from Ecuador and other countries. In 1998, the Ecuadorian government created the Galápagos Marine Reserve, where only Galápagos-based artisanal fishing is allowed.

Marine life flourishes within the reserve, which is well enforced and protects a wide range of species including migratory sharks, cetaceans and turtles (*top map*). As a result of the abundant marine life within the reserve, large numbers of industrial fishing vessels, mostly from China, work around its periphery. Even within the reserve, fish are not safe from large vessels, as they may be caught by fish aggregation devices – rafts with GPS trackers and nets beneath – which attract fish because they cast a shadow. They are used to catch tuna, but net other pelagic fish, and may ensnare marine mammals and turtles before drifting out of the protected area. One large vessel might deploy 300 of these devices,

In January 2022, the Galápagos Reserve was expanded by 60 000 km² bringing the total area to 198 000 km². The extra 60 000 km² – named the Hermandad Marine Reserve – includes a 700 km-long 'Swimway' to connect the Galápagos Marine Reserve with protected Costa Rican waters, around Cocos Island (*lower map*). The Swimway, of which the central part is a no-catch zone, has proved surprisingly effective. According to a recent satellite-based study* of industrial fishing from 2019 to 2023 in the exclusive econcomic Zone (EEZ) around the Galápagos, there was a small increase in fishing effort in anticipation of confirmation of the expansion of the Reserve, but there was an 88% drop in fishing in the Swimway the following year, despite no increase in enforcement. The study's authors consider that this impressive compliance with new restrictions highlights the importance of a consensus-building approach between scientists, government officials and fishers in determining the scope of the reserve, and speculate that the fact that there were already well enforced MPAs in the region may have had a positive effect. They also consider the results demonstrate that industrial fleets may be influenced by the growing importance to customers and buyers of sustainable sourcing of fish.

*Industrial fishing compliance with a new marine corridor near the Galapagos Islands (preprint, Oct. 2023) White *et al.* doi: 10.32942/X2J60N

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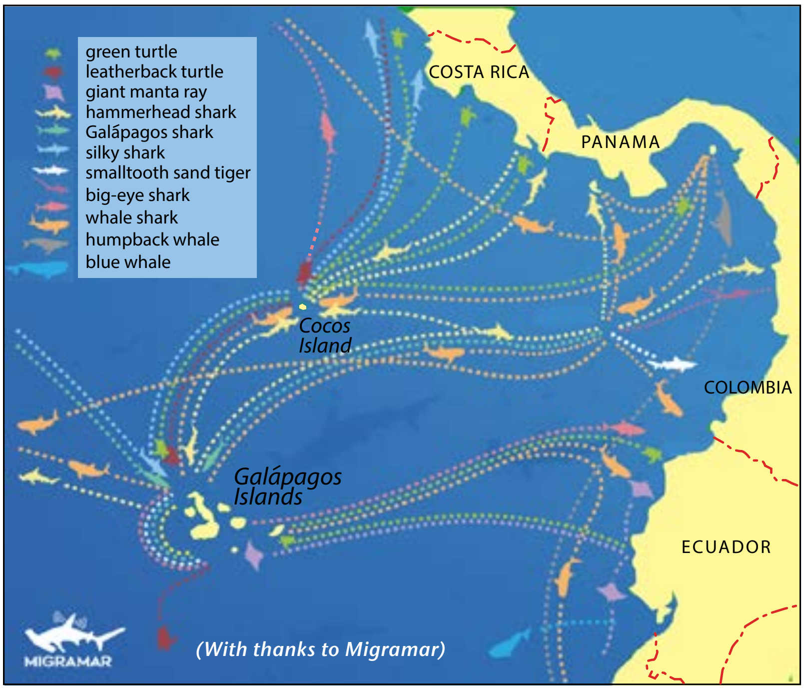
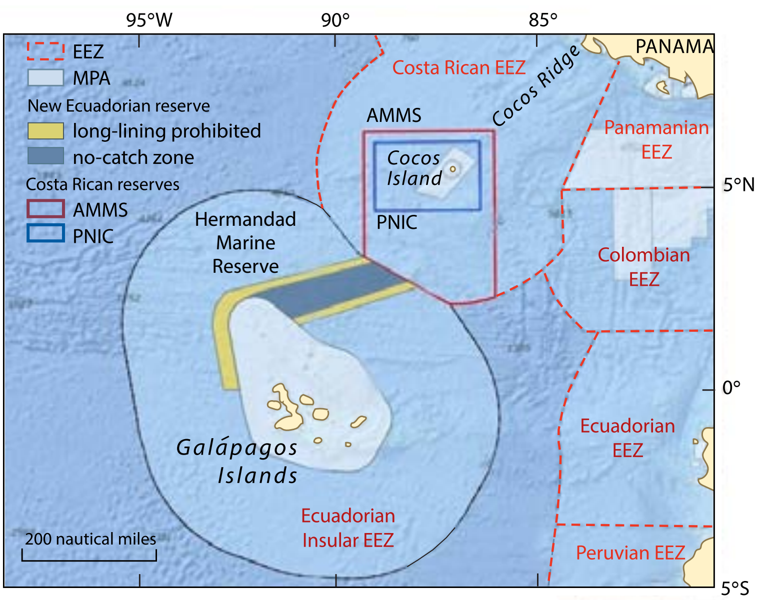
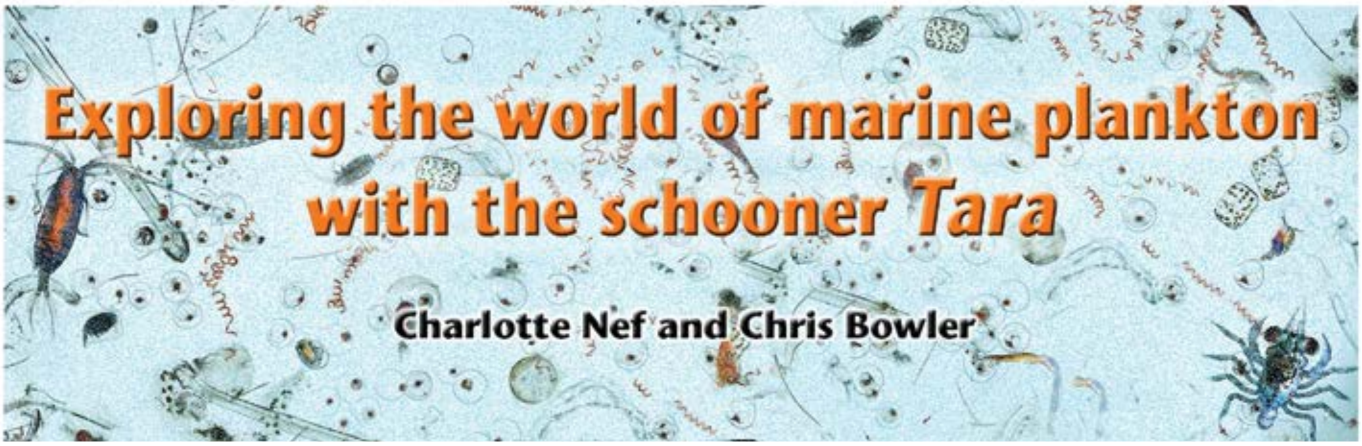


Above *Schematic map to show migration routes of key species in the eastern tropical Pacific.* ***Below*** *Protected areas in the tropical eastern Pacific. The original Galápagos reserve and other established MPAs are shown in pale blue; MPA = Marine Protected Area; AMMS = Cocos Seamounts Marine Management Area; PNIC = Cocos Island National Park. All these reserves are part of an international initiative known as the Marine Corridor of the Eastern Tropical Pacific (CMAR).*





Exploring the world of marine plankton with the schooner *Tara*

Charlotte Nef and Chris Bowler

Plankton, consisting of viruses, archaea and bacteria, unicellular eukaryotes (including algae, fungi, and protists) and small animals, constitute the bulk of marine biomass, are at the base of trophic webs sustaining life in the oceans (and beyond), and are major players in global biogeochemical cycles, such as the carbon cycle. A holistic appreciation of planktonic life in the oceans is the long-term goal of the *Tara* Oceans project, conceived in 2008 by a small group of scientists led by Eric Karsenti and inspired by historical expeditions to explore the marine world, such as that of HMS *Beagle* (1831–1836) which carried Charles Darwin, and that of HMS *Challenger* (1872–1876) led by Charles Wyville Thomson. The plan was to use the research schooner SV *Tara,* owned by the *Tara* Ocean Foundation, to collect seawater samples on a global scale using highly standardised protocols, and to analyse the planktonic organisms present within them using modern methods of biological research.

