OCEAN Challenge

The Challenger Society for Marine Science

The ocean in the Anthropocene • Monitoring the seas by buoy, ASV, glider, float and satellite • The spirit of *Challenger* lives on • Why the eastern Med is different

Vol. 21, No.1

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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.

Ocean Challenge is sent automatically to members of the Challenger Society. 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 Challenger Society for Marine Science

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

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

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

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

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

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

Holding regular scientific meetings covering all aspects of marine science.

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

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

Membership provides the following benefits:

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

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

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

MEMBERSHIP SUBSCRIPTIONS

The subscription for 2015 costs £40 (£20.00 for students in the UK only). If you would like to join the Society or obtain further information, see the website (given 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. If at all possible, they should be well illustrated. Copy may be sent electronically.

For further information (including our 'Information for Authors') please contact the Editor:

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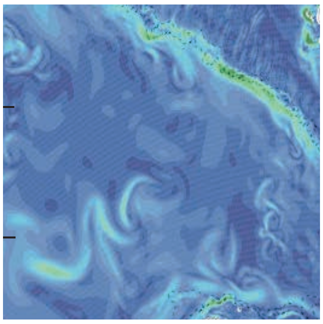

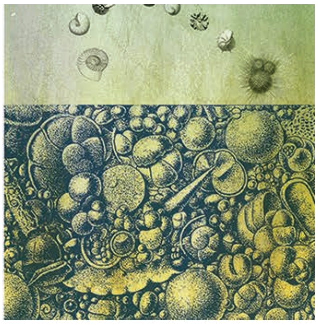

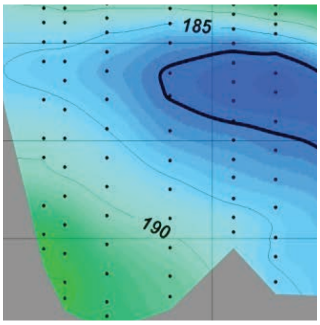

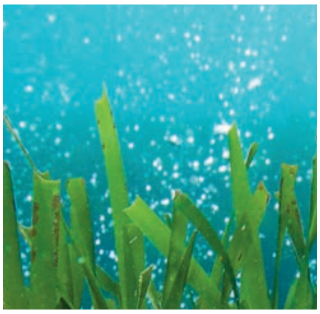

Most of the maps and diagrams were drawn by The ArtWorks.

Cover and heading graphics designed by Ann Aldred.

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Message from the President of the Challenger Society

Challenger Society Conferences

For many of us, the biennial Challenger Conference is an important event. The conferences have run very successfully since the 1980s and over that time have rotated around important centres of marine science in the UK. Until now the conferences have been hosted in Bangor, Southampton, UEA, Plymouth, Liverpool and various venues in Scotland. The locations and running of these conferences have always depended on willing volunteers locally and more widely in the Society, and we are grateful to all of them.

Marine science in the UK is not confined to the centres above and the Challenger Council were therefore very pleased to receive a proposal from Newcastle University to host a future Challenger Conference. Council have accepted this offer and, having consulted relevant host institutions, taken the slightly unusual step of now scheduling not just the next Challenger Conference (Liverpool 2016, further details opposite) but also the following two – 2018 in Newcastle and the one after that in Scotland.

This note is to alert all members to these plans, and also to invite any other institutions interested in hosting the conference to contact us. Inevitably, with a biennial conference, the inclusion of new venues will be a slow process, but the process is open to all.

Tim Jickells
President, for Challenger Council

(this alert appeared in Challenger Wave *earlier this year)*

Message from the Editor

In this issue, there are many echoes from the days of *Challenger*, which is particularly appropriate now that plans for the next Challenger Conference are underway. If you have never been to a Challenger Conference, do take the time to read the winning report on the 2014 event, overleaf.

Unusually, two pieces in this issue relate to the creative interface between science and art. On a less positive note, another theme is the worrying state of the ocean in what many are now calling the Anthropocene. This topic arises in various news items, and is the background to Jason Hall-Spencer's feature article 'Ocean acidification in a changing world'. The other feature article, by Mike Krom and Yair Suari, deals with the unusual nutrient cycling in the Eastern Mediterranean Sea, so bringing up to date Mike's article published in an early Volume of *Ocean Challenge*.

Liverpool Challenger Conference

The 17th biennial Challenger Conference will be held in Liverpool on 5–9 September 2016, hosted jointly by the National Oceanography Centre, the University of Liverpool and Liverpool John Moores University.

In a slight change of format from previous years' conferences, talks and posters will be presented on Tuesday to Thursday, allowing days either side to host special interest meetings, outreach opportunities and early career/student events. A call for sessions is expected in October 2015, so marine scientists and technologists are encouraged to start discussing ideas with colleagues over the summer months. Requests from special interest groups that wish to take advantage of the free facilities made available during the conference for 'town hall' meetings can contact the conference chair Matthew Palmer directly (matthew.palmer@noc.ac.uk). Industry sponsors and exhibitors are welcome and are asked to contact our industry liaison coordinator Terry Sloane (terry@planet-ocean.co.uk) or the Chair to discuss. The local organising committee expect to have the website active by September when details will start becoming available prior to the call for sessions.

Matthew Palmer
Conference Chair: Challenger Society Conference Liverpool 2016

Challenger Society Updates

As this is the first *Ocean Challenge* since the 2014 conference, it seems appropriate to record here the awards and prizes presented at that event (previously announced in *Challenger Wave*) – not least to inspire those of you who would like to carry off a prize in 2016.

Challenger fellowships are awarded to early-career scientists for their achievement or promise. In 2014 fellowships were presented to Will Homoky (University of Oxford) and Mark Moore (NOC).

The Norman Heaps Prize for the best early-career talk was won by Mike Blackett (University of Southampton and SAHFOS), for his presentation on 'Long-term variability of the calycophoran siphonophores *Muggiaea atlantica* and *M. kochi* in the Western English Channel'.

The Cath Allen prize for the best poster by a student/early career scientist was won by Eleanor Jameson (University of Warwick), for 'Data-mining bacterial pathways of TMA production'.

The IMarREST prize for the best poster on operational oceanography was won by Hemanaden Runghen (Mauritius Oceanography Institute) for 'Managing geophysical data in the South West Indian Ocean using GeoMapApp'. The MBA prize – a special award in 2014, when the conference was in Plymouth – was won by Natalie Wager (UEA) for her poster 'Distribution of sea surface nitrous oxide and methane in the Atlantic Ocean'. The winner of the Tripartite Award (a prize given jointly by IMarEST, the SUT and the Challenger Society) was Christine McKenna (University of St Andrews). Her dissertation title was 'A reconstruction of water mass distributions in the Faeroe–Shetland Channel using Parametric Optimum Multi-Parameter analysis'.

The winner of the President's Photographic Competion was Rob Cook, whose striking image of a diver collecting maerl can be seen on the cover of this issue. (The diver in the photo is Rebecca Grieve, a Ph.D student at Heriot–Watt.)

Challenger Conferences aim to have an interactive session on a topical issue. For the 2014 Conference, the session addressed the question: 'Marine research priorities: do the public and scientists agree?' The outcomes of the session are discussed in 'Public perceptions of the marine environment' on pp.10–12 of this issue.

Communicating Science in Plymouth

A young delegate recalls Challenger 2014 in her home town

Hayley Evers-KIng

My journey to becoming a marine scientist began in Plymouth. Despite being born in the city, I had never really had a strong connection to the marine environment and, to be brutally honest, I was probably guilty of never really embracing all that the city had to offer whilst I studied for my undergraduate degree (Environmental Science). However, Plymouth was the place where I was introduced to oceanography. At Plymouth University I first learned about the role our oceans have in the global Earth System, and (still not keen to get my toes wet) became fascinated by how we could use models and satellites to investigate them. This set me on a journey – leaving Plymouth for Southampton and eventually spending four years in South Africa conducting my Ph.D research. It was with great joy that I managed to bring my journey full circle, and present my research at the 2014 Challenger conference, held in my home city.

Coming from a broad natural science background, I was impressed by the vast diversity of research topics covered by delegates who presented at Challenger. Many presenters moved seamlessly between the physical, chemical and biological aspects of oceanography, integrating tools from the *in situ*, satellite and modelling realms. The need for this interdisciplinary diversity was highlighted in several of the keynote talks, with Professor Icarus Allen of Plymouth Marine Laboratory suggesting a focus on 'back-of-the-envelope' thinking, and bringing in outside perspectives, and Professor Nick Owens reiterating the classic maxim that 'all observationalists should model, and all modellers should make observations'. This provided much validation for me, as I often feel like a 'jack of all trades' with my research approach involving *in situ*, modelling and satellite-based optical techniques.

How we communicate our science was an issue that popped up again and again at Challenger. I was pleased to finally attend a conference with a lively Twitter hashtag, after seeing the value of this through following a number of conferences I hadn't been able to attend. The hashtag provided a great way for me to network with fellow researchers – I gained 54 new followers during the conference! It was also a chance for me to share research between the two countries I currently split my life between – the UK and South Africa. Chatting with the UK consulate in Cape Town via Twitter allowed me to keep up to date with the consulate's Science and Innovation meeting whilst sharing with them examples of marine modelling of South African waters presented by UK collaborators at Challenger.

A lot of attention was given to communication of science with regards to policy during Challenger – through both a policy session and an evening lecture by DEFRA chief scientist, Professor Ian Boyd. Despite overheard comments prior to the policy session, I think by the time it was finished, most of us were convinced that almost all marine research has something to contribute to policy. I guess my work is a prime example – I've mostly worked on the technical and theoretical aspects of ocean colour data, and within 5 minutes of the first talk, the speaker had highlighted an area where the sort of research I do could help improve decision-making about offshore energy!

Whilst we like to think of science as evidence-based, the reality is that both scientists and other stakeholders can have different personal values. In the interactive session from PEGASEAS (see pp.10–12) – where we were asked to vote on which marine issues we considered important – I noticed that, possibly as a result of a few years in South Africa, my priorities were different from those of the majority in the room (I seem to rate economic stability and job creation more highly than most). The question of values was raised again by Professor Ian Boyd who questioned whether scientists should lobby on issues that often come down to political decisions. Like Ian, I feel that it's important to have a degree of separation between my science and my values, so that those who don't share my values will hopefully still trust my science. But not everyone agreed with me, and this topic was debated thoroughly amongst delegates during a number of the social events, and I'm not sure we really reached a consensus!

Beyond the exceptional science and intriguing discussions on the wider reach of research, Challenger also provided me with the opportunity to reconnect with my home country, my home town and their associated research communities. I mentioned previously that I credit Plymouth with being the catalyst for my career in marine science. This was largely down to the mentorship that I received from academics in Plymouth University, and subsequently from staff at the universities of Southampton and Cape Town. It was great to catch up with supervisors and tutors at Challenger, but it was also an opportunity to meet new mentors and to learn how, as I move on from the position of student, I can be a good mentor to others.

The array of social events organised as part of the conference provided a great way for everyone to get together. In between my Ph.D and the next part of my career, I have plenty of questions and concerns about what I should do next. Through the social events of Challenger I found a more than willing community to get this crucial advice from. Further advice came from the excellent careers session, covering both academic and non-academic pathways beyond Ph.D.

Visiting the National Aquarium, the Barbican, the University and the Guildhall during the social events really highlighted Plymouth's position as a maritime city, something I had neglected to notice growing up here. Attending Challenger felt like the perfect way to round off my formal academic journey from undergraduate to Ph.D, from Plymouth, around the world and back! I would thoroughly recommend the Challenger conference, particularly to early-career scientists, and hopefully I will see you in Liverpool in 2016!

Hayley Evers-King has obtained her Ph.D and has taken up a position as a Marine Earth Observation Scientist at Plymouth Marine Laboratory. Her research focusses on developing different uses for ocean colour satellite data (e.g. study of harmful algal blooms and climate variability). hek@pml.ac.uk

Hayley at sea

Has anyone seen Buchanan's books?

John Phillips

On the 25th of January 2012 six slim quarto volumes bound in red leather changed ownership as part of an auction lot that sold for £2200. They contained most of the sections of the *Challenger Report* dealing with physics and chemistry, but, more important because unique, are the manuscript notes and papers that accompanied them. These were the work of the man for whom the books had been bound: John Young Buchanan (1844–1925).

Buchanan was the chemist and physicist of the *Challenger* expedition, responsible for measurements on the water samples and the chemical examination of sediments. He made almost 1500 determinations of specific gravity using a hydrometer, as well as collecting samples of dissolved gases for later analysis.

Buchanan used his data to prepare the first charts representing the global distribution of salinity, not as such but in terms of specific gravity referred to a standard temperature (15·56 °C) – an efficient proxy for salinity that he called 'saltness'. He presented these important results, together with his closely reasoned interpretation in terms of climate and currents, in a paper read at the Royal Geographical Society on 12 March 1877, less than ten months after *Challenger* returned to Sheerness. The more detailed official report did not appear until 1884.

That was his principal contribution to oceanography; hence the most significant item in the auction lot was a hand-drawn graph for adjusting measured specific gravities in order to obtain the corresponding values of 'saltness'. Written on the back are the words 'This is the plan I constructed and used on board the "Challenger". JYB'. The lot also contained photographs, sketches, notes, tables and calculations related to the expedition and to his later researches.

In this context it is perhaps ironic that Buchanan wrote no books himself, but he did publish more than a hundred papers and articles, many of which were collected in three volumes from Cambridge University Press: *Scientific Papers* (1913), *Comptes Rendus of Observation and Reasoning* (1917) and *Accounts Rendered of Work Done and Things Seen* (1919). The key paper on the distribution of 'saltness' is reproduced in the first of these, together with most of his other papers connected with HMS *Challenger*.

Buchanan remains the least well known of the *Challenger* scientists. After the expedition he went his own way, continuing his oceanographic researches on the vessels of cable companies and on yachts belonging to Prince Albert I of Monaco. According to the late David Stoddart, writing in 1975, 'He left extensive manuscript notes on his work, including diaries illustrated with his own water-colours, but of these only his letters from the *Challenger* and some personal mementoes still survive.' After their brief public appearance at auction the items in the lot returned to obscurity under a new, but still anonymous, ownership.

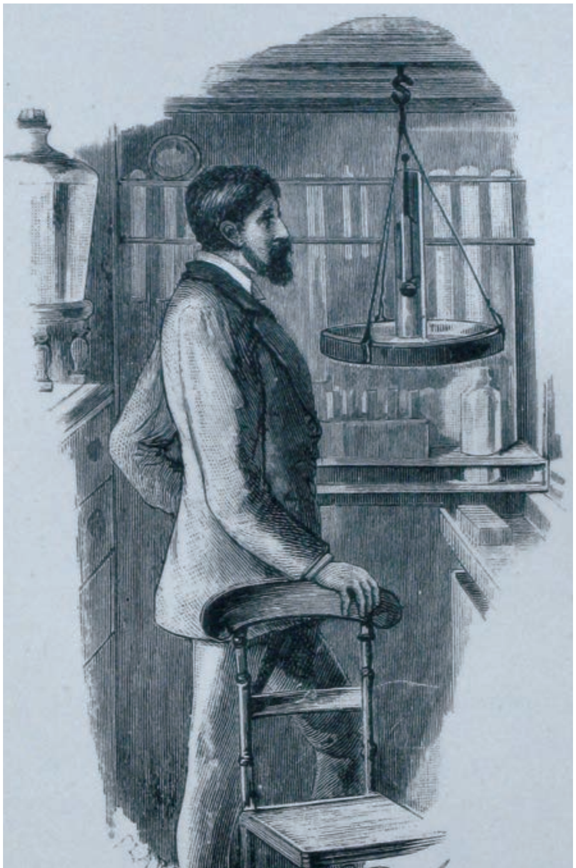
Information concerning the whereabouts of any unpublished material about this pioneering oceanographer that is not already available in open archives would be a valuable addition to the history of oceanography and welcome news for the Editor and/or this author at periplus@btconnect.com.

