OCEAN Challenge

Challenger Expedition
150th Anniversary

Luigi Marsigli's 17th century insight into flow through the Bosporus • Investigating tides and circulation in the Atlantic during the Last Glacial Maximum • Updates on increasing CO_2 uptake by the ocean

Vol.27, No.2

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**)

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OCEAN Challenge

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, where you can find the Society's strategy for 2024–2029, 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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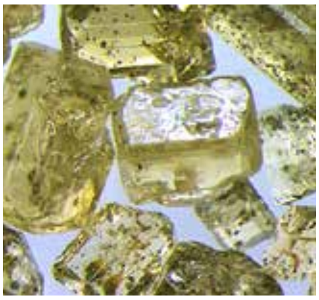

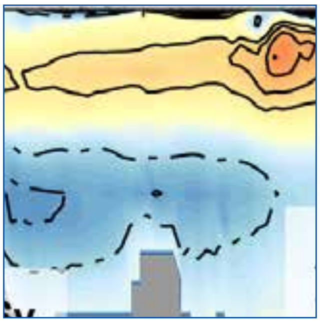

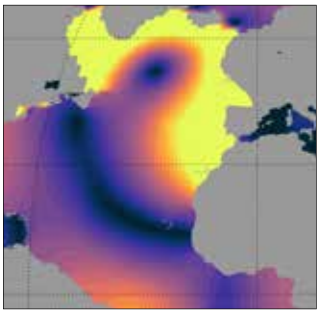

Most of the maps and diagrams were drawn by The ArtWorks.

The cover and heading graphics were designed by Ann Aldred.

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

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Message from the Editor

Welcome to the lastest issue of *Ocean Challenge*, which is coming out much later than planned. The delay is due to a haitus in the arrival of articles, which we think may be a side-effect of the disruption that Covid-19 caused to many marine science careers. Unfortunately, the meeting reports are being published much later than intended, but they nevertheless make very interesting reading. The two intriguing feature articles are very different, and illustrate the development of ideas about current flow in the ocean over four centuries – i.e. since long before *Challenger*!

The next issue will bursting with reports from the hugely enjoyable Challenger Society Conference, recently held in Oban.

The Challenger Society Strategy, 2024–2029

The Challenger Society has a long and distinguished history of supporting marine scientists in their endeavours to better understand the ocean, the life within it, and how it affects all aspects of human society and the planet as a whole. Founded in 1903, the Society takes its inspiration and its name from the voyage of HMS *Challenger,* now 150 years in the past and regarded as a landmark in the development of modern ocean science.

Without diminishing the importance of this history, it is important that the Society is forward-looking, and that it seeks to position itself as strongly as possible to meet current and future challenges relating to marine science, and to help provide the knowledge of the ocean required by all those in sectors outside academia.

To that end, a couple of years ago we undertook a survey of members, seeking views on what the Society did well and where it could improve, and opinions on what new directions the Society should take as it develops into the future. The response was strong, and we are very grateful to all those who contributed their ideas.

The messages overall were clear, and have been used to develop the new Challenger Society Strategy and Implementation Framework (2024–2029). This covers the next five-year period, with the intention that it is renewed at the end of that time, and with the possibility of it being refreshed periodically in between. The Strategy can be found at https://www.challenger-society.org.uk/challenger_strategy.

Three overarching strategic aims were identified:

1 Support and grow the UK marine science community

2 Enhance connections within the marine science community and stimulate new scientific thinking and activity

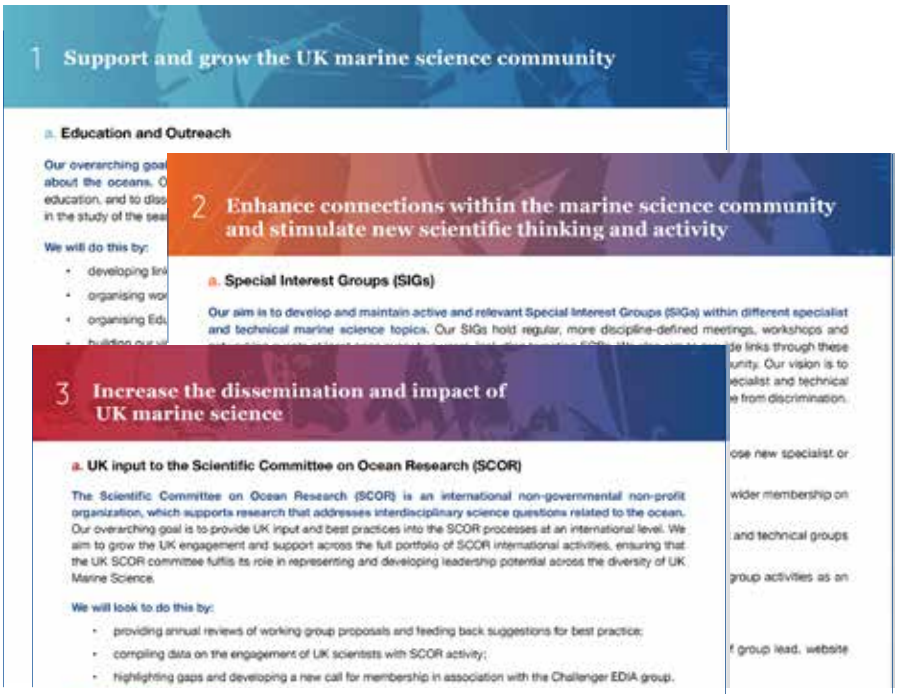
3 Increase the dissemination and impact of UK marine science

Each of these aims has multiple distinct areas of activity within them, some of which are areas where the Society has traditionally been strong (e.g. support for early-career researchers, liaison with industry etc.), and others which are being developed as new activities (e.g. liaison with policymakers). For each area, the Strategy explains how the aims are intended to be met within the five-year period that it covers, and what measures will be used to judge success.

It is not intended that this Strategy is overly prescriptive, and new areas and actions can be developed at any point where sensible – but it gives the Society a clear vision and direction of travel that will help optimise the positive work that it does, and help it broaden its impact. It is hoped that this will enable the positive influence of the Society to reach new levels, across academia and beyond, and enable it to provide even better support and opportunities to those involved in marine science.

Mike Meredith
Challenger Society President, 2021–2024

The Strategy was developed by all on Challenger Council based on responses to the survey of members. Sincere thanks go to Council members: Kate Hendry, Chelsey Baker, Alessandro Tagliabue, Dave Carlin, Siddhi Joshi, Angela Colling, Stephen Dye, Terry Sloane, Alex Brearley, Cecilia Liszka, Robyn Tuerena, Sophie-Berenice Wilmes, Anna McGregor, Gillian Damerell and Ben Fisher; also to a range of people outside of Council, whose input was also extremely helpful, including Liz Bentley, Paul Hardaker, Gideon Henderson, Ed Hill, Katy Hill, Mark Inall, Peter Liss, Jenny Ramarui and Ralph Rayner.



A meeting of science and social history

Beyond the ocean's depths: Revisiting the Challenger *Expedition (1872–1876)*

Those of us who were disappointed by the lack of time available for history at the Challenger 150th Anniversary Conference in 2022 were amply recompensed by this event, held at the National Maritime Museum, Greenwich, in October 2023. This interdisciplinary meeting brought together marine scientists and social historians, and each group learnt a little about the other's approach to its area of study, its specialist vocabulary and its conventions (this report will inevitably reflect the fact that I'm from the first group). Erika Jones (Royal Museums Greenwich), who had conceived the event, made us all feel extremely welcome.

The 15-minute talks were in groups of three, each followed by a session where the audience could quiz the panel of speakers. The first three speakers showed how measurements and samples collected by *Challenger* are still providing important scientific data today. John Gould (National Oceanography Centre) explained why the timing of the *Challenger* voyage, near the beginning of the industrial era, means that the temperature and salinity data collected then are useful in providing baseline values for climate change research today. Deep-sea temperatures were measured on *Challenger* using a maximum and minimum thermometer and, reassuringly, temperature values of deep water, away from warming surface layers, match well with modern measurements made using *Argo* buoys.

Biological samples collected by *Challenger* are also still providing useful information. Giles Miller (Natural History Museum) discussed how a comparison of the thickness of the calcareous shells of planktonic foraminiferans collected by *Challenger* with those of modern planktonic foraminiferans, can be used to quantify how ocean acidification has been affecting such shells since the 1870s.

Hugh Carter (Natural History Museum) spoke about echinoderms (starfish, brittlestars etc.) of which almost 200 new species were identified as a result of the *Challenger* Expedition. Study of specimens collected from the Expedition onwards has shown that patterns of biodiversity of deep-sea starfish are determined by more complex factors than are the patterns of starfish biodiversity in shallow waters, which are closely related to temperature. Echinoderms were a source of fascination long before *Challenger*'s Wyville Thomson became obsessed with them – a brittlestar was the first deep-sea organism to be collected, by SIr John Ross in 1818.

At the start of the afternoon session, Adrian Webb (Hydrographic Office, UKHO) explained why the UKHO, established in 1785, and now located in Taunton, is a valuable resource for historians. The UKHO has been actively collecting navigational and hydrographic records for at least 225 years, and had acquired maps and documents long before that: its oldest document is a 1620 map of Portsmouth drawn on animal skin. In addition to charts, the UKHO houses dozens of other kinds of documents, from correspondence to aerial photographs, and from notices to mariners to tidal records. For advice about locating a document, email research@ukho.gov.uk.

Challenger was a naval frigate, and had been a warship for 14 years before she was adapted for the Expedition. Jeremy Mitchell (Royal Museums Greenwich) showed some beautifully drawn plans of *Challenger*'s conversion, including the plumbing system, which allowed for flushing toilets and hot baths for the scientists and officers – but only two baths for the entire crew.

The hard-pressed crew – without whom the scientific work would not have been possible – are largely forgotten. Philip Pearson, an independent scholar with a strong link to *Challenger* – his great grandfather was a stoker on the vessel – spoke of the unrecognised contribution of the 240 ordinary seamen, who spent long hours depth sounding, and deploying nets, trawls and dredges. There were injuries (some fatal), desertions at many ports of call, and food shortages – a cooked turkey for the officers' first Christmas dinner mysteriously disappeared! (For more, see https://a-challengers-song.co.uk/.)

Challenger's scientific reports are voluminous, and there are *Challenger*-related writings and samples scattered across the globe. Replying to a question about what historians and others could do to help scientists make better use of *Challenger* data, the panel suggested that there needed to be a 'one-stop shop' for those in search of *Challenger* information, even if it was in the form of a collection of internet links. Also, although there are digital versions of the *Challenger Report*, most of the data they contain have not been extracted, so researchers need to spend many hours reading them and copying out data. This task could form the basis of a really useful citizen science project.

Challenger scientists had been tasked by the Royal Society's Circumnavigation Committee with undertaking ethnological studies by 'obtaining photographs of native races' and 'making such observations as are practicable with regard to their physical characteristics, language, habits, implements, and antiquities'. Many of the remaining presentations addressed how the *Challenger* scientists went about their ethnological work, and how they communicated their results. The scientists were privileged men of their time – untroubled by the disparity between conditions onboard for the crew and those for themselves and the officers. They were also living at a time when Britain was colonising lands where the indigenous peoples were assumed to be inferior to white Europeans.

Three talks addressed different aspects of photography during the Expedition. During the voyage, over 800 photographs were taken or acquired, and Stephanie Hood (Max Planck Institute for the History of Science, Berlin) explored the idea that the large number of photographs was not because they were generally regarded as particularly scientifically objective (drawing and painting were generally preferred for making visual records). Photography was expensive but it had practical advantages – photographs were relatively quick to obtain, and could be easily reproduced. Some, especially the more romantic images, appeared in the *Illustrated London News*, or were circulated commercially as postcards.

Martin Gölnitz (University of Marburg, Germany) discussed how the photographs and letters of the young *Challenger* naturalist, Rudolf von Willlemoes-Suhm, convey his enthusiasm for British imperialism, and his belief in the superiority of Europeans over colonised indigenous peoples. He felt his photographs were important scientific records, and sent them home to his mother, asking her to keep them safe until his return – which never took place, as he became ill and died at sea.

Rebecca Martin (Royal Museums Greenwich) spoke about the 'photographed contributors' to *Challenger*'s mission, some of whom contributed practically by hosting *Challenger* officers and assisting in the collection of scientific specimens. A number of those photographed were high status individuals who were happy to be photographed (e.g. the King of Portugal) as they could control how they were shown, but the demeanor of others (e.g. indigenous women in Tierra del Fuego) suggests that they were being photographed against their will. In the second part of her talk, Rebecca highlighted the confusion that can be caused when labels or descriptions of photographs that various *Challenger* scientists and officers included in their personal albums do not seem to match the images themselves.

After a short documentary film, 'Beneath the Blue: The Maluku's Abyss', directed by Isma Yanti (University College London), we were treated to the first keynote talk, by Sujit Sivasundaram (University of Cambridge), which had the intriguing title of 'The slimiest of creatures and when history goes under the sea'. The slimey creatures are in fact sea-cucumbers, but much of the talk was about Georg Rumpf – an employee of the Dutch East India Company who studied the natural history of the Indonesian island of Ambon. Rumpf is best known for his botanical work but also studied rocks and minerals, and marine animals around Ambon's shore, including sea-cucumbers. Despite his many hardships and tragedies, Rumpf's contribution to science was considerable. If you would like to know more about this extraordinary man, it's easier to hunt online if you know that he called himself 'Rumphius'.

The second day began with a link to New Zealand where the artist Alice Strange introduced her film 'Wondrous things'* which explores how Alice's interest in the ocean links to her art, and contrasts the rigour of 19th century scientific research with the ethnographic investigations of the time, facilitated by the exchange of trade goods. You can see the film at www.alicestrange.com/wp-content/uploads/2023/12/ChallengerWeb.mp4. To see Alice's *Challenger*-inspired art, go to www.alicestrange.com/challenger/.

The *Challenger* naturalists had been told to pay particular attention to the zoology of the sea to the north and west of New Zealand because there could be geographical/zoological connections between the South Pacific and inaccessible Antarctic regions. Emma Zuroskski (independent scholar, Aukland, New Zealand) described how *Challenger*'s time in New Zealand was an example of how the local knowledge of colonial participants (in this case, particularly a local man, William Travers) was invaluable, while at the same time inevitably influencing how the scientists approached their work.

As part of their ethnological/evolutionary studies, *Challenger* scientists collected skulls from South Africa, New Zealand and Australia, Tierra del Fuego and Patagonia, and a number of Pacific islands. Daisy Chamberlain (Royal Museums Greenwich) explained how these skulls were housed in the University of Edinburgh's Anatomical Museum, whose collection had underpinned the excellence of medicine in Edinburgh in the 19th century. Daisy described how colonised peoples were considered part of animal life, and even the *Challenger* scientists seem to have thought of them as part of the local fauna (their discussion in the *Challenger Report* appears under Zoology).

Esteban Del Pozo-Márquez (Complutense University of Madrid) discussed the impact of *Challenger*'s port calls in Spanish-speaking regions. Local papers included only brief reports, but *La Epoca*, published in Madrid, provided quite a lot of detail. Natural history was of greatest interest, and seen by scientists as important for the future. Later, announcements were made in *La Epoca* of publication of the results of the Expedition.

The next two talks addressed ideas about changing experiences of time and space. Nicholas Pritchard (University of Cambridge) examined this in the context of the experience of *Challenger*'s young assistant steward, Joseph Matkin, writing to his family, painfully aware of his separation from them, not only in terms of great distance but also time: correspondence between *Challenger* and Britain could take many weeks – it was four months before Matkin learnt of the death of his father.

Gary McLeod (University of Tsukaba, Japan) may be known to *Ocean Challenge* readers through his project to arrange the rephotographing of locations where images were captured during the *Challenger* Expedition.* Gary described how he later revisited sites in Japan photographed by the third photographer to serve on *Challenger*, Jesse Lay. The landscape has changed enormously, so it's hard to recognise some of the original sites; furthermore some '*Challenger*' photographs seem to be photographs of pre-existing images, and others have been mislabelled. For more, see www.garymcleod.co.uk/imagesets.

Gillen Wood (University of Illinois) has developed a searchable database of deep-sea species collected by *Challenger*, hosted at the Scottish Association for Marine Science (SAMS) and displayed, along with associated bottom temperature data, as an interactive map (challenger-expedition.sams.ac.uk/). Gillen described some of the challenges in compiling the information, e.g. the animal names used by the *Challenger* scientists often differed from modern ones, and some of the specimens that found their way into the *Challenger* collections were bought in local markets! Gillen told us about a miscatalogued 400-page journal whose author – a Lieutenant Bromley – has been identified by matching the handwriting in the journal to a signature in a naval pay book!

We then heard three presentations about museums whose exhibits relate to maritime heritage. Until March 2025, the National Museum of the Royal Navy (NMRN) is hosting an exhibition showing connections between the scientific work undertaken on *Challenger* and present-day work of the Royal Navy and, in particular, the National Oceanography Centre. Victoria Ingles (NMRN) explained how objects relating to *Challenger* represent just a tiny part of what can be seen at the NMRN. The museum's main aim is to raise appreciation of the Royal Navy, and highlight the advantages of a scientific career in the Navy. It showcases modern work supporting marine research, including that relating to climate change.

Perhaps surprisingly, there are quite a few *Challenger* specimens in Worcester Museum; it acquired duplicate specimens in 1900 and these have been cleaned and preserved. Kerry Whitehouse (Museums Worcestershire) explained that amongst the museum's many other exhibits are objects associated with HMS *Rattlesnake*, which set sail in 1846. A steward, Robert Gale, had traded ship's supplies with indigenous Pacific islanders, to obtain what he called 'curiosities', and later donated a collection of these to Worcestershire Natural History Society. Like speakers before her, Kerry emphasised that even items that had been given or traded by local people, may have ritual, sacred or religious significance, and this may be meaningful to the descendants of those people today.

Stuart Slade (National Maritime Museum Cornwall) described the 'Monsters of the Deep' exhibition, in Falmouth in 2022 and then in Chatham for most of 2023. The 'sea monsters' ranged from a killer whale skeleton to those drawn on the 1539 'Carta Marina' by Olaus Magnus; Stuart explained how people thought that the sea contained animals equivalent to those on land (sea horses, sea cows etc.). The *Challenger* Expedition featured prominently in the form of a replica of one of the laboratories and beautifully displayed bottled specimens. (The museum's current exhibition is about pirates.)

Meredith Greiling (National Museums Scotland) told us about the fisheries research vessel *Explorer*, built in 1955. *Explorer* was essentially a side trawler with three labs and an analogue computer, and she represented the best of Scottish shipbuilding at the time. She nevertheless used steam power (then largely replaced by diesel–electric) as it was quieter and allowed easier testing of new acoustic technology. *Explore*r was decom-

*Sailing in the virtual wake of HMS *Challenger* *Ocean Challenge,* **18**, 10–11.

missioned in 1984, and is now cared for by the SS *Explorer* Preservation Society: www.theexplorer.scot/.

Nick Owens (SAMS) then looked at the importance of Scotland in the development of marine science. He highlighted an amazing number of influential scientists who were Scottish or had Scottish connections, from influential thinkers of the Scottish Enlightenment (18th and early 19th century) to Charles Wyville Thomson, who led the *Challenger* Expedition, and *Challenger* naturalist John Murray (a Canadian-born Scot), who oversaw the publication of the 50-volume *Challenger Report*. Murray later founded the Marine Laboratory in Edinburgh, the first of its kind in the UK and effectively the fore-runner of SAMS, near Oban.