Building on the success of J. Craig Venter's Global Ocean Sampling expeditions on his sailboat *Sorceror II* (2003–2008), which had applied large-scale DNA sequencing to investigate the diversity and biological role of marine microbes within ecosystems, the *Tara* Oceans scientists made a plan to exploit similar sequencing techniques but on an even grander scale. Their aim was to undertake genomics analysis of entire plankton communities, and to support their analyses they established high-throughput advanced microscopy-based imaging systems to visualise individual organisms. Collectively, the *Tara* Oceans scientists aimed to study planktonic biological systems from the genes present in individual species up to the entire assemblages of organisms making up the planktonic communities within the ecosystems being sampled.

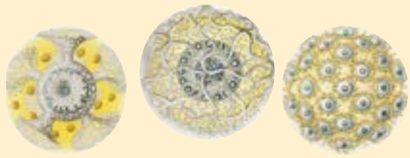
The schooner Tara

SV *Tara* is a 36 m schooner built in 1989 for the French explorer Jean-Louis Étienne, and designed to drift in pack ice in polar regions. Étienne was inspired by the Norwegian Fridtjof Nansen's attempt, in the 1890s, to be the first to reach the North Pole by remaining on the schooner *Fram* while she was trapped in the ice. *Tara* was initially named *Antarctica*, but was later renamed *Seamaster* by the late New Zealand yachtsman Sir Peter Blake who used the vessel to raise environmental awareness, until he was shot and killed by pirates at the mouth of the Amazon delta in Brazil in 2001. The schooner was finally given the name *Tara* when she was purchased in 2003 by Étienne Bourgois, Chief Operating Officer of the agnès b fashion house, who created the philanthropic *Tara* Ocean Foundation (https://fondationtaraocean.org/en/foundation/). This was the first foundation in France to be recognised for promoting public interest in the ocean, and its objective is to build on the legacy of *Tara*'s previous owners by collaborating with scientists to support ocean research and by raising awareness of the ocean's importance and its fragility. *Tara*'s first success was during 2006–2008 when she repeated Nansen's Arctic drift experiment, and by reaching 88°N travelled further north than any other sailboat in history.

Figure 1 *The schooner* Tara *off an iceberg in the Weddell Sea in March 2022. The onboard team typically involved 14 people: six sailors, six scientists, an on-board correspondent and an artist in residence.*

A brief history of early plankton research

The first systematic scientific observations of the microbial world (organisms invisible to the naked eye) go back to the invention of the practical microscope by the Dutch tradesman Antoni van Leeuwenhoeck, based on Robert Hooke's design, and use of the word 'plankton', from the Greek *planktos* (for drifters or wanderers), dates back to Victor Hensen from Kiel University in 1887. This was two years before his participation in the first expedition specifically devoted to the study of microscopic marine organisms in the North Atlantic under the patronage of the German Emperor Wilhelm II. It was carried out using the 58 m 835 ton steamer SMS *National* and is now known as the Plankton Expedition. Although focussed on deep-sea exploration, this expedition, which we would now think of as 'big science', was also the first to draw attention to 'the world of free floating animals that inhabit the open sea', and samples from the expedition were used by Ernst Haeckel (who also worked with *Challenger* Expedition samples) for some of his magnificent drawings.



The Radiolaria shown are some of the many planktonic organisms drawn by Haeckel

Hensen recognised the importance of plankton as the base of all marine life, describing them as 'this blood of the sea'. The later design and use of specific nets was a key advance in plankton sampling. To our knowledge, their first recorded use was by French naturalists Francois Péron and Charles-Alexandre Lesueur during an expedition to Australia from 1801 to 1804.

Later on, plankton were divided into different subcategories (refined particularly by both Hensen and Haeckel and subsequently debated by the scientific community): phytoplankton (plants), zooplankton (animals) and meroplankton.* The term microbial marine plankton is now considered to encompass a wide spectrum of diverse organisms, from viruses, archaea† and bacteria to unicellular eukaryotes (organisms with nuclei, including algae, fungi and protists) and small animals (e.g. copepods and fish larvae), all intertwined into complex and highly dynamic communities.

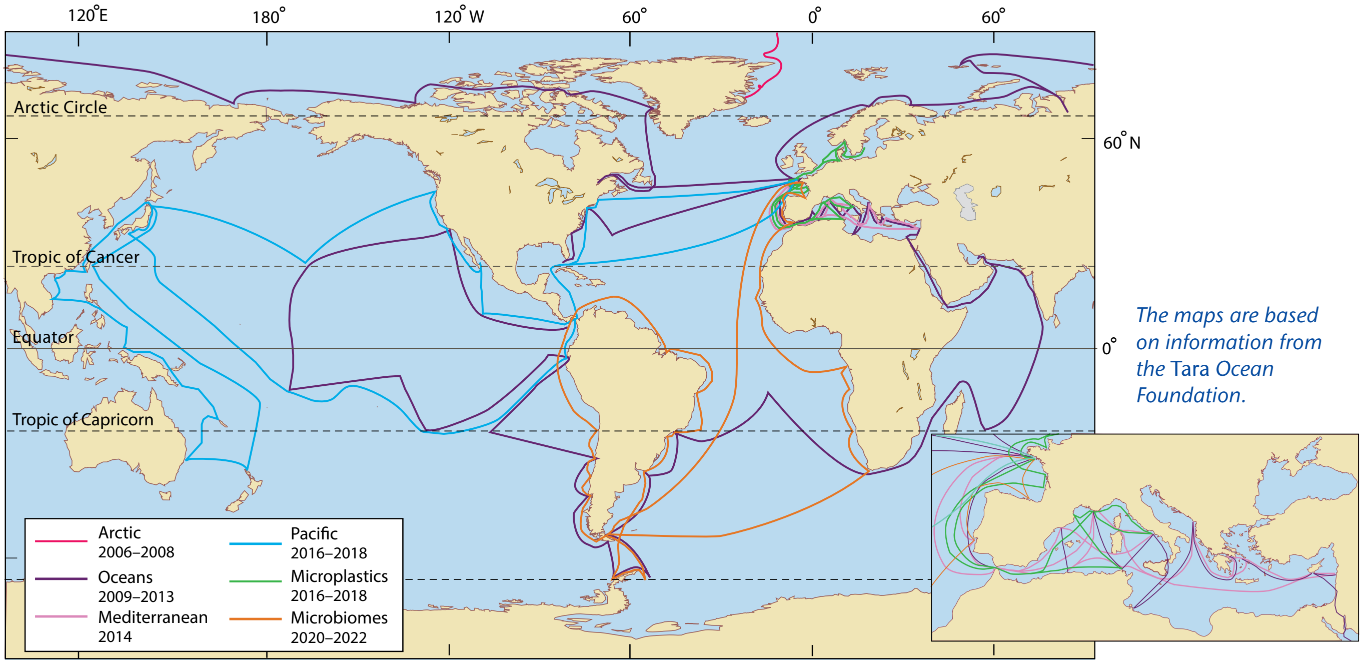
*Meroplankton are organisms in a temporary planktonic stage, e.g. crustacean larvae.

† Archaea are similar in some ways to bacteria but are radically different in molecular organisation.

Philosophy/planning of the Tara Oceans project

The *Tara* Oceans project began in September 2009 with a three-year expedition to sample marine plankton on a global scale. Eric Karsenti and the other scientists together formed a multidisciplinary consortium providing a broad range of complementary expertise, and they worked with the Foundation to exploit the unique capabilities of *Tara* for large-scale open ocean sampling for biological analysis. In 2013, the consortium undertook the *Tara* Oceans Polar Circle campaign, using similar approaches in sampling ocean life. During this expedition, *Tara* became the first sailboat in history to traverse the perilous North East and North West Passages in the same season, establishing another record for polar research. The 5000 samples collected from all around the Arctic Circle (Figure 2) represent a valuable addition to the 30 000 samples collected during *Tara* Oceans, especially considering the current difficulties in performing scientific research in Russian waters. *Tara* Oceans Polar Circle is now considered part of the *Tara* Oceans campaign.