Further Reading

Buchanan, J.Y. (1877) On the Distribution of Salt in the Ocean, as indicated by the Specific Gravity of its Waters *J. Roy. Geographical Soc.*, **47**, 72–86.

Stoddart, D.R. (1975) The RGS and the Foundations of Geography at Cambridge *Geogr. J.,* **141**, 216–39.

John Phillips is an amateur historian and bibliographer.



Buchanan measuring the specific gravity of a seawater sample on board HMS Challenger

(By Elizabeth Gulland, from Challenger Report, Narrative, *Vol. I part 2, p.1003)*

An interview with an artist inspired by Challenger

Alice Strange explains how scientific exploration fuels her creativity

In May this year, an unusual exhibition celebrating the *Challenger* Expedition was held at the Scottish Association for Marine Science (SAMS), as part of the Oban, Lorn and the Isles Festival of the Sea. So how did its creator, Alice Strange, a one-time an electrical engineer, become an artist intrigued by early oceanography?

How did you become an artist?

An electrical engineering degree led to working in the energy industry for twenty years (time flies!). Then in 2002 chance meetings with masters of printmaking Thelma Sykes and Eric Martin caused me to take Obi Wan Kanobi's advice and rethink my life. I bailed out of the corporate world soon after to study art history at the Open University and make stuff.

Expert tuition and guidance from the people at the Glasgow Print Studio, and Claire McVinnie and Scott Hudson at the Dundee Contemporary Arts Print Studio, added mosaic, flax weaving, painting, collagraphy, screenprinting, digital printmaking, bookmaking and laser cutting to my toolbox.

My mind is a non-stop machine, fuelled by everything I see, hear, do – music, art, literature, people, conversations, travels, memories, the earth, the sea, the sky, feats of engineering, the search for knowledge. Making stuff helps me process the input. I'm constantly seeking the 'That's it!' moment, when an image captures a thought, documenting my world view.

Originally from Port Glasgow on the Clyde, I lived in Christchurch and Wellington in New Zealand, and London, Much Hadham and Farthinghoe in England, before moving to Oban on the west coast of Scotland in 2004.

Why oceanography?

A house by the sea, a son with an interest in marine biology, a request from SAMS to use my artwork in conference publicity material for the 2006 Challenger conference, a television documentary featuring the Challenger *Expedition (1873–76), a conversation with Laurence Mee from SAMS – the sea cast its spell and an artistic exploration was underway. In 2011, I started reading the 50-volume* Report of the Scientific Results of the Exploring Voyage of HMS Challenger during the years 1873–76 *(printed to order from Amazon, and online).*

My line of inquiry moved seamlessly from the Challenger *Expedition and oceanography to NASA's space exploration programme. I was thrilled to discover that NASA acknowledged the importance of the* Challenger *Expedition by naming a space shuttle and the* Apollo 17 *lunar landing module after the ship, and that one of my favourite iconic photographs was taken from space shuttle* Challenger *– Bruce McCandless II taking the first untethered spacewalk using a Manned Maneuvering Unit.*

Over four years, twenty artworks inspired by the Challenger *Expedition emerged. These works acknowledge and celebrate the courage, determination and achievements of those who explore the unknown to give us a better understanding of our world and ourselves.*

Many of the works were made as computer-generated collages, which enabled me to incorporate maps, diagrams, text and images from the Report, *altered and composed in Adobe Photoshop to create multi-*

This boxed assemblage (410 mm x 255 mm) incorporates text and images from the Challenger *Report: paper, shells, glass bottles, twine, an HMS* Challenger *commemorative stamp and a* Challenger *Space Shuttle commemorative medal.*

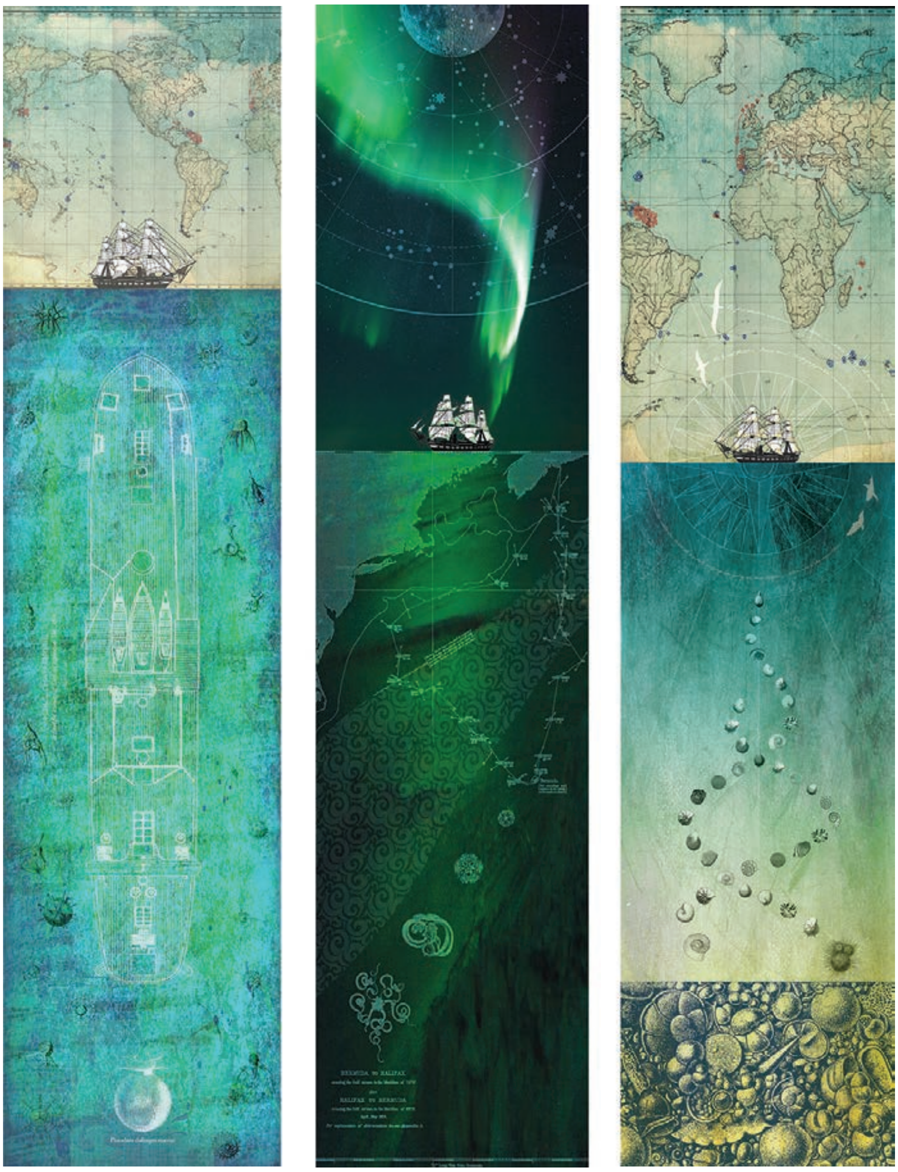
layered digital compositions. These images are intended to be viewed on paper. They are printed using archival quality ink and paper in various formats, the largest panels are up to 2.5 m long. These prints are unlimited editions.

A few of the works are limited edition screenprints, printed at the Glasgow Print Studio. Since the images included fine detail, I used the photo-emulsion screen printing process. I created stencils using elements of the digital collages, and applied these to aluminium-framed polyester mesh screens coated with UV light-sensitive emulsion and exposed to UV light. Images were printed by positioning the screens over paper and pressing water-based ink through the stencil using a squeegee. A number of stencils – one for each colour – were over-printed to create multi-coloured images.

Early patrons were the Austrian metal band Sensylis, who selected 'Flight Paths' (right-hand image of the triptych shown here) as the basis for the cover artwork and promotion material for their debut album 'Aquila'.

My *Challenger*-inspired works were first shown publicly as part of the 2013 Oban Winter Festival. They are currently on show in the John Murray building at SAMS in Dunbeg, where they were installed as part of SAMS' 130-year anniversary celebrations. The event included a dedication of the Sir John Murray Building by Murray's great grandson, Alex Murray. I created some new portraits of John Murray for the occasion (http://www.alicestrange.com/category/ocean-cat).

Recent works in the series include specially designed fabrics, embellished with printed text, driftwood and mother of pearl, and an assemblage – a three-dimensional collage – of objects relating to *Challenger*'s voyage (opposite).



Challenger III 'The vast ocean lay scientifically unexplored. All the efforts of the previous decade had been directed to the strips of water around the coast and to enclosed or partially enclo sed seas; great things had certainly been done there, but as certainly far greater things remained to be done beyond. This consideration led to the conception of the idea of a great exploring expedition which should circumnavigate the globe, find out the most profound abysses of the ocean, and extract from them some sign of what went on at the greatest depths.'

Aurora 'In investigating the strength and direction of the ocean currents, such as the Gulf Stream, when out of sight of land or unable to anchor a boat, observations of the heavenly bodies are the only resource … The ship remained at Halifax from the 9th to the 19th May. On the 15th, at 11pm, the sky was brilliantly illuminated by an aurora borealis …'

Flight paths '… of albatross, petrels, penguins and foraminifera …'

The quotations are from the *Challenger* Report (1885).
The artworks are digital collages, maximum image sizes: 60 x 250 cm

Any more ocean/science-related works in the pipeline?

I'm currently researching James Cook's voyages of scientific discovery, as well as shipbuilding on the Clyde. I also watch NASA's *Voyager* and *Mars* missions and CERN's research with interest – and recently a chance meeting with film-maker John Simmons pointed me in the direction of Svalbard and polar oceanography – the artistic exploration continues!

To see more of Alice's work, please visit www.alicestrange.com
Alice's 32-page book about the SAMS exhibition, entitled simply *Challenger*, can be obtained via http://www.blurb.com/user/store/alicestrange.

An interview with the Director of the COAST Laboratory, Plymouth

Deborah Greaves describes why she finds her career as an ocean engineer so satisfying

Deborah Greaves is Professor in Ocean Engineering at the School of Marine Science and Engineering at the University of Plymouth, and Director of the COAST (Coastal Ocean and Sediment Transport) Laboratory. Here she discusses her rewarding career in a field in which women are still under-represented.

What was your path to a career in ocean engineering?

I started with a degree in Civil Engineering at Bristol University and then worked as a civil engineer in London for 4 years. I worked on the Jubilee Line extension, designing tunnels and underground stations, and also spent a year on the construction site for the Cardigan Bypass and river Teifi Bridge. I took a year off work to travel independently around the world, during which time I also worked in civil engineering in Australia. By the time I returned to the UK, I had decided to move into an academic career and embarked on a D.Phil at Oxford University in computational fluid dynamics for wave structure interactions.

Brought up by the sea, near Plymouth, I was keen to work in coastal or ocean engineering. I took my first lecturing appointment in Mechanical Engineering at UCL, where I was responsible for teaching naval architecture and continued my research in computational fluid dynamics for steep wave interactions. My first child was born in 1998 and soon after that we moved to Bath, where I secured a lecturing appointment in the School of Architecture and Civil Engineering at the University of Bath. At this time, I also won a Royal Society Research Fellowship, which gave me freedom to develop my own research interests in marine renewable energy, and work flexibility during the early childhood of my three boys. I moved to Plymouth University in late 2007 to take a post in the School of Marine Science and Engineering and was able to further develop my research in marine renewable energy. I led the development of the COAST Laboratory, which is now an important test facility for marine renewable energy. As well as providing important facilities for teaching and research, it is used by national and international commercial clients and research groups.

In researching offshore energy generation, how would you assess the relative usefulness of computer modelling, lab simulations and in situ *experiments?*

The COAST laboratory provides a facility for laboratory-scale modelling of marine renewable energy devices. Laboratory testing is an important part of the development of a marine energy device. Devices are often tested at small scale in the laboratory during early stages of development to prove the concept, and then at larger scale to optimise the design, to test the power take-off, to assess extreme loads and mooring arrangements. During each of these stages, a computational model of the marine energy device is also an essential tool and can be used to test parameter changes, to optimise geometry and make design changes. At all stages it is important to validate the computer model with the physical experiment results in order to give confidence in the computer model. The computer model can then also add insight to the results of the physical experiments.

Once fully tested and understood at model scale, the device should be tested at sea. This can be done initially at a nursery site, where the device is tested at 1/2or 1/3 scale, not necessarily grid-connected, but tested for reliability. Also, installation and performance may be tested in a relatively mild environment, for example at FabTest in Falmouth Bay. The next stage is demonstration at full scale in operating conditions and with grid connection, producing electricity to the grid, for example at WaveHub off the north coast of Cornwall. This is an important stage for demonstrating the viability of the device as a commercial proposition and for giving confidence to investors.

During all stages of the development pathway, computer modelling and laboratory modelling of the device will be carried out to continue optimisation of the design and operation. So each of computer modelling, laboratory simulations and in situ *experiments are important components of the development pathway and they each complement one another.*

What are your feelings about the popular view that wind turbines are best sited at sea?

There are advantages and disadvant-ages to siting wind turbines at sea: they are exposed to greater wind resource offshore and are less likely to suffer community objections at *the planning stage, but are more expensive to build and maintain offshore. The UK is highly populated and so it is natural to look to offshore deployments for wind turbines. As we move to further offshore wind farms, the cost increases with water depth and distance from the shore, and novel floating offshore wind turbine structures are being developed. As with all new technologies, the cost is initially very high, but would be expected to decrease as the technology and its market develop.*

What do you enjoy most about your job?

I enjoy all aspects of my job, especially the research in marine renewable energy and wave–structure interaction. My research background is in computer modelling, but I have always wanted to run physical experiments as well, and so having the opportunity to lead the COAST Laboratory, and run experiments in the wave basins alongside developing computational fluid dynamics and running computer simulations is very exciting. I enjoy teaching – we run undergraduate programmes in civil and coastal engineering, mechanical engineering and marine technology, and Masters in Marine Renewable Energy and in both Civil and Coastal Engineering. As part of these programmes, students develop their own research ideas through research dissertations and supervising these can be very rewarding. At Plymouth University we have established the School of Marine Science and Engineering, in which engineers work closely with marine physical scientists and marine biologists and this gives a unique opportunity for collaboration across areas relevant to developments in the marine environment, which is particularly valuable to our marine renewable energy research.

I also enjoy collaborating with others nationally and internationally on research projects, working closely with industry and end-users of the research, and working on research that has practical applications to design.