Sam Robinson (University of York) highlighted aspects of the Expedition that fed through into more modern expeditions. For example, a round-the-world voyage became regarded as important by nations newly engaging in oceanography, and reseach publications have continued to be seen as an integral part of any expedition. Sam ended by pointing out that it was only in the 20th century that *Challenger* became the 'model expedition', emphasising the influence of Eric Linklater's well told *Voyage of the Challenger (1872)* in developing the idea of the Expedition as the start of modern oceanography, so downplaying the importance of, for example, 19th century Scandinavian expeditions.

Rounding off the event, in her lively keynote talk Helen Rozwadowski (University of Connecticut) speculated on purposes served by histories of the *Challenger* Expedition and *Challenger* scientists. Some of the points she made echoed those made by Sam Robinson, for example the perceived need for oceanographic expeditions to be global; these voyages were planned as 'great exploratory voyages', but the colonial ambitions of the countries involved in them were also important. In an aside, Helen referred to the often quoted 'fact' that 'we know more about the surface of the Moon than we do about the deep sea'. This outdated comparison came from a 1954 article (in the *Journal of Navigation*), in which oceanographer George Deacon alluded to a claim by geophysicist Edward Bullard.

In the following discussion session, Helen and others regretted the naming of a 'World Ocean Day', as opposed to 'World Oceans Day'. People have their 'own' ocean, and a feeling of ownership can engender a sense of resonsibility. Reflecting on the development of the history of oceanography as a field of study, Helen noted that it was started by scientists, and only a third of those attending early meetings about the subject were historians. This is no longer the case, and Helen believes that climate change would be better tackled if oceanographers and historians worked together.

Erika and her team should be proud of how well the meeting went. The programme seemed to go like clockwork – except when delegates were reluctant to stop networking and go back to the lecture theatre. For me, attending virtually, the technical aspects mostly worked well. I was glad to have attended, though sad to have missed out on the chance to chat with other delegates, and sorry to have missed the opportunity to study the original 1872 HMS *Challenger* refit ship plans, photographs, manuscripts and archives.

The meeting was attended by 106 people (either in person or online) and was supported by the Challenger Society for Marine Science, the UCL Department of Science and Technology Studies, and the British Society for the History of Science.

Ed.

Challenger Society's History Special Interest Group

Should you join?

It is easy to think of the history of our science as being focussed on the pioneering work of HMS *Challenger* 150 years ago. However, the changes that have happened since then are just as important, and those in the past 50 years have brought about a revolution in our ability to understand how the oceans 'work'. This SIG is for anyone who wants to improve our understanding of how our present knowledge evolved.

Our members are:

- Researching the histories of UK marine laboratories and institutions
- Studying the development of instrumentation and observing platforms
- Analysing and re-interpreting historical data and samples
- Ensuring that such data and samples are preserved and made accessible
- Researching the lives of those who have contributed to UK marine science
- Promoting the management and resourcing of marine science archives

The 50 members correspond by JISCMail.
In the coming year, the SIG is planning a series of online, history-focussed webinars and a visit to the Science Museum archives at Wroughton near Swindon.

If, having read this, you think the answer to the question above might be 'Yes!' please go to http://www.jiscmail.ac.uk/ocean-history and click 'subscribe'.

John Gould and Phillip Woodworth
SIG Co-ordinators

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 the most recent meetings of two of the SIGs. We apologise sthat they are appearing rather late, given the delay in publication.

Ocean Modelling

Dave Munday

The Ocean Modelling Special Interest Group (colloquially known as OMG*) aims to connect UK ocean modellers of all flavours and interprets 'ocean modelling' in the broadest possible way. Our goals are to promote interaction and networking, especially amongst early career scientists, and to showcase the breadth and brilliance of UK ocean modelling. We hold an annual meeting every September as a chance to meet old friends, make some new ones and, most importantly, listen to some exciting science! The meeting is particularly student-centric, with Ph.D students and early-career researchers taking priority in the schedule, and is intended to be relatively informal.

The 2023 annual OMG meeting was held on 5–6 September at the National Oceanography Centre in Southampton. We are grateful for support offered by the Challenger Society, which enabled us to keep costs low for all of our attendees. The meeting was organised by Alice Marzocchi, who wrangled over 70 scientific cats into the same room at the same time. After Alice opened the meeting, our volunteer chairs, including Alethea Mountford (Northumbria University), Aditya Narayanan (University of Southampton), Helen Johnson (University of Oxford) and Ric Williams (University of Liverpool), took over, holding our enthusiastic speakers to their short 10-minute time slots, which included questions and change of speakers. This format has become a feature of the meeting and ensures that we pack in as much modelling as possible. The format also acts to prompt further detailed discussions in the breaks, and helps promote networking between junior and senior scientists.

*This acronym has occasionally caused alarm when used as the subject of an email, for which the organisers apologise whilst continuing to use it.

The four sessions of the meeting were split across two half days and we heard over 30 presentations. Over 20 of these were from students and early-career researchers and our speakers covered a huge variety of subjects. They ranged from the seasonality of Southern Ocean ventilation to the practicality of ocean alkalinity enhancement by spreading the mineral olivine on beaches, via an assessment of pollutant dispersal from a major shipwreck off the coast of Sri Lanka and DNA exchanges between coral reefs. Some out-of-this-world inspiration came in the form of ocean tidal mixing on exoplanets. Collectively, the speakers highlighted not just the excellence of UK ocean modelling, but also its potential global impact and its importance in understanding the ocean wherever you are (including other solar systems).

For some of our student members, our annual meeting is their first conference experience. For this meeting, these included Stephanie Hodnett, a final year Open University student, who said that she was put at ease by the friendliness and openness of our group, as well as pleasantly surprised by the number of other early-career researchers. Stephanie found our session chairs to be impressively efficient at keeping the speakers to their time limit. In Stephanie's case, the meeting was a valuable experience, one she will take forward as she looks to pursue a career in oceanography.

Noam Vogt-Vincent, who attended his first OMG meeting a few years ago, found it to be a great forum in which to learn about ocean modelling in the UK, and ensured that the 2023 meeting was a calling point before he departed for warmer climes for his new role in Hawai'i.

From left to right: Rosie Eaves, winner of the prize for the best student presentation, Jenny Graham, chair of the judging panel, and meeting organiser, Alice Marzocchi. (Photo: Chelsey Baker)

Each year a prize is awarded for the best student presentation. Given the ever increasing quality of presentations from ocean modelling students, this is becoming tough to award and is sometimes split in two to acknowledge the brilliance of the best two students' talks. At this meeting, the prize for the best student presentation was awarded to Rosie Eaves of the University of Oxford, by a panel led by Jenny Graham of Cefas. Rosie's well deserved win was for her presentation on 'A new parameterisation for barotropic eddies'. She gave an excellent talk on how to better represent bathymetrically influenced flows, in a very clear style that impressed the panel. Rosie found the presenting experience to be exciting, but not stressful; OMG is a place where nascent ideas can be presented as well as polished work. Rosie said that she left the conference feeling buoyed and enthusiastic about her work and the field as a whole. She received encouraging feedback, both at the conference and afterwards via email.

OMG is convened by me, Dave Munday of BAS. If you'd like to be involved in the SIG and attend our annual meeting, I will be very happy to add you to the OMG mailing list (see email address below). The 2024 OMG annual meeting was held as part of the 2024 Challenger Society Conference in Oban, Scotland, in September.

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Sea-ice

Jeff Ridley

The UK Sea-Ice Group, founded in 2002, became a Challenger Special Interest Group in 2012. Each year it holds a meeting to bring together scientists from around the country to discuss state-of-the-art sea-ice investigations through observational, modelling or combined studies. In 2023, the event was held at the Department of Earth Sciences, University College London, on 18–19 September. The local organisers were Michel Tsamados and Rosemary Willatt.

Nearly 50 scientists participated in the event, mostly in person but with some joining online. There was a strong emphasis on and substantial time dedicated to poster presentations to facilitate lively engagement and discussion, encouraging exchange of ideas and collaborative working around the country and across the field. In a quick-fire presentation before each poster session, authors were each given a one-minute slot to outline their key messages, highlighting their topics and findings. More than 90% of poster authors said that the feedback on their presentations was helpful.

My favourite posters were one by Claire Penny (Durham University) on reconstructions of Antarctic sea-ice extent from snow petrel stomach oil deposits, and another by Deborah Cotton (University of Oxford) who described frazil ice crystal collisions in Antarctic coastal polynyas (semi-permanent areas of open water within winter sea-ice cover).

Sessions of 15-minute oral talks were presented by researchers at all career stages. The science presented covered a huge breadth of topics relating to sea-ice, including polynyas, waves, melt ponds, snow depth and interactions with the ocean and/or atmosphere. Techniques presented included modelling, data assimilation and Artificial Intelligence (AI), observations from satellites, buoys, *in situ* and laboratory measurements. One talk which stood out for me was by Miriam Bennet (University of East Anglia) who described the atmospheric forcing and ocean response of the North-East Polynya to the north of Greenland.

Melting sea ice in the Barents Sea *(Photo: Sebastian Menze, Alfred-Wegener-Institut)*

Welcoming presenters at any career stage, the option for online attendance, and the focus on (alcohol-free) poster sessions, were all designed to support increased diversity in sea-ice science, and feedback on the event was positive.

Jeff Ridley is a climate scientist working for the Met Office. jeff.ridley@metoffice.gov.uk

Stepping Stones to a successful career

Reasons to apply for a Challenger Society Early-Career Bursary

The Stepping Stones Bursary scheme is designed to support career development for members of the UK marine science research community currently without employment (for how to apply, see p.8). Below, a recent beneficiary of the award explains how he used the Bursary to help move his career forward.

Using a Stepping Stones Bursary to hone specialist technical skills

Charel Wohl

I am an early-career researcher whose Ph.D and post-doc research focussed on measuring volatile organic compounds (VOCs) and sulfur-containing compounds dissolved in seawater. Combined with measurements of the atmosphere, they can be used to calculate air–sea fluxes.

After completing my Ph.D at Plymouth Marine Laboratory in summer 2021, I moved abroad to pursue a post-doc in Barcelona at the Institut de Ciències del Mar (ICM-CSIC), to expand my mass spectrometry skills and use a Vocus-PTR-ToF* mass spectrometer to measure dissolved gases in seawater and to take part in Antarctic fieldwork in spring 2023. The aim of the cruise, on the Spanish research vessel, the *BIO Hespérides*, was to study the connection between ocean biology and sources of aerosols in this climate-sensitive region.

I applied for the Stepping Stones Bursary in April 2023, hoping to visit Aerodyne in Boston, MA, to learn more about the details of operating a Vocus-PTR-ToF and of the analysis of the data collected during the cruise. The aim of my visit was to access some of the atmospheric data collected by another

Figure 1 *Charel during a trip ashore from the BIO Hespérides, visible in the background.*

*A Vocus-PTR-ToF samples air directly to identify and quantify volatile organic compounds (VOCs) in real time.

Vocus on board the same cruise. Data from the two instruments will be used to calculate sea-to-air fluxes of sulfur compounds around Antarctica and will allow us to speculate on the biogeochemical sources of these compounds.

Like many researchers coming straight out of their Ph.Ds, I had little to no experience of independently applying for external funding to complete a short project. At that point in my career, writing a justification to complete a piece of work was an extremely valuable experience and it has subsequently helped me when applying for more recent funding opportunities.

My application for the Bursary was successful and I was able to use it to fund the trip on the back of a visit to AGU 2023, with the intent of saving some carbon emissions. During the three-day visit, I worked closely with Leah Williams from Aerodyne. I had not received in-person training on the instrument due to the Covid-19 pandemic, and this visit allowed me to consolidate my knowledge and talk about some artefacts I observed during the cruise. I also gave a presentation to the scientific staff at Aerodyne and interacted with a range of people with different interests, including high resolution mass spectrometry, gas chromatography, and measuring VOCs in seawater and soil using a membrane.

The decision to apply for the Bursary has paid off. Half a year after receipt of the Bursary, I was able to use my expertise in running the Vocus-PTR-ToF in the laboratory at the University of East Anglia, and fieldwork is underway at the university's Weybourne Atmospheric Observatory.

I also shared some insights from my trip with Aerodyne instrument-users in the UK science community. In the meantime, I'm working on a publication focussing on sea-to-air fluxes from the cruise, and involving many of the people I interacted with during my visit.

Figure 2 *Charel with the Vocus-PTR-ToF at the end of the cruise.*

Figure 3 *Charel with Leah Williams showing him one of the laboratories at Aerodyne Research Inc., which hosts an impressive number of instruments.*

I would encourage other early-career researchers to apply for a Stepping Stones Bursary. For those having doubts about applying, I would like to highlight that the flexibility of the Bursary means that it can be used in many different ways, and the funding is upfront and not conditional on any research output. It helped me learn new research skills and eventually helped me feel more confident in my Vocus analytical skills, which will hugely benefit the UK science community.

Charel Wohl is now working as a Senior Research Associate at the University of East Anglia with the National Centre for Atmospheric Science, where his research focusses on transport and processing of marine sulfur emissions over the North Atlantic. His work is also funded by the FAAM Airborne Laboratory Mid-Life Upgrade and involves making measurements using a high spec Vocus-PTR-ToF refitted to fly on the FAAM aircraft. Charel enjoys taking good measurements at remote sites, be they aloft or at the poles, to help us better understand the global climate system and the marine atmosphere.

How to apply for a Stepping Stones Early-Career Bursary

Stepping Stones bursaries are designed to support career development for members of the UK marine science research community who are not employed. Applications are not accepted from researchers holding permanent positions, but those on fixed-term contracts may apply up to three months before the end of their contract. Individuals may receive only one bursary in any three-year period and the maximum amount that any individual can be allocated in any one funding round is £1000. Bursaries can be used for research-related activities which could enhance career prospects including, but not limited to, travel, collaborative visits, laboratory time, fieldwork and conference participation. It cannot be used to pay salary. The Society aims to fund four bursaries per year, and applications will be considered quarterly (deadlines: 15 January, 15 April, 15 July and 15 October).

The application form and guidance notes for applicants can be found at https://www.challenger-society.org.uk/Stepping_Stones

Applications should be sent to Sophie Wilmes (s.wilmes@bangor.ac.uk).

Deep-sea mining: short-sighted, unnecessary and dangerous

Claudiu Eduard Nedelciu

In January this year, the Norwegian Parliament voted 80 to 20 to allow activities relating to sea-bed mining in Norwegian waters. This decision was made despite clear advice from scientists – in Norway and abroad – that there is a need for more knowledge about the fragile ecosystems in the deep sea. The Norwegian Institute of Marine Research, the Norwegian Environment Protection Agency and the Council of European Academies of Science are just some of the scientific voices who criticised the exploration opening process in Norway and called for a reorientation of sustainability efforts towards economic circularity and better management of mineral resources on land to meet demand.

However, the Norwegian government claims that mining on the sea bed is necessary to meet the increasing demand for minerals for the energy transition away from fossil fuels. From their perspective, it goes without saying that mining on the sea bed is key to solving the climate crisis. This perspective is not limited to the Norwegian state. It has been embraced by the International Seabed Authority (ISA) and by corporate players in Norway and abroad – from The Metals Company and Global Sea Mineral Resources operating in the Clarion–Clipperton Zone in the Pacifc, to Green Minerals, Loke Marine Minerals and ADEPTH Minerals in Norway, to name but a few. Their logic is that minerals from the deep sea are needed to sustain current rates of consumption, and to provide the additional supply required by the energy transition and a shift to renewable energies. This argument is, in my view, not only short-sighted, but ignorant and dangerous.

The Norwegian economy is 2.4% circular, which means more than 97% of the materials used in the country are not cycled back into the economy. This means that the current demand for minerals is calculated for business-as-usual in an extremely inefficient and wasteful system of production and consumption. Making the economy more circular is an obvious choice to satisfy a considerable part of the mineral demand while also reducing the negative socio-ecological impact of extraction and waste production. The demand for minerals that proponents of deep-sea mining are basing their arguments on is created by how our society manages natural resources, and by why it uses particular natural resources in the first place. In its current form, the global economy is following a type of 'development' emanating from the Global North which depends on an assumption of perpetual economic growth, a growth that can only be possible if labour, energy and materials are cheaply produced and supplied from elsewhere. In this worldview, 'development' prioritises the use of individual cars, short-haul flights and private jets rather than reliable and sustainable public transport. It prioritises planned obsolescence in electronic devices rather than long-lasting, easy-to-repair products; aggressive advertisements to buy new gadgets rather than consumption guided by sufficiency; and production of e-waste rather than repairing, reusing and recycling. This phenomenon has been referred to as 'the scarcity machine' by economic anthropologist Jason Hickel, and as the 'treadmill of production' by sociologist Allan Schnaiberg. The growth-seeking goal of the capitalist system transforms productivity gains into new forms of scarcity, bringing no added value to human wellbeing, but leading to significant environmental damage.

These vicious cycles of destructive consumption and production mean that the so-called 'energy transition' is actually an 'energy addition' wherein renewable energy capacity is simply added to the energy mix, while most of the global energy production remains fossil-fuel-based. For 2000 to 2022, the era of exponential growth in renewable sources such as wind and solar, the share of renewables in the total energy consumption mix only increased from 2.6% to 6.2% worldwide. This limited increase is observed even though solar energy increased 1150 times, wind energy increased 60 times and hydropower almost doubled. Over the same period energy consumption of fossil fuels increased from 83% to 84.5%. An increasing number of researchers are sounding the alarm that avoiding climate and ecological breakdown cannot be accomplished in an economy that perpetually grows its material and energy footprint, something also recently recognised by the Intergovernmental Panel on Climate Change and the Organisation for Economic Cooperation and Development.

Proponents of deep-sea mining, rather than tackling the systemic problems of our extraction-dependent economic system that brought us to the brink of ecological and climate collapse, are actively choosing to create new ecological problems. With this, they show that they are not interested in helping to answer some of the most complex and urgent questions of our time: Which parts of our economy provide little added value for social and ecological prosperity and how can we reduce these sectors? Why do we glorify a wasteful consumer culture that can only survive by exploiting nature and people? What decisions must we make to ensure a common and sustainable future globally? These are difficult questions that require leadership and vision, neither of which the proponents of deep-sea mining appear to exhibit.

Further Reading

An easy-to-read commentary on the topic: Hickel, J. and 7 others (2022) Degrowth can work—here's how science can help. *Nature* **612** (7940), 400–403. doi: 10.1038/d41586-022-04412-x.