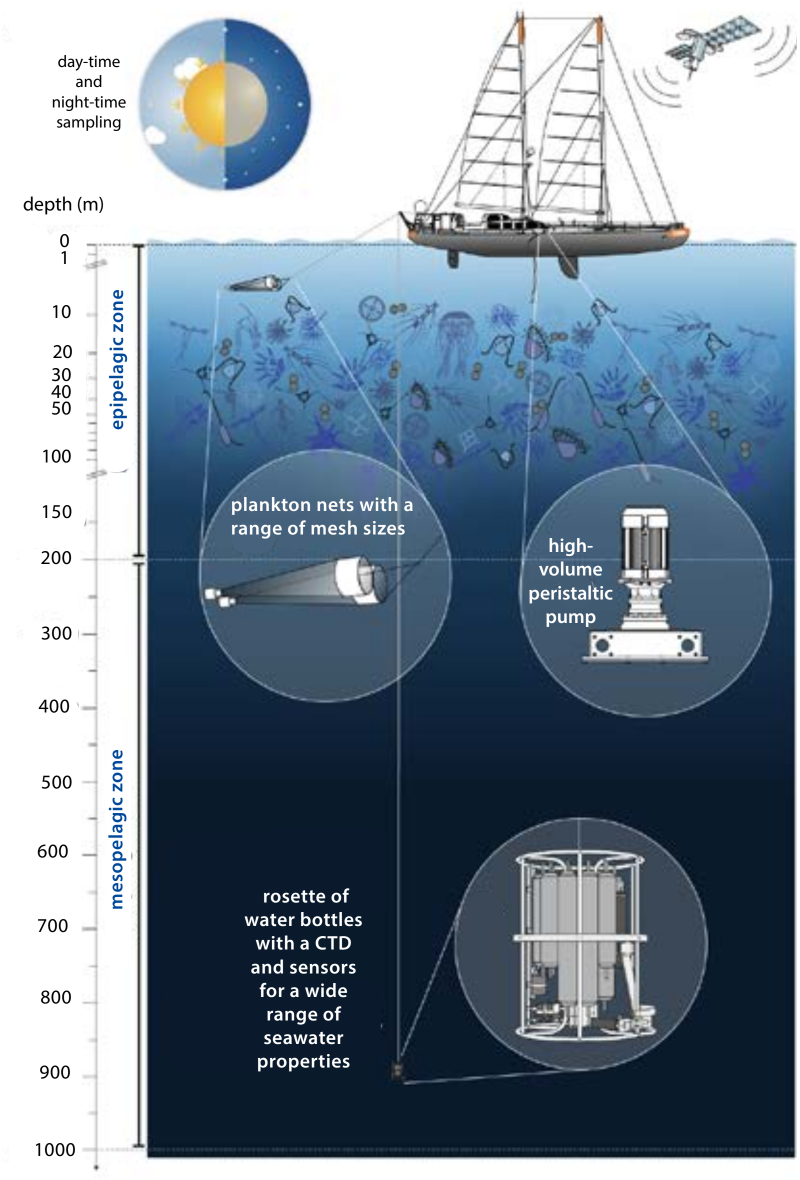
Figure 2 *Sampling routes of* Tara *during different expeditions from 2007 to 2022, including the* Tara *Arctic Expedition (2007–2008) that aimed to measure the effects of climate change on sea-ice extent in the central Arctic Ocean. The purple track represents* Tara *Oceans (2009–2012) and* Tara *Oceans Polar Circle (2013).*



The maps are based on information from the Tara Ocean Foundation.

Tara Oceans gathered together scientists covering a wide range of disciplines, and the consortium comprised specialists from 19 partner institutions in eight countries (see Box on p.28) who were all involved in the diverse preparatory and logistical aspects of the expeditions. The wide range of disciplines covered included biological and physical oceanography, cellular, molecular and systems biology, microbial ecology, genomics, informatics, modelling, taxonomy and data-management. There was also a need to develop dedicated computational approaches and data management strategies. In addition to the science, planning and negotiation of access to ports and to sampling sites in territorial waters were also challenging but essential tasks, and these aspects were coordinated by the *Tara* Ocean Foundation.

Science communication to school children and the general public were additional activities coordinated by the Foundation, as were interactions with policy-makers aiming to improve ocean governance. The credibility of the *Tara* Oceans project was also enhanced by outreach efforts: the vessel was opened to the public during port-calls, results were translated for the general public (see for instance http://oceans.taraexpeditions.org/ and http://www.planktonchronicles.org), and life on board was broadcast regularly to schools to raise awareness about the importance of understanding and appreciating ocean microbes.



Sampling strategy and analytical imaging techniques

The sampling strategy of *Tara* Oceans was intended to explore a wide range of principally open ocean ecosystems such as biodiversity hotspots, upwellings, and oxygen minimum zones. Interesting features such as the persistent phytoplankton bloom in the waters around the Marquesas Archipelago, or Agulhas rings transporting water from the Indian Ocean into the South Atlantic, were also targeted.

Plankton sampling and measurements of environmental parameters were undertaken at 210 stations, with work at each station typically lasting 48–60 hours. Special care was taken to keep the boat within a radius of 10 km and to sample a homogeneous environment as far as possible.

Plankton sampling The project entailed designing a standardised sampling process for collecting organisms whose sizes ranged over seven orders of magnitude (0.1 µm–10 mm) corresponding to viruses, prokaryotes (bacteria and archaea), unicellular eukaryotes (such as protists) and multicellular eukaryotes (such as metazoans/small invertebrates) (see p.25). As far possible, at each sampling station plankton were collected from the surface mixed layer, the deep chlorophyll maximum (DCM), and the mesopelagic zone, and once on board were size-fractionated (Figures 3 and 4). The sequence of sampling deployments generally followed the same order: the surface mixed layer and mesopelagic zone during daytime on the first day, then night sampling over fixed depths, and the DCM again during day-time on the second day. Sampling devices for plankton consisted

Figure 3 *At each open-ocean station,* Tara *sampled plankton during the day and at night, from surface and subsurface sunlit waters (including the deep chlorophyll maximum) to dark mesopelagic waters down to 1000 m depth. Positioning was guided by satellite data, and plankton were collected using five types of plankton nets with different mesh sizes, an industrial, high volume peristaltic pump and a rosette water sampling system equipped with Niskin bottles. Physicochemical parameters of the sampled water were measured* in situ *or back in the onboard laboratory. Samples collected from the rosette, and sensors mounted on it, measured 25 pigments, five nutrients, dissolved oxygen, chlorophyll, particle backscattering, coloured dissolved organic matter, dissolved organic carbon (DOC), the intensity of photosynthetically active radiation, photosynthetic efficiency, pH and other parameters related to the carbonate system.*

essentially of a high-volume peristaltic pump, Niskin water bottles on a Rosette Vertical Sampling System (RVSS), and instrumented plankton nets. Viruses were concentrated by precipitation with iron chloride. Overall, the sampling plan thus combined both traditional and more modern methods (Figure 3).

All samples were analysed using processes specific to each size fraction. Biological samples for microscopy were preserved using diverse fixation methods. Plankton images were obtained by different devices ranging from imaging flow cytometers (for objects typically the size of bacteria) to Zooscan (for large protists or small animals) and an Underwater Vision Profiler (UVP) for *in situ* detection of organisms larger than 0.6 mm (Figure 4(b)).