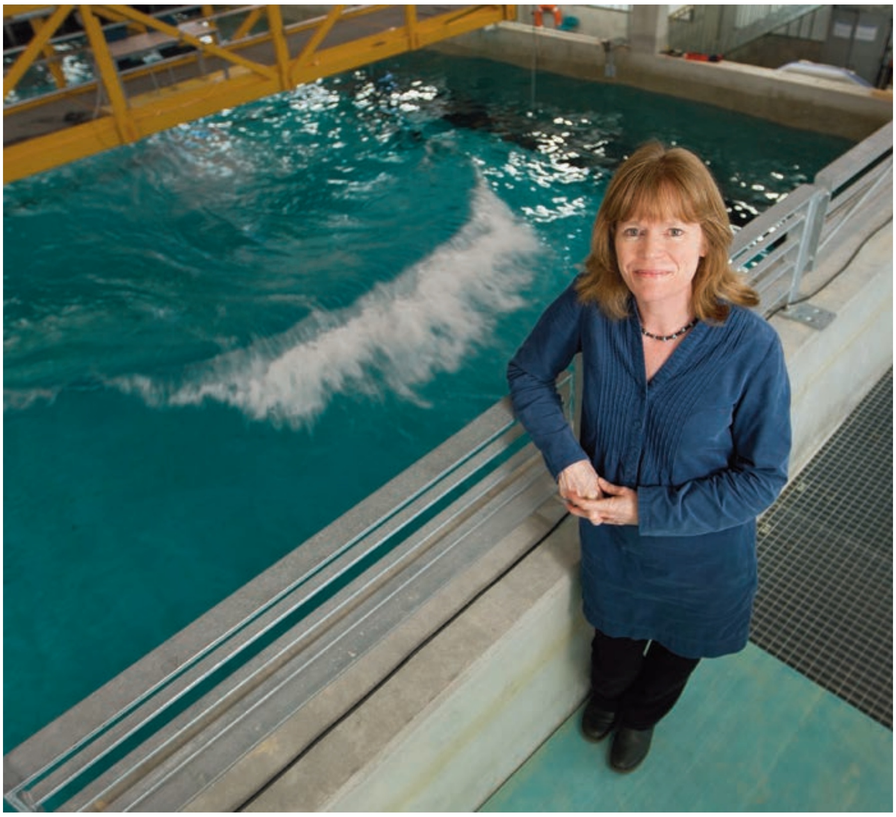
What advice would you give to someone with a first degree in physical oceanography who is wondering about changing course towards ocean engineering?

Graduates with a science degree in physical oceanography or similar will have learnt about the theory of waves and tides and this is very relevant to coastal and ocean engineering. Taking a Masters in Marine Renewable Energy or Coastal Engineering would be a good way to move into the field of marine renewable energy and of analysis of coastal and ocean structures.

What prompted you to get involved in Women in STEM?

I am very aware that the proportion of girls choosing civil engineering degree courses has not increased at all since I went to Bristol in 1985. I think this is a great shame and that girls are missing out on a rewarding and exciting career choice, and that the engineering profession is missing out on a significant pool of talent. Many reasons have been put forward as to why this situation persists, and WISE (https://www.wisecampaign.org.uk/) have recently published a very interesting report on the matter. I feel that I have a successful and rewarding career and would like to do what I can to help others achieve the same.*

* Macdonald, Averil (2014) WISE: 'Not for people like me?' Under-represented groups in science, technology and engineering. A summary of the evidence: the facts, the fiction and what we should do next. This report can be downloaded from the WISE website https://www.wise-campaign.org.uk/resources



Deborah at the COAST Laboratory Ocean Basin facility

The Ocean Basin is 35 m long by 15.5 m wide with a moveable floor that allows different operating depths. It is a unique facility in which 24 paddles can produce uni-directional and directional wave fields, regular waves and wave spectra. Currents are produced by a recirculating hydraulic system, and waves and currents may be generated at any orientation relative to one another. Future developments include the provision of wind generation.

There is also a Coastal Basin, where sediment transport and coastal structures can be studied in a controlled environment at reduced scale, and two Sediment Wave Flumes.

Public perceptions of the marine and coastal environment

Rebecca Shellock and Angela Carpenter

In the face of the rapid deterioration of our global ocean, governments have increasingly been developing policies to protect marine and coastal environments and their extensive resources. At the EU level, countries are working to achieve 'good ecological status by 2020' through measures such as the 2000 *EU Water Framework Directive*. However, it is becoming increasingly evident that it is not enough simply to formulate policies and conservation measures. To be successfully implemented, marine and coastal policies need support from the public, not just the backing of governments and scientists.

This article looks at current research which explores public perceptions of the marine and coastal environment, using the English Channel/La Manche as a case study. It will also provide an update on the findings of the Policy Session held at the 2014 Challenger Conference in Plymouth.

Oceans are a 'low priority for the public'

Despite increasing media coverage of the deterioration of the marine environment as a result of fishing, pollution and many other impacts, 'Ocean health is a low priority for the public'. This shocking statement is taken from recent work that investigated the views of over 7000 Europeans across the UK, France, Germany, Spain, Portugal, Italy and Poland. Environmental issues, including ocean health, are losing ground in the battle against immediate concerns such as the cost of living, human health, education and the economy. Scientists are now presented with the challenge of raising the profile of the oceans, which are worth billions of pounds to our economy and are vital for society's well-being.

Why do we need to know what the public thinks?

The public are the key to the success or failure of marine policy and conservation measures for our seas and oceans. They will play an important role in contributing to marine planning, and supporting marine renewable energy and measures intended to promote marine conservation, all of which will have social and economic consequences. A greater understanding of the public's perception of the marine and coastal environment would help policy-makers and scientists increase public engagement with the coasts and seas. The extent to which this can be achieved will be critical to the future of marine policy and how it unfolds.

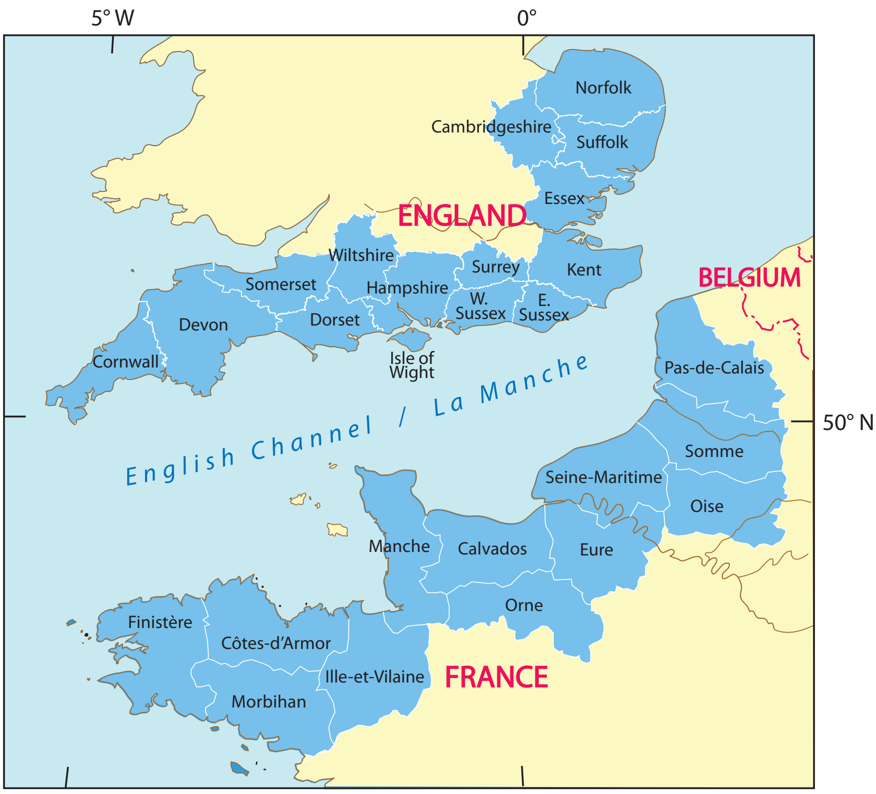
A UK example of marine conservation measures that can only work with the input and support of the public is the setting up and management of Marine Conservation Zones (MCZs) (see Further Reading). Protecting our marine environment is a societal choice and the public therefore need to be involved in decision-making.

Connecting society with the sea

There is increasing need to connect society with the seas and oceans, and this is acknowledged as a significant challenge at both the national and global scale. However, there is a global lack of research investigating the public's use of, and views about, the marine and coastal environment. Recent studies in the UK are beginning to pave the way towards a better understanding of social values, attitudes and uses of the marine and coastal environment. These studies have helped to provide some initial insight into public perceptions and form a basis for further investigations, including our current research which investigates the public's vision for the future of the Channel. The Channel was selected as a case study because of the variety of habitats and human activities in the region, and the lack of previous research. Alongside this, management of the Channel is made more complex because of significant differences between the UK and France in areas such as governance and policy, including legal frameworks, approaches to planning and political objectives.

Funded by the INTERREG IVA project PEGASEAS (Promoting Effective Governance of the Channel Ecosystem) Plymouth University collected the views of over 2000 residents of the Channel region in both the UK and France (Figure 1). The

Figure 1 *Map showing the study area for the PEGASEAS research into public perceptions of the marine and coastal zone. The survey gained responses from individuals across English counties and French departments within the Channel region.*



survey gathered information about (1) the public's use of the Channel, (2) the public's priorities for funding (what they would spend public money on) and (3) the public's pro-environmental behaviours (for example, whether they buy fish from sustainably managed fish stocks or use fewer plastic bags). This article provides a brief summary of the results; for more information about the PEGASEAS survey and the project overall, please see the Further Reading.

The Channel coast is particularly valued for its scenic views, and as a space in which to relax and explore

Public perceptions of the Channel

The research revealed a range of useful information; here we present four key findings from the survey.

- **The Channel is important for recreation and tourism**

Respondents were asked what types of activities they carry out on either side of the Channel. The study identified that the Channel is an important area for recreation and tourism and is valued by both residents and visitors in both countries. The Channel is particularly used for the following four activities: (1) enjoying the scenery, (2) relaxing and unwinding, (3) visiting historic areas and landmarks, (4) walking along coastal paths.

- **The environment is a top priority for the public**

Respondents were asked to rate thirteen priorities that could be funded to improve the Channel coast. The priorities spanned the following themes: business, renewable energy, tourism, regeneration and the environment. Overall, we found that environmental priorities were very important to respondents, over 70% of whom rated natural resource management and conservation, pollution and environmental risk as key priorities for funding.

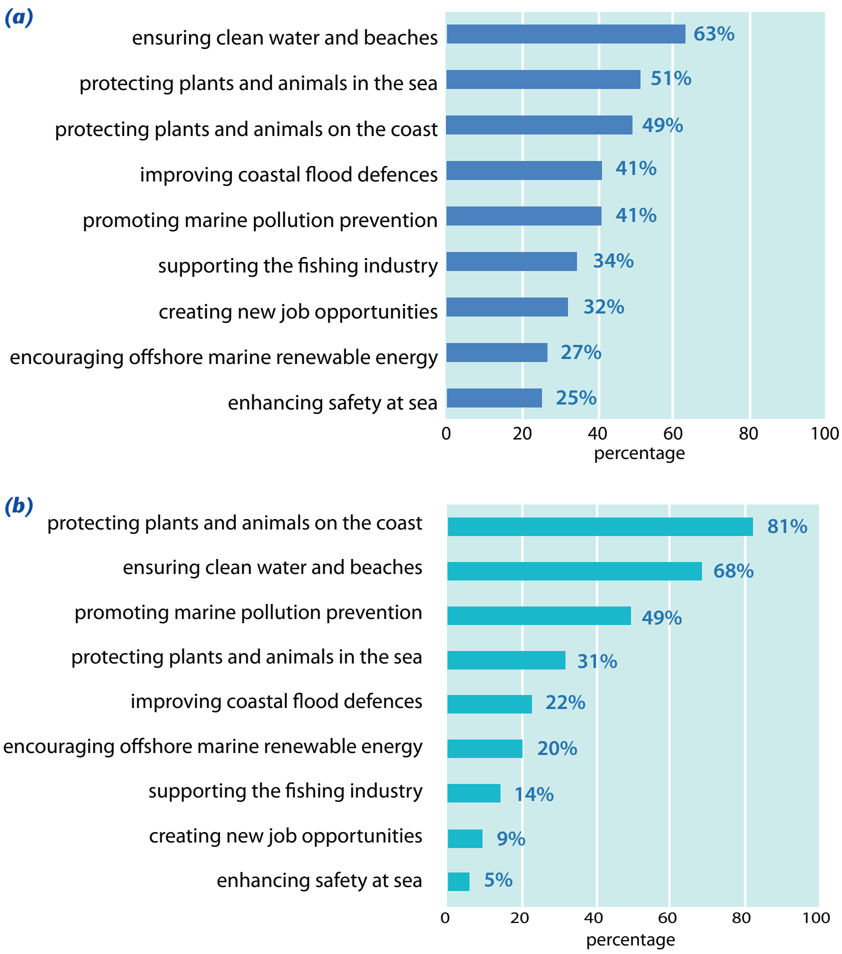
- **Cleaner water and beaches are important to the public**

Respondents were asked to select their top priorities for the management of the Channel's marine and coastal environment. As shown in Figure 2(a), cleaner water and beaches were a top priority for the public, favoured by over 63% of respondents. This was closely followed by protecting plants and animals in the sea (51%) and on the coast (49%). The lowest priorities were related to 'creating cultural links across the Channel' and 'developing transport links across the Channel' (not shown in Figure 2) (see Carpenter *et al.* 2015, Further Reading).

- **Pro-environmental behaviours are not readily adopted in the Channel region**

Respondents were asked about their current engagement in pro-environmental behaviours, i.e. behaviours which are thought to benefit the natural environment (including buying choices, recycling and participation in environmental organisations). They were given a list of pro-environmental options including buying fish from sustainably managed stocks, using fewer plastic bags and belonging to marine conservation groups. We found that the most common pro-environmental behaviour favoured by the Channel community is the use of fewer plastic bags. Over half of respondents indicated that they already do this to protect the environment. However, less than half of them participate in most other pro-environmental behaviours, including buying sustainably sourced fish, using renewable energy, attending relevant public meetings and belonging to marine conservation groups.

Figure 2 *Most favoured priorities for management of the Channel according to* ***(a)*** *the public who responded to the PEGASEAS survey and* ***(b)*** *marine scientists at the Challenger Society Conference. Please note that least favoured priorities are not displayed. For the full dataset, see Carpenter* et al. *(2015) in Further Reading.*



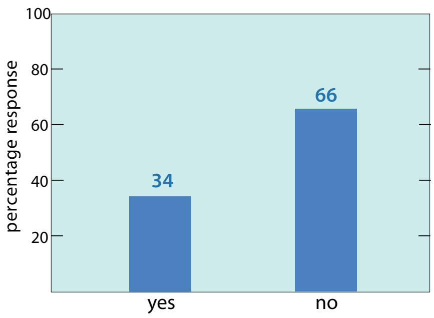
Do we all want the same for our marine environment?

Previous work in 1997 showed that the US public think that scientists and citizens disagree on the most important issues facing our oceans (see Further Reading). But what about in the UK? Do scientists and the public agree what the priorities for our marine environment, specifically the Channel, should be? We set out to test this question at the Challenger Society Conference in Plymouth (September 2014). Using an electronic voting poll, we compared the public's priorities (as shown by the 2000 responses from the PEGASEAS survey; Figure 2(a)) with those of over 70 marine scientists.

The first question we asked the marine scientists was whether they agreed with the statement that '... scientists and the public agree on priorities for the Channel'. We found that two-thirds of the 73 marine scientists answered 'No' to this question: they believed that they think about priorities for the marine and coastal environment in a different way from the public (Figure 3). However, when we compared the public's priorities with those of marine scientists at the Challenger Conference, we actually found that scientists and the public have very similar priorities (Figure 2).

Scientists and the public had the same five priorities for improved management of the Channel's marine and coastal environment: cleaner water and beaches, good coastal flood defences, marine pollution prevention and conservation of plants and animals in the Channel region. Overall, both the public and scientists prioritised environmental protection and conservation. Scientists agreed with the public in not seeing creation of cultural links and the development of better transport links for the Channel region as a priority for future funding.