O'Neill, D.W., A.L. Fanning, W.F. Lamb and J.K. Steinberger (2018) A good life for all within planetary boundaries. *Nature Sustainability* **1** (2), 88–95. doi: 10.1038/s41893-018-0021-4

OECD (2020) *Beyond Growth: Towards a new economic approach* (in the series 'New approaches to economic challenges') OECD Publishing. doi: 10.1787/33a25ba3-en

An IUCN summary of what deep-sea mining is and the main concerns presented in an accessible manner: https://iucn.org/resources/issues-brief/deep-sea-mining

Claudiu Eduard Nedelciu is a postdoctoral researcher at the System Dynamics Group, University of Bergen. He is a systems thinker working on pathways for sustainability transformation, with an interest in demand-side energy and material scenarios. Claudiu.Nedelciu@uib.no

An interview with a multifaceted polar oceanographer

After a research career spanning 30 years, Professor Finlo Cottier is now Chief Executive of the Royal Yachting Association Scotland. His Arctic research at the Scottish Association for Marine Science (SAMS) in Oban resulted in new insights into interactions between ice and the ocean and how light (or the lack of it) affects the marine ecosystem. Here, he reflects on his career in research and tells SAMS communications manager Euan Paterson how his new job is not so very different. *Ed*

(Photo: Andy Crabb, SAMS)

You've got a new job now Finlo, but I know you as an oceanographer. Take us back to the start: how did you get into marine science?

Well, you'd probably think that having grown up in the Isle of Man, with the sea air and marine biological station, and all that, that I would be a shoo-in for marine biology. But I actually wanted to be a dentist! My first job was as a dental nurse. Why? I don't know. I just quite fancied it. Then I thought about engineering and was studying chemistry and physics in school because they were subjects I was quite good at and, more importantly, enjoyed. I didn't have a career planned out, I just carried on doing what interested me.

A key moment was when my high school built a new library and was giving old books away. I got myself a copy of Endurance *by Alfred Lansing, which is the story of Shackleton's expedition to cross the Antarctic continent, which didn't happen because the ship got trapped in ice, drifted, and sank. It made a big impression on me. Boats have always been something I've been interested in and it's a very good maritime story.*

So that's when you knew you wanted to be an Arctic scientist?

Not really, no. I got a degree in chemistry and physics from Manchester University and in my third year, I spent a year in industry, working for British Nuclear Fuels Ltd. That helped me to work out what I didn't want to do. I then discovered the Scott Polar Research Institute in Cambridge, and managed to get myself on a Ph.D course down there. It's part research institute, part museum – I was actually able to see the artefacts from Shackleton's expedition in the museum. I did my Ph.D on sea-ice physics and managed to get a fantastic trip to the Arctic on the German ship Polarstern. *After that, I was very fortunate to spend some time in the Arctic and the Antarctic on tourist ships and just followed my nose, really. I just did whatever seemed interesting. I still didn't have a career plan, but in 1999 I was sailing on the west coast of Scotland, and I was tied up in a marina at a place called Ardfern. There was a knock on the hatch, and somebody said: 'We've received a fax for you.' A friend, who knew where I was berthed, had sent me a job advert for a physical oceanographer at Dunstaffnage Marine Laboratory (now SAMS). The deadline for applications was the following day, so, again following my nose, I went to the phone box in Ardfern Marina, put in 50p and spoke to Mark Inall, who was setting up a new marine physics group at SAMS. The rest is history.*

You were at SAMS for about 30 years. You must have enjoyed your time there.

I remember in the first year doubting whether I was doing the right thing. I don't think I really understood what an academic career was. I'd landed in this academic world, and I was trying to learn the rules of the game. But I had some very good people around me. Mark backed me, gave me lots of opportunities, and I learned a lot of practical stuff from Colin Griffiths. I also had some great support from key individuals from my Ph.D days, like Mark Brandon and David Thomas. Around that time the SAMS Director Graham Shimmield basically put a marker down to say we were going to do more work in the Arctic, so I did a lot of work up there. Eventually, I was able to carve out a niche for myself. I worked with Geraint Tarling, who showed me the links between physics and biology, so I ended up sitting in an interesting space between physical oceanography, sea-ice physics and biology. That then led to all sorts of interesting things about illumination in the high Arctic and circadian rhythms, the role of sea ice in reducing the light reaching the ocean, and the effects of loss of sea ice. I've never regarded myself as a pure physical oceanographer. I suppose, ultimately, that meant I was reasonably well equipped to then lead multidisciplinary projects because I had an understanding of all sorts of pieces of the marine system. I wasn't an expert in any of them but I could understand what was important and translate it to people elsewhere in the project. I also got involved in a lot of teaching, which I loved, and I got so much enjoyment from supervising Ph.D students.

Is there anything that you would say to your younger self that would have encouraged you at the start of your academic career?

I think being aware of multiple paths is good and one of the great things about an academic career is the ability, if you believe in yourself, to just carve out your own path. There are many people at SAMS who have started at one thing and shifted into something else. A good example is Bhavani Narayanaswamy. She is a deep-sea ecologist and is now deeply involved in plastics and pollution. Liz [Finlo's wife, Elizabeth Cottier-Cook] started off doing integrated aquaculture and then got into non-native species, and now she's investigating the economics and management of seaweed industries internationally. She's gone from Scottish salmon farms to Indonesian seaweed farms! The people you meet are also crucial in your development and the Norwegian connection was really important for me. I was in a meeting, giving a project update where I talked about vertical migration and zooplankton, and there was a visitor to the project in the room. It was Jørgen

Berge. He was so interested in the topic – that was in 2003 – and we ended up working together for the next 20 years. Another big influence on my life was the late Andy Brierley. He was just hugely enthusiastic and entertained any mad idea. Also influential was Sian Henley who I worked with on Arctic projects. She was a never-ending source of questions and possibilities. Then there was Stig Falk-Petesen, who I met at a ceilidh in Oban. His projects always seemed really fun. I learned that he didn't necessarily pick the world's best scientists, rather colleagues he enjoyed working with.

Towards the end of your time at SAMS, you led a multinational Changing Arctic Ocean project and forged strong links with UiT Tromsø, gaining a professorship in Norway, as well as with the University of the Highlands and Islands. At that stage, did you feel you had achieved everything you wanted to, or had you fallen out of love with science?

I always said, I've never felt pushed from science; I felt a pull from somewhere else. There was a moment at the end of that Changing Arctic Ocean programme where we had completed three cruises in six months. The first was in winter and it was really, really challenging. It was hard work and the weather was awful, but people worked together really well. The spring cruise was better, we had daylight and people were into the swing of it, and by the time the summer cruise came we had a great way of working and I was left with this feeling of 'what a fantastic team of people'. If I'm honest, I had become more interested in the people than in the scientific data that had been collected. The team was totally committed to the data and the science, but I realised I had changed. I started to see that what I really, really enjoyed was working with people and supporting people and giving people opportunities, connecting them, building teams, so I started thinking of possibilities beyond science. Then the job with RYA Scotland came up, which allowed me to do all of those things.*

You have also been working with the RNLI for more than 20 years. Can you tell me more about that?

Growing up, I was always around boats and it's an environment I know, so it was quite a natural thing for me. In science, the job is never really done. There's always more to find out, another paper to write, another conference, and you put in a whole heap of time and effort, wondering if anyone will even notice. The lifeboat was mainly locals, who had no connection with SAMS, so the chat was everything other than work. You went out with a very specific task, you knew when it was completed and very often you got a thank you at the end. So, the roles were the very antithesis of each other, although still both on the water. The lab has always supported the RNLI through fundraisers and providing crew and there's a bunch of SAMS students who are fundraisers, so there's actually a really strong connection, but for me they were two separate lives.

What's the best bit of advice you can give an early-career researcher?

Try to get in your own small pots of money: travel grants, collaboration grants, small research grants, and give yourself that bit of autonomy to pursue your thing and build your own networks. Mentors are there if you look for them. A lot of my best connections were through social interactions, so I got to know them as people, through talking about family or interests. I'd go sailing or hill-running or skiing with people and you have that shared interest other than work.

I think 'imposter syndrome' is something I dealt with throughout my career. I had 20 years of feeling someone is going to catch me out but I eventually learned the best thing is to talk about it with people you trust. So much of academia is about critique, be it a paper, or a proposal, or a talk. So, on almost a daily basis you're being critiqued – or for want of a better word, criticised – and if you dwell on that, it can only fuel the imposter syndrome you're feeling. That's why it's important to talk about it. When you're in a room with other scientists, it's easy to presume that they all know a lot of stuff, but the reality is everyone contributes a little bit of the bigger picture.

You have a very different job now, as CEO of RYA Scotland. How difficult has that change been?

It's interesting, because we've been discussing imposter syndrome and there's me walking into a sports governance environment, with no previous experience of sports governance. So, I might have expected to experience imposter syndrome again in the new role, but curiously I didn't. With lots of the situations that come across my desk, I can see parallels with working in science. I often think to myself 'I've seen this before'. I've learnt a lot about how the skills and experience I've gained over the years are relevant outside of academia. For example, as scientists we need to be creative to generate new ideas; we're constantly working in partnerships with other scientists, or funders, or industry; and we have to demonstrate impact, whether that's at local or international level, or in terms of monetary value. So, I don't feel the career shift is such a major change and I think academics can bring a lot of relevant experience to new roles.

Finlo Cottier is CEO of the Royal Yachting Association Scotland.
Finlo Cottier/LinkedIn

Finlo at the helm of an Ocean Youth Trust vessel out on the Clyde. RYA Scotland works with the Ocean Youth Trust to support sailing opportunities in Scotland.
(Photo: Marc Turner, RYA Scotland)

* The Royal Yachting Association Scotland (https://www.rya.org.uk/gbni/scotland) looks after the interests of members, clubs, training centres and affiliates of the RYA in Scotland. It is the recognised governing body for sailing in all its forms in Scotland.

Enhancing ocean alkalinity for CO_2 removal

PML plays an important role by monitoring field trials

Reducing emissions of greenhouse gases is essential if global temperature rise is to be kept to 2°C or less, but actively removing CO_2 from the atmosphere is also now widely accepted as having a key part to play in tackling global warming, and is explicitly called for in the Paris Agreement, a legally binding agreement under the *UN Framework Convention on Climate Change*. Here is a brief overview of the ways in which CO_2 uptake by the ocean could be increased, beginning with news of a small scale trial recently undertaken in Cornwall.

Enhancing ocean alkalinity via waste water

At present, rising atmospheric CO_2 is continually driving CO_2 into the ocean, where it dissociates, raising ocean acidity (Figure 1). Increasing ocean alkalinity* increases the capacity of the surface ocean to take up atmospheric CO_2 by shifting the equilibria shown in Figure 1 to the right, so reducing ocean acidity while adding to the amount of dissolved inorganic carbon (DIC) being stored long-term in the body of the ocean.

Scientists from Plymouth Marine Laboratory (PML), and its commercial subsidiary PML Applications, have recently confirmed the viability, and potential scalability, of using wastewater outflows to increase ocean alkalinity – 'ocean alkalinity enhancement' – and hence draw more CO_2 down into the ocean.

The PML team was commissioned by Canada-based carbon-removal specialists Planetary Technologies to provide independent monitoring and seawater analysis during a trial of alkalinity enhancement in September 2022. The trial, which followed an extensive series of lab-based tests and modelling experiments, involved adding a suspension of powdered magnesium hydroxide ($Mg(OH)_2$) – a substance used in many household products, including antacids – to the wastewater at the treatment plant in St Erth, Cornwall. The treated water was released ~6 km offshore through the existing outflow pipe. Although the pipe is near the sea bed, shallow coastal waters are well mixed, so water with raised alkalinity came into contact with the atmosphere.

*The alkalinity referred to here is 'total alkalinity' which is not a value on the pH scale but a measure of the capacity of a sample of water to resist acidification, defined as the excess of H^+ acceptors over H^+ donors. The expression includes not only the main contributors, HCO_3^- and CO_3^{2-} but eleven other constituents of seawater, including H^+ itself, expressed as molar concentrations.

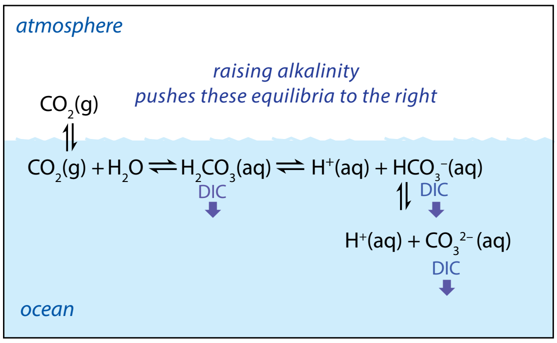


Figure 1 *An increase in ocean alkalinity pushes the equlibria shown to the right, converting dissolved CO_2 gas to dissolved forms of inorganic carbon – H_2CO_3, and HCO_3^- and CO_3^{2-} (bicarbonate and carbonate ions). This shift allows more CO_2 gas to enter surface water from the atmosphere, while increasing dissolved inorganic carbon (DIC) which will remain in the oceans for millennia.*

The analyses provided by PML and PML Applications (see Further Reading) confirmed that adding magnesium hydroxide to the wastewater increased its total alkalinity, increased the pH from 7.4 to 7.8 and reduced dissolved CO_2 levels by up to 74% (Figure 2). Offshore, lower dissolved CO_2 concentrations and lower acidity levels were detected up to a few metres away from the discharge site, but the small scale of the trial meant that it was not possible to detect a change in atmospheric CO_2 levels. The alkalinity and pH returned to normal soon after the addition of magnesium hydroxide was stopped.

There have been earlier proposals to add magnesium hydroxide (and other alkalinity enhancing substances) at sea but adding them at wastewater treatment plants would have a number of big advantages. Around 1000 km³ of wastewater are released to the sea each year globally, about 300 km³ of municipal wastewater via sewage treatment plants and over 600 km³ from industry. Adding magnesium hydroxide at locations on land would be much cheaper and more convenient than adding it from ships at sea, as well as not involving the use of large amounts of fuel. The 'added alkalinity' could be carried offshore by river plumes and dispersed by ocean currents to achieve CO_2 removal at scale over the ocean.

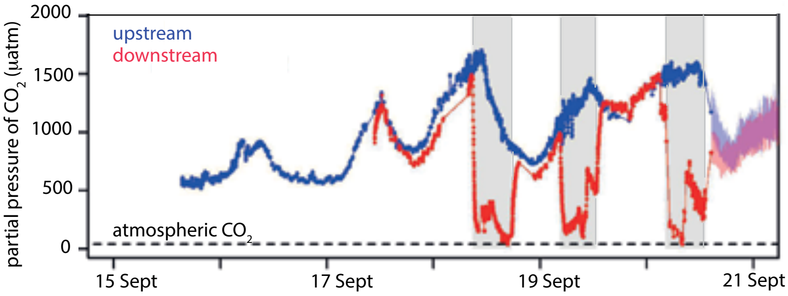
Another advantage of adding alkalinity at the coast is that effluent from wastewater treatment is typically rich in biologically produced CO_2 which, in the vicinity of outfalls, drives a flux of CO_2 to the atmosphere. In principle, alkalinity enhancement of wastewater re-establishes the carbonate equilibrium in Figure 1 so that dissolved CO_2 gas continues to be converted to HCO_3^- and CO_3^{2-}.

Raising ocean alkalinity via enhanced weathering of minerals

The alkalinity-raising method monitored by the PML team can be thought of as mimicking the result of natural weathering of continental rocks, which takes place naturally over millions of years. Ideas about raising the alkalinity of the ocean by spreading crushed carbonate or silicate minerals onto land, or adding them to the surface of the ocean, have been developing since the early 1990s.

Calcium carbonate is abundant in the Earth's crust, but would not be suitable for adding to surface waters of the open ocean as these are generally supersaturated with $CaCO_3$, which would hinder dissolution. One alternative would be to use CaO (quicklime), produced industrially from $CaCO_3$, although this industrial process not only uses energy but also releases CO_2, which would need to be captured. At present, silicate minerals

Figure 2 *The partial pressure of CO_2 in wastewater in the St Erth sewage treatment plant upstream and downstream of the addition of $Mg(OH)_2$, showing a clear reduction in downstream pCO_2 when $Mg(OH)_2$ was being added (grey shaded areas). (With thanks to PML)*



such as olivine (Mg_2SiO_4) are generally seen as better options.

However, mining the source rocks and spreading finely ground mineral particles over the surface of the open ocean would be expensive in both money and CO_2-production. A cheaper and more easily attainable method is to add olivine to coastal sediments during activities that already occur, such as dredging operations, land reclamation and beach nourishment. Adding olivine to beaches to increase ocean alkalinity is already being trialled (Figure 3), providing opportunities to study resulting changes to local ecosystems.

There will inevitably be ecological consequences of using enhanced weathering to raise ocean alkalinity. It is thought that adding quicklime to the ocean would benefit planktonic calcifiers, like coccolithophores, while adding olivine would benefit diatoms and cyanobacteria. However, the effects would be greatly affected by where and at what time of year the mineral is added, and its exact composition would also be relevant; for example, olivine may contain iron alongside the magnesium, as well as traces of other elements (e.g. nickel and cadmium).

Other methods of increasing CO_2 uptake by the ocean

A number of other ways have been proposed for enhancing drawdown of atmospheric CO_2 into the ocean. The one that has been studied the longest and is considered to have the most potential is increasing phytoplankton growth through artificial fertilisation of the ocean, particularly by addition of the micronutrient iron. Plankton growth could also be enhanced by bringing up nutrient-rich water by artificial upwelling (which would of necessity be accompanied by artifical downwelling). One concern about the latter is that vertical exchange of water could affect the density field and pressure gradients in the ocean and hence affect currents, perhaps in unexpected ways. Another is that upwelled water reaching the sea surface would release CO_2 to the atmosphere, which would reduce the net drawdown of CO_2 and would need to be quantified.

Some proponents of increasing primary productivity note that it will support organisms higher up the food chain, including fish that could be caught commerically. However, we do not know what the full effect on ocean food chains might be, and any increase in biomass at higher levels would be a one-off effect. Furthermore, a large increase in primary productivity could result in oxygen depletion at depth as sinking organic remains decay. Furthermore, decaying remains could produce methane and nitrous oxide, which are more potent greenhouse gases than CO_2.

Commercial seaweed cultivation already occupies large areas of coastal water and yet larger areas of cultivation have been proposed as a way of trapping CO_2 as well as, in some cases, providing food. There are concerns that seaweed grown in deeper water, with the idea of harvesting it to be dropped to the sea bed where it would be incorporated into sea-bed sediments, might in fact decompose in the water column before this could happen, again with the risk of oxygen depletion and the problems mentioned above.

Regeneration of natural coastal ecosystems such as saltmarshes, mangroves and seagrass beds would play an important role in reducing atmospheric CO_2, but on its own, increasing the stocks of naturally occurring 'blue carbon' would not have enough effect over the short time-scales available.

A small number of electrochemical systems have been investigated as methods for increasing ocean alkalinity or for CO_2 removal from seawater. Amongst the research that needs to be undertaken is identification of electrode materials that could minimise the production of unwanted by-products such as chlorine gas, and of hybrid approaches that both remove CO_2 and increase ocean alkalinity.

Scaling up and proceeding responsibly and legally

For the UK, ocean alkalinity enhancement has the potential to allow it to meet its net-zero targets. Up to 20 Mt of CO_2 a year might be removed through water treatment outflows, without environmental regulatory limits for pH and suspended solids in coastal waters being exceeded. Using discharges of cooling water from nuclear plants is also a possibilty and it has been estimated that one such discharge site could remove several hundred times more CO_2 than a wastewater treatment site.