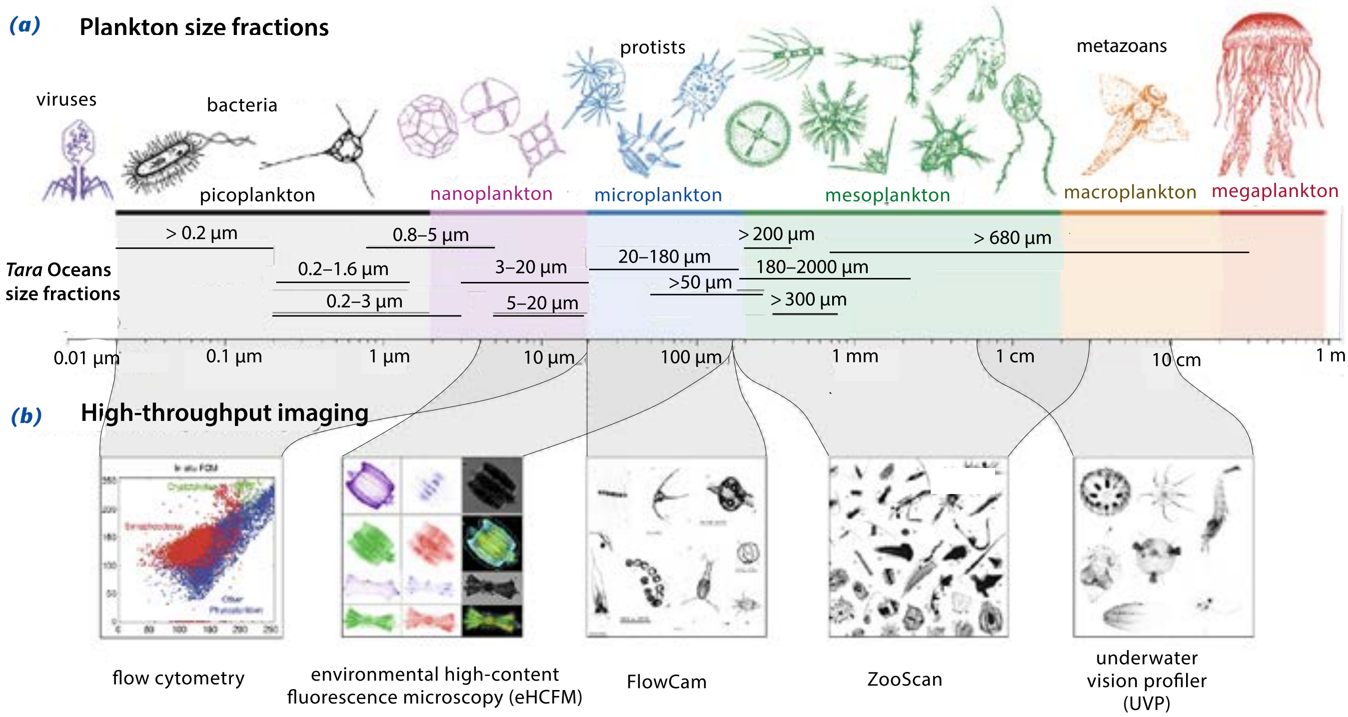
Environmental observations Temperature and salinity were measured using a CTD which was mounted on the rosette with the water bottles, along with sensors to collect other environmental data, including pH and related parameters, dissolved oxygen concentration, nutrient concentrations, and chlorophyll (see caption to Figure 3 for details).

The onboard Continuous Surface Sampling System In addition to the data collected while *Tara* was on station, continuous measurements were also made between stations using devices making up a Continuous Surface Sampling System (CSSS) installed onboard *Tara*; this comprised temperature and conductivity (salinity) sensors, a spectrophotometer, and chlorophyll fluorometers to assess the photosynthetic efficiency of phytoplankton. Continuous measurements of surface-water properties provided useful information for estimating positions of boundaries between water masses, along with the homogeneity/heterogeneity of ecosystems at specific sampling sites and the connectivity between them.

Data-recording All data were recorded simultaneously and archived daily in a single file, including navigational information, date/time and GPS position. Additional near real-time remote sensing measurements from satellites were recorded to gain insights into oceanographic context and physicochemical features, and to detect oceanographically interesting zones (e.g. fronts and eddies). This combination of approaches allowed for improved comparisons between ecosystems and better analysis of complex systems, therefore limiting the impact of spatial heterogeneity inherent in global ocean sampling and avoiding 'snapshot' effects, where a single measurement does not reveal the entire complexity of a system.

Genetic analyses The samples collected for genomic (DNA) sequencing analyses were kept in liquid nitrogen onboard *Tara,* and back on land were transferred to Genoscope in Evry (France) for further processing. A range of techniques were applied using DNA sequencing methods, in particular metabarcoding, metagenomics and metatranscriptomics, where the 'meta' refers to the bulk

Figure 4 (a) *The* Tara *Oceans sampling protocol targeted 12 organismal size fractions from picoplankton to megaplankton, i.e. across more than seven orders of magnitude.* ***(b)*** *The high-throughput imaging methods were used to quantify organismal richness, sizes, biovolumes and morphological complexities. It was not always possible to collect every sample type at every station, and to subject every sample to all possible types of analyses, but each sample was cross-referenced to a rich set of metadata to allow researchers to compare different samples and data types.*



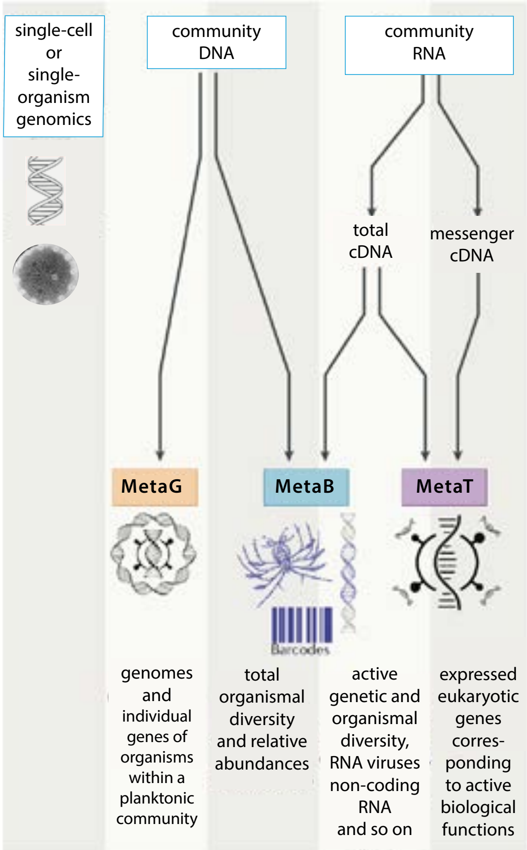


Figure 5 Diagram summarising how the Tara Oceans *high-throughput sequencing pathways generated datasets for assessment of the diversity and relative abundance of genomes, genes and taxonomic barcodes across the kingdoms of life: MetaB = metabarcoding; MetaG = metagenomics; MetaT = metatranscriptomics. cDNA = complementary DNA, synthetic DNA used as a tool in gene cloning.*

genetic information coming from an environmental sample (in this case, a sample of seawater) rather than individual organisms (Figure 5).

Barcoding is a technique for identifying species by amplifying and sequencing fragments of conserved universal genes (i.e. genes that have remained essentially unchanged throughout evolution) and comparing them with known references. Metabarcoding (MetaB in Figure 5) applies the same principle but to bulk communities rather than to individuals. This allows the simultaneous assessment of the different species within a community and is used to estimate species richness within a given environment. Exploring the amount and variability of the genetic information from planktonic organisms across different ecosystems can provide clues about how the communities respond and adapt to changes in their environment.

The environmental response of plankton on short time scales (over the lifetime of the cell) is called acclimation and involves the modulation of gene expression – the degree to which a gene is active. By contrast, adaptation to a specific environment refers to genetic changes that accumulate over many generations. Responses to environmental cues also include shifts in the community structure. Therefore, in addition to taxonomic analyses based on metabarcoding data, functional analysis of plankton communities – the identification of the biological role of species within communities (e.g. carbon fixation) – was carried out by metagenomics and metatranscriptomics (MetaG and MetaT in Figure 5).

Metagenomics is the process of getting information from the genes of organisms within a community to study, for instance, their genetic diversity. Metatranscriptomics, on the other hand, refers to the study of changes in gene expression of organisms within a community. It can provide information about the broader life strategies used by different plankton groups (such as parasitism, pathogenesis and symbiosis), or their metabolic lifestyles (such as photosynthesis or heterotrophy, i.e. relying on dissolved organic matter or other organisms for nutrition, through predation or decomposition).

Towards ecosystems biology of the ocean

The project has given rise to an unprecedented catalogue of DNA sequences from marine plankton, with about 50 million genes from prokaryotes and 100 million genes from microbial eukaryotes, an impressive delineation of sequence information for nearly 200 000 types of DNA viruses and ~5500 RNA viruses, ~35 000 bacteria and archaea, and an estimated 150 000 taxa of microscopic eukaryotes of which only 10% were previously known. Results so far indicate that most plankton biodiversity is found in size fractions smaller than 100 μm and, contrary to what was formerly thought, in eukaryotes rather than viruses or prokaryotes. Most of this eukaryotic diversity dwells in poorly described lineages, for the most part uncultured and uncharacterised. All these results from the *Tara* Oceans project make it the most successful global multidisciplinary exploration of plankton diversity to date. Its results were initially reported in a special issue of *Science* on 22 May 2015, and have continued in more than 150 publications so far.