Figure 3 *Scientists' responses to the question: 'Do you think that scientists and the public agree on priorities for the Channel?' (sample size = 73)*



Overall, this exercise at the Challenger Society Conference revealed a potentially very positive result. Against popular belief, scientists and the public are not so dissimilar in their priorities for the Channel's marine and coastal environment.

What's next?

This research has provided a snapshot of the perceptions of English and French residents, living either side of the Channel. The public in this case had very similar environmental priorities to scientists, choosing marine and coastal protection and conservation as the most important areas for future investment. But the public are *not* engaging in many behaviours and activities that will help to protect and conserve the marine and coastal environment, indicating a disconnect between society and the sea.

Connecting society with our seas and oceans presents a significant challenge to achieving marine conservation goals across the UK, EU and globally. 'Marine citizenship' – the recognition that each citizen holds significant power in conserving and enhancing the marine environment – has been proposed as a way of connecting society and the sea. This will require the public to have a greater understanding of environmental issues, of the role of personal behaviour in resolving environmental issues and in shifting values to promote behavioural choices that will benefit the marine environment. The extent of knowledge of the public and their current and future engagement with the environment will be key to the success or failure of marine citizenship. Future research will need to be focussed on public perceptions, social values, attitudes and knowledge of the environment, both in the Channel region and globally.

The benefits to the research are two-fold. First, being aware of social attitudes should allow a meaningful debate about what policies are acceptable to the public, so aiding the development and implementation of policy mechanisms which may be used to achieve a sustainable marine and coastal environment. Secondly, it will help us to understand the degree to which information on marine issues and policies have been communicated to the public and incorporated into their own values.

This research needs to be reinforced by more effective and increasing interaction between scientists, government and the public, aimed at improving the way the seas are managed.

The public will play an important role in supporting marine and coastal policy including marine planning, marine renewable energy and MCZs, all of which will have social and economic consequences for society. The public are central to the success or failure of marine conservation goals for the Channel, as well as for our oceans and seas worldwide. Overall, an understanding of public perceptions should help to ensure that governments are implementing policies and measures that are supported by both the public and science, helping to make the vision of a sustainable marine environment a reality.

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From film-making to virtual fish

Amy Scott-Murray explains how an art degree led to a career in marine science

I have not had an entirely straightforward route to working in marine science. My undergrad degree was in digital animation from art college in Dundee, where my honours film was 'The Luminous Deep' – a short animated documentary describing bioluminescence at a whale fall. Over the next few years I went on to make several similar pieces, working freelance as a digital filmmaker for clients such as the Census of Marine Life (CoML) and the Biogeography of Deep-Water Chemosynthetic Ecosystems Project (ChESS). However, I always suspected that contemporary digital visualisation techniques could have other applications in marine science, beyond communication and outreach. My MASTS-funded Ph.D research at Aberdeen University allowed me to investigate this.

The main thread of my work is on the use of photogrammetry to create virtual replicas of marine animals. Photogrammetry is a process whereby many photographs of an object are used by specialised software to construct an interactive, photorealistic, highly detailed 3D model. This is not a new process and it is used quite widely both commercially and by researchers in palaeontology, archaeology and visual culture. It has even been applied to very slow-moving terrestrial animals such as seals and tortoises. Making these techniques work underwater and on live active animals, however, presents an entirely unique set of challenges.

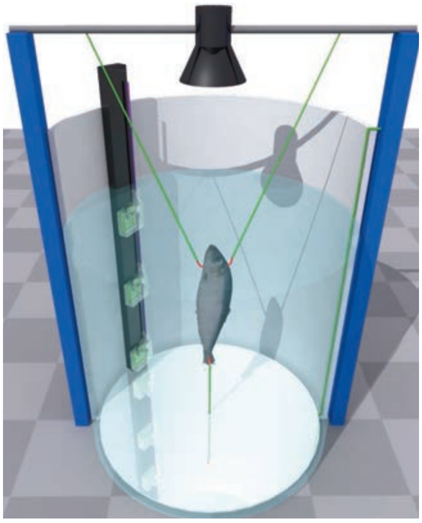
Using widely available and inexpensive equipment I succeeded in finding a way to make underwater reconstructions of static dead fish specimens. The fish is suspended in a large bucket or bin filled with water. Using water complicates the photography but is worthwhile because it helps to support the weight of the animal and reduce tearing. It also means that fins are positioned more naturally. I use a single camera in a simple waterproof housing and move it around the fish, taking a set of images that together cover every angle. Lighting is very important as it must be both plentiful and constant. The photo sets are then processed to produce 3D objects.

Although developed here at Oceanlab in Aberdeen, this procedure has also been carried out on research cruises to the North Sea and South Pacific. Digitising specimens on board ship means that they are as fresh as possible and undamaged by preservation. The scans are therefore closer to the fishes' appearance in life.

These virtual specimens are intended to act as references which can help researchers who are working with remote images, such as those filmed from benthic landers or AUVs. Traditional taxonomic illustrations follow a formal visual grammar where black-and-white linework illustrations present the fish laid flat and viewed directly from the side. Real fish underwater are rarely obliging enough to match this presentation, but virtual references can be manipulated by the researcher to more closely match the fish in the footage they are working with. In addition, the appearance of the virtual fish is closer to the animal in life than is a line drawing or a preserved specimen.

I have also made reconstructions of dissected fish specimens, which are intended to help students identify the organs they see in real-life dissections. I don't feel that virtual specimens should ever take the place of physically interacting with real specimens, but they can give a big boost to understanding when used in parallel with more traditional lab practicals. Most of these reconstructions – both entire fish and dissections – are available online through Sketchfab which is a sharing service – like Youtube for 3D models.

Above *Amy's photogrammetry set-up*
Below *A virtual haddock*



Studying live populations using photogrammetry

While working with these scanned specimens I realised that there is a very direct relationship between the volume of a fish (which can be measured digitally from the virtual object) and its wet weight. This raises an intriguing possiblity: in the future, it should be possible to digitise fish *in situ* as a non-destructive survey method. A great deal of work is being done by people in the computer science field on the automatic identification of objects in images. Their research, in parallel with mine, would mean that we could one day have an entirely new way to monitor not only which species are in an area but also their weight and numbers.

In order to make this happen, some more specialised equipment is needed. We will be dealing with living fish moving in their own environment, so we need a way to capture photo sets instantaneously, covering all angles at once. At the moment I am working on designing and building fully programmable, networkable underwater cameras that are small enough to construct an array for photogrammetry captures. These cameras are based on the inexpensive Raspberry Pi platform. The array will be valuable for gathering data on fish populations. It will also massively improve the quality of illustrative virtual references, since the fish will be digitised while alive and undamaged by recovery and storage.

The work I have done so far has, I believe, only scratched the surface of what is possible when applying 3D visualisation to marine science. I hope that over the coming years myself and others will be able to unlock much more of this potential.

Further browsing

www.virtual.fish will take you to my public Sketchfab page where most of the fish scans are available for everybody to use.

http://tinyurl.com/fishdissections is the dissection page – please do have a look!

http://vimeo.com/28572032 my short film 'The Luminous Deep'.

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Unmanned Surface Vehicles: The Future of Data-Collection

Kira Coley

As we enter a new era of robotic research, unmanned surface vehicles are becoming increasingly useful to the UK's marine science community. The collection of accurate scientific data is an essential component of all research, providing the foundation for knowledge about the marine environment and its interaction with the rest of the Earth system. Interpretation of these data can be used to advise government agencies, industries and the public on key topics, so influencing policy and socio-economics. Platforms commonly used to gather data from surface and near-surface marine waters include research vessels, data buoys and satellites. These all have disadvantages, such as high costs and low temporal or spatial resolution. The new robotic technology is intended to allow UK scientists to achieve continuous ocean data-collection at a fraction of the cost and time required by other platforms, and to access remote regions of the ocean, study of which was previously economically unviable.

Background

In September 2012, a competition organised by the National Oceanography Centre (NOC), under a UK Government-backed Small Business Research Initiative (SBRI), invited proposals for innovative long-endurance marine unmanned surface vehicles for use in environmental research. The initiative was co-funded by the National Environmental Research Council (NERC), with the Technology Strategy Board (TSB) and the Defence Science and Technology Laboratories (DSTL). The winners of the competition were the 'C-Enduro' and the 'AutoNaut', both built by UK-based companies – ASV Ltd and MOST (AV) Ltd, respectively.

Unmanned Surface Vehicle (USV) was the standard term used by the industry to define surface vehicles operating without persons onboard. As a result of technological developments, some unmanned vehicles are no longer just unmanned, they are autonomous, capable of completing pre-programmed tasks without operator input, so giving rise to the term Autonomous Surface Vehicle (ASV). As discussed later, the 'C-Enduro', for example, can be operated as both a USV and ASV.

'C-Enduro' specifications: Length: 4.2 m. Height (including antennae): 2.8 m. Weight: 350 kg (lightship), 500 kg (fully loaded). Speed: 0.7 knots. Endurance: Up to 3 months with solar/wind/diesel energy.

While Autonomous Underwater Vehicles (AUVs) are vital for many aspects of data-collection, USVs can generally carry more sensors for longer durations due to their larger size and power capabilities. Furthermore, they can combine collection of both surface and sub-surface measurements and are not limited by depth or location. For these reasons, USVs have been recognised globally as a solution for long-term scientific monitoring.

In the field

Even in these early days of unmanned and autonomous vehicles, separate classes of vehicles are emerging, powered in different ways and with different capabilities to service a variety of mission requirements. One class of USVs, which includes the MOST 'AutoNaut' and 'Waveglider' by Liquid Robotics, are powered solely by renewable energy sources. These vehicles, designed to produce zero emissions, are propelled by wave motion and use solar energy to power their sensors. The design of the 'AutoNaut', for example, means that in the right environment it could be deployed almost indefinitely, providing speeds up to 5 knots for a 5 m vessel. As it depends on waves for motion, on a flat day the 'AutoNaut' travels at reduced speeds of around ½ knot. To help overcome this limitation and improve mobility, vehicles can be fitted with an additional propulsion pod which can be activated when necessary, e.g. during deployment and recovery. Overall, wave propulsion offers the potential for very long endurance times.

The 'C-Enduro' belongs to another class of USV – rugged, self-righting powered vehicles which use a lightweight diesel engine alongside energy from solar and wind generators, for deployments up to 3 months. The robust design of such vehicles enables them to operate in coastal or open ocean conditions. They have the ability to support up to 500 watts of sensor power and can travel at speeds up to 7 knots.

The environment in which the USV will be operating can influence the choice of power source and the performance of the vehicle. The tri-powered system of the 'C-Enduro' allows the user to select the power source to best suit the operational requirements. For example, the diesel generator can operate alone for two to three days, allowing the system to travel between waypoints in the absence of solar or wind energy. With full sunlight and light to moderate winds, the system has the potential to operate indefinitely, as renewable energy would continue to charge the onboard batteries.

The duration of data-collection, and the volume of data to be collected during deployments, will also determine how the vehicle needs to be configured. The 'AutoNaut' is scalable up to 10 m in length to allow a greater sensor payload. As mentioned above, the 'C-Enduro' can carry a large payload as part of its original configuration and can be set to run on a combination of solar, wind and diesel power. The size of the vehicle and its area of operation will also often affect how it is deployed and recovered.

Built to operate in all marine environments, 'C-Enduro' uses a lightweight diesel engine along with energy harvesting technology. It has an efficient self-righting hull and a large payload capacity. (Source: ASV Ltd)

While still being improved through user experience, USVs are robust and have been known to survive hurricanes and trans-Pacific crossings. Systems such as the 'C-Enduro' can correct itself if capsized during rough conditions, providing reliability and safeguarding datasets stored onboard. The 'AutoNaut' has various levels of remote control which allows users to change to modes better suited to overcome strong surface currents, and it can be fitted with modified sensors that can survive submersion. It has also successfully faced gale force winds of 70 m.p.h. and a significant wave height (H_s) of 7 m.

Most USV systems can be adjusted to best meet the requirements of the researchers using them and, to some degree, the environment in which they will be navigating. Both classes of vehicle – those that use only clean energy and those that also have an engine – are already in the next stages of development, continually improving the performance and reliability of the platform for a growing range of missions.

'AutoNaut' stats: Length: 3.5 m (scalable up to 10 m); height: 0.43 m; weight: 130 kg (and up to 60 kg payload). Speed: 2–3 knots. Endurance 3+ months.

'AutoNaut' about to be recovered from the sea near one of the Western Channel Observatory buoys. A command and control system allows 'AutoNaut' to be ordered via satellite or UHF to return to a single waypoint and circle to await pickup when the conditions are right. (Source: James Fishwick)

Applications

in October 2014, the MASSMO project, coordinated by NOC, tested various USVs and AUVs in one of the most ambitious trials of its kind in Europe. While travelling up to 500 km off south-western Cornwall, over the course of 20 days, vehicles, including 'C-Enduro', 'AutoNaut' and 'Waveglider', recorded key parameters of the ocean, including temperature and salinity. The vehicles also logged additional information ranging from concentrations of plankton to the clicks and whistles of dolphins and porpoises. Onboard GoPro cameras were used to capture images and video footage for use in of litter surveys and surveys of seabirds, and acoustic 'pingers' were used to track various fish.

A paper published in May 2014 by a team of researchers at the Pohang University and National Fisheries Research and Development Institute in Korea, discussed the use of USVs for continuous monitoring of harmful algal blooms. The study aimed to develop an algorithm to operate a USV to help avert disaster caused by (say) a 'red tide'. Real-time data transmitted from the robot – position, concentration of harmful algal cells, temperature, salinity and the speed and direction of drift of toxic algae – could be monitored, and warnings delivered to nearby fishery users. The paper concludes by assessing the technology's potential to lead to a breakthrough in the field of environmental surveillance (see Further Reading).

Back in the UK, the 'C-Enduro' is to be used by Heriot–Watt University for research into long-term activity involving multiple remote and autonomous marine platforms. The USV will be utilised as a moving navigation and communication platform for AUVs. By using a variety of telemetry channels such as GPRS, MESH radio or satellite, USV systems have the capacity to harvest data from multiple landers, sub-sea nodes, AUVs or fish tags, and transmit the information without the need to recover the deployed sub-sea instrumentation.

The future

Development of technology for remote data-collection is moving faster than the ability to transmit the information home. Autonomous and unmanned vehicles have increased their capacity to collect large volumes of data during deployments, but currently most satellites do not have the bandwidth available to send data inexpensively when the vehicles are out of range of radio or cell-phone-based receivers. This makes real-time monitoring away from coastal areas difficult to accomplish. As the capacity to transmit large volumes of data via satellite grows, real-time monitoring and delivery of large datasets will be achieved without recovery of the instrumention, relocation or large associated telemetry costs.

In the future, USVs will develop into truly autonomous systems, where vehicles with individual tasks and the ability to adapt the mission, communicate and work together in clusters. USVs are already being used like this, to some extent.

While USVs are now being used by science and research institutions, much of the technology is transferable to the military and security sector. The technology is already being expanded and tested for applications which include improving the efficiency of large ships, developing autonomous rescue vehicles, and contributing to maritime defence solutions.

USVs have the potential to grow in size and intelligence. Their ability to replace large research ships is just beginning to be explored. In the future, a lot of work at sea could be carried out autonomously, not only saving costs but potentially saving lives.