As new technologies emerge, and trials of methods to increase CO_2 drawdown by the ocean are scaled up, the care and caution used in the PML work needs to be replicated across the globe. Before there are any large-scale trials, research involving modelling, lab work, mesocosms (large seawater tanks), followed by large-sale monitoring, will all need to be undertaken. Meanwhile the legal framework is evolving. Ocean fertilisation and other marine geo-engineering proposals are covered by the 2013 Amendment to the 1966 London Convention and Protocol (which relates to pollution caused by dumping); this provides a framework to assess the legitimacy of proposed research. In the case of interventions enacted from land (such as alkalinisation of wastewater) individual states are encouraged to adopt legislation that incorporates internationally agreed rules and standards.

Further reading

More about the PML study can be found in:

Kitidis V.and 9 others (202?4) Magnesium hydroxide addition reduces aqueous carbon dioxide in wastewater discharged to the ocean. *Commun. Earth and Environ.* **5**, 354. doi: 10.1038/s43247-024-01506-4

See also: https://pml.ac.uk/news/q-a-and-video-on-the-ocean-alkalinity-enhancement/

Other sources consulted include:

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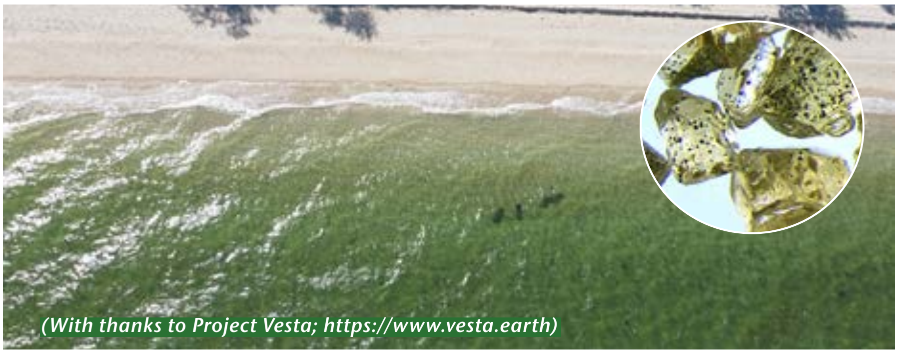
Renforth, P. (2017) Preventing climate change by increasing ocean alkalinity, *Eos* **98**, 9 Aug.doi.:10.1029/2018EO076919

Vivian, C. and L. Del Savio (2024) The London Convention and Protocol: Adapting to address the ocean–climate crisis *The International Journal of Marine and Coastal Law* **39**, 519–27. doi:10.1163/15718085-bja10178

Ed

Figure 3 *Southampton Beach, NY, which in July 2022, became the site of the world's first field pilot of coastal carbon capture when the addition of 500 m³ of olivine sand (~5% of the total sand volume) was incorporated into their beach restoration project.* ***Inset*** *Olivine crystals extracted from the naturally green sand of Kokee Beach, Oahu, Hawaii. (Alain Couette)*



(With thanks to Project Vesta; https://www.vesta.earth)

Tides and ocean circulation during the Last Glacial Maximum

Sophie-Berenice Wilmes

Throughout the Pleistocene (2.58 million to 11 700 years before present), Earth's climate fluctuated between cold glacial periods and warm interglacial periods. During the Last Glacial Maximum (26 500–19 000 years BP) – the period when ice caps were at their greatest extent during the most recent glacial period – global mean surface temperatures were on average 4–8 °C lower than at present, and vast ice sheets covered the Northern Hemisphere. The enormous volumes of fresh water locked up in these ice sheets meant that global mean sea level was approximately 120–130 m lower than today, so that continental shelves, which today are covered by shallow seas, were exposed if they were not covered by ice. It is thought that this lack of shelf seas affected tides and the strength of tidal currents in the ocean, and in turn the meridional overturning ocean circulation. With colleagues I set out to explore how changes in tidally driven ocean mixing may have affected the Atlantic meridional overturning circulation and whether sediment cores could provide information to help determine the strength of tidal mixing in the past.

Tidal waves travel around ocean basins with their amplitudes increasing outwards from central points with zero amplitude

Global tides today and during the Last Glacial Maximum

The substantially lower sea level during the Last Glacial Maximum is thought to have profoundly affected global tidal dynamics. As today, the dominant force generating the tides was the gravitational attraction of the Moon; this results in two high tides and two low tides a day, with the main semi-diurnal or twice-daily tidal component of tidal motion associated with the Moon known as M_2. At present, the largest tidal amplitudes globally are observed in the shelf seas, for example, along the coastlines of the British Isles or in the Bay of Fundy on the east coast of North America (Figure 1(a)). In contrast, open ocean tides are generally small – mostly less than 1 m in amplitude. As tidal waves propagate from the open ocean into the shelf seas, they feel the effect of the sea bed, and the bottom friction slows the propagation of the tidal wave – similar to what happens when a wave approaches a beach. This process, together with resonance effects, leads to increased tidal amplitudes in the shelf seas. For example, regional resonance effects lead to the very large tidal amplitudes in the Bristol Channel of 6–8 m and the largest tidal amplitudes globally in the Bay of Fundy at 8 m.

The tides lose energy – termed 'tidal dissipation' – due to two main processes: at present, most of the tidal energy (over two-thirds) is lost

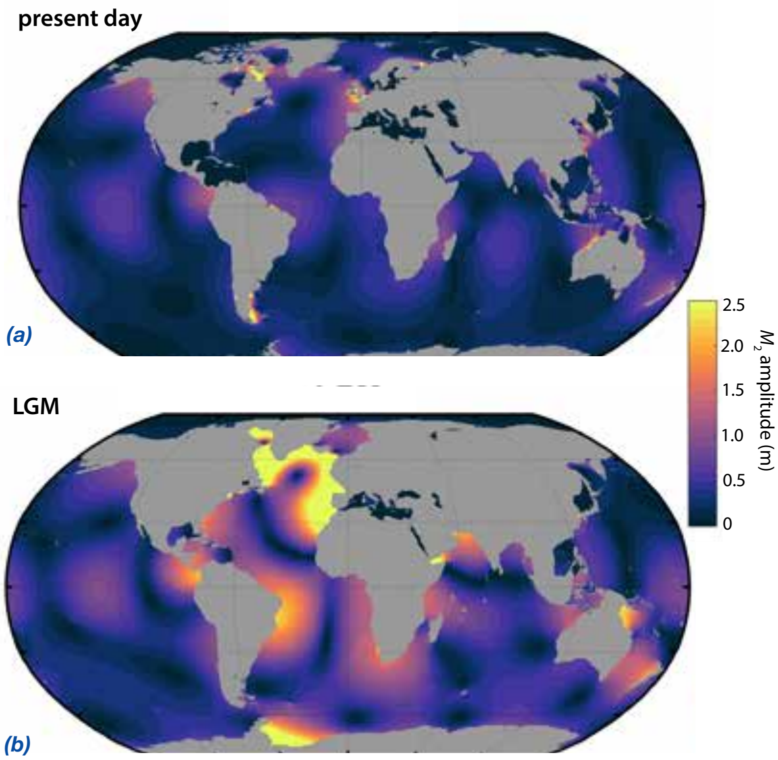


Figure 1 *Modelled tidal amplitudes for the* M_2 *tidal constituent for **(a)** the present day and **(b)** the Last Glacial Maximum. Today large tidal amplitudes are mainly restricted to shelf seas, but during the LGM occurred over a large part of the open oceans, especially the Atlantic.*

(Adapted from a figure in Green and Duarte (2022); see Further Reading)

by bottom friction in the shelf seas. Only around one-third of tidal energy is dissipated in the open ocean, mainly by the generation of internal waves. Interactions between shelf-sea tides and open-ocean tides affect global tidal dynamics: for example, the present-day Atlantic is close to resonance at the frequency of the M_2 tidal constituent due to its depth and basin length but does not have as much energy as it might have because of the large amount of energy lost in the shelf seas.

During the Last Glacial Maximum, however, the lower sea level and expanded ice coverage greatly reduced the extent of shelf seas, thus limiting the areas where tidal energy could dissipate. Consequently, open ocean tides were significantly more energetic than they are today, particularly in the Atlantic due to its near-resonant state (Figure 1(b)) – LGM tide model simulations have suggested amplitudes of over 4 m in the northern North Atlantic, in the Labrador Sea and in the Weddell Sea. As a result, the amount of tidal energy dissipated in the open ocean also substantially increased. Our models show that globally integrated tidal dissipation may have been a factor 2–3 larger than at present, and up to 8 times greater than at present in the Atlantic, depending on the sea level change and ice sheet extent applied in the tide model.

Tidal energy and the Atlantic meridional circulation

In the present-day Atlantic, the north–south circulation, known as the Atlantic meridional circulation or AMOC, is characterised by warm surface waters flowing northward into the subpolar North Atlantic transporting heat from the tropics to high northern latitudes, and a deeper, colder and more saline southward return flow (Figure 2). In the subpolar North Atlantic, heat losses to the atmosphere cool the water, and sea-ice formation increases its salinity, and the waters become dense enough to allow deep-water formation to take place. Cold and high salinity North Atlantic Deep Water (NADW) flows southward at depths between 1000 m and 4000 m (palest pink in Figure 2). Antarctic Bottom Water (AABW) is formed around Antarctica through cooling, ice formation and mixing, creating very dense and cold water which flows northward below NADW (pale blue in Figure 2). Crucially, vertical mixing sustained by the tides and winds and wind-driven upwelling eventually helps bring the deep water back to the surface, closing the circulation loop (various processes that redistribute water vertically are shown schematiclly in Figure 2). The AMOC contributes to redistributing heat, salt, nutrients and oxygen across the Atlantic and ultimately the global oceans.

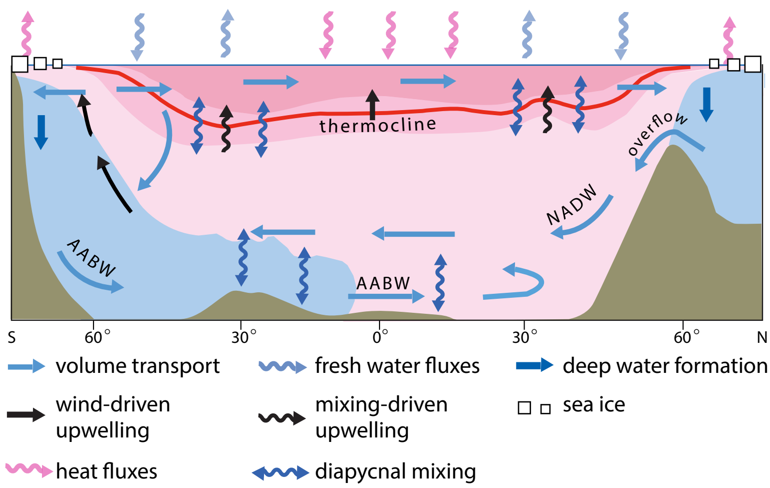
In the open ocean, the movement of the tide over areas of rough topography such as mid-ocean ridges or seamounts generates turbulence in the interior of the ocean leading to local mixing and it can also cause the formation of internal waves. These waves can propagate across the oceans for 1000s of kilometres along density interfaces (e.g. the thermocline) until they eventually break and cause vertical mixing between waters with different densities (i.e. diapycnal mixing; see Figure 2). Vertical mixing in the ocean reduces density gradients between water masses so reducing the density of the deep water sufficiently to allow it to return back to the surface. Tidally driven mixing, together with mixing by the wind, therefore contributes to sustaining the global large-scale meridional ocean circulation.

Reconstructions of the AMOC during the LGM suggest that its circulation structure and strength may have differed substantially from its modern state. Water mass tracers such as radiocarbon ages and stable carbon isotope ratios (see Box on p.17) indicate that the deep North Atlantic was occupied by waters originating from around Antarctica (i.e. AABW) rather than deep waters formed in the subpolar North Atlantic, as today. The tracers also suggest that whilst deep water formation in the subpolar North Atlantic was active during the LGM, the depth glacial NADW extended down to was much shallower than at present. It has also been suggested that the AMOC during the LGM may have been less vigorous. Additionally, reconstructions of the Atlantic water mass structure indicate that the Atlantic was much more stratified than at present, i.e. there was a greater density difference between NADW and AABW.

Several studies have attempted to explain such differences in ocean structure and circulation during the LGM by exploring whether the balance between vertical mixing and stratification was different during the LGM. It has firstly been

Water that sinks at high latitudes eventually returns to the surface through large-scale movement of water masses and vertical mixing processes

Figure 2 *Highly generalised schematic cross-section of the Atlantic Ocean meridional overturning circulation with North Atlantic Deep Water flowing above Antarctic Bottom Water. Darkest pink shading corresponds to least dense water, blue shading to most dense. Arrows indicate processes that redistribute water vertically, and air–sea fluxes of heat and fresh water.*
(Adapted from Kuhlbrodt et al., 2007)



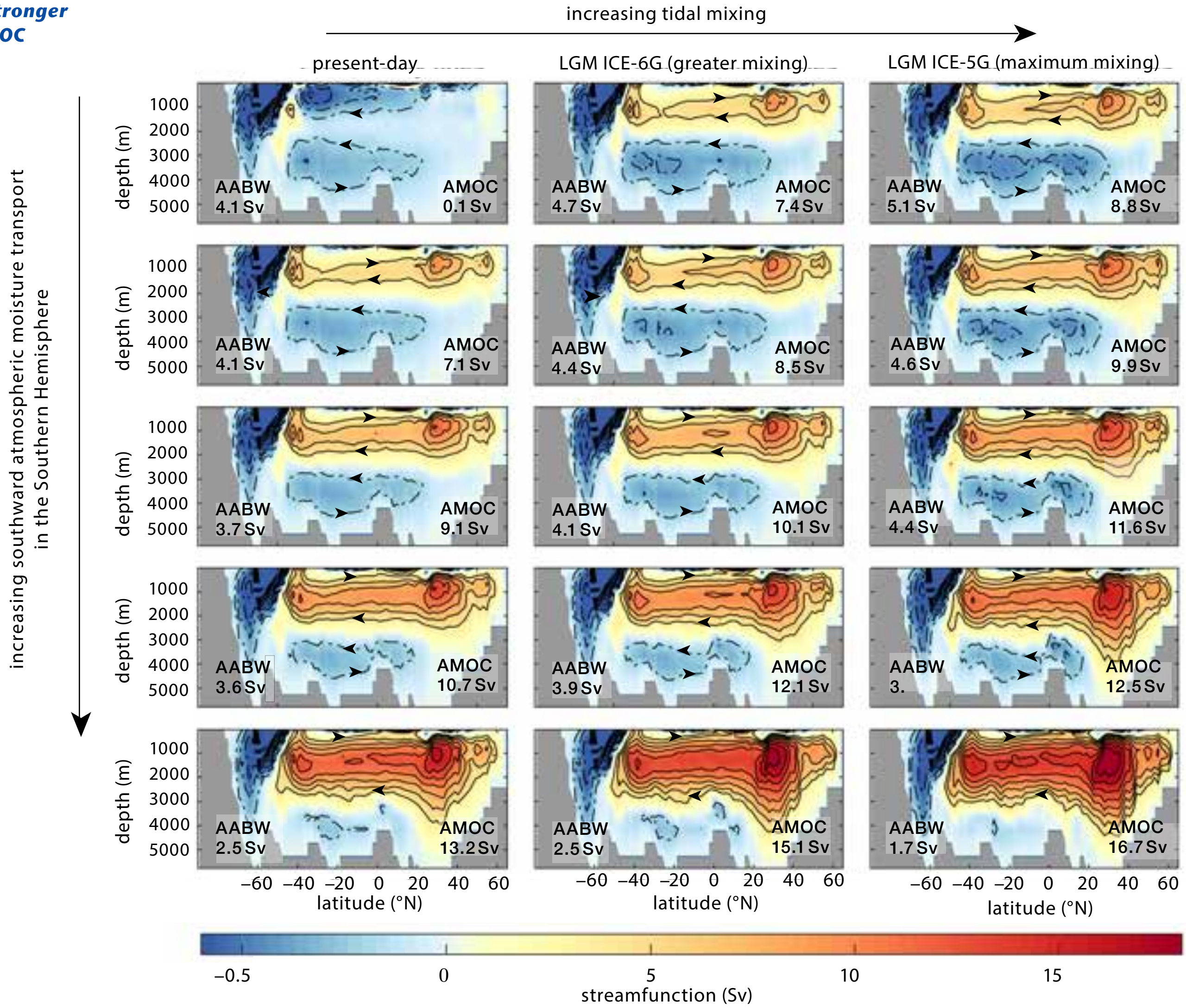
hypothesised that the amount of vertical mixing between NADW and AABW may have been less because a shallower NADW would have meant that the interface between NADW and AABW was further away from the sea floor where the highest rates of turbulence, and thus of mixing, occur. Secondly, an increase in the density difference between AABW and NADW, as suggested from tracers and seen in climate model simulations, would have led to increased stratification which means that a greater amount of energy would have been needed to mix the two water masses. However, neither hypothesis considers that dissipation of tidal energy in the LGM could have been different from today.

Therefore, our work set out to explore how tidal mixing might have affected the strength and structure of the AMOC during the LGM. We also wanted to investigate whether information from carbon isotopes in microfossils in deep-sea sediments (see Box on p.17) could provide useful information on past vertical mixing rates and thus on tidal energy, and potential effects on the AMOC.

To address these questions, using the intermediate complexity climate model UVic we generated an ensemble of different Atlantic circulation states ranging from a shut-down to a vigorous AMOC. This was done by producing simulations with varying amounts of tidal mixing and varying amounts of meridional atmospheric moisture transport in the Southern Hemisphere, shown in Figure 3. Column 1 in Figure 3 shows simulations using present-day tidal mixing, and columns 2 and 3 show simulations which we refer to as ICE-6G and ICE-5G. Both correspond to increased tidal mixing during the LGM but with slightly different bathymetries and ice sheet extents; the scenario represented in column 3 (ICE-5G) produced the maximum possible amount of tidal mixing. Atmospheric meridional moisture transport increases from top to bottom.

In our models, increasing the amount of tidal mixing, and increasing the southward transport of water in the atmosphere, both produced a stronger AMOC

Figure 3 *Our ensemble of simulations of the Atlantic meridional overturning streamfunction in sverdrups (1 Sv = 10^6 m^{3}s^{-1}) for the Last Glacial Maximum, arranged by the strength of the tidal forcing (left to right) and the Southern Hemisphere forcing through meridional atmospheric moisture transport. A streamfunction describes the flow of a fluid, and its streamlines represent the paths followed by fluid particles, making it easy to visualise the flow pattern. Yellow/orange/red shading indicates a clockwise circulation (when viewed from the east), blue values an anti-clockwise circulation.*



Our simulations show a number of interesting features. Assuming present-day tidal mixing, in our simulations, a stronger AMOC* (i.e. more vigorous and voluminous NADW flow) corresponds with a less vigorous and less expansive AABW circulation (first column in Figure 3) because one water mass displaces the other. However, surprisingly, LGM tidal mixing strengthens both the AMOC and AABW circulation (second and third columns). This is because increased LGM tidal dissipation drives a stronger drawdown of deep water in both hemispheres, causing AABW and NADW to be formed at a greater rate, while also allowing deeper water to return to the surface more rapidly (upward arrows in Figure 2).