Tara's comprehensive and highly standardised global sampling encompassed a wide diversity of plankton life strategies (as shown in Figure 6 for eukaryotes) and enabled environmental effects to be teased apart from geographic effects. This made it possible to perform large-scale studies investigating the vulnerability of plankton communities to modelled climate change scenarios. It highlighted, for example, that temperature is a crucial variable in determining the organisation and composition of plankton communities within and across ecosystems. Polar plankton communities appear to be highly vulnerable to temperature changes while more temperate communities appear to be more vulnerable to changes in nutrient availability. By providing a list of plankton taxa that would not be able to tolerate the projected environmental changes, these results constitute a useful guide for identifying indicator species that

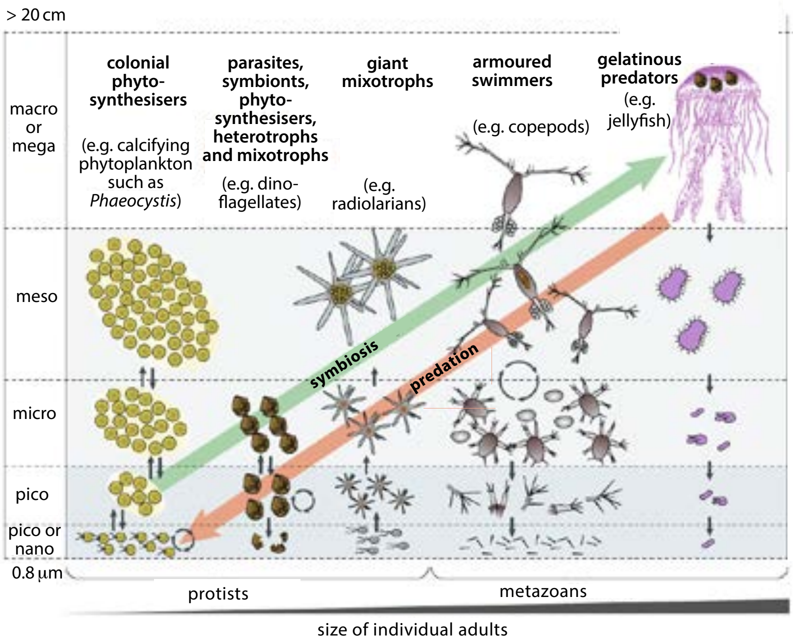


Figure 6 *Diagram to show the biological and functional complexity of planktonic eukaryotes across the size fractions analysed in* Tara Oceans.
The horizontal axis goes from smallest to largest adult size (from the smallest single-celled protists to larger multi-celled animals); the vertical axis goes from smallest individual organisms (including gametes and juvenile stages) to colonies of phytoplankton and larger organisms and assemblages, including heterotrophic protists which in association with phytoplankton can form giant ecological units. The different size ranges, linked by small bold arrows, correspond to different life strategies (e.g. different colony sizes of colonial phytosynthesisers) and to results of degradation (e.g. fragmentation after death).
Green arrow: Small organisms may form symbiotic relationships with larger ones; orange arrow: larger organisms typically predate smaller ones.

Note *Mixotrophs can use a mix of different sources of energy from autotrophy (photosynthesis or chemosynthesis) to heterotrophy (relying on dissolved organic matter, or other organisms).*

(The viral, bacterial and archaeal diversity associated with eukaryotes is not represented in this diagram.)

can be useful in environmental monitoring and for assisting policy-makers in establishing guidelines.

An ongoing scientific and human adventure

Tara Oceans became a model for how the *Tara* Ocean Foundation could successfully interact with scientists and contribute to the advance of scientific knowledge, and was soon followed by other *Tara* expeditions with other scientific consortia following the same model. The tracks of these expeditions can be seen in Figure 2. Specifically, *Tara* Mediterranean (2014) quantified plastic pollution and its relationship with plankton; *Tara* Pacific (2016–2018) targeted coral reefs in the Pacific Ocean to investigate their health and resilience to anthropogenic perturbations; *Tara* Microplastics (2019) investigated the nature, fluxes and fate of plastic waste from nine European rivers to the sea to find their origins; and *Tara* Mission Microbiomes (2020–2022), endorsed by the UNESCO International Oceanographic Commission for contributing to the UN Decade of Ocean Science for Sustainable Development, explored the function of marine microorganisms and assessed their vulnerability to climate change and pollution. *Tara* Europa was launched in April 2023 as part of the TREC project (www.embl.org/about/info/trec/) to explore the land–sea interface around Europe.

Another major success of *Tara* Oceans resides in its fundamental policy of generating high quality open access data that can be exploited extensively by the scientific community. In particular, the raw genetic information obtained after sequencing the plankton samples is available at the European Bioinformatics Institute (www.ebi.ac.uk/ena/), e.g. in the MGnify metagenome portal (www.ebi.ac.uk/metagenomics/), while all biogeochemical, oceanographic and meteorological data are gathered in the PANGAEA database (www.pangaea.de/) and are fully accessible. Most of the microscopy images are available through the EcoTaxa databases (ecotaxa.obs-vlfr). Other curated datasets include the Ocean Barcode Atlas (oba.mio.osupytheas.fr/ocean-atlas/) and Ocean Gene Atlas (tara-oceans.mio.osupytheas.fr/ocean-gene-atlas/) which allow users to explore the distribution and abundance of organisms or genes of interest, respectively, by providing visualisation tools to build charts and maps. Also, to facilitate the dissemination of results, most of the *Tara* Oceans publications are accessible through open-access journals and the data are archived within public repositories. This promotes major advances in addressing questions of general interest to humankind. Thousands of papers authored beyond the *Tara* Oceans consortium now cite *Tara* Oceans data, and there continue to be major surprises, such as the discovery of entirely new phyla of life, and of new genes of biomedical interest.

The project stands as a long-lasting illustration of how fundamental science can benefit from public and private entities: it was supported by a philanthropic non-governmental organisation (the *Tara* Ocean Foundation), which graciously provided the *Tara* schooner for the benefit of scientific research, led by specialist scientists in public research institutions; seed funding was obtained from the French National Centre for Scientific Research (CNRS), the French National Research Agency (ANR), the European Molecular Biology Laboratory (EMBL) and the Région Bretagne; other philanthropic organisations, such as the Prince Albert II of Monaco Foundation, the EDF and Veolia Foundations, as well as private individuals, also provided support for the expedition, while individual consortium members obtained competitive research grants, and invested in-house resources and expertise from their labs.

The *Tara* expeditions accommodate not only scientists but also artists – see for instance manonlanjouere.com/Les-Particules and vincenthilaire.fr/expeditions/tara-arctic/, as well as journalists, educators and even politicians. The Foundation also runs workshops to alert educators to resources based on *Tara* Oceans research outputs which they can use in projects to improve ocean literacy and promote sustainable development.

With more than 580 000 km covered since 2003 (almost the equivalent of going to the Moon and back!), and more than 250 stopovers in 56 countries, *Tara* has definitely left her mark on the scientific landscape. Beyond her record-breaking achievements in the Arctic and the thousands of children she has inspired, through the *Tara* Oceans project *Tara* has provided the first planetary-scale analysis of marine plankton ecosystems and is now beginning to contribute to microplastics and coral reef research through publications led by the *Tara* Microplastics and *Tara* Pacific scientific consortia.

With due acknowledgement to the children's book *The Little Engine that Could* by Watty Nobel, in the realm of marine biology we should think admiringly of *Tara* as 'The Little Boat That Could – and does'!

Further Reading

Ball, C.S. (1966) The early history of the compound microscope. *Bios* **37**, 51–60.