There is a real potential for autonomous USVs to provide a wealth of new data which researchers and operational oceanographers have, as yet, been unable to obtain, opening possibilities for many new scientific discoveries and robust climate modelling. As various types of vehicles continue to be developed, and participate in science projects, the technology is set to advance at an accelerated pace, hastening the time when there will be an integrated global real-time coastal and open-ocean monitoring network.

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Continuing the Challenger *Mission*

Addressing global problems of the Anthropocene

Scott Glenn, Josh Kohut and Oscar Schofield

The team on the HMS *Challenger* expedition was charged with collecting a global dataset on the physics, biology, chemistry, and geology of the ocean. The expedition, which began in 1872, sought to answer the most significant scientific questions of its day. Could Charles Darwin's theory of evolution be tested by sampling the deep sea? Would the deep sea, with its crushing pressure and low temperatures, be devoid of life, as predicted by the azoic theory that was widely supported at that time?

The pioneers who made up that scientific and naval team travelled nearly 70 000 nautical miles (128 000 km) around the globe (Figure 1), using the latest sampling technologies to painstakingly profile the ocean depths and then telegraph their discoveries to a waiting world. In the process, they discovered 4000 previously unknown species, found under-sea mountain ranges, and living fossils in the deep sea. Their effort, the first dedicated nautical expedition for science, heralded the epoch of ship-based expeditionary research in oceanography that continues today. While ships, instruments, sensors and understanding have matured much since 1872, expeditionary oceanography remains relatively unchanged. Scientists still spend years of their lives on board ships conducting research into pressing questions of the day.

Tackling challenges of the Anthropocene

What *has* changed since 1872 is the size and footprint of the human population. Humanity has become a global force that is driving planetary changes in ways that are still not understood. This human pressure will continue to increase. By 2050 the human population will have grown by another 2 billion, with expansion concentrated in less developed countries and crowded mega-cities along vulnerable coasts and rivers. With these new challenges, the global community will increasingly look to the sea for sustainable ways of meeting the growing demand for water, food and energy.

Understanding the ocean's carrying capacity and resilience are some the most the pressing questions facing this and future generations of oceanographers. Given the immense scale of the ocean, international partnership and collaboration is required to meet the challenge. Progress will require building a globally informed community of ocean citizens and improving our ability to forecast the average conditions of tomorrow's climate and the variability in tomorrow's weather. To this end, a consortium of collaborators – academic instiutions, learned societies (including the Challenger Society), and sponsors from industry and government – has initiated the Challenger Glider Mission, which re-imagines the historic four-year voyage of HMS *Challenger*.

In contrast to the first *Challenger* expedition of a single vessel carrying around 200 crew and scientists, the modern mission will involve a fleet of autonomous underwater glider robots making coordinated flights, controlled by a distributed global science community. These underwater gliders will be fitted out with sensors that sample the most energetic currents associated with the basin-scale gyres, and will be controlled remotely via the global Iridium* network. Robotic vehicles owned and operated by other institutions around the world will be able to join the mission by contributing their real-time data to the global portal which will have an open data policy.

Progress so far

The *Challenger* Mission was officially announced at Oceanology 2014 in London. The first test flight began in 2011 with the initial leg completed by the Slocum glider *Silbo* (see Box opposite), which was launched from Reykjavik, Iceland, on 23 June (Figure 2). *Silbo* flew to Gran Canaria where technicians from Teledyne Webb, PLOCAN, University of Las Palmas, Gran Canaria, and Rutgers assisted in the recovery, refurbishment and redeployment during July 2012. The glider then continued south near Cape Verde, turned west to cross the Atlantic north of the Equator and was eventually recovered near Barbados in the Caribbean. This leg of the mission was 6384 km long. *Silbo* is currently being prepared to

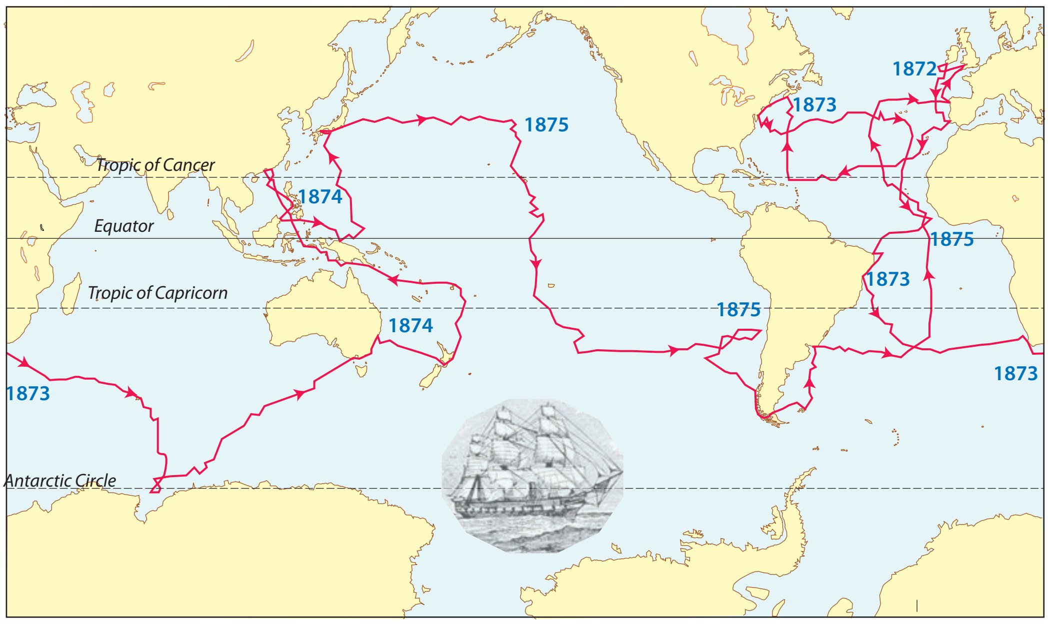


Figure 1 *The track of HMS* Challenger*, between December 1872 and May 1876*

*The Iridium system uses 66 satellites for worldwide voice and data communication from hand-held satellite phones and other transceiver units. The network is unique in that it covers the whole Earth, including the poles and the ocean.

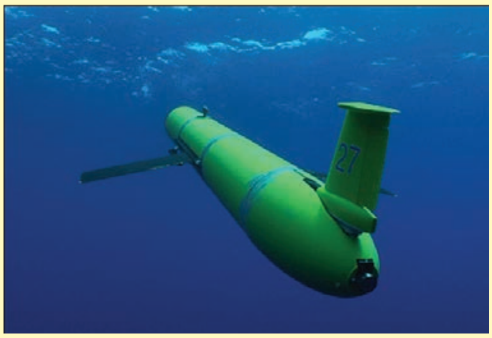
be launched from the eastern seaboard of the United States and take to a northern route towards England during 2015. Previously, the glider *RU29*, was launched on 11 January 2013 from Cape Town, South Africa. *RU29* travelled north-westwards and on 26 October 2013 arrived near Ascension Island where it was refurbished and launched westward. It was eventually recovered off Brazil on 18 May 2014 (Figure 2). This leg was 4720 km, and was undertaken in partnership with the University of Cape Town and the Southern Ocean Carbon and Climate Observatory. During 2015 and 2016 *RU29* is making a return west-to-east crossing along the southern boundary of the South Atlantic subtropical gyre.

Planning discussions are underway with the South Korean Institute of Ocean Sciences and Technology about the possibility of adding a series of Pacific glider flights. Now that the reliability of ocean-crossing gliders has been demonstrated with the long missions by *Silbo* and *RU29*, efforts are underway to increase the number of partners in the *Challenger* Mission. There will be flights in the Atlantic, Pacific and Indian Oceans, the Arctic Ocean and the Southern Ocean, and the total distance to be travelled by gliders as part of the Mission is expected to be far in excess of the original *Challenger*'s 128 000 km.

Buoyancy-driven gliders

This new *Challenger* Mission will be underpinned by buoyancy-driven gliders – underwater vehicles highlighted in Henry Stommel's science fiction vision of the future of oceanography (see Further Reading). There are several different types of buoyancy-driven gliders, but they are generally ~2 m long, and maneouver up and down through the water column in a sawtooth trajectory, at a forward speed of 20–30 cm s^{-1}. A glider adjusts its height in the water column by changing its buoyancy, by sucking in or discharging a small volume of seawater through its nose; hull-mounted wings then redirect the vertical sinking motion under gravity into forward movement. A tailfin rudder provides steering as the glider 'falls' and 'floats' its way through the ocean.

A glider's navigation system includes an onboard GPS receiver coupled with an attitude sensor, a depth sensor, and an altimeter. The vehicle uses this equipment to perform dead-reckoning navigation, where current position is calculated using a previously determined position, or fix, and that position is then updated on the basis of known or estimated speeds over elapsed time and course. In addition, the altimeter and depth sensor can be used to program the location of sampling in the water column. At predetermined intervals, the vehicle sits at the surface and extends an Iridium antenna out of the water to retrieve information about its position via GPS, transmit data to shore, and check for any changes to the mission.



A buoyancy-driven Slocum *glider patrolling the waters of the North Atlantic. The glider is travelling into the picture, and the tailfin rudder can be clearly seen.*

Because their motion is driven by buoyancy, the gliders' power consumption is low and their battery packs enable them to coast for up to year. They have a modular construction, allowing researchers to attach sensors customised for a particular science mission, and to reprogram what variables the sensors are recording in near real time, as the need arises. All gliders carry sensors to measure temperature and salinity; these data are open access and are made available for use in regional and global data-assimilation models. The data collected will be used to monitor heat content along specific transects of the upper ocean, assess heat transport, and how it is changing.

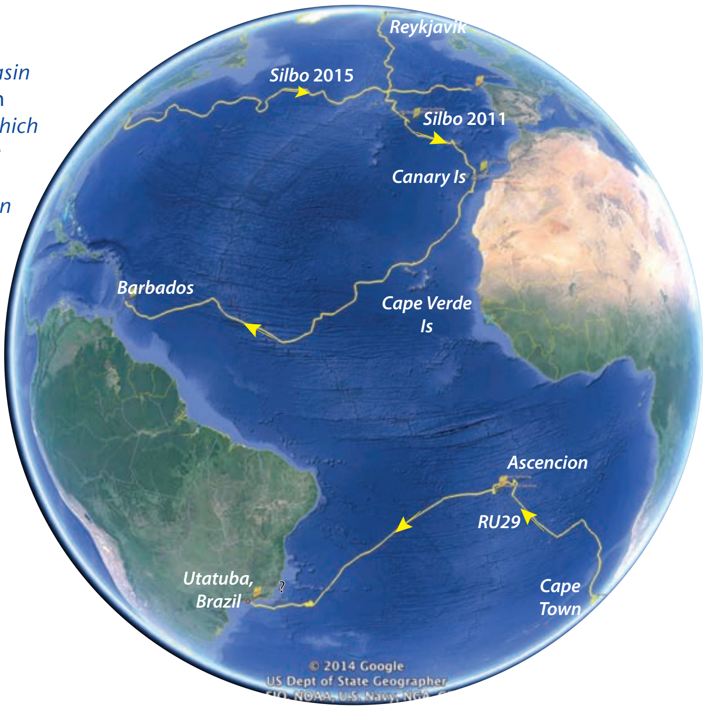


Figure 2 *Ocean-basin crossings by* Slocum *gliders. The first, which helped motivate the Challenger Mission, was from the eastern seaboard of the US to Spain. The first two legs of the Mission were from Iceland to Africa, and then to the Caribbean. The second leg was a flight from South Africa to Brazil.*

(Map by courtesy of Google)

Advantages of using gliders

A number of existing technologies already contribute pieces of the overall picture of the oceans. Satellites provide global maps of sea-surface temperatures. Argo, the global array of over 3000 free-drifting profiling floats (http://www.argo.ucsd.edu/), measures the temperature and salinity of the upper 2000 m of the ocean, but does not resolve the boundary currents and eddy fields. Altimeters provide information about surface currents, but calculation of heat transport depends on a combination of the temperature structure and the current profile. Most currents in the open/deep ocean run parallel to density fronts, so profiling drifters usually travel along the fronts. Data critical for assimilation need to be collected *across* the strong gradients that define the fronts. Autonomous robots not only use the currents to move along a front but can also fly across the fronts, gathering the high-resolution cross-frontal data that have a major impact on the accuracy of ocean models. Will the increase in the amount of frontal data reveal stronger currents and alter estimates of heat transport? To assess this question, data collected by the *Challenger* Glider Mission will be made available for assimilation experiments that can compare simulations with glider data with ones with no *in situ* data, and with any available Argo profiler data. The impact on the modelled currents, and the corresponding impact on regional heat transport, can then be assessed.

Contribution to climate modelling

One of the most pressing scientific needs today is an improved capacity to predict future environments. This requires a quantifiable understanding of the predictive capabilities of our present models for the atmosphere, the ocean, and the relationships between them. While global models of the atmosphere have existed for decades, accurate global coupled atmosphere–ocean models are a much more recent development. Our questions now focus on the prediction of our future ocean–atmosphere climate. How accurate are the models? How does that accuracy vary in space and time around the globe? What roles will new robotic ocean observation capabilities have in improving and evaluating the forecasts?

One goal of the *Challenger* Mission is therefore to provide data to improve global numerical models. To facilitate this effort, data from *Challenger* gliders will be available to modellers from different institutions and agencies. This is made possible by making use of data management tools of the US Integrated Ocean Observing System (IOOS) and the education tools of the US National Science Foundation's (NSF) Ocean Observing Initiative (OOI).

Educational aspects

A central goal of the *Challenger* Glider Mission is to build a global ocean-literate population through hands-on education and engagement in order to inspire the next generation of ocean scientists, provide an open-access training test-bed, and provide a forum for people to join a global science team.

Web-based Education Visualization (EV) tools are being configured to display real-time glider data with intuitive interactive browser-based tools. Using real-time glider data combined with an evolving suite of data-visualization tools reduces barriers to student participation. In brief, model-forecast ocean data are harvested as snapshots along glider tracks, allowing for direct comparison. The observed and forecast datasets, both evolving in real time, are accessible via web visualization tools which allow students to ask questions such as: Do the models and *in situ* data agree? If not, where is there a mismatch and what might be the cause?

This mode of student exploration has been tested over the last several years at Rutgers, and student projects have produced studies that have been published with undergraduate students as first authors (Further Reading). We hope the *Challenger* Mission will expand this model and allow this part of the project to become a crowd-sourced ocean predictive global skill experiment with communities of students from universities around the world interacting with one another.

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For more information on the *Challenger* Glider Mission please contact Patty Gillen at the Center for Deep Sea Ecology and Biotechnology. pgillen@marine.rutgers.edu

Ambergris: a 'morbid secretion' with mysterious properties

Ambergris has been greatly valued from earliest times. Today, it is best known as an important component of perfume, both as a fragrance in its own right and as a fixative. In the past it has been used in magic, and as a condiment.

It was first recorded early in the 9th century by an Arab traveller who came across trade in ambergris amongst the islands of the Indian Ocean. Presumably because of its odour, he supposed that it was a mushroom or truffle that grew at the bottom of the sea. In the 17th century it was thought to be the dried foam of the sea, or a foam from seals, or the excrement of a bird that lived on sweet-smelling herbs, or even a bitumen erupted from fountains at the bottom of the sea. This last had also been proposed as the origin of true amber, and the confusion continued with the suggestion that ambergris was solidified gum that had been produced by the roots of certain trees living near the coast.

Despite its exotic reputation, ambergris is unprepossessing in appearance – yellow, gray, black or variegated masses, somewhat resembling lard. Less dense than water, it may be found floating on the sea-surface, or cast up on the shore. Whalers have long known that it may also be extracted from dead sperm whales.