Furthermore, simulations that use present-day tidal mixing (column 1) show less mixing at the interface between NADW and AABW due to the shallower NADW. In these simulations, the shallower AMOC moves the NADW–AABW interface away from the sea bed where, as previously hypothesised, mixing is strongest, thereby reducing the mixing between the two. However, the hypothesis of less mixing at the NADW–AABW interface does not hold true for simulations using LGM tidal mixing rates. Here, even simulations with a much shallower and weak AMOC have mixing rates at the AMOC–AABW interface that are stronger than at the present day. This is because the LGM tidal energy dissipation was sufficiently great to result in more overall mixing between the water masses rather than less mixing (as hypothesised), even though the NADW–AABW interface was shallower, and so further from the sea bed. This suggests that the difference in water mass structure during the LGM was not caused by reduced availability of energy for mixing.

*Conventionally, the strength of the AMOC is indicated by the maximum northward transport below 300 m at 25°N. AABW strength is given as the minimum meridional transport below 1500 m depth at 32°S.

How we used isotopes of carbon to constrain water mass structure and mixing

The UVic setup used includes a biogeochemistry model based on ocean model physics and biogeochemical processes to simulate global distributions of radiocarbon (^{14}C) and the stable carbon isotopes ^{12}C and ^{13}C expressed as a ratio known as $\delta^{13}C$ (see box below). We used global compilations of sea-bed radiocarbon and $\delta^{13}C$ values for the LGM, both of which were deduced from sediment core data, to compare with our modelled carbon isotope distributions. This allowed us to find the simulations which best fitted the isotope distribution from the sediment core data. Our simulated $\delta^{13}C$ distributions for the scenarios in Figure 3 are ahown in Figure 4 overleaf.

Using carbon isotopes to infer past ocean conditions

Microscopic marine single-celled organisms with calcium carbonate tests (shells) such as foraminifera preserve information about their surrounding environment in their tests. They incorporate isotopes, including stable isotopes of carbon (^{12}C and ^{13}C), into their tests at specific ratios which reflect factors such as water mass characteristics (e.g. temperature) or productivity. Foraminiferal tests are often well preserved in sediments and are thus widely used to reconstruct past environmental conditions through the use of sediment cores. In our research, we use distributions of carbon isotopes from the shells of benthic foraminifera (those living on the sea bed) recovered from sediment cores – ^{12}C and ^{13}C, along with radiocarbon (^{14}C) – to gain information about past water mass properties.

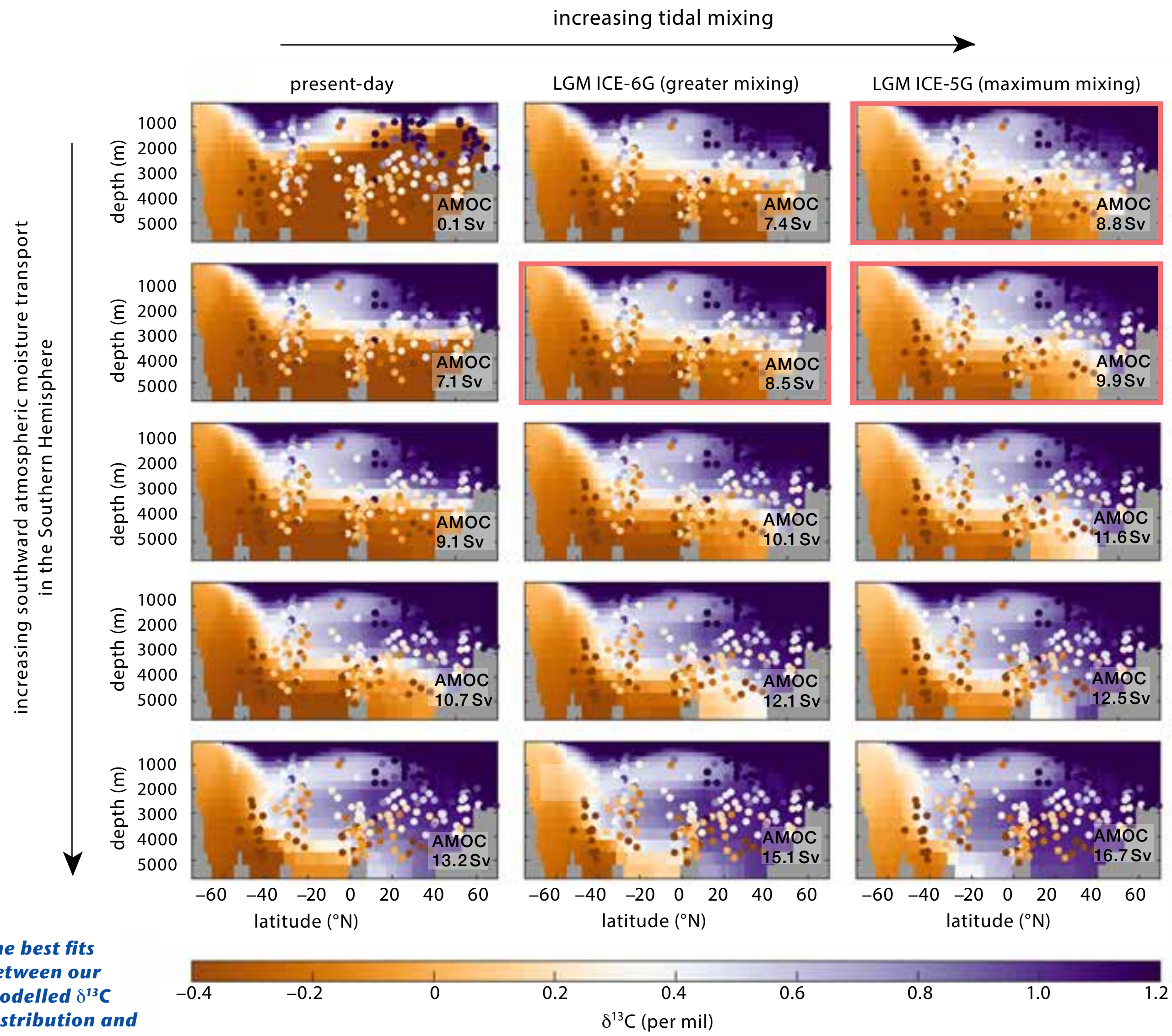
The relative abundance of the stable carbon isotopes ^{12}C and ^{13}C in dissolved inorganic carbon in seawater, as recorded in fossil foraminifera, can provide insights into past ocean dynamics. The ratio between ^{12}C and ^{13}C, expressed as $\delta^{13}C$* (per mil or ‰) and normalised to a standard, changes due to phytoplankton preferentially incorporating ^{12}C during photosynthesis, enriching surface waters in ^{13}C. As particulate organic matter sinks and decomposes, it releases ^{12}C at depth, creating $\delta^{13}C$ gradients from surface to deep ocean. These gradients are influenced by ocean circulation, with well ventilated waters (i.e. waters recently in contact with the atmosphere) having higher $\delta^{13}C$. Thus, variations in foraminiferal $\delta^{13}C$ are used to infer changes in past ocean circulation and ventilation.

Radiocarbon ages in fossil foraminifera also provide crucial data for reconstructing past ocean circulation. Radiocarbon dating uses the decay of the radioactive isotope ^{14}C in the shells of fossil foraminifera. Since ^{14}C decays at a known rate, the radiocarbon content in foraminifera shells can be used to estimate their age.

The distribution of ^{14}C throughout the oceans reflects differences in the rates of mixing between the surface and deep waters, and the large-scale flow rates of water masses. Well ventilated surface waters have higher ^{14}C levels, while deep waters, which have been isolated from the atmosphere for longer periods, have lower ^{14}C levels. By analysing radiocarbon ages of fossil foraminifera from different sea-bed depths and locations, patterns of past ocean circulation can be inferred. For example, variations in ^{14}C ages can reveal shifts in the rate of deep-water formation and changes in the pathways of ocean currents over time.

In our research, we use compilations of LGM radiocarbon and $\delta^{13}C$ from many different sediment cores from across the global oceans in order to obtain a spatial picture of water mass distribution during the LGM, with a specific focus on the Atlantic. Figure 4 overleaf show our results for $\delta^{13}C$.

$$^{*}\delta^{13}C = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} \times 1000\ ‰$$



The best fits between our modelled δ^{13}C distribution and that recorded in sediment cores is for a weak but active AMOC

Figure 4 *Modelled δ^{13}C distributions for the Atlantic during the Late Glacial Maximum, with δ^{13}C values from foraminifera in sediment laid down at that time, taken from sediment cores collected at different depths in the Atlantic (dots) overlain for comparison. In the simulations with a shut-down (top-left) or vigorous circulation (lower panels), the fit between the sediment isotopes and modelled distributions is poor, especially in the deep North Atlantic. The best fit is for a weak but active AMOC (the three simulations highlighted with a red box have the lowest errors when compared with the sediment isotope data; cf. the corresponding simulations in Figure 3).*

As seen in modern carbon isotope distributions obtained from core top (i.e. sea bed) and bottom water samples (and consistent with a present-day control simulation which we also generated), the modelled LGM isotope ratios show a strong circulation imprint (background colours in Figure 4): in most of the simulations, the general pattern of NADW originating at high northern latitudes overlying AABW originating at high southern latitudes, can be clearly seen.

In most simulations, the sediment-derived δ^{13}C values (dots in Figure 4) are negative in all or most of the deep Atlantic, indicating low concentrations of ^{13}C, which are characteristic of AABW, whereas the overlying NADW shows much more positive δ^{13}C values which reflect a water mass that has been in contact with the surface relatively recently.

When the distributions of δ^{13}C from foraminifera in sediment cores (dots in Figure 4) are plotted over the modelled isotope distributions, it becomes obvious that, overall, the fit between the modelled and the isotope distributions from the sediment cores is dominated by the AMOC strength and structure. The scenario with a shut-down of the AMOC (top left; cf. Figure 3) and also those with a very vigorous AMOC (lowermost rows) display the worst fit between the modelled and the sediment-derived distributions. Scenarios with a weak but active AMOC (simulations outlined in red in Figure 4) show the best fit.

Similarly, in the simulated distributions of radiocarbon ages (not shown) AABW and NADW are clearly defined, with AABW having much older radiocarbon ages than the shallower and younger NADW. Simulations with a weaker AMOC and a shallower boundary between NADW and AABW lead to very old waters in the deep North Atlantic. In contrast, a more vigorous and deeper AMOC decreases the age of the deep water. In the LGM scenarios, the more vigorous tidal mixing reduces the age gradient between the younger NADW and the older AABW because stronger tidal mixing means that more young NADW is transported downwards into the older AABW.

For distributions of both δ¹³C and radiocarbon ages the closest correspondence between the modelled and sediment-derived isotopes, as determined on the basis of the smallest root-mean square error between the two, is for a weak (but active) and shallow AMOC of 9–10 Sv (Figure 5; see also the simulations highlighted in red in Figure 4); present-day AMOC strength is around 17 Sv. Interestingly, the fit is around 10% better for the circulation states where LGM tidal mixing is applied.

So, using both δ¹³C and radiocarbon age, we find that when present-day tidal mixing is used, the interface between NADW and AABW is abrupt, but the stronger LGM tidal mixing leads to a more gradual gradient between the two water masses. The sediment-derived isotopes thus indicate that tidal mixing rates were probably much greater during the LGM, in accordance with tide model simulations of this period. Our results thus confirm that more energy was available for mixing than at present, rather than less.

They also demonstrate that the shallower AMOC did not lead to a reduction in mixing rates at the NADW–AABW interface. However, despite the greatly increased LGM tidal mixing rates, the glacial ocean was still much more strongly stratified than at present. What drove the much stronger stratification in the LGM Atlantic is still an ongoing debate. More recent work suggests that the stronger formation of AABW during the LGM may partly have been driven by the enhanced glacial tidal mixing, suggesting that the large LGM tides may have – counterintuitively – actually contributed to a strongly stratified glacial ocean. This enhanced stratification would have allowed vast amounts of carbon to be locked away in the deep ocean, lowering atmospheric CO_2 levels to less than half those of the present-day.

Implications for ocean circulation in deep time

Going further back in time, throughout Earth's history continents have undergone major rearangements, assembling into supercontinents such as Pangea during the Permian (298.9–251.9 million years BP) and then breaking up into dispersed states as at present or during the Ordovician (485.4–443.8 million years BP). With these changes in ocean basin geometry, tidal dynamics may have varied greatly, going through periods of larger tides such as at present and quiescent periods such as during the Permian. These changes

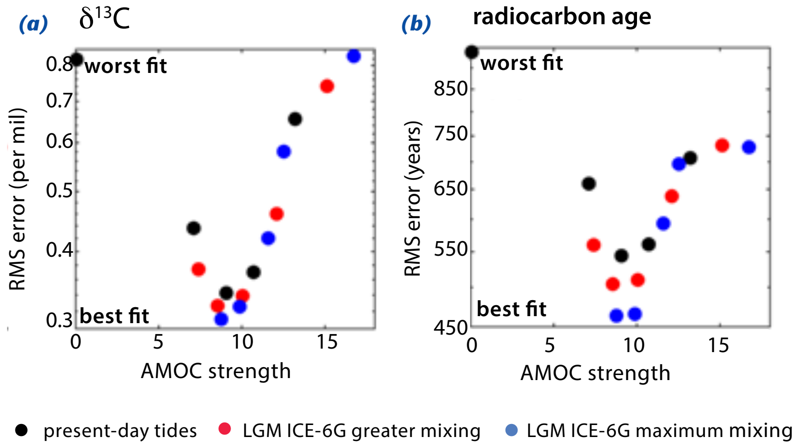


Figure 5 ***(a)*** *Root-mean square error between modelled δ¹³C distributions and distributions obtained from sediment cores (shown in Figure 4) plotted against modelled AMOC strength. Data points are coloured according to the tidal forcing applied.* ***(b)*** *A comparable plot for radiocarbon age.*

The best fits between the modelled distributions and those deduced from data from sediments occur with stronger mixing during the LGM and an AMOC strength of 9–10 Sv

in tidal dynamics had the potential to substantially affect ocean mixing and thus ocean circulation and climate. Our work suggests that changes in the tides need to be taken into account when investigating the ocean circulation of the past.

This article is based on Wilmes, S.-B., J.A.M. Green and A. Schmittner (2021) Enhanced vertical mixing in the glacial ocean inferred from sedimentary carbon isotopes. *Commun. Earth Environ.* **2**, 166. doi: 10.1038/s43247-021-00239-y

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The Bosporus Strait

A special place in the history of oceanography

Bruno Soffientino and Michael E.Q. Pilson

This is an abridged and slightly edited version of an article first published in **Oceanography** *(see Further Reading for details)*

The Bosporus Strait, which links the Black Sea with the Sea of Marmara (Figure 1), holds an important place in the history of oceanography. In 1680, the impressive geographical features and remarkable current patterns of the Bosporus inspired young Luigi Ferdinando Marsigli to solve the long-standing puzzle of two-layer flow. The story of Marsigli in Istanbul, the breadth of his observations, and the premises of his innovative experiment are fascinating but relatively unknown to oceanographers. This article therefore has two objectives: the first is to give an account of Marsigli's measurements and techniques; the second is to explore how a 21-year-old man from a town uninvolved in matters of the sea managed to explain a phenomenon that had occupied the minds of many prominent British scientists and engineers for the previous 30 years.

Travelling to Istanbul

Luigi Ferdinando Marsigli's eventful journey began on 22 July 22 1679 when he set sail from Venice for Istanbul. He was a 'junior member' of the Venetian embassy to the Ottoman court, where he would be working as a messenger between the Turkish and Venetian diplomats. This was the first trip abroad for the 21-year-old.

Figure 1 *Map to show how the Bosporus Strait links the Black Sea with the Sea of Marmara and hence with the more saline Mediterranean.*

The connection with the Venetian embassy was a wonderful opportunity to spend time with scholarly people, Italian and foreign, and to learn about other cultures and religions, including Islam, that westerners found fascinating and disquieting in equal measure. In the mid to late 1600s, Ottoman relations with the rest of Europe significantly chilled, and the work of Western diplomats became proportionately more difficult. Harassment of foreign envoys and restriction of their movements in and around Istanbul was a frequent occurrence.

Within the overall dismal spectrum of European–Ottoman relationships, Venice's was among the worst. Accused of espionage immediately upon arrival, Marsigli's diplomatic party faced an uphill battle from the start and prematurely left Istanbul less than a year later, carrying sanctions against Venice that were to be enforced for more than a century. Despite all of this, Marsigli was surprisingly immune from any hostile situation, most likely as a consequence of his young age and lower rank, and his willingness to learn the local language and customs. This was fortunate, as he certainly could not have carried out the range of observations that we know about without the ability to freely move about the region and without access to local people.

Marsigli made a remarkable range of observations during his voyage to Istanbul and the 11 months that he was there. He illustrated an oil seep in the Ionian isle of Zakinthos. He gave an account of the seasonal migrations of fish to and from the Black Sea. He observed and noted details of the fauna and flora, and dissected and illustrated the anatomy of a mollusc, probably a mussel. He was also interested in political and military aspects of the place, which would become very useful to him a few years' later, when fighting the Turks as a Habsburg army officer.

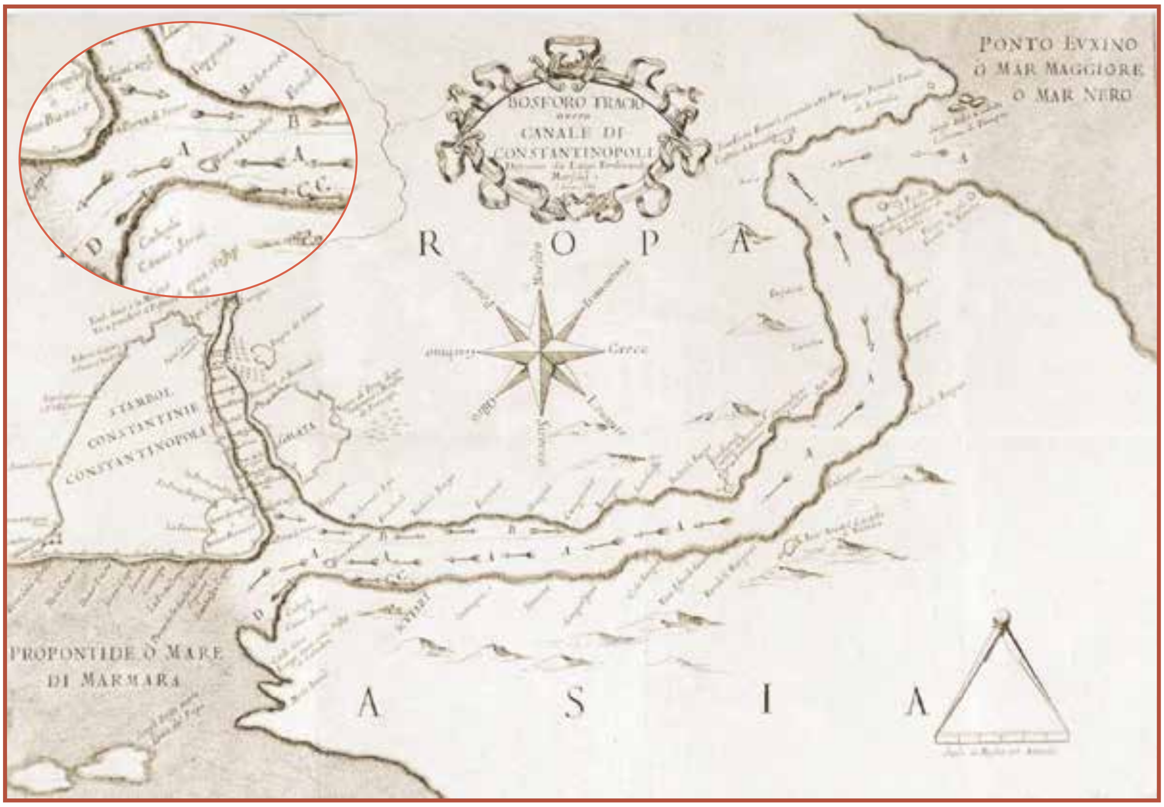
For the purposes of this article, we will only concern ourselves with those of Marsigli's measurements and observations that are pertinent to his model of two-layer flow.