Pierella-Karlusich, J.J., F.M. Ibarbalz and C. Bowler (2020) Exploration of marine phytoplankton: from their historical appreciation to the omics era. *Journal of Plankton Research* **42**, fbaa049. doi: 10.1093/plankt/fbaa049

Tara Ocean Foundation *et al.* (2022) Priorities for ocean microbiome research. *Nat. Microbiol.* **7**, 937–47. doi: 10.1038/s41564-022-01145-5

Karsenti, E. *et al.* (2011) A holistic approach to marine eco-systems biology. *PLoS Biol.* **9**, e1001177. doi:10.1371/journal.pbio.1001177

Baudena A., I. Ser-Giacomi, E. Jalón-Rojas, F. Galgani and M.L. Pedrotti (2022) The streaming of plastic in the Mediterranean Sea. *Nat. Commun.* **13**, 2981. doi: 10.1038/s41467-022-30572-5

Planes, S. *et al.* (2019) The *Tara* Pacific expedition—A pan-ecosystemic approach of the '-omics' complexity of coral reef holobionts across the Pacific Ocean. *PLoS Biol*. **17**, e3000483. doi:10.1371/journal.pbio.3000483

Sunagawa, S. *et al.* (2020) *Tara* Oceans: towards global ocean ecosystems biology. *Nat. Rev. Microbiol.* **18**, 428–45. doi: 10.1038/s41579-020-0364-5

Chaffron, S. *et al.* (2021) Environmental vulnerability of the global ocean epipelagic plankton community interactome. *Sci. Adv.* **7**, eabg1921. doi: 10.1126/sciadv.abg1921

Ibarbalz, F.M. *et al.* (2019) Global trends in marine plankton diversity across Kingdoms of Life. *Cell* **179**, 1084–97.e21. doi: 10.1016/j.cell.2019.10.008

Tara *Oceans Coordinators*

First scientific *Tara* Oceans consortium

Eric Karsenti, EMBL, Scientific Director; Etienne Bourgois, Director of *Tara* Expeditions; Romain Troublé, General Secretary of *Tara* Expeditions; Stephanie Kandels Lewis (EMBL) and Didier Velayoudon (DVIP consulting), Operational Managers.

Tara Oceans scientific coordinators

These interdisciplinary partners from various international institutions elaborated the scientific planning and sampling strategy, fixed the general objectives of the project, led the expedition, and have conducted most of the analysis of results over the past ten years.

Silvia Acinas, Department of Marine Biology and Oceanography, Institut de Ciències del Mar (CSIC), Barcelona, Catalonia, Spain.

Peer Bork and Shini Sunagawa, Structural and Computational Biology, and Uros Krkic, Cell Biology and Biophysics, European Molecular Biology Laboratory, Heidelberg, Germany.

Emmanuel Boss and Lee Karp-Boss, School of Marine Sciences, University of Maine, Orono, Maine, USA.

Chris Bowler, PSL Research University, Institut de Biologie de l'Ecole Normale Supérieure (IBENS), CNRS UMR 8197, INSERM U1024, Paris, France.

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Book reviews

Sharing a fascination with shelf seas

Home Waters: Discovering the submerged science of Britain's coast by David Bowers (2023) Adlard Coles. 280pp. £10.99 (paperback, ISBN 978-1-472-99068-6). Also available as an ebook.

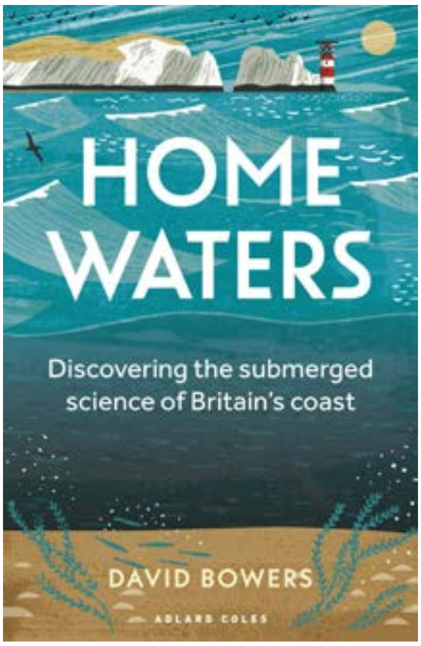
This book is concerned with the coastal waters around our islands. It is not a textbook about the science of shelf seas but, instead, focusses on a selection of topics which interest the author. It is written in a personal style and one of the author's aims is to make some of the science of shelf seas accessible to non-specialist readers. He succeeds in this aim because the book can be read easily by just about anyone, even though there is a lot of science in it. I especially liked the way that each chapter has figures drawn in a similar way and embedded in the right places in the text (no need for any figure numbers).

Each chapter focusses on a particular aspect of marine science with occasional digressions into local history or geography. As an emeritus professor of oceanography at Bangor, David Bowers knows a lot about these topics. However, I liked the way that if something crops up that he doesn't understand, then he is honest enough to say so, sometimes suggesting that it be researched in more detail by someone else. I also liked the way that he has visited most of the places mentioned in the book himself, and that useful references are given to pubs discovered on the way.

Most of the topics covered are to do with physical oceanography, because that is the speciality of the author, but the book does include aspects of coastal chemistry, biology and geology. One thing we learn is how much of the first research on coastal waters was undertaken by British scientists, and there are references to people whose names are probably well known to members of the Challenger Society, if not to the general reader. I will mention below just some of the chapter topics.

Chapter 1 is concerned with the great depths of most of the ocean (with mentions of the *Challenger* Expedition) and explains what happens when the Gulf Stream encounters the continental shelf and the 'home waters', which being shelf seas, behave differently from the deep ocean.. This leads to discussion of coastal currents in Chapter 2 and a description of how measurements are made of their properties. Chapter 3 is concerned with the temperatures of coastal waters, when and where stratification occurs, and how that affects the biology. Chapter 4 moves onto the important role of waves, mentioning the work of several pioneering British scientists who have studied waves, such as George Stokes, Jack Darbyshire and George Deacon, and also Vaughan Cornish who reappears later in Chapter 7. In this and other chapters, one learns about the importance of making observations, even if at first the physical mechanisms are not understood. Chapter 5 describes the 1953 storm surge in the North Sea and how that led to the development of the electronic surge prediction machine of Shizuo Ishiguro, now to be found in the Science Museum.

Chapter 6 describes the complexity of the tides around our coasts. I particularly enjoyed Chapter 7 which gives the history of measuring the tidal bore on the Trent, known as the Eagre. This research started with observations by an enthusiastic school inspector called H.H. Champion who compiled a considerable amount of data on the bore between 1929 and 1931. After Champion died, his sister asked Arthur Doodson and R.H. Corkan at the Liverpool Tidal Institute to see the work through to publication. Doodson asked some basic questions (such as 'Why are there bores on rivers anyway?'), the answers to which can be found in Doodson and Warburg's *Admiralty Manual of Tides*, published in 1941. The double tides at Port Ellen and Southampton, and the double lows at Weymouth, are features of the tide that occur due to frictional effects, and these are discussed in Chapter 8. Chapter 9 describes how light penetrates into the ocean depths and how its colour is modified by different concentrations of suspended matter. Finally, Chapter 10 is concerned with how different layers of water occur in a loch, with comparisons to the way that layers form in deep ocean basins or even in the ocean as a whole.



The fact that the value of observations is mentioned throughout the book makes the point that everyone can benefit from making them, whether they be casual visitors to the coast or professional marine scientists. As the author says, the ocean is the last great unexplored frontier on our planet, so we should all take notice of it. As for oceanographers, he suggests that they should all go to sea occasionally, rather than always be glued to computer screens.

In summary, this book makes for a most pleasant read in which the author's enjoyment of researching the oceans and seas is apparent in every chapter. It can be read by people who just have a general interest in the sea, and by oceanographers who will relate more to the science. It would be a great book to read during a holiday by the coast.

Philip Woodworth
National Oceanography Centre

Creatures bright and beautiful

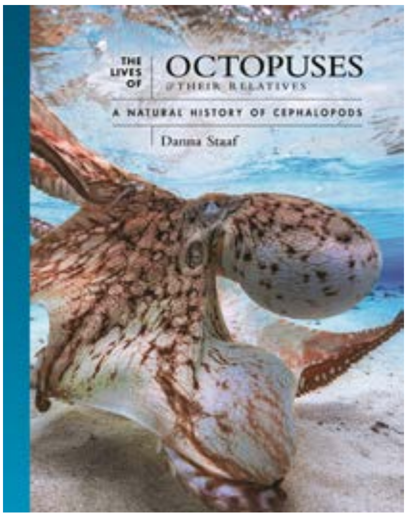
The Lives of Octopuses and their Relatives: A natural history of cephalopods by Danna Staaf (2023) Princeton University Press 'The Lives of the Natural World' Series, 288pp. £30 (hardback, ISBN 978-0-691-24430-3).