So what is ambergris? It is often said that it is 'whale vomit'. Not so. It is true that every couple of days a sperm whale will vomit into the ocean, producing a floating slurry of indigestible material, including squid beaks. A sperm whale might eat a tonne of squid a day, amongst which will be several thousand hard beaks. If this indigestible material leaks into the intestine, the tangled mass is pushed into the rectum, where faecal matter is precipitated onto it to form a smooth concretion, allowing liquid faeces to pass again. As this process is repeated, the size of the mass increases. Long incubation in an environment teeming with bacteria transforms the coprolith into the material we know as ambergris, which is only released when the whale eventually dies.

A lump of ambergris, which may be as small as a tennis ball or the size of a very large boulder, is made up of concentric layers, each studded with beaks of squids of varying species, and encoding characteristics of all the waters that the whale has been feeding in. In theory, this could be a great source of information, but ambergris is flotsam, and may have travelled thousands of kilometres in ocean currents before being found, so unravelling its history would be very difficult.

For more about ambergris see:

Clarke, R. (2006) The origin of ambergris. *Latin American Journal of Aquatic Mammals*, **5**, No.1, 7–21, doi: http://dx.doi.org/10.5597/lajam00087

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Ed

Celebrating 30 Years of the South Atlantic Tide Gauge Network

Angela Hibbert, Philip Woodworth, Peter Foden and Jeff Pugh

May 2015 will be a milestone for staff at the National Oceanography Centre (NOC) Liverpool, as it will mark 30 years since the foundation of the South Atlantic Tide Gauge Network (SATGN) (Figure 1). SATGN was created in 1985 at the instigation of David Cartwright (Director of what was then the Institute of Oceanographic Sciences, Bidston) under the auspices of the ACCLAIM programme (ACCLAIM = Antarctic Circumpolar Current Levels from Altimetry and Island Measurements). Since variability of transport in the Antarctic Circumpolar Current (ACC) was poorly understood at that time, a primary aim of both the programme and the SATGN network itself was to provide a means of monitoring ACC variability and of validating numerical models. This objective eventually led to one of the key activities of the World Ocean Circulation Experiment (WOCE).

The open-ocean islands of many British Overseas Territories in the South Atlantic are ideal locations for tide gauges used to calibrate satellite altimeters. Islands are preferred for this role because the near-shore dynamics of continental coastal sites are more likely to influence the sea level measured by a gauge; also, the echo from land is different from that from the ocean and can distort the processed altimetry signal.

Another objective of SATGN was to initiate measurements of long-term sea-level change in the South Atlantic – an historically under-sampled region. SATGN contributes data to the Global Sea Level Observing System (GLOSS)* of the Intergovernmental Oceanographic Commission (IOC), and to the major databanks such as the Permanent Service for Mean Sea Level. In this way, information on long-term sea-level change and variability in this data-sparse region could be input to programmes such as WOCE, and scientific assessments such as those of the Intergovernmental Panel on Climate Change.

The first SATGN gauge was established at Clarence Bay, Ascension Island, in May 1985, and was rapidly followed by installations at Tristan da Cunha and St Helena. By the early 1990s, there were also systems at Port Stanley (East Falkland), Rothera (on the Antarctic Peninsula) and at Signy Island (one of the South Orkney Islands). An additional pressure gauge was established at Vernadsky (formerly Faraday), Antarctica, in 1997, complementing a stilling well and float gauge that had been installed by the British Antarctic Survey in 1958. The network in its present form (Figure 1) was completed in 2008, with the addition of a tide gauge at King Edward Point, South Georgia. A new tide gauge at Gibraltar is also now considered part of the network.

Since its inception, NOC engineers have used SATGN to develop ground-breaking sea-level technology, whilst NOC scientists have surpassed the original aims of the ACCLAIM programme, making significant advances in our understanding of processes affecting sea level in the South Atlantic and Southern Ocean.

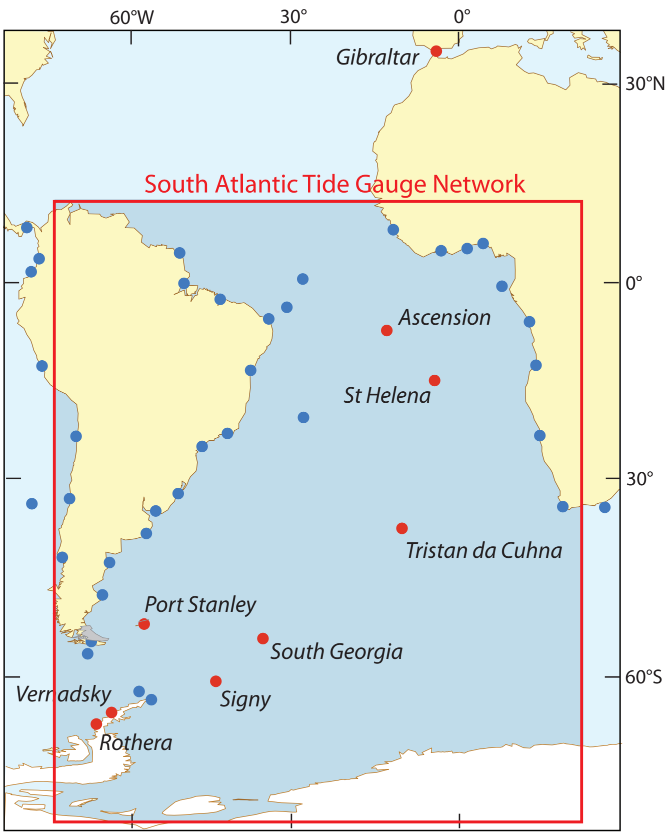

Figure 1 *Sites of coastal tide gauges belonging to the UK South Atlantic Tide Gauge Network (red dots). Gibraltar is also part of this network. Blue dots are gauges (not necessarily operational) committed to the GLOSS programme by other countries.*

* In addition to coastal tide gauges, there are sea-bed pressure recorders which are used to monitor sea level in open ocean locations, such as those shown at http://www.psmsl.org/data/bottom_pressure/

Technological innovations

By their nature, SATGN stations must be equipped with tide gauge instrumentation that is suited to hostile environments in remote locations – a factor which has been fundamental to the development of NOC sea-level monitoring technology. One key issue affecting these remote sites is that datum control (i.e. the referencing of tide gauge measurements to a fixed point on land) can be difficult because the measuring points of the gauges are submerged, and traditional methods of imposing a datum, such as employing manual observations using a tide pole, are impractical. Yet datum control is essential if tide gauge records are to be used to assess long-term trends in sea level.

To overcome this problem, NOC devised the 'B' gauge, which incorporates an additional measuring point at approximately mean sea level, which is exposed for half of the tidal cycle. The essential point is that the height of this mid-tide sensor can be related to the heights of benchmarks on land using conventional levelling. By fitting the rectified tidal curve of the mid-tide sensor to the curve of the fully submerged sensor, it is possible to provide precise datum control to the fully submerged sensor.

Figure 2 *The GPS receiver at King Edward Point, South Georgia*
(Photo by courtesy of Norman Teferle)

To further improve datum control of SATGN, NOC staff are currently working in collaboration with colleagues at the University of Luxembourg to install Global Navigation Satellite System (GNSS) receivers at South Atlantic tide gauge sites. These are usually Global Positioning System (GPS) receivers, such as that on South Georgia (Figure 2). Positioning GPS receivers close to tide gauges is useful, because as well as geographical position, GPS systems record vertical land movement due to various geophysical processes such as glacial isostatic adjustment (i.e. post-glacial rebound of the land). This allows us to estimate long-term trends in both absolute and relative sea level at a tide gauge site and thereby contribute to studies of both climate change and solid Earth processes.

A further challenge to operating remote tide gauge systems is the need for robust communications systems that rarely fail and are capable of storing large amounts of data locally in the event of a failure. As a result, NOC Liverpool engineers designed a real-time telemetry system that connects tide gauges (sampling at intervals of between 1 and 40 seconds) to a Linux-based data logger which returns data through the Inmarsat Broadband Global Area Network (BGAN) system every 15 minutes (Figure 3). Importantly, the system allows remote configuration of tide gauges – ideal for operating in remote locations. Such was the success of this system that in 2008 it was adopted by the IOC as one of the main forms of telemetry for the Indian Ocean Tsunami Monitoring System.

To further improve the resilience of SATGN, at a number of sites NOC Liverpool engineers have installed specialist data-loggers capable of storing data for up to 5 years in the event of communications failures. They are also currently experimenting with low-powered communications systems that use Iridium/cellular technology, and aim to test these in the Network during 2015–16.

One final issue that hinders sea-level measurements in hostile environments is the maintenance of underwater equipment, particularly at the highest latitude gauges in the Southern Ocean. In an attempt to address this, in the past few months NOC Liverpool engineers have custom-designed a radar gauge (Figure 4), which will be fitted to a stilling well that is insulated and heated to keep it ice-free. The major advantage of this instrument is that the radar is situated above the sea surface and so is easily accessible for maintenance purposes. The pilot installation will be made at Rothera later this year and will become the most southerly radar gauge in the world.

Figure 3 *The BGAN telemetry system, as used in the Indian Ocean Tsunami Monitoring System (see Further Reading).*

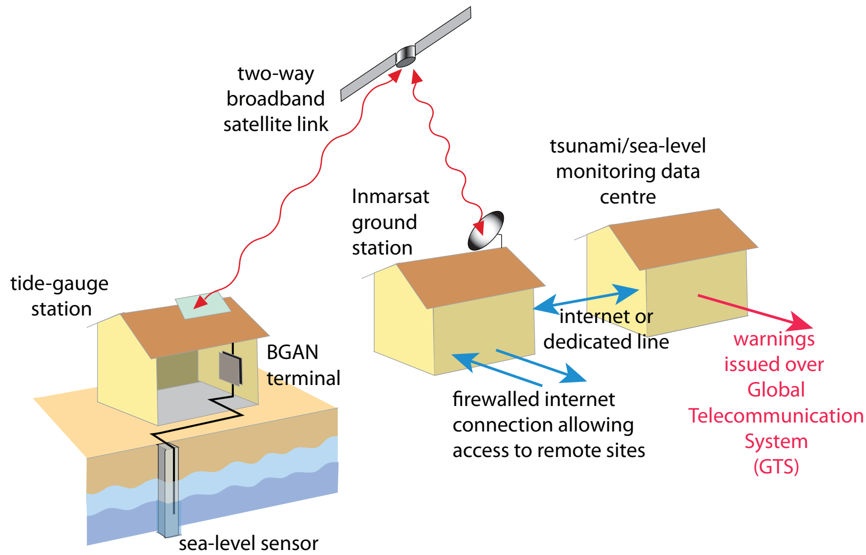

Figure 4 *The radar gauge for installation at Rothera. This unit emits high-frequency microwave pulses which are reflected by the sea-surface, allowing the height above sea level to be inferred from the transit time between emission and detection of the signal. The pulses are guided down the stainless steel cable to prevent them from reflecting off the walls of the stilling well and the cable itself is weighted to minimise vertical movement.*

Scientific developments

As described earlier, SATGN was, in part, established to improve understanding of ACC variability, and a number of NOC Liverpool scientists rose to the challenge – amongst them Phil Woodworth, Chris Hughes, Mike Meredith and Angela Hibbert. Using South Atlantic tide gauge data, they identified the 'Southern Ocean Coherent Mode' – a persistent, synchronised and ring-like pattern in sea level around Antarctica. This mode was found to covary with ACC transport on inter-annual and shorter time-scales and also to covary with an atmospheric pressure pattern known as the Southern Annular Mode which is an indicator of the strength of the westerly winds around Antarctica. Stronger westerlies would lead to an increased sea-level divergence around the Antarctic coast, causing the sea surface to tilt upwards from the coast. In response, an onshore flow would develop, but due to Earth's rotation, it would be deflected eastwards, increasing the flow of the ACC. This realisation was an important breakthrough, since it meant that sea-level slope could be used as a proxy for ACC transport. Interestingly, a further NOC study showed that the Southern Ocean Coherent Mode and ACC transport were modulated by a periodic reversal in the direction of the stratospheric winds in the Tropics. Most of these studies were focussed on interannual variability; decadal and longer term sea level and ACC variability are less clearly understood, which emphasises that the continuity of these tide gauge records is essential.

Since a secondary purpose of SATGN was calibration of satellite altimetry, an initial evaluation of this benchmarking was undertaken using data from Port Stanley. This showed that open-ocean island gauges such as that at Port Stanley were ideally positioned for this role, particularly given the accurate datum control that the tide gauges in question afforded. Consequently, many of the South Atlantic Network sites now form part of a subset of the GLOSS network which delivers 'ground-truth' for altimetry (Figure 5).

Over the past 30 years, numerous other studies have used SATGN data to explore sea-level variability on various time-scales. For example, tide gauge records from Port Stanley, and from decommissioned tide gauges at other sites in the Falklands, have been used to examine seiches, extreme events, tides and seasonal variability, as well as long-term trends. Port Stanley data have also been used to demonstrate that where tidal constituents K_1 and O_1 are of similar magnitude, they act as a carrier wave that is phase-locked with the M_2 tide, leading to asymmetry in the probability distribution function (PDF) of tidal elevation. Other studies evaluated the magnitude of the response of sea level to an increase in atmospheric pressure, known as the inverse barometer effect. Generally, an increase of ~1 mbar in atmospheric pressure will result in a ~1 cm drop in sea level, but studies using SATGN data showed how pressure waves in the Tropics caused significant departures from this standard response, even in extra-tropical areas (see Further Reading).

Even higher frequency fluctuations were the subject of studies of propagation across the oceans of the 2004 Indonesian tsunami, which was recorded at Signy, Stanley and St Helena, and also propagation of the 2011 Tohoku (or Sendai) tsunami. A 1999 study of wave activity identified swell in excess of 1 m and 2 m at St Helena and Ascension respectively; the swell lasted several days and resulted from a North Atlantic hurricane one week earlier, demonstrating how Northern Hemisphere swell can impact coastal communities in the Southern Hemisphere (see Further Reading).

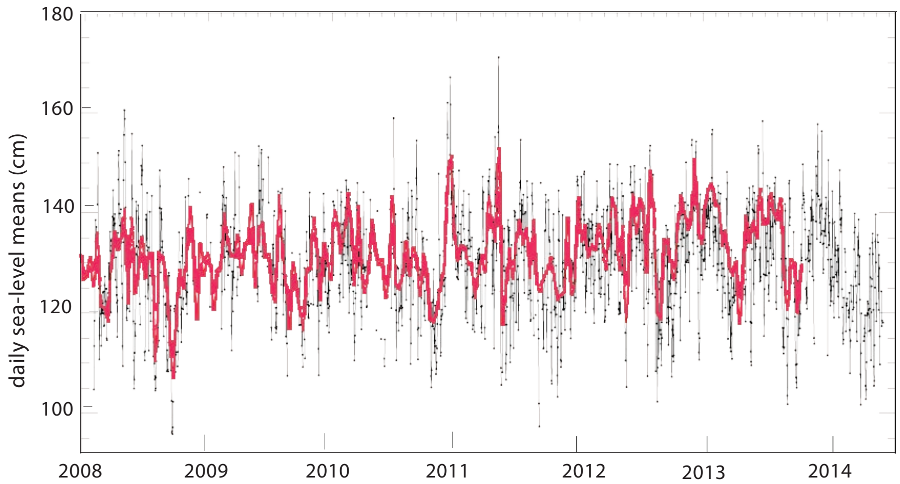

Figure 5 *Sea-level data from the King Edward Point tide gauge on South Georgia (black) and sea-level at the same location from satellite altimetry (red). (Neither has been corrected for the effect of atmospheric pressure.)* *(Altimetry time-series by courtesy of Brian Beckley)*

Clearly, data from SATGN have proved to be useful in many aspects of scientific research, and they have also been valuable in many practical applications such as the design of coastal infrastructure at Port Stanley. SATGN now contributes some of the longest Southern Hemisphere sea-level records to GLOSS, and has helped to improve understanding of long-term change in the region. For example, it has provided estimates of sea-level trends in the Falklands during recent decades, and has compared them with trends over much longer time-scales (i.e. since 1842, making use of measurements by James Clark Ross), establishing that sea level is now rising faster in this part of the world than previously. Similar studies have been made using data from Ascension Island (1955 onwards), again demonstrating a recent increase in the rate of sea-level rise. Furthermore, records from the Gibraltar tide gauge now span 50 years and have been employed in numerous studies of exchange flows between the Mediterranean Sea and the North Atlantic.