Marsigli investigates currents in the Bosporus

Marsigli was intrigued by local reports of the current patterns of the Bosporus. Fishermen told him that fishing nets cast from the stern of boats anchored in the channel would resurface in front of the boat if allowed to sink to a certain depth. He also found out from an English merchant, Sir Dudley North, that an English ship captain had lowered a weight in the water and had seen it change direction of drift when it reached a certain depth.

Encouraged by John Finch, the English ambassador in Istanbul, Marsigli set out to investigate the currents. He surveyed the Bosporus and sketched a chart showing the essential features of the area (Figure 2). Compared with a modern map, the scale is only approximate, but considering the fact that it was drawn using only a compass and no surveying instruments, it is remarkably good for such a large geographical area. The compass orientation is fairly accurate, and the localities are in the right relative positions. The surface currents also mostly appear correct. The small nearshore currents running opposite to the main direction of flow (A) are obviously eddies caused by local topography. Marsigli correctly interpreted currents C and D (see inset) as such, but he incorrectly interpreted current B as a freshwater plume from the river that discharged into Istanbul harbour. Current D is a curious case: it is located in what is today the harbour of Haydarpasa, in the Asian part of Istanbul; however, there is no report of this eddy in modern sources. Consulting a navigation chart, it is apparent why. Today the harbour is protected by two large breakwater jetties that prevent any significant circulation.

Figure 2 *Marsigli enjoyed many opportunities to explore the Bosporus and its surroundings during his stay in Istanbul; this map summarises many of the observations that he made. It is remarkably accurate considering it was drawn without surveying instruments, using only a compass for orientation.* ***Inset*** *Enlargement of the southern end of the Bosporus to show the surface currents A, B, C and D mentioned in the text. (From Marsigli's* Observations**)*



*Marsigli's book *Observations around the Bosporus Strait or Canal of Constantinople, Presented in a letter to Her Sacred Royal Majesty Queen Christina of Sweden by Luigi Ferdinando Marsigli* published in 1681, and translated into English by the authors (see later).

To measure the intensity of the surface flow from the Black Sea, Marsigli had someone build him a paddle-wheel current meter:

'... a machine [made] out of wood, consisting of a wheel with six paddles, each two palms, four inches, and two quarts of Roman measure in length; in the wheel I placed an axle seven palms long, on which I mounted an index [rotating pointer] one palm and two quarts long at one end, for the purpose of showing the revolutions that the wheel made as it was held horizontally and was propelled by the water, that struck it at right angle in its submerged portion. In such position, the index made thirty-eight revolutions in the time of one-hundred swings of a pendulum eight inches and six eighths long.'

Observations, p.27.

This is the first recorded use of this current meter design. Translation of the dimensions into modern units reveal that the paddles were between 33.1 cm and 42.9 cm long, and the axle about 87.5 cm to 156.4 cm long.* The current was measured by counting the revolutions of the index during 100 swings of the 16.8 cm-long pendulum. Marsigli does not report in *Observations* whether or not someone assisted him with the measurements, but we find it difficult to imagine that he could have done it alone. A pendulum of those dimensions has a relatively short period, so counting swings and revolutions at the same time would seem quite a challenging exercise. Either way, at the southern end of the Bosporus, the current generated 38 revolutions per 100 swings, which translates to approximately 2.0–2.5 knots accounting for the uncertainty in the dimensions and assuming a one-to-one correspondence between current velocity and tangential velocity of the wheel. This flow velocity is lower than the modern value of 3 to 4 knots known in that locality. The underestimation might have been due to the fact that one of the paddles broke shortly after deploying the instrument (!), as Marsigli reported; otherwise it could have been that the instrument was deployed near shore, where the current is weaker. By comparing this measurement with others in different parts of the Strait, Marsigli correctly concluded that the surface current was fastest in the narrowest part of the Bosporus, at the Rumeli Castle, and that at that location it was one-third greater than at the southern mouth.

*The range of metric values arises from the fact that 'palms' and 'quarts' varied from city to city, and from trade to trade. Because Marsigli did not specify which ones he used, we translated all the ones that seemed likely candidates.

Marsigli did not have the means to measure the undercurrent flowing from the Sea of Marmara, but he investigated it by lowering into the water a weighted piece of wood painted white, or a simple lead weight, and noticing the direction and strength with which the rope pulled his hand as it changed depth (Figure 3). At the southern end of the Bosporus, Marsigli found the current switching direction *'... with great haste and strength at a depth of 8, 10, or 12 Turkish Paces, each Pace being approximately equivalent to the distance between the open arms of a man of average size'*. Given that an arm span is approximately equal to height, a reasonable metric guess for the Turkish Pace would be around 1.7 m, and the measured depths would correspond to 14 m, 17 m and 20 m. These figures are consistent with modern knowledge: the depth of the interface is known to vary between 10 m and 20 m at the southern mouth where Marsigli was stationed.

Marsigli's density measurements

The most important measurement that led Marsigli to understand the causes of the two-layer flow that he observed in the Bosporus was water density, or 'weight', as he describes it. Marsigli brought from home a 'hydrostatic ampoule', or hydrometer, which he acquired from one of his teachers, Geminiano Montanari. With this instrument he measured the 'weight' of water from the Adriatic and Aegean Seas, of water from several locations in the Sea of Marmara and the Black Sea, and of water retrieved from the undercurrent (see p.25). We have found no evidence that Montanari encouraged Marsigli to make those measurements, and as far as we can tell, Marsigli was at the time of departure for Istanbul unaware of the two-layer flow problem. The hydrometer is not pictured in *Observations*, but from its sketchy description, it seems to have been similar to a late design found in Marsigli's 1725 book *Histoire Physique de la Mer*. It consisted of a small, long-necked bottle weighted with enough lead shot that it could float upright, on which metal rings of known weight could be placed until it sank to a

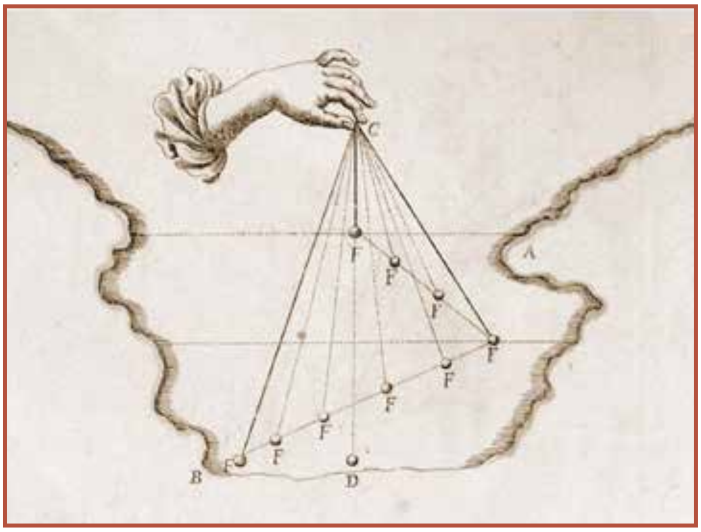


Figure 3 *This cross-sectional drawing depicts the behaviour of a tethered weight lowered through the water column from a boat anchored in the middle of the Bosporus channel. The upper horizontal line represents the sea surface and the lower one represents the interface between the two layers. As the weight passed through the interface between the two layers, it began to be dragged in the opposite direction. Marsigli correctly estimated that the depth of this boundary varied between 10 m and 20 m.*

(From Marsigli's Observations*)*

reference mark.* From Marsigli's reported weight of rainwater (42 grains†), of water off the coast of Izmir, on Turkey's Aegean coast (82.5 grains), the average value of salinity in that region (~38), and a metric conversion of 0.055 g /grain, we calculated that the bottle had a volume of about 79.1 ml, a reasonable size for that type of instrument.

Marsigli found that Black Sea water at the northern mouth of the Bosporus weighed 56.25 grains. This corresponds to a salinity of about 12.5. Such a value is not inconsistent with what is found today at that location (16.5). Marsigli managed to get a sample of water from the undercurrent: *'... with the use of a vessel, closed with a valve that I could open with a rope while submerged, I collected waters that I found weighed ten grains more than on the surface of the Canal.'* Ten grains corresponds to a salinity difference of about 8.7; this is less than the difference between the two end-member waters, so it is probable that his sample did not come from the bottom of the channel, where the salinity would be close to that of Mediterranean water. Unfortunately, no further description of the vessel is given. It would be interesting to know whether it was some *ad hoc* design, or whether it was similar to the design of Robert Hooke, who had, a couple of decades earlier, constructed a vessel for sampling subsurface water.

Marsigli made repeated observations of the water level and meteorological conditions in Istanbul and correctly concluded that tides were imperceptible in the area, and that wind and weather were instead most important in determining water height. Finally, he checked whether the Black Sea was at a higher elevation than the Sea of Marmara. He did this by taking a barometer to various locations and comparing the height of the mercury column, and found that, if anything, the Black Sea was lower than the Sea of Marmara. Of course, this seems like a useless exercise to us, as a barometer would never be able to detect such small differences in elevation above sea level amidst the meteorological variations of atmospheric pressure. In *Observations*, Marsigli made the remarkable statement that '... although I don't consider inclination important in this Canal, I report ... the relative level [of the Black Sea and Sea of Marmara] that can be read with the Mercury, or Torricellian Tube ...' . It is hard to tell whether this statement is made with the benefit of hindsight, or whether Marsigli truly thought all along that channel slope would not account for the flow.

*The weight of the water displaced by a hydrometer equals the weight of the hydrometer. Therefore the depth to which a hydrometer sinks is determined by the density of the water it is displacing.

†Grains were standard weights; the ones Marsigli used were made by the Mint in Venice.

Having established that the two-layer current flow that he observed in the Bosporus was the result of the water from the Mediterranean being significantly denser than that flowing from the Black Sea, upon his return to Italy from Istanbul Marsigli built his famous 'box' (Figure 4).

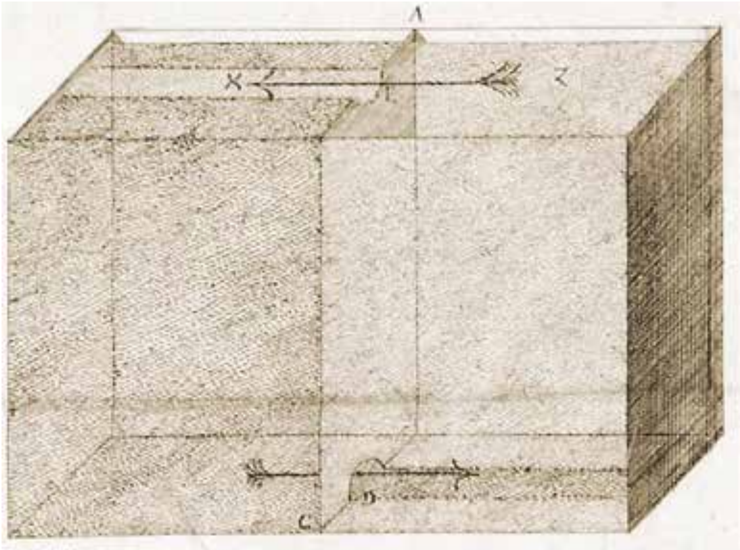


Figure 4 *Marsigli's physical model of gravity-driven, two-layer flow. The model consists of a box divided by a partition (A) with openings at top and bottom, containing water of different densities in the two compartments. Denser water (darker coloured side) flows to the opposite compartment through the bottom opening, causing lower density water (lighter coloured side) to move in the opposite direction through the top opening. (From Marsigli's* Observations*)*

He tested it in the presence of Luc'Antonio Porzio, a physician from Padua who later made his name for writing the first treatise on water purification using sand filters. Upon encouragement from (ex) Queen Christina of Sweden, whom he visited in Rome, Marsigli wrote up his Istanbul experiences and results in the compact little book that was published in Rome in 1681 and dedicated to Queen Christina (i.e. *Observations;* see p.27). The book reached the Royal Society of London in 1684, and although the two-layer flow problem had interested British scientists for some time – it was suspected that two-layer flow was occurring in places like the Strait of Gibraltar and the Skagerrack – the significance of this work went largely unnoticed.

Marsigli's background

What special attributes of Marsigli's background put him in the position to understand the causes behind two-layer flow? The evidence points to an unusually diverse education. Marsigli was born in an affluent, noble family of Bologna, and had access to good education in the form of private tutoring by local university professors. His teachers were some of the best Italian scientists of the time: the astronomer, mathematician and hydrologist Geminiano Montanari; the physician Marcello Malpighi; and the botanist Lelio Trionfetti. Though Marsigli showed considerable inclination toward mathematics and the natural sciences, he never enrolled in the university and never obtained a formal degree. There is no evidence that he ever considered an academic career. Instead, he was interested in politics and government, and ultimately he became an army officer at the service of the Habsburg Empire and remained a professional soldier, with varying degrees of fortune, for the rest of his life. The most peculiar aspect of this eccentric character is that throughout his life he remained a scientist at heart, making observations, drawing, publishing, and being a patron for science under the most extraordinary and often unfavourable circumstances.

Geminiano Montanari appears to have had the most significant influence on Marsigli's thinking on water movement. An astronomer and mathematician by training, Montanari was hired by the University of Bologna in 1664, and soon after arriving he founded the Accademia della Traccia, a scientific society that he led from 1665 until 1677. Montanari became interested in problems of hydrostatics and water movement, and with his student Guglielmini (a contemporary of Marsigli), he became a central figure in the late 1600 Italian school of hydraulics. Curiously, Montanari never formally taught this subject at the University, despite the fact that Bologna had long been confronted with water issues because of the recurrent floods of the River Reno. Montanari performed experiments on the equilibrium level and flow of fluids of different density (e.g. water and mercury) in various systems of connected vessels, and discussed the results at gatherings of his Accademia, which were held in an informal and convivial atmosphere mostly in his own home. These meetings could be attended by anybody with an interest in the discussions without distinction of social status, an unusual arrangement in those days. In the spirit of this casual organisation, detailed records of the minutes and participants were never kept, but from Montanari's correspondence, it is known that Marsigli was a frequent attendee. The conceptual ancestry of Marsigli's physical model of the Bosporus is suggested by the descriptions and drawings of some of Montanari's experiments, and by the fact that, in *Observations*, Marsigli often refers to the teachings of his mentor Montanari.

The young man from Bologna was, therefore, well equipped to tackle the two-layer flow problem: he had learned principles of hydraulics and hydrostatics from a pioneer of the field, and he had participated in experiments and demonstrations of fluid processes akin to those he would find in nature.

Serendipity

As we thought about the details of Marsigli's methods, experiments and background, we realised that in and of themselves they were not suffi cient to have led Marsigli to his conclusions about two-layer flow. The Bosporus was the other necessary ingredient. We could not think of a place other than the Bosporus where Marsigli could have fruitfully applied his knowledge. In no other place where two-layer flow is known to occur are two basins with so strikingly different water properties as the Black Sea and the Mediterranean Sea connected by such a small channel over such a small geographical area. As keen an observer as he was, it is unlikely that Marsigli would have understood the causes of two-layer flow had he not been able to observe so closely the conspicuous current pattern, and to make measurements of density in water from the two communicating basins and from the oppositely flowing layers. The causal association of the currents with the differing densities of the two layers was possible because the Bosporus represented a natural analogue to the experimental settings that Marsigli had seen. It was close enough in spatial scale and properties to allow the conceptual extrapolation.

Imagining Marsigli carrying out his observations in the Strait of Gibraltar makes this apparent. He could not have anchored a boat in the middle of the channel, and he could not have unmistakably detected a change in the flow direction with depth. Water samples clearly coming from the bottom layer would have been very difficult to retrieve. Furthermore, to realise that Mediterranean and Atlantic waters have different densities, samples of the Mediterranean would have had to be collected hundreds of miles from Gibraltar, and even then they would have been only slightly different (by hydrometer measurement) from samples from the Atlantic. This reasoning also suggests why the British did not come up with an explanation for two-layer flow despite their long-lasting concern with the currents in the Strait of Gibraltar. Although British scientists had anecdotal evidence for an undercurrent in Gibraltar similar to that available to Marsigli for the Bosporus, they could never take the next step and produce irrefutable, tangible evidence by systematic investigation. They were simply working in a setting that was inaccessible to human measurements. They could not go to the Strait of Gibraltar day in and day out and observe the undercurrent and convince themselves that it existed. When Edmond Halley satisfactorily explained the surface current in Gibraltar as the result of net evaporation in the Mediterranean, he and other British scientists had no urgency to search for a new model, in the absence of pressing evidence for an undercurrent.

In conclusion, Marsigli owes his place in oceanography to two equally important elements: his conceptual preparation toward explaining what he would eventually see, and the unique and easily accessible features of the Bosporus region. Upon close inspection, there is a third ingredient in Marsigli's success story that cannot be disregarded: a lucky twist of fate. At the time the voyage to Istanbul was scheduled to leave Venice, Marsigli was travelling in Italy: who knows if he would have had a place in the history of science had the departure of the Venetian ambassador not been delayed for personal reasons, allowing young Luigi Ferdinando Marsigli to join the party leaving for Istanbul?

Acknowledgments

We owe special thanks to Ms Roberta Doran, Head Librarian of Pell Library, Graduate School of Oceanography, University of Rhode Island, for her efforts in finding and obtaining copies of Marsigli's book and other references.

This is an abridged and slightly edited version of *The Bosporus Strait: A special place in the history of oceanography* by Bruno Soffientino and Michael E.Q. Pilson (2005), which first appeared in *Oceanography* **18**(2), 16–23.

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The title page of Marsigli's Observations


OSSERVAZIONI
INTORNO
AL
BOSFORO TRACIO
OVERO
CANALE DI CONSTANTINOPOLI
Rappresentate in Lettera
ALLA SACRA REAL MAESTA
DI
CRISTINA
REGINA DI SVEZIA
DA
LVIGI FERDINANDO
MARSILII.
In Roma, Per Nicolò Angelo Tinassi 1681.
Con Licenza de' Superiori.

A translation into English with notes may be found in: Soffientino, B. and M.E.Q. Pilson (2009) Osservazioni Intorno al Bosforo Tracio Overo Canale di Constantinopoli Rappresentate in Lettera Alla Sacra Real Maestá Cristina Regina di Svezia da Luigi Ferdinando Marsili, 1681. *Earth Science History* **28** (1), 57–83. doi: 10.17704/eshi.28.1.m24qw2611176j35w

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Michael E.Q. Pilson is Emeritus Professor of Oceanography, University of Rhode Island Graduate School of Oceanography, Narragansett, Rhode Island, USA.