This is not a typical academic textbook – the writing style is informal, easy to follow and almost conversational. This is not surprising, as the author also wrote the prize-winning *The Lady and the Octopus*, about the pioneering marine biologist, Jeanne Villepreux Power (see article in Vol.26 (2)). The many photographs of cephalopods are extraordinarily beautiful, and even before diving into the text, who could not be charmed by names such as Wunderpus, Bellybutton Nautilus, and Warty Bobtail Squid?

Despite the title, there is a lot more in this book than descriptions of the lives of octopuses, squid, cuttlefish and nautiluses. In an early chapter entitled ‘What is a cephalopod?’ we learn that cephalopods appeared around 500 million years ago, and have survived five mass extinctions. They were the first swimming predators, and became involved in an ‘evolutionary tussle’ with fish. The rest of this chapter looks at fundamental aspects of cephalopods: life-cycles, camouflage, vision, and basic anatomy, including the fact that – out-doing Dr Who – all cephalopods have not two, but *three* hearts.

The main part of the book looks in more detail at 47 cephalopod species (there are around 700 in all). For each selected cephalopod there is information about its physical characteristics and its life style, and a map of its distribution globally, along with a stunning photograph. In fact, beautiful photos are scattered throughout the book, some of other marine animals and others of yet more cephalopods.

This main section is divided into chapters corresponding to different marine environments: Beaches, tide pools, sandflats and mudflats; Seagrass beds, kelp forests and rocky reefs; Coral reefs; Open ocean; Midwater; Deep sea; Antarctica and the Arctic. The author has used this structure to explore a wide range of topics relating to the oceans. To take a few examples: the introduction to the chapter on the deep sea includes discussion of sea-floor bathymetry (with mention of the *Challenger* Expedition, naturally), whale falls, hydrothermal vents and seeps, resource extraction, and reproduction and growth in the deep sea; the chapter on the open oceans includes migration, fishing, plastic pollution and marine research; and climate change and the thermohaline circulation come up in the chapter on Antarctica and the Arctic. I can well imagine someone who had decided to become a marine biologist discovering that other aspects of oceanographic science are equally fascinating.



The introductory sections often include more detailed science, written in accessible language. Some of these more detailed discussions are more successful than others. For example, the introduction to ‘Beaches, tide pools, sandflats and mudflats’ includes two pages about ‘the cause of the tides’, but for the reader keen to learn about the lives of octopuses, it might have been better to concentrate on (say) the challenges of living in such a changeable environment as a tidal pool, rather than the underlying astronomical cause of the tides.

These more detailed scientific explanations include line drawings which provide extra information. The line drawings are interesting and useful, but are not always well linked with the text, and the labels, which are unnecessarily small (as are the captions, and much of the text, at least for this reader) sometimes include terms that are not explained anywhere (not even in the Glossary). Unfortunately this gives the impression that these drawings were afterthoughts, along with the scattering of ‘boxes’ of interesting facts that don’t necessarily fit anywhere else.

Despite these reservations, the author’s idea to use the animals she is clearly so passionate about as a kind of ‘excuse’ to explore others aspects of the ocean, works well. It’s a shame that the book’s title doesn’t highlight this valuable aspect of what its pages contain. Indeed, the Contents list could usefully have included the subsection titles, as interesting material is to be found in places that the reader might not expect. So, although the book is undeniably beautiful, the design does not help the reader through its rather complicated structure. For me, the variety of typefaces and type sizes, and the differently coloured pages, which might have been intended to help here, are annoying rather than useful.

None of these criticisms alters the fact that I think this book is a wonderful introduction to octopuses and their relations, and the environments they inhabit. Great pleasure can be obtained by just opening at random, being amazed by whatever stunning cephalopod you find an image of, and learning about it.

Angela Colling
Editor, *Ocean Challenge*

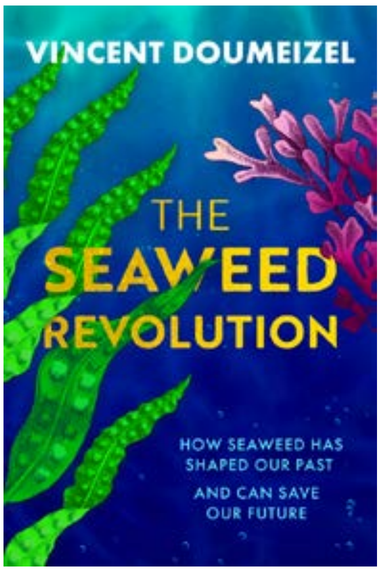
Wonderful weed

The Seaweed Revolution: How seaweed has shaped our past and can save our future by Vincent Doumeizel, translated by Charlotte Coombe (2023) Hero Press. 320pp. £18.99 (hardback, ISBN 978-1-915-64385-8); £12.99 (ebook, ISBN: 978-1-915-64386-5).

The world is in crisis, but fear not – Doumeizel’s *Seaweed Revolution* is here to tell you how seaweed can help save us! Turns out that seaweeds are pretty damn amazing and potentially even more useful than most of us could possibly have imagined. Food. Feeds. Fertilisers. Fuels. Additives. Carbon Stores. Cosmetics. Pharmaceuticals. And so much more. You name it, seaweeds have got it covered. The only problem is that we don’t seem to be making the most of their potential and the opportunities they offer us.

Aptly named, Vincent Doumeizel’s *The Seaweed Revolution* is an interesting read that paves the way for a brighter industrial future for seaweed by looking to the past; hoping for a recycling of currently out-of-vogue historical applications, yet on a bigger, better and grander scale in a new era of technological and scientific expertise. Combining historical anecdotes and interesting examples from around the globe, Doumeizel paints a vivid picture of the impact that seaweeds have had on planetary function and how they have shaped human society. He provides a tempered yet inspirational vision for how they can be of value in a future society that seeks to wean itself off fossil fuels and starts putting sustainability and the environment first.

Considering the topic is marine-based algae, the ground this book covers is staggering: from early climate manip-



ulation, fossil fuel formation, human migration, burping cows and greenhouse gases, and the grazings of remote island sheep, to gunpowder and World War I. Doumeizel makes a compelling case by looking backwards; we have already learnt (and it seems forgotten) so much about seaweed, that if we can now somehow apply this knowledge looking forward, a much greener, redder and browner future awaits us. Seaweed can feed us and our animals, clothe us, help us fight climate change, remediate our environment and provide hope, improved health and social and economic justice for coastal communities across the world. All that's needed is a seaweed revolution to make it happen. Let's hope it starts here.

If you're a seaweed scientist or lover of all things seaweed-related already, this book is probably not for you. Whilst it brings together many varied applications and uses for seaweeds, there are just too many to cover in sufficient depth to really teach you something new. But as a tome encompassing the entirety of the seaweed world, for seaweed fans, this is the ultimate tool for converting the uninitiated to their cause! With sweeping generalisations, a rapid pace and just the right amount of detail, for someone new to the topic, this is a powerful read which will enlighten, enthuse and inspire in equal measure. If you know nothing about seaweed or want to know more, this is a great introduction and will change your way of thinking.

Vive la revolution! Merci Doumeizel.

Mike Allen
Exeter University

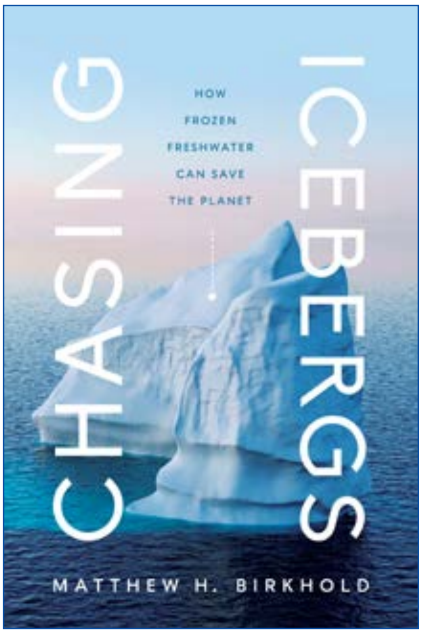
Frozen assets

Chasing Icebergs: How frozen freshwater can save the planet by Matthew H. Birkhold (2023) Pegasus Books, 228pp. £22.95 (hard cover, ISBN 978-1-639-36343-8). Also available as an e-book.