SATGN has been a great success in terms of meeting its original objectives, but NOC Liverpool believes that research using the network is far from complete. Sustained sea-level observations are extremely important in the context of climate change, particularly in data-sparse regions like the South Atlantic, and if we are to improve our understanding of interannual, decadal and longer term variability, SATGN is only just at the beginning of its useful life.

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Mathers, E.L., P.L. Woodworth (2004) A study of departures from the inverse barometer response of sea level to air pressure forcing at a period of 5 days, *Quarterly Journal of the Royal Meteorological Society*, **130**, 725–38.

Vassie, J.M., P.L. Woodworth and J.W. Holt (2003) An example of North Atlantic deep-ocean swell impacting Ascension and St. Helena Islands in the Central South Atlantic. *Journal of Atmospheric and Ocean Technology*, **21**, 1095–103.

For more on different kinds of tide gauges see http://noc.ac.uk/science-technology/climate-sea-level/sea-level/tides/tide-gauges/tide-gauge-instrumentation?page=0,3

Angela Hibbert and **Philip Woodworth** are the current and former scientific coordinators of SATGN; **Peter Foden** and **Jeff Pugh** are responsible for the development, testing, installation and maintenance of SATGN instrumentation. All are at the National Oceanography Centre (NOC), Joseph Proudman Building, Liverpool. anhi@noc.ac.uk

Stop Press NERC recently announced that it will provide funding to allow all SATGN tide gauges to have customised radar gauges, GPS receivers, specialist data-loggers and Iridium/cellular communications technology.

Tides on the wind

Looking for links on the Links

David Pugh and Ian Vassie

Golf is never easy. The fairways are too narrow, the rough is too rough, and the greens are not flat. And then there is the wind, which is often strongest by the sea. Even Rory McIlroy struggles for good scores in high winds.

As part-time golfers, and one-time tidal scientists, we have often argued about the television commentators' mantra, regularly repeated every July at the Open Golf Championship, that 'the wind changes with the tide'. All the Open Golf courses are seaside links, and there is usually plenty of scenic tidal activity for the cameras to capture, but what 'the wind changes with the tide' means is rather vague. We suppose it suggests that high tidal sea levels are accompanied by a change in wind direction, or an increase in local winds.

Our recent interest in the tide–wind relationship was stimulated by the 2014 Open Golf at Hoylake on the Wirral Peninsula, near Liverpool, which incidentally, Rory McIlroy won, at seventeen under par, despite some windy days! For our investigations, Hoylake, specifically the Royal Liverpool Golf Club, has the advantage of a nearby long-term meteorological station. This station, which is only accessible at low tide, is maintained on Hilbre Island in the Dee Estuary (Figure 1(a)) by the National Oceanography Centre. The Hilbre Island Meteorological Observatory, which records many environmental parameters including wind speed and direction, air pressure and solar radiation, is only 2 km from the Championship Course, across an expanse of intertidal sands (Figure 1(b)). The continuing series of meteorological measurements, begun in 2004, is available from the British Oceanographic Data Centre (BODC) of the Natural Environment Research Council. Our aim was to use these data to detect tidal effects on the local atmospheric circulation, associated with tidally generated variation in local sea level.

Analysis

The basic data supplied by BODC were in 10-minute values. These basic values were filtered and edited: wind speeds and directions were resolved into northward and eastward wind components – we adopted the oceanographic convention of direction being defined as where the wind or current is going, rather than the meteorological convention of where the wind comes from. We restricted our work to data from the months June, July and August in each of the years from 2004 to 2012. The main golfing months are in this period and the daily land/sea solar heating cycle is strongest then. Spectral analyses (Figure 2) show a major spike in the wind at one cycle per day in both the eastward and northward wind components, but there are high levels of background noise at all lower frequencies. However, other spikes in the wind energy, including the small energy increase at the semidiurnal frequency (solar and moon terms, symbolised as S_2 and M_2) are detectable, but not obvious.

The once-a-day diurnal spike is the globally well known onshore–offshore diurnal wind driven by land heating and cooling over the course of 24 hours. During the day, the land warms so the overlying air rises, to be replaced by winds from the cooler sea; at night the temperature difference reverses as the land cools, so at night the winds blow offshore. This regular onshore/offshore cycle is strictly a radiational tide; unlike marine tides, it is not driven by gravitational forces, and in fact, the exact 24-hour period is not present in the full gravitational forcing spectrum.

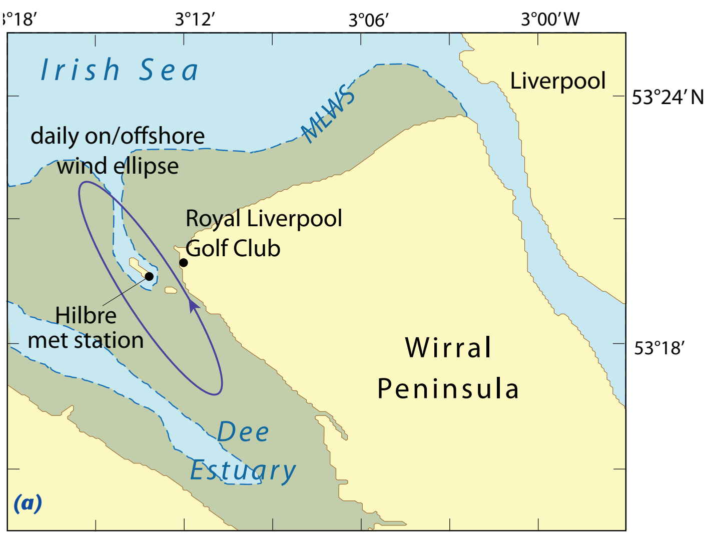
Results

To investigate further we made tidal harmonic analyses of the three summer months of data from each of the nine years 2004 to 2012, and compared the results. There is no difference in principle in applying a tidal analysis program to any geophysical parameter, though of course the normal application is to sea level and tidal stream analysis. For this tidal analysis of the winds we selected a special set of tidal frequencies, related to the problem.

Our seven constituents were:

MS_f The 14.8-day spring–neap period; this nomenclature derives from being a fortnightly tide generated by effects of both the Moon and Sun.

Figure 1 ***(a)*** *Map of the area of the River Dee Estuary, showing locations of the Royal Liverpool Golf Course and the Hilbre Island Meteorological Observatory. The green region corresponds approximately to the area of intertidal sands exposed at low water spring tides (MLWS = mean low water springs).* ***(b)*** *Hilbre Island and the weather station, seen from the Royal Liverpool Golf Course, Hoylake (inset).*



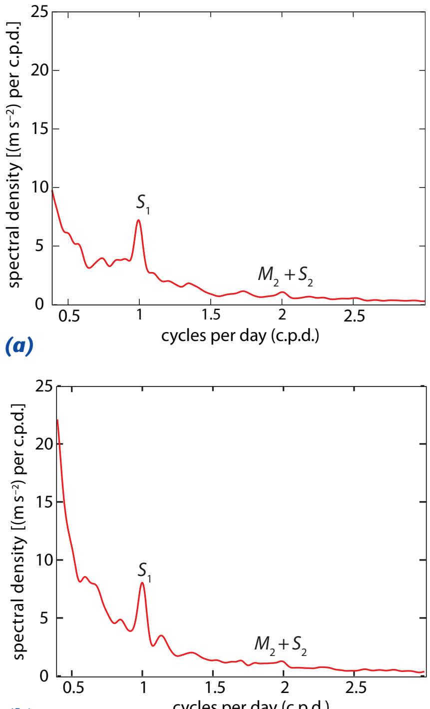


***Figure 2** Spectrum of the low-frequency components of the **(a)** northward and **(b)** eastward wind components at Hilbre Island. The scales are the same. In each spectrum there are small peaks around one cycle per day, and a smaller one at two cycles per day, but most of the energy is at lower frequencies.*

S_1 The classic diurnal sea breeze frequency

M_2 The standard lunar semidiurnal tide, dominant in the UK

S_2 Twice-daily solar tide, a harmonic of the diurnal sea breeze S_1

S_4 A higher harmonic of the diurnal sea breeze

A_1 Lower sideband of S_1, representing a spring–neap modulation

B_1 Another spring–neap sideband, at the higher frequency

The S_1 and M_2 harmonics were directly part of our investigation. The other terms need some explanation. The S_2 and S_4 higher harmonics of the S_1 term cover asymmetry in the main diurnal term. The A_1 and B_1 terms are at frequencies above and below the regular diurnal cycle of S_1, which can increase and decrease the amplitude of S_1, if there is any influence over a 14.8-day spring–neap cycle. We wanted to test for possible wind effects of the bigger and smaller tidal excursions of the sea up and down the shore, as the tide changes from large spring ranges to smaller neap ranges. The MS_f term is included to capture related effects, if they are present. The A_1 and B_1 frequencies, included here, are not part of the gravitational tidal forcing and so are not included in normal marine tidal analyses.

The first and obvious conclusion from our data is that the tidal part of the winds is much smaller than the irregular general wind variations. Table 1 shows that nearly 97% of the wind energy, or variance, is at non-tidal frequencies; these winds are part of the general weather patterns over the British Isles. Against this high non-tidal energy background, the 3% of tidal energy is harder to determine, and our analyses showed a lot of variability.

Table 2 shows the arithmetically averaged results of the harmonic analyses of the wind components, over the nine years of three-month periods. The standard deviations capture the year-to-year variability about the long-term average values.

Z_0 is the mean wind speed; the first row of Table 2 shows that winds to the east are dominant – as expected, given that the prevailing wind direction is from the west. The spring–neap fortnightly harmonic term MS_f, although relatively large, is very variable from year to year and is probably only due to a noisy low-frequency background. The twice-daily term S_2 is significant and represents a slight asymmetry in the daily onshore–offshore wind cycle. The four-times-a-day term S_4 is very small.

The strongest tidal term is the S_1 diurnal wind component, which in total comprises 2.5% of the total wind energy. Figure 3 shows how the tidal energy in the winds is dominated by S_1, with the M_2 lunar constituent significantly smaller than S_2, the first harmonic of S_1. The A_1 and B_1 sidebands are discussed later.

***Table 1** The distribution of wind energy/variance for tidal (blue) and non-tidal components (data are from 2004 to 2012, for the months of June, July and August). Only ~ 3% of the energy is tidal. Kinetic wind energy is related to the square of the wind speed; this is conveniently linked to the variance, which is the square of the standard deviations.*

	wind energy/ variance $(\mathrm{m\,s^{-1}})^2$	%
S_1	1.05	2.41
M_2	0.06	0.13
S_2	0.08	0.18
S_4	0.01	0.01
A_1	0.13	0.29
B_1	0.07	0.17
non-tidal	42.17	96.81
total winds	43.56	100

***Figure 3** A pie chart showing how tidal signals at Hilbre contribute to the 3% of wind energy that is due to the tides, averaged over nine years of June, July and August.*

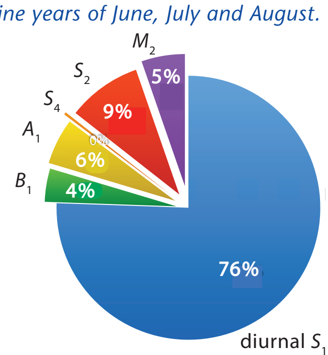


***Table 2** Harmonic analyses of the wind components; Z_0 = mean wind speed. The values are the means of nine separate years of analyses of data from the months June, July and August. The standard deviations are based on inter-annual variability. The Greenwich phase lag column shows how maximum values lag after the Moon's transit of the Greenwich Meridian, the standard zero time adopted in tidal studies.*

		Eastward winds		Northward winds	
Constituent	speed (deg yr⁻¹)	amplitude $(\mathrm{m\,s^{-1}})$	Greenwich phase lag (deg)	amplitude $(\mathrm{m\,s^{-1}})$	Greenwich phase lag (deg)
Z_0	0	2.71 ± 0.64		0.60 ± 0.72	
MS_f	1.02	0.90 ± 0.49	233 ± 69	0.89 ± 0.47	231 ± 82
S_1	15.00	0.73 ± 0.19	62 ± 17	0.72 ± 0.22	221 ± 12
M_2	28.98	0.19 ± 0.08	214 ± 52	0.14 ± 0.06	80 ± 40
S_2	30.00	0.19 ± 0.09	77 ± 62	0.21 ± 0.08	249 ± 15
S_4	60.00	0.06 ± 0.03	179 ± 99	0.05 ± 0.02	162 ± 96
A_1	13.98	0.25 ± 0.14	235 ± 115	0.25 ± 0.18	206 ± 94
B_1	16.02	0.20 ± 0.11	216 ± 111	0.18 ±0.08	152 ± 97

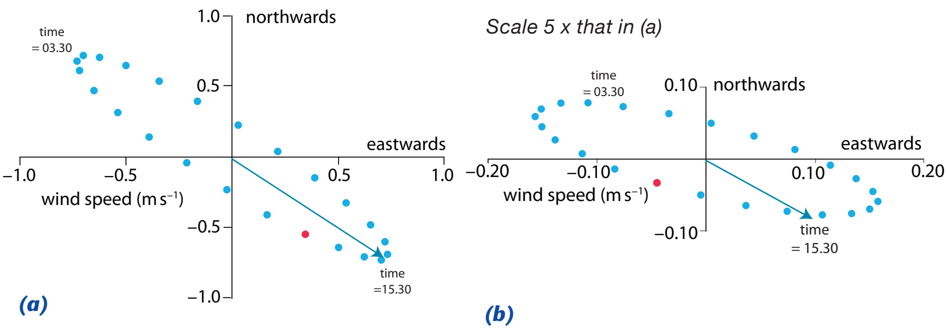


Figure 4 (a) *The tidal wind ellipse for the S_1 offshore/onshore winds, averaged over nine years. The main axis lines up along the Dee Estuary (cf. Figure 1), with the maximum onshore wind around 15.30 in the afternoon. The red point coincides with local mid-day. The wind vector, shown for 15.30, rotates anticlockwise.*
(b) *The tidal wind ellipse for M_2, which has much smaller amplitudes than S_1 (scale 5 x that in (a)) The wind vector again rotates anticlockwise. The components are the vector averaged ones shown in Figure 5.*

We can combine the eastward and northward wind components into wind vector ellipses, where the vector sweeps around the ellipse as the direction changes through the cycle, and where its length from the centre represents the wind strength.