Books and people on my path to the sea

Grant Bigg

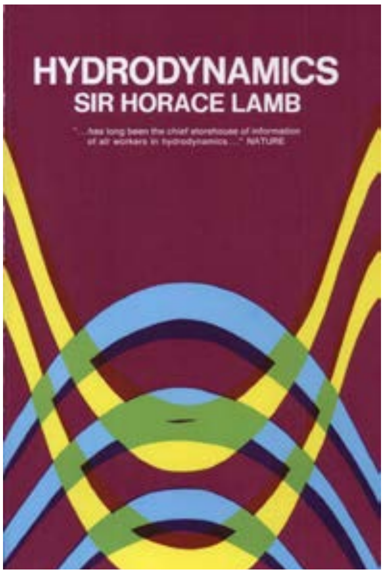
This was meant to be one of the series on 'books that inspired'. However, on thinking over my path to being an oceanographer I realised that, overall, my career has been shaped by inspiring individuals and places as much as by certain key books.

My path to the sea began subconsciously. As a young child I used to enjoy visits to my Dad's office, where, as shipping manager of a wholesale firm, he had on his wall a map of the world covered in coloured pins showing the current positions of ships bringing goods to the port of Adelaide, South Australia. Sometimes we had exciting trips to the port to see ships arriving or unloading. I first learnt the names of the world oceans in German as a global map from Hapag Lloyd covered a wall in my bedroom at home! The house was in the foothills of the Mt Lofty Ranges and from our upstairs landing window you could look across the Adelaide Plains to St Vincent Gulf, visible most days as some seven or eight miles away; on exceptionally clear days you could see across to Cape Yorke Peninsula on the other side of the Gulf. The ocean was a daily presence.

My first conscious step on the way to the sea, though, occurred in Second Year High School, when I was inspired by my Social Science (Geography for a UK audience) teacher's introduction of meteorology to set up a weather station at home. Further inspired by trips to the South Australian State Library's collection of the Royal Meteorological Society's journal *Weather* (I later fulfilled an ambition to be its editor), this pushed my journey towards a science degree at the University of Adelaide, in preparation for becoming a meteorologist. However, in the final, Honours, year of this degree I was introduced to oceanography through a combination of studying Horace Lamb's classical fluid dynamics text, ***Hydrodynamics,*** and tackling a project on modelling the ocean circulation during the Alaskan tsunami of 1963, under my supervisor, ***Ernie Tuck***.

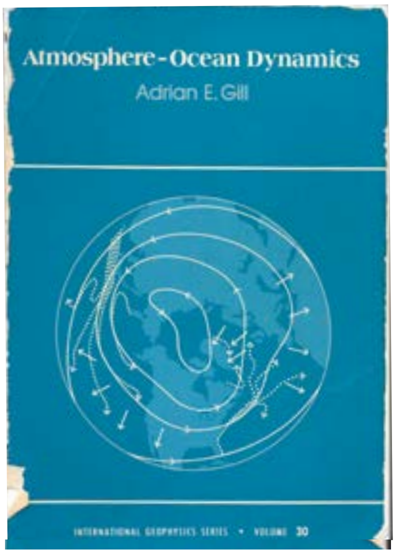
Horace Lamb was a distinguished British applied mathematician (1849–1934), who was founding Professor of Applied Mathematics at the new University of Adelaide in the 1870s and 1880s, as well as being the grandfather of the founder of the Climate Research Unit of the University of East Anglia, Hubert Lamb. *Hydrodynamics* was largely prepared during Horace's time in Adelaide, but not published until Lamb returned to Britain, and became a Professor at the University of Manchester. It is still in print today and well worth a read by an aspiring numerate oceanographer. It is a very clear exposition of the mathematics behind fluid flow, tides, viscosity and what we now refer to as 'vorticity'– a term that Lamb coined in 1916.

The inspiring combination of using mathematics and coding to study large-scale real world phenomena led me to continue oceanography with Ernie for a Ph.D, this time on modelling Helmholtz resonators in harbours. Ernie also introduced me to then new ideas about icebergs (a topic I focussed on later in my career), and helped me gain the opportunity of spending a summer in Woods Hole in the 1982 Fellowship Programme on Geophysical Fluid Dynamics.



2002 reprint of the 6th enlarged 1932 edition of Hydrodynamics*, available from Dover Books Inc. The 1st edition was published in 1892.*

The stimulation of the international exposure of the Woods Hole Summer School meant I wanted to take the next step of my career overseas, and after many job applications, I was successful. I next joined the Cambridge (later Oxford) group of another inspiring oceanographer – ***Adrian Gill***. Adrian, another Adelaidean, was well known for his book ***Atmosphere–Ocean Dynamics***, which is still a great introduction to the physics of atmosphere–ocean interaction across all scales. Adrian was not only a great mathematician but he made you think about how different geophysical fluids interacted, not just physically but beyond, and at large scale down to small. Being in his caring group, combined with my cross-disciplinary science degree exposing me to mathematics, programming, physics and chemistry, pushed me towards being an oceanographer interested in a wide range of processes and scales.

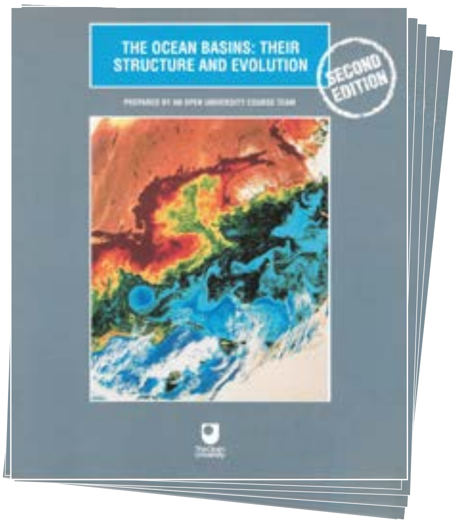


My well worn copy of Gill's Atmosphere–Ocean Dynamics *(Vol.30 in the International Geophysics Series) first published in 1982 by Elsevier Science & Technology Books and now available from Academic Press.*

This new breadth of outlook I'm sure helped me get my first permanent post at the University of East Anglia in 1987. This was the home of tackling environmental science from a range of perspectives, with the ambition to cross-fertilise between disciplines. Not only did exposure to the exciting

Tracers in the Sea*, published in 1982 by the Lamont–Doherty Geological Observatory, Columbia University. It can now be found at https://www.ldeo.columbia.edu/~broecker/Home_files/TracersInTheSea_searchable.pdf* classic *Tracers in the Sea*, by Wallace Broecker and Tsung-Hung Peng, inspire a widening of my interests into marine biology and chemistry, but **Brian Funnell** convinced me in the early 1990s that my ocean modelling skills could be turned to answer questions about the geological past, which led me to icebergs.

Brian was a marine geologist, who co-founded the School of Environmental Sciences at the University of East Anglia with Keith Clayton in the 1960s. He indirectly influenced a generation of oceanographers through his contribution, along with UEA colleagues, to the first version of the Open University course on oceanography, S334. The course that grew out of S334 – S330 – had a set of books that I found inspirational. As a tutor for S330 during the 1990s I was exposed to the real interdisciplinarity of the subject through having to teach across the intellectual breadth of its multiple volumes.



The Open University's Oceanography books for course S330, which covered all disciplines of marine science along with Law of the Sea.

Since my first foray into past oceans and icebergs almost 30 years ago, I've intellectually covered a wide range of topics and disciplines across the field of oceanography. Hopefully (!), this has also inspired some dozens of Ph.D and Masters students to think about the marine world differently …

Grant Bigg
Emeritus Professor
School of Geography and Planning
University of Sheffield
grant.bigg@sheffield.ac.uk

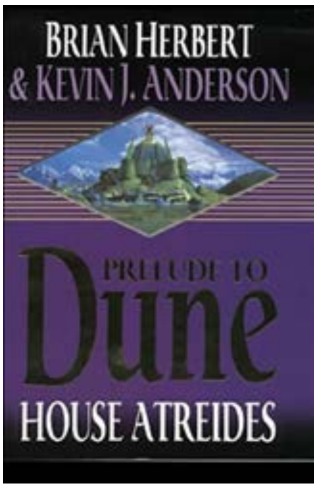
Books that have inspired us

Here is the third in a series about books that have influenced our lives as marine scientists. Do you have such a book? If so, please let us know. This time, the first inspirational book is a work of fiction – read on to find out why! *Ed.*

Prelude to Dune: House Atreides

by Brian Herbert and Kevin J. Anderson

published in 1999 by Bantam Dell Publishing Group in the US, and Hodder and Stoughton in the UK



Chosen by Dave Munday, a physical oceanographer with a special interest in eddies in the Antarctic Circumpolar Current

If you haven't read *Dune* and its sequels, beware – what follows contains some spoilers! If you have read it, I look forward to discussing it and its film adaptions with you some day.

Frank Herbert published the original *Dune* in 1965 and wrote five sequels before passing away in 1986. I first read *Dune* when I was a teenager doing my 'A' levels in the late 90s and I was fascinated by how Herbert had built up a universe in which artificially intelligent 'thinking machines' have been replaced by exploiting the human mind's computational potential, and genetic memories of past lives are the ultimate superpower. Much is left unexplained but the delightful weirdness is part of its charm.

Herbert was fascinated by ecology and deserts, with a special interest in the Oregon Dunes. The importance of the environment is an ever-present theme in *Dune*, both in its own right and in terms of human development. The role of oil as a commodity has been replaced with the use of the mysterious spice 'melange', which improves human health and extends human lifespan whilst also being used to make everything from fabric to beer. Herbert's ecological interest is perhaps focussed in the character Liet-Kynes, who has the title of Imperial Planetologist. Alas, Liet-Kynes dies tragically early in the story before we discover what an Imperial Planetologist does.

In 1999, Frank Herbert's son, Brian Herbert, and Kevin J. Anderson, both authors in their own right, published *Prelude to Dune: House Atreides*, the first of many books to follow. I read *House Atreides* soon after it was published, when I was still an oceanography undergraduate at the University of Southampton. I finally got to discover exactly what an Imperial Planetologist does because in the book we meet Pardot Kynes, father of the tragic Liet-Kynes, and his predecessor as Imperial Planetologist. Pardot Kynes is an ecologist, geologist, meteorologist, botanist and microbiologist, who wants to understand and transform Dune via large-scale climatic change to make the planet more hospitable; the opposite of humanity's on-going climate experiment with carbon dioxide. He designs an entire ecosystem from the ground up and introduces new species of plant life and animals, with the intention of stabilising the ever-shifting sand and controlling Dune's water cycle. At some point while reading how Kynes is busy analysing seemingly everything about his planet, I found myself thinking 'I want to do that!'

I studied meteorology (useful on Dune) as a Master's student and returned to oceanography (not so useful) for my Ph.D. Since then, I've come to appreciate that no single person could truly master all the disciplines that Pardot Kynes is an expert in. More than that, I've seen how entire teams of scientists must work together to understand even a small part of our planet's climate system. These teams are made up of specialists from many disciplines, rather than a lone genius with mastery of all.

I can't say for sure whether I might have chosen a different academic discipline, or even foregone postgraduate study, had I not read *House Atreides*. But it had an impact and that's why, instead of the original (which won both the Hugo and the Nebula Award), I've chosen the sometimes maligned, possibly inferior, prequel, as the book that inspired me as a scientist.

An Account of the Arctic Regions With a History and Description of the Northern Whale-Fishery

by William Scoresby

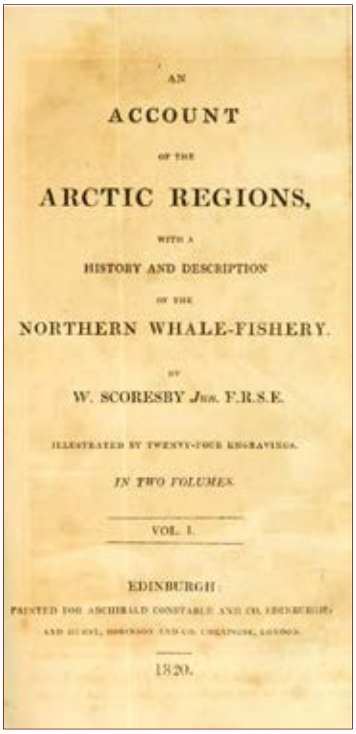
published in 1820 by Jr. Archibald Constable and Co., and reprinted frequently

along with

The Arctic Whaling Journals of William Scoresby the Younger: Volume I, The Voyages of 1811, 1812, and 1813

edited by C. Ian Jackson

published in 2003 by the Hakluyt Society



AN
ACCOUNT
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ARCTIC REGIONS,
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OF THE
NORTHERN WHALE-FISHERY.
BY
W. SCORESBY Jun. F.R.S.E.
ILLUSTRATED BY TWENTY-FOUR ENGRAVINGS.
IN TWO VOLUMES.
VOL. I.
EDINBURGH:
PRINTED FOR ARCHIBALD CONSTABLE AND CO. EDINBURGH;
AND HURST, ROBINSON AND CO. CHEAPSIDE, LONDON.
1820.

Chosen by Bob Deal, a historian specialising in early American legal history

My contribution to these pages might seem rather surprising given my personal history and academic training. Born and raised in the American Midwest in close proximity to the Missouri and Mississippi rivers, my first encounter with the ocean was not an altogether happy experience. A day fishing excursion with my father and brother in 1966 off the coast of Miami resulted in a single fish being hooked which while still flopping on deck received the regurgitated remains of the breakfast consumed by the boy who caught it (not me). What might be most charitably termed an indifference to the sea was born that day. That indifference endured through my undergraduate years as an art history major, and then my time at law school and that spent working as a lawyer. When I returned to university in my mid-forties to earn a Ph.D in early American history, I asked my advisor Drew Isenberg to suggest a dissertation topic. His single word response of 'whales' struck me a bit like the career advice of 'plastics' that Dustin Hoffman's character in *The Graduate* receives from a well meaning family friend, but I decided to give it a try. What resulted was a dissertation and then a book on how whalemen in the 18th and 19th centuries created an informal legal order that allowed them to peacefully resolve property disputes at sea by use of customs and norms of their own design.

It was while researching this topic that I came across a reference to an 1812 dispute over a bowhead whale near Spitsbergen between competing captains who just happened to be father and son. Fortunately for me, the dispute was referenced by the younger man, William Scoresby Jr, in his journal of that voyage, and that journal had been published by the Hakluyt Society with the invaluable editorial notes of C. Ian Jackson. Jackson's introductory essay helped me to understand the logistics of early 19th century bowhead whaling, but it was Scoresby's descriptions of the water and ice encountered prior to the dispute that fundamentally changed how I looked at the story I was trying to tell. The ocean was not just a sort of neutral background to my legal story about how a close-knit community of people managed to resolve legal disputes without violence or even frequent resort to litigation. It was, instead, a major player in the story. Every aspect of Scoresby's dispute with his father, and all other similar arguments, were shaped by the water and how it moved, its temperature, and where and what variety of ice was encountered.

I quickly discovered that Scoresby had extensively studied, pondered on, and written about the waters in which he worked and this inevitably led me to his two-volume *An Account of the Arctic Regions with a History and Description of the Northern Whale-Fishery*, published in 1820. While I knew that in order to better understand Scoresby's dispute with his father I needed to pay attention to what he wrote in Vol. 1 about the Greenland Sea, I was not prepared for how much I enjoyed reading his detailed descriptions of the environment. It was all quite thrilling and surprising for someone whose last encounter with science education had decades earlier ended rather poorly. I decided that it might be possible to understand the mechanics of the ocean and its currents as Scoresby understood them, which is obviously not how the readers of this publication understand them. I figured that if a grasp of 21st century oceanography was way beyond my powers of comprehension, that of the early 19th century might be possible, even for a math-intolerant rank amateur science autodidact such as myself. Whether I ever achieved this is open to debate, but what is certain is that Scoresby's descriptive prose meant that, led by him, I enjoyed every step of the journey to remarkable places I will never experience in the flesh. But then I suppose that historians always spend their days in fascinating places just beyond their reach.

Frontispiece of An Account of the Arctic Regions*: Representation of the ship* Esk*, of Whitby, damaged by ice and almost full of water. (Drawn by R.K. Greville after a sketch by Scoresby)*

Book reviews

How to design a marine nature reserve

Spring Tides: Exploring marine life on the Isle of Man by Fiona Gell (2022) Weidenfeld and Nicolson (W&N), 288pp. £16.99 (hard cover, ISBN: 978-1-474-62185-4); £9.99 (paperback, published 2023, ISBN: 978-1-474-62186-1). Also available as an ebook.

I picked up this book from the Manx Museum whilst on holiday on the Isle of Man. I'm incapable of walking past an ocean-themed book with a beautiful cover without buying it, and this book ticked both boxes.

Spring Tides follows Fiona Gell's career journey, beginning as a marine biologist focussing on seagrass, transitioning to marine conservation, particularly around the Isle of Man, and then working on climate change policy for the island. Fiona takes the reader on an inspiring exploration of the fauna and flora around the beaches and coastal waters of the Isle of Man whilst describing the journey towards getting the island's first Marine Nature Reserve designated.* We learn about eelgrass, maerl, scallops, dog whelk, mussels, eels and much, much more. The book is accessible to all, not just those with a marine science degree, and has vivid descriptions and many images of key species (sadly only in black and white).

I gained a real appreciation of the importance and necessity of high-resolution habitat mapping in coastal waters in order not only to design conservation zones, but also to fully consider different stakeholders' needs, wants and perspectives. The book outlines key milestones in the island's journey of marine conservation which Fiona spearheaded, and highlights the importance of extensive stakeholder engagement with the local fishing community as a crucial factor in the progress that has been made, especially allowing the fishers ownership and agency in data-collection and management of the fishing zones.

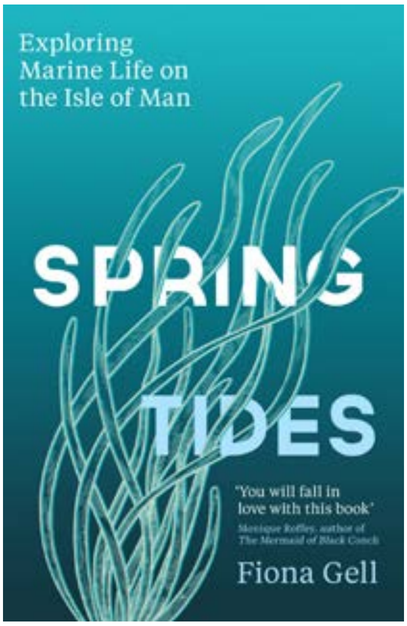
One particular story that stuck with me highlighted the need for natural and social scientists to work together. During the designing of a new no-take conservation zone, local anglers were concerned as the proposed area included their main bait-digging spots. The black lugworm is their preferred bait and whilst there are other sites around the island where black lugworms are found, this is the only one with a car park nearby – a great example of how accessibility and convenience can shape human interactions with the environment!

*There are now eleven marine reserves around the Isle of Man.

The story of how the Isle of Man's first marine reserve came into being is told from a very personal perspective – not just through Fiona's career journey, but also her personal journey. There are charming anecdotes, stories and personal reflections that perfectly capture how a scientist's career path can be shaped, influenced and driven by their personal circumstances. For Fiona, these included returning home to the Isle of Man after studying abroad to be closer to family, becoming a mother, and experiencing loss and grief – it is a poignant narrative in which everyone could find something to relate to.