With ongoing climate change leading to more weather and climate extremes – both wet and dry – this is a very topical book looking at the long-standing idea of using icebergs as a source of freshwater, from a historical, cultural and environmental point of view. Icebergs calve from polar glaciers, formed from compaction of millennia of snowfall, and flow of the resulting ice downhill to the nearest ocean.

Despite floating in the salty ocean, icebergs transport (fairly) pure freshwater. The Inuit have long known of this source of freshwater, and James Cook realised, and exploited, the utility of icebergs transporting freshwater far into the Southern Ocean during his circumnavigation of Antarctica in the 1770s. Discussion of and planning for retrieving icebergs from polar regions and transporting them to the tropics and subtropics so as to harvest their water has gone on since the 1970s. However, to date, only small-scale, local harvesting of small icebergs or fragments has actually occurred, producing highly expensive and limited supplies of 'iceberg water' for wealthy clients.

This book examines plans being proposed by several organisations (of varying credibility) for towing icebergs across the Southern Ocean to supply drought-prone areas of southern Africa and the Middle East with precious freshwater. Matthew Birkhold talks up the possibility of such an enterprise, as his book's subtitle suggests. However, I feel he doesn't succeed in producing a convincing argument for the imminent realisation of this dream. Despite the fact that icebergs originating from Greenland have indeed been towed limited distances in the seas off eastern Canada, to deflect them from being carried by the Labrador Current through a field of oil drilling platforms off Newfoundland, he is unable to point to any serious attempts for long-distance towing. Yes, iceberg–ocean modelling suggests that icebergs ought to be able to be towed hundreds of kilometres without completely melting – and historically the occasional iceberg in the North Atlantic has reached Shetland and even as far south as the Azores. However, no long-distance trial tow has yet occurred, as can be seen from the absence of any discussion of it in Matthew Birkhold's book.



Where I thought the book was a real success was its chapter on the 'Law of Icebergs', which was a comprehensive examination of the legal position of harvesting icebergs from the ocean. Oceanographers will be generally familiar with the concepts of territorial waters and exclusive economic zones offshore of a maritime state, but icebergs form a rather novel resource. Most limited iceberg harvesting to date has gone on in territorial waters but, with some exceptions, implicitly follows the principal of *res nullius* – i.e. icebergs are seen as owned by no-one – so there is open competition for their use. Nevertheless, if they were to be exploited more generally the legal position of icebergs would clearly fall under the more general provision of the *UN Convention on the Law of the Sea*, according to which resources in territorial waters and exclusive economic zones (as opposed to in the high seas) 'belong' to the coastal state. Maritime states are likely to be able to argue for monitoring of icebergs and legalising their use within exclusive economic zones, although whether icebergs fall into the category of non-living resources that don't require conservation or, because of their origin and climate implications, fall into a grey area legally, is not established. Icebergs' capture and utilisation in the open ocean is likely to be unchallenged, at least north of 60°S and so outside of the Antarctic Treaty region. At present, countries like Greenland, Canada and Norway make whatever rules they wish regarding icebergs – indeed Greenland currently bans commercial harvesting of icebergs. If this book is an indication that iceberg utilisation is on the horizon, a formal international legal position for icebergs would be a vital next step.

Overall, this book is an entertaining and easy read, factually accurate and well narrated and structured. Nevertheless, the reader is left feeling a little disappointed at the end as the optimism conveyed by the book's subtitle – 'How frozen freshwater can save the planet' – seems misplaced. One is left realising that icebergs are not likely to be saving the planet any time soon.

Grant Bigg
University of Sheffield

continued >

An island community's response to disaster

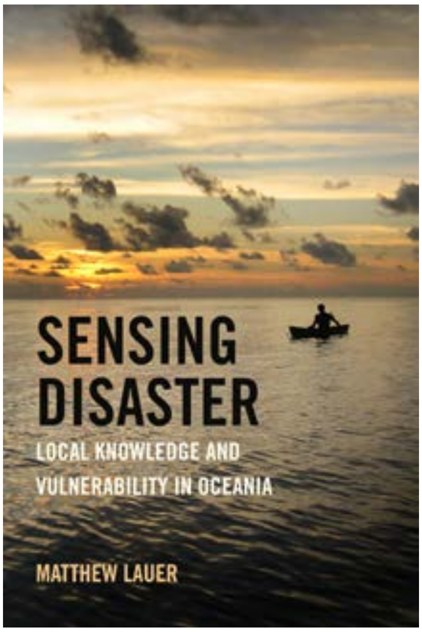
Sensing Disaster: Local knowledge and vulnerability in Oceania by Matthew Lauer (2023) University of California Press, 292pp. £71 (hardcover, ISBN: 978-0-520-39205-2); £25 (paperback, ISBN: 978-0-520-39207-6); £25 (ebook, ISBN: 978-052-0-39208-3).

Sensing Disaster opens with a description of a volatile and dangerous ocean, an ocean that is 'boiling', 'monstrous' and frothing around the people caught up in its powerful waves. This book is an in-depth depiction of the 2007 tsunami and its impact on Oceania – Australasia, Melanesia, Micronesia, and Polynesia – with a particular focus on Simbo in the Solomon Islands, and the lived experiences of the communities on the island. Each of the seven chapters takes the reader on a detailed anthropological journey aimed at understanding the community response to the tsunami – a response that was viewed as expected by those outside of the community, despite there being no mention of tsunamis in their communities' historical knowledge or folklores.

The book's preface begins by putting the reader in the centre of the disaster. On the morning of 2 April 2007, an 8.1 magnitude earthquake occurred 50 km from Simbo, resulting in a devastating tsunami. While you might think that the focus would be solely on the period immediately before the tsunami and then its resulting aftermath, *Sensing Disaster* focusses on the community response to the rushing water – their fleeing to safety in the hills. In particular, this book explores how Simbo's people knew to respond in this way, how they *sensed disaster*, and assumptions about local, traditional and Indigenous knowledge in the context of disaster awareness and response.

Through exploration of how the Simbo community has changed throughout history, *Sensing Disaster* explores the value placed on different types of knowledge, the power dynamics and whose knowledge is considered to be valid in an island community, and what factors contribute to how knowledge is developed and preserved over time. The chapters talk us through the impact of colonialism, which resulted in a general move from higher land to the coast, also through changes in access to education and economic markets; and even the complexity of recovery after the tsunami, which needed to take account of traditional land ownership and access for rebuilding.

This book considers not only the relatively recent tsunami of 2007, but also the island's history and how this has shaped the people of Simbo's relationship with the surrounding ocean. I thoroughly enjoyed this detailed description of how Simbo's people have adapted to change on their island, with each chapter building on the previous, so providing a deep dive into the island's history, and showing how this has shaped the relationship between the island, the sea and the people of Simbo, as well as their ability to read and respond to disaster. The book provides detailed accounts of key events on Simbo and characters from the island, drawing on lived experiences, as well as community memories and stories in order to explore how these processes shaped the creation, and indeed the loss, of knowledge.



The book also raises important points about the neutrality of researchers, and the need for those of us working in and with communities that are not our own to be conscious and cognisant of our own biases, influence, and power within those contexts. We are not, and often could not be, neutral. With this in mind, it is worth noting that the book raises questions as to how researchers, and others who are external to a community, can inadvertently shift perceptions of knowledge and security – for example, after the tsunami, Simbo's coastline was viewed by local people as a dangerous place, a place of risk and vulnerability.

I found the last three chapters a really interesting discussion about both local and global responses to disaster, and how interventions aimed at supporting resilience may have unintended consequences.

As someone whose own research is centred around understanding the relationships between people and ocean spaces, I really appreciated the time and energy that had clearly been dedicated to the development of deep, respectful relationships between the author and the people of Simbo. The glossary and 'notes on language' at the beginning of the book are a wonderful addition – and definitely something I availed myself of while reading! This is a book for anyone with an interest in disaster response and management, but also a book about human stories, community, language and knowledge development, and how each of these are shaped by a multitude of influencing factors.

Emma McKinley
Cardiff University

Challenger Expedition
150th Anniversary