This is a relaxing, interesting and delightful read, with a good dose of humour as well. It was the last book I read over the Christmas break in 2023 and it left me feeling hopeful for the future of marine conservation and more convinced than ever that natural and social scientists must work closely together in order to protect marine habitats for the benefit of marine ecosystems and wider society.

Chelsey Baker
National Oceanography Centre
Southampton



A walk through our polluted planet case study by case study

Polluted Earth: The science of the Earth's environment by Alexander Gates (2023) Wiley, 379pp. £76.50 (paperback, ISBN: 978-1-119-86252-9). Also available as an ebook.

Environmental pollution is undoubtedly a complex and multifaceted issue, which stems from a multitude of coalescing factors, and results in harm to the environment, economies and society. To effectively understand and overcome pollution therefore requires an integrated approach to these components which Gates has incorporated throughout the book, and I find to be a refreshing perspective.

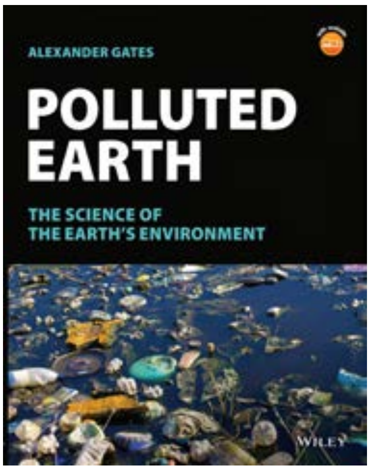
Aimed at undergraduate students, *Polluted Earth* takes a new approach to introducing readers to environmental pollution through a plethora of highly illustrated case studies. From the opening section, Gates encourages readers to think deeply, taking an almost philosophical approach to consideration of environmental pollution, and stimulating discussion and independent thought by posing questions such as 'Is climate change really that bad?'.

Polluted Earth promises to combine 'the best features of a textbook and a popular science book' and in some ways, it achieves this. The book is clearly a scientific textbook, but its organisation into discursive case studies does indeed give it a popular science book feel. The book is rich in figures, including illustrative diagrams, photographs and maps, which support the key themes in an engaging way. Additionally, the layout of the book facilitates dipping in and out, so readers won't feel obliged to read each section in its entirety. This makes the book feel more 'manageable'; however the very short sections and case studies don't give enough of the fundamentals to enable readers to fully comprehend each overarching topic, and in many instances, I am left wanting more.

Perhaps as a way of keeping the popular science book feel, citations of primary literature are generally not included, and the recommended resources on the associated website are mostly online videos. I felt this was an oversight, and that key supporting references for the pollution events referred to would have really elevated the scientific content and signposted readers to further information.

The range of topics considered is extensive: natural and anthropogenic pollutants across atmospheric, aquatic and terrestrial domains, organised by environment (e.g. pollution of groundwater), and by theme (e.g. nuclear energy). There is also a handy A-Z list of pollutants, giving readers the opportunity to, at a glance, gain an overview of the mechanisms and effects of various pollutants. That being said, the sheer quantity of topics covered means that none can be covered in much detail, and readers purchasing this book specifically for its marine content may be disappointed as this is rather limited. There is one chapter (17 pages) dedicated to 'Ocean Pollution', which encompasses fundamentals in ocean processes (e.g. tides), and a few case studies considering oil pollution and the dumping of waste at sea. Major sources of ocean pollution, e.g. sewage discharge, agricultural runoff, the sinking of vessels, plastic pollution and harmful algal blooms, are illustrated in a figure but no details are provided on the mechanisms by which they cause impacts or what the effects or scale of such events could be. Again, I am left with more questions than answers. One can find some discussion of other marine pollutants, but these references are isolated and contained within other chapters; for example, the eutrophication of oceans by fertiliser runoff is mentioned in the 'Agricultural Chemicals' chapter. Readers may not be inclined to scour all chapters to access this marine content.

On balance, I must conclude by saying that *Polluted Earth* takes a refreshing approach: the sheer wealth of case studies really does set it apart, as do the links it makes with social and economic dimensions. However, its content feels a little basic especially when evaluated against that in books of a similar price on the market, and it is perhaps designed for younger readers or those without a scientific background. In the context of marine pollution specifically, this is probably not the book for you, but if you seek to gain a broad understanding of a range of pollutants across diverse ecosystems (atmospheric, terrestrial and aquatic) then *Polluted Earth* would make an easily accessible accompaniment to other textbooks.



Winnie Courtene-Jones
University of Plymouth

Sharks and sea mammals in their glorious variety

Sea Mammals: The past and present lives of our oceans' cornerstone species by Annalisa Berta (2023) 224pp. £25 (hard cover, ISBN: 978-0-691-23664-3).

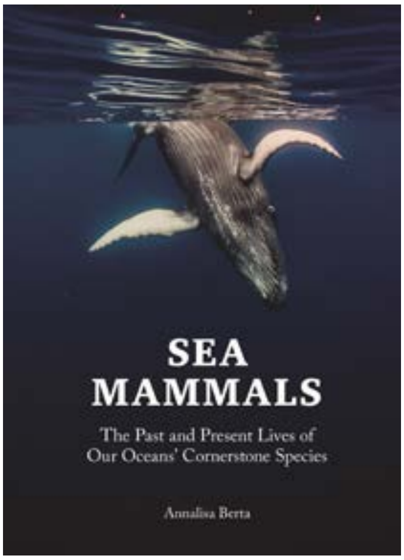
The Lives of Sharks: A natural history of shark life by Daniel C. Abel and R. Dean Grubbs (2023) 228pp. £30 (hard cover, ISBN: 978-0-691-24431-0).

Both books are in the Princeton University Press 'The Lives of the Natural World' Series.

Sea Mammals

In a former existence as a museum curator, I had the fascinating though somewhat odoriferous pleasures of retrieving a few cetaceans from beaches in Devon, to render them down to obtain their skeletons for museum collections – I was not the most popular member of staff during the long cooking and degreasing processes, but I learned more than most about these denizens of the marine world.

As anyone who has an interest in sea mammals will know, much has been written about these enigmatic creatures, so is there room on the bookshelf for yet another book? If that book is *Sea Mammals – the past and present lives of our oceans' cornerstone species*, the answer is 'Yes'! Annalisa Berta, Professor Emerita at San Diego State University, hasn't written just another catalogue of the world's species of sea mammals but rather uses her background as a specialist in anatomy and evolutionary biology of marine mammals to consider the diversity of marine mammals – which include whales, dolphins, seals and sea lions, walruses, polar bears, manatees and sea otters – in various contexts. Following a short introduction which provides a summary of the entire 'group', she goes on through five sections to unravel the Evolution, Discovery, Biology, Behaviour and Ecology and Conservation of more than 50 species, living and extinct. Her selection of species of living and fossil sea mammals was chosen to demonstrate the similarities between species and those evolution-driven features that set them apart from each other and from their terrestrial forbears.

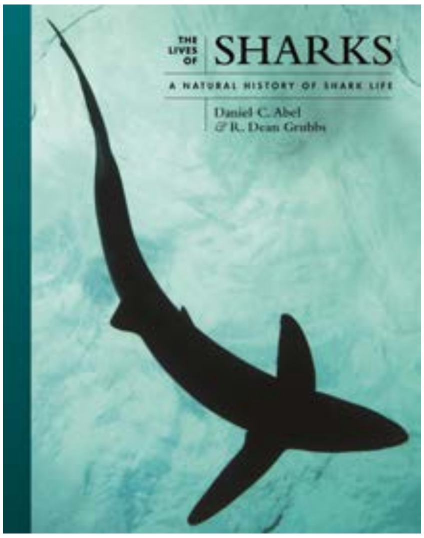


Within the 211 pages are many species that are familiar thanks to blockbuster TV programmes, from the mighty blue whale, getting on for 30 m long and weighing in at close to 150 tonnes and the largest animal to have lived on this planet, to the tiny vaquita at a mere 1.5 m in length and around 6–8 kg in weight. These are animals of differing fortunes: the blue whale was hunted to near extinction with only 0.1% of the previous population being left in the Southern Ocean but thanks to protective measures has made a dramatic recovery, only to face new threats from climate change and overfishing which together result in declines of the whale's favoured food of krill. The vaquita, Berta tells us, now has 'the unfortunate distinction of being the most endangered of the world's sea mammals'. Discovered as recently as 1958, it has declined by 99% since 2011 and there are now thought to be only around a dozen left alive.

Often the sea mammals we see today represent a vestige of what used to be; *Sea Mammals* fills the gaps around our present-day snapshot, to repopulate the ocean with precursors and side shoots, now extinct. Meet the tuskless walrus, the tusked walrus-like whale, the walking whale, the weird oyster bear, and the 2.5 m aquatic sloth. Written in a journalistic style, accessible and to-the-point, with numerous high quality images and accompanying maps and diagrams, this book is the ideal primer for the non-academic interested in sea mammals, and even for those who know a lot it is the perfect summary of those mammals that have populated our ocean – past and present.

The Lives of Sharks

I've swum, quite by accident, with a mako shark in the Mediterranean, and floated above a circling school of scalloped hammerhead in the Galápagos, where it's easy, even when snorkelling, to spot a handful of species in just an hour or so. But my first ever shark was a lesser spotted dogfish, swimming below our hired rowing boat off the Scottish coast when I was about 7 years old; decades later, my second encounter was with three giant basking sharks cruising for plankton in Plymouth Sound. I'm an enthusiast but not a shark-twitcher, and I don't dive, so I think I have been lucky to see around 10 species in their natural habitats; according to *The Lives of Sharks* another 533 species have so far eluded me. What is obvious is that unless you dedicate your life to ticking sharks off the list, they are hard to spot. The typical image of a shark is of a streamlined, fast, ruthless predator, but between the smallest sharks, like the pygmy shark at 15 cm, and the mighty whale shark at 18 m, there are hundreds of species each perfectly adapted to its way of life and favoured habitat.



The Lives of Sharks successfully introduces this amazing variety in four habitat-linked chapters: Open Ocean, Deep Sea, Estuaries and Rivers, and Continental Shelves; preceded by sections on Evolution and Diversity, Adaptations, and Ecology, culminating in the inevitable but necessary look at the relationships between Sharks and Us. Within these pages we meet all of the usual suspects, but also gain tantalising glimpses of the weird and wonderful. I especially like the cookie cutter shark which challenged the US Navy by biting cookie-sized chunks out of rubber-coated sonar domes on nuclear submarines, mistaking them as a food source. When we think of the predators our minds stray to great white, tiger and bull sharks but the world's second largest predatory shark, at around 8 m in length, is the sluggish, seldom-seen Greenland shark, which despite its name can be found almost from the Equator to the Arctic, if the water remains at about 4 °C. The Greenland shark, blinded by parasitic copepods on its eyes, is one of the longest-lived sharks, capable of attaining an age of 272 years or more – it's sobering to think that there are sharks in the deep, cold ocean that were in their twenties when the US declared its independence in 1776.

The authors, Daniel C. Abel and R. Dean Grubbs, are respected names in shark research, and they have distilled many years of research into 228 amazing pages. Every one of those pages has a story, and with its beautiful photographs and clear text the book is a must for anyone even vaguely interested in sharks or the ocean. This is a book for the desk not the shelf; each random dip inside will reveal a fascinating *'did you know'* nugget – it will be a long-lived reference for amateur and expert alike.

Kelvin Boot
Freelance Science Communicator
Exeter

A timely exploration of algae

The Lives of Seaweeds: A natural history of our planet's seaweeds and other algae by Julie A. Phillips (2023) Princeton University Press, 288pp. £30 (hard cover, ISBN: 978-0-691-22855-6). An ebook is also available.

There is currently a wave of interest in algae in the marine environment, in connection with blue carbon, and harvesting and farming for food and for chemical products. Yet many marine scientists and regulators may have only the most superficial knowledge of this group of plant-like organisms. *The Lives of Seaweeds* can address that lack of knowledge. Appropriately the author, while very knowledgeable about algae, is an environmental consultant in marine ecosystem health and so knows how to bridge the gap between algal specialists and general environmental scientists or marine biologists.

Seaweeds are macroscopic marine algae but are not the only algae in the sea. While the book is mainly on seaweeds it does digress considerably into all the other algal groups in the sea and other habitats, such as diatoms and dinoflagellates. It is lavishly illustrated with high quality, large colour plates which make it a pleasurable book to scan through. Many of these are pictures of seaweeds and other algae – over 40 species in all – both macroscopic and under the microscope, but there are also well drawn explanatory diagrams.

The book begins by explaining what algae and seaweeds are and what distinguishes them from the other major kingdoms of organisms. The fascinating origin of algae 3.5 billion years ago is covered, with the evolution of procaryotic and eucaryotic cells and the period of dominance of cyanobacteria, previously known as the blue–green algae. The diversity of the evolutionary lines of algae is covered. The seaweeds are a small part of the overall algal story but one which dominates in that they are the algae that most people can see, and some are very large, for example the giant kelp, *Macrocystis pyrifera*.

The book then describes in simple terms, but in a scientifically full and correct way, with excellent illustrations, many aspects of the world of seaweeds and other algae, covering the great range of diversity in form from single-celled organisms, through colonial forms and many types of filamentous and leaf-like forms, to the giants of the algal world in the kelp forests. Much of the book surveys in simple, well-illustrated language all the range of things we need to know about algal biology, such as growth patterns, cell types, life-cycles and their different generations, reproductive methods and resistant stages.

Following this overview of the algae the book devotes about 120 pages to two main topic areas, ecology and the importance of algae to human societies. In these areas algae as a whole are considered although the emphasis is most strongly on seaweeds. The section on ecology introduces the great diversity of algal habitats on land, in the sea and in freshwater and then goes on to a more detailed treatment of marine habitats

with emphasis on seaweeds. This includes mudflats, rocky shores, kelp and fucoid forests and the deeper sea, and covers special topics such as the Sargasso Sea, bioluminescence, algal blooms and climate change.

In considering the importance of algae to humans there is a general review of algal roles in marine chemical cycles, especially the carbon cycle. Then the book considers humanity's use of seaweeds for food, phycocolloids, pharmaceutical products and biofuels. Important to all these is the consideration of seaweed aquaculture which is currently resurfacing in Britain. Toxic algae are also introduced.

The book ends with a useful table of the distinguishing features of all the major algal groups followed by a glossary of algal terms.

This book is a very well produced and well structured overview of what algae, especially seaweeds, are, how they live, what they are like and how important they are. It is ideal as a reference to non-algologists who want to learn more about the scientific and social importance of seaweeds. The colour illustrations are excellent for showing the great range of algal diversity and the forms of important seaweeds. The book is not a guide to use for identification of species collected on the seashore, but it provides all the background you might need to know about seaweeds, not covered in such guides.

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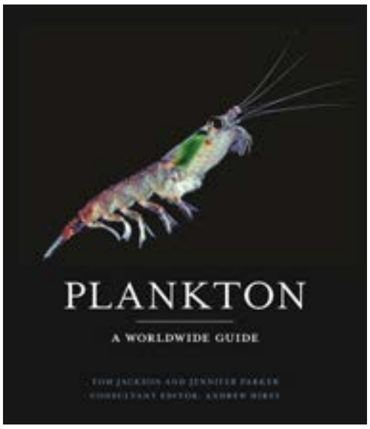
Sharing a passion for the small but mighty

Plankton: A worldwide guide by Tom Jackson and Jennifer Parker, edited by Andrew Hirst (2024) Princeton University Press, 224pp. £25 (hardback, ISBN: 978-0-691-25599-6) £17.50. An ebook is also available.



This book introduces the reader to the mesmerising world of plankton, including both marine and freshwater species. It explains how and why plankton are essential to life on our planet, details scientific concepts such as trophic exchange and the carbon cycle, and provides plentiful examples of planktonic species which may be encountered from polar waters to the tropics.

The contents are nicely laid out with an even balance between text and illustrations, which is very pleasing to the eye and makes for an enjoyable read. There are many beautiful photos of plankton from a range of phyla, which the authors have clearly gone to great effort to engage the audience with.

The first chapter introduces the reader to the wonderful diversity of life that can be found in the plankton and explains the difference between prokaryotes and eukaryotes, before going on to give examples of single-celled organisms such as protozoans, and multicellular life such as jellyfish, crustaceans and echinoderms. This chapter also mentions the often overlooked categories of mycoplankton (fungi) and viroplankton (viruses). The chapter concludes by spotlighting a number of species, with information on each organism thoughtfully paired with a representative photo (examples include Antarctic krill, a rotifer and the highly abundant coccolithophore *Emiliania huxleyi).*

Chapter 2 discusses fascinating 'lifestyles and adaptations', vertical depth zones in the ocean, ocean currents, nutrients and bioluminescence. At the end of the chapter is a section looking at specific organisms, with quality images; examples include the dinoflagellate *Ornithocercus*, cyanobacteria and various gelatinous species.

Chapter 3 is concerned with how plankton feed and reproduce. Here, phytoplankton are discussed, followed by the zooplankton grazers and predators; also mentioned are the curious in-betweeners, the mixotrophs. Concepts related to energy exchange, trophic interactions and the carbon cycle are well illustrated in this section. Descriptions and stunning photos of plankton are again found at the end of the chapter, and include diatoms, radiolarians and sunfish.

Chapter 4 introduces the concept of latitudinal diversity gradients and migration patterns found in the plankton. The subject of aeroplankton – that's right, plankton found in the air – is also included here, together with a page on freshwater plankton. Chapter 5 considers how plankton sustain life in our oceans and ultimately provide us humans with food. The carbon cycle is again mentioned, together with the importance of the microbial loop, plankton in fisheries, and algal blooms. End-of-chapter highlights include diatoms and crustaceans. Chapter 6 moves on to the important subject of the future of our planet and how this may affect plankton. Climate change, ocean acidification, pollution and mineral extraction are covered here, together with the importance of long-term monitoring.

The book does a good job of discussing many important topics and showcases many planktonic species, but it is not without fault. Sadly, it does contain some errors: for example on p.46 it suggests that all dinoflagellates are photosynthetic, but this is not the case; p.66 states that copepods jump by using appendages on the head – this again is inaccurate. OK, so these details might not be of much consequence to a general reader, but on p.114, when discussing the toxic alga *Pseudo-nitzschia*, it dangerously states that 'cooking shellfish to ... 65 °C will destroy the toxin'. Let me stress, domic acid from *Pseudo-nitzschia* cannot be destroyed by heat.

I enjoyed looking at the book, and those I've shown it to have commented how pleasing and easy to read it is. It is well laid out, showcases the extraordinary beauty and diversity of planktonic organisms, and covers the subject comprehensively. The authors are not plankton experts, so perhaps inevitably some of the details are off the mark. Despite this, I have learnt things from reading the book. I see it as a mix between an academic textbook and coffee table book, and would recommend it to an enthusiast in marine biology in general.

Marianne Wootton
Marine Biological Association
Plymouth

The Life and Works of Ernest W.L. Holt 1864–1922: context, connectedness and content

Noël P. Wilkins,

Ernest W. L. Holt was one of the founders of the Challenger Society and the first exponent of the discipline of Fishery Science in the UK. This book, now in press, is expected in January 2025 in a very limited print run.

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