Figure 4(a) shows the resulting plot for the S_1 wind using the arithmetically averaged values of amplitude and phase in Table 2. The principal axis of the ellipse is very closely aligned with the axis of the River Dee estuary (cf. Figure 1), reaching a maximum onshore speed of nearly 1.0 m s^{-1} at around 15.30 in the afternoon, and the maximum offshore 1.0 m s^{-1} winds at 03.30 in the night. This close alignment with the Dee Estuary axis suggests that the local winds behave similarly over the whole estuary.

The M_2 wind ellipse shown in Figure 4(b) is very much weaker than S_1. It is also aligned along the axis of the estuary. In Figure 5, the eastward and the northward components of the M_2 wind tidal constituents are plotted in frequency space, for each of the nine separate summers. There is a definite pattern confirming a real M_2 signal, but also considerable year-on-year variability. The red arrows are the vector-averaged tidal components of the nine annual analyses used for the spatial ellipse in Figure 4(b).

There is no obvious explanation for the alignment along the estuary, except perhaps that when the estuary is full of water it offers less wind drag resistance compared with wind flowing over land vegetation, and so the winds are preferentially directed along the estuary.

Incidentally, our analyses of the other weather parameters were consistent with accepted theory. The air pressures had a significant twice-daily S_2 cycle with amplitude 0.26 ± 0.2 millibars and a local maximum at 10.41 ± 12 minutes (a.m. and p.m.) adjusted for local time at 30 22' west of the Greenwich meridian. The solar radiation, also adjusted for local time, was a maximum at 2 ± 2 minutes after noon.

The MS_f, A_1 and B_1 terms, which would capture any spring–neap effects on the wind, were not detected against the background noise, which increases rapidly at low frequencies. This background noise also increases around the S_1 frequency. So the spring–neap tidal effects were negligible.

Conclusions

From our analyses we see that only ~ 3% of the wind energy at Hilbre is associated with the tides. Most of the wind energy is due to wide-scale weather patterns, and the passage of cyclones and anticyclones extending over hundreds of kilometres.

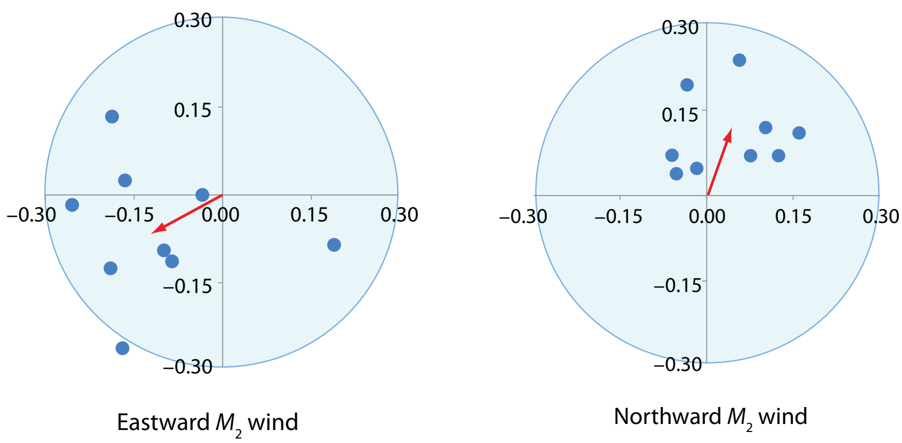
The only clear tidal signal in the winds is the daily land/sea breeze cycle, S_1, which in summer, on average blows onshore up the estuary, with a maximum speed of around 1.0 m s^{-1}, around 15.30 in the afternoon. This effect will be directly noticeable only on otherwise relatively calm days.

Our search for a pure tidal semidiurnal lunar tide in the winds has shown only a small though significant wind that blows along the estuary axis with maximum ellipse amplitudes of around 0.15 m s^{-1}. This result is based on rigorous analyses of long periods of data: nine years, averaged over the three summer months of June, July and August. Any analysis of a single month, or even three summer months in single years, produces very variable results for M_2, as shown in Figure 5. Even over such a long period of analysed data, we could find no clear tidal spring–neap wind effects.

The physical cause of the weak M_2 winds is not known. Possible candidates include migration of the sea/land interface as the tide moves in and out, generating very local thermally generated winds, and changes in surface roughness (land versus sea) as the tide ebbs and flows. It should be noted that the anemometer on Hilbre is fixed 27 m above Ordnance Datum Newlyn, while the sea surface moves up and down tidally by as much as 10 m, meaning that the winds are measured at heights which vary tidally from 22 m to 32 m above the sea.

In summary, our analyses found a definite, but very weak effect of the local tides M_2 on the local winds. The onshore/offshore winds S_1 are easily detectable. Of course these results apply only for one location, and it would be interesting to make similar comparisons at other coastal sites. However, it is unlikely that there will be many long-term coastal meteorological

Figure 5 *The eastward and northward components of the* M_2 *wind tidal constituents are plotted here in frequency space, for each of the nine separate summers (blue dots). In this polar plot the phases are in the usual Cartesian sense, rotating positive, anticlockwise from zero. There is a definite pattern, but also considerable year-on-year variability. The red arrows are the vector-averaged tidal components of the nine annual analyses.*



observatories with such high quality wind data available for analysis.

Discussion

This leads to the question: is the axiom ‘the wind changes with the tide’ a total myth? Strictly this seems to be the case. However, there are possible explanations why the story persists, particularly when related to the locations of the British Open Golf Championship. We offer the following hypothesis as one such explanation.

There are currently nine courses where the Open Golf Championship is held. Eight of these cluster together in three regions, each of which has locally characteristic tides. These regions are eastern mid-Scotland (St Andrews, Carnoustie, and Muirfield), south-west Scotland (Turnberry and Troon) and Liverpool Bay (Birkdale, Lytham and Hoylake). Royal St George’s is at Sandwich in Kent, alone in the south-east of England (see Table 3). The tidal ranges are large in all these regions, with the exception of south-west Scotland.

Table 3 Locations and tidal characteristics of the nine links seaside golf courses used for the British Open Golf Championship. The regional groupings are discussed in the text; note the similar tidal characteristics in each region.

	Most recent event	Next event	Spring range (m)	Time of max. spring tide
St Andrews (St Andrews)	2010	2015	4.4	15.30
Carnoustie (Carnoustie, Angus)	2007	2018	4.4	15.36
Muirfield (Gullane, East Lothian)	2013		4.6	15.14
Turnberry (Turnberry, South Ayrshire)	2009		2.7	13.00
Troon (Troon, South Ayrshire)	2004	2016	2.8	13.06
Royal St George’s (Sandwich, Kent)	2011		5.2	12.50
Royal Birkdale (Southport, Merseyside	2008	2017	8.0	12.10
Royal Lytham (Lytham St Annes, Lancashire)	2012		8.0	12.10
Royal Liverpool (Hoylake, Merseyside)	2014		7.8	12.02

Where there are large expanses of foreshore, neap tides are generally not noticed or considered, as they don’t reach the local higher beach levels. Spring tides are generally noticed and commented on as they often come right up to the edges of the links courses. It is a general feature of semidiurnal marine tides that, because of the changes of high-tide times through the day, the big spring tides have their maximum high waters at specific times of the day, and this time is unchanging for a particular coastal location.

Table 3 shows in the final column the time of day when maximum tidal heights occur at each Open Golf location. For all these, the time of maximum tidal incursion is between noon and just after 15.00. The time of maximum onshore diurnal winds, in all coastal locations, is also close to 15.00, mid-afternoon. Hence for all nine sites the onshore diurnal winds are increasing as the spring tides are flowing in. This regular relationship may perhaps explain the belief that ‘the wind changes with the tide’.

More generally, at all coastal sites, there will be a definite correlation between the big spring tides and the phase of the diurnal land–sea breezes. This is not a direct causal link, but occurs because both high water on the big spring tides, and the onshore diurnal winds, are both independently phase-linked to the solar day.

A similar explanation might apply to the reported enhanced swing of a cricket ball when the tide is high alongside the Sussex ground at Hove. Also, coastal sailors may sail more often in the afternoon and on spring tides, which may give rise to a similar misleading connection.

Of course, all this speculation and analysis is of no use to the golfer standing ready to play the ball. Wind predictions days or weeks in advance are no substitute for allowing for the observed winds at the time. Our advice to seaside golfers is clear: forget the wind theories, allow for the actual wind. And remember, it’s always further to the flag than you think!

Acknowledgements

We are grateful to Philip Woodworth for helpful discussions and assistance with the spectral analyses and diagrams. Polly Hadziabdic supplied the data from BODC. Thanks also go to Judith Wolf and Trevor Guymer for useful discussions.

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Cautious optimism for cod?

After many gloomy reports about over-exploitaiton of fish stocks, it is heartening to be able to write that ICES, the International Council for the Exploration of the Seas, has proposed an increase in this year’s North Sea cod quota of about 5000 tonnes, raising it from an earlier agreed quota of 35 100 tonnes up to 40 419 tonnes, and is recommending an even higher catch for 2016. The move indicates what most fishermen have been claiming for some time – that cod stocks in the North Sea have improved significantly. Things also look brighter for cod stocks on the Canadian Grand Banks, where there has been a moratorium on catching cod since 1992. Here, cod stocks are up for the third year in a row, although the moratorium remains in place.

There was also good news on North Sea haddock, with a recommended increase of 14 000 tonnes in the 2016 quota, to a total catch of 74 854 tonnes. However, stocks of whiting are still declining, as are some stocks of *Nephrops* (‘scampi’).

It has been known for some time that rising sea temperatures are pushing cold-water fish polewards**.** While this has been of concern in the case of North Sea fisheries, in the Barents Sea, which has warmed by 0.8°C since the early 1980s, stocks of many species, including cod, haddock, herring and mackerel, are increasing – at least for now. Ed

Improving understanding of shelf-sea exchange

Karen Guihou and Jeff Polton

Understanding coastal dynamics and ocean–shelf exchange

Coastlines along north-west European continental shelf seas are largely protected from the influence of open-ocean variability by the shelf break, which presents a formidable barrier to the transport and exchange of oceanic and shelf-sea water masses and properties. Understanding the processes that mediate exchange across the shelf break is critical to understanding how our shelf seas respond to climate variability.

The shelf around the British Isles is irregular, with a broad shelf in the Celtic Sea and the North Sea, and a narrower shelf off the north-west coast. The contribution of different processes to the shelf-sea exchange varies from one region to another, even if the tides stay the predominant forcing. The seasonal cycle, with a stratified state in summer and a mixed water column in winter, produces a strong seasonal variability, with internal tides propagating onto the shelf in summer. The intense current that flows polewards along the continental slope can get unstable and generate eddies and meanders, which can penetrate onto the shelf. All these processes, as well as the wind and shelf currents, play a key role in cross-shelf exchanges, but work is still needed to fully understand the impact of these various factors on each region.

The FASTNEt project (FASTNEt = Fluxes Across Sloping Topography of the North East Atlantic) is funded by a Directed Research Grant from the Natural Environment Research Council, and is being undertaken in collaboration with SAMS, NOC, PML and the universities of Bangor, Liverpool and Plymouth. It aims to resolve key seasonal, inter-annual and regional variations in ocean–shelf exchange, through observations (gliders, cruises, moorings, drifters etc.) and modelling. Resolving the different scales of variability is fundamental in the context of research into climate change and global warming. Most fisheries activities take place on the shelf, which is a place of high primary production, so also playing an important role in the uptake of carbon from the atmosphere. A better understanding of the high frequency variability of coastal processes is also necessary in the context of increasing numbers of storm surges and extreme events.

The limits of observation and new insights from modelling

Within the framework of the FASTNEt project, *in situ* measurements (from CTDs, gliders, scan-fish, drifters, or along mooring lines) have been conducted on the shelf and at the shelf break, mainly in the Celtic Sea, over the Malin Shelf and the Faeroe–Shetland Channel. These high-frequency data (of the order of per minute) capture high-frequency processes such as internal tides or eddies, which play an important role in mixing and shelf-sea exchange. However, *in situ* measurements are made at one location (CTD deployments, moorings) or along sections (gliders, drifters, scan-fish). This restricted spatial coverage limits understanding of the general circulation and the propagation of high-frequency patterns. Moreover, observations are generally limited to the summer months, when the weather permits campaigns at sea.

Improvements in numerical models over past decades has made them powerful tools for studying the ocean. The temporal frequency of the numerical simulations is often lower than that of the observations (seconds/minutes vs hours/days (due to computing and storage cost), but they allow complete spatial coverage of a simulation domain, which can be used to monitor the spatio-temporal evolution of a hydrodynamic feature, such as a current or eddy.

The lower the resolution of the model, the fewer structures can be simulated (as the sub-grid processes, i.e. processes with a scale smaller than the grid resolution, cannot be resolved). With the increase of calculation power, we are now developing higher resolution configurations, which permit the resolution of finer scales over wider areas. Global or basin-scale models (1/12th of a degree) reproduce the general circulation offshore and on the shelf, but are too coarse to study the details of shelf-sea exchange and mesoscale processes. Therefore finer scale models, with more limited regional domains, are required to study these processes for the same computational cost.

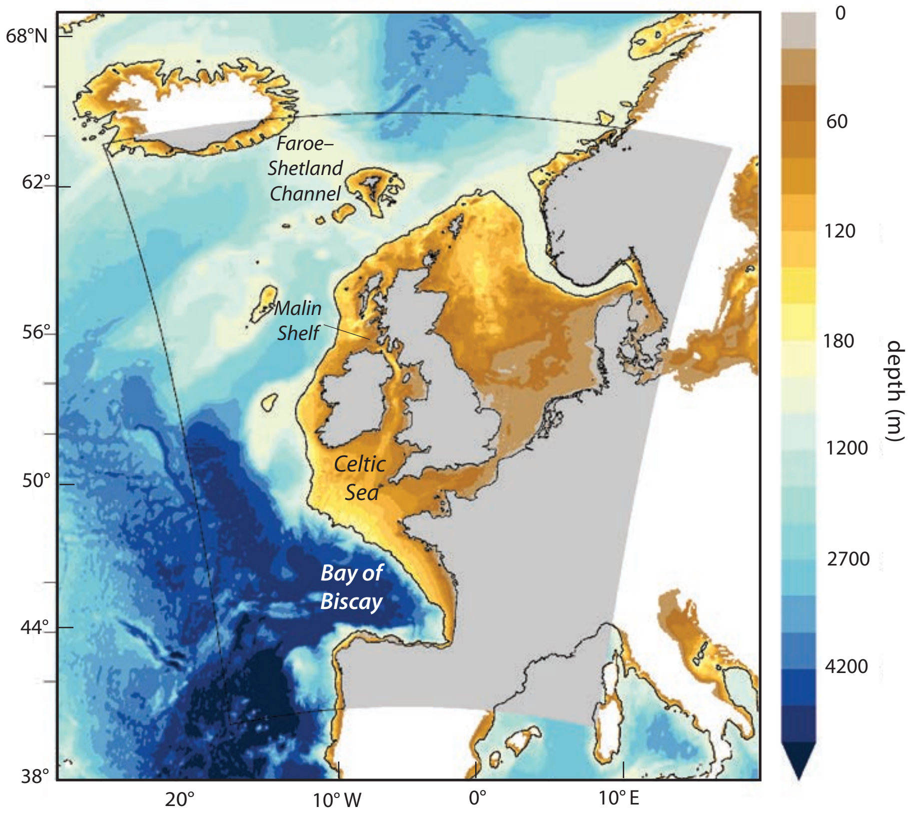

Figure 1 *Bathymetry off north-east Europe, with the area covered by the AMM60 configuration delimited by the black line. The black 200 m depth contour marks the approximate position of the shelf break – the marked change in gradient between the continental shelf and the continental slope.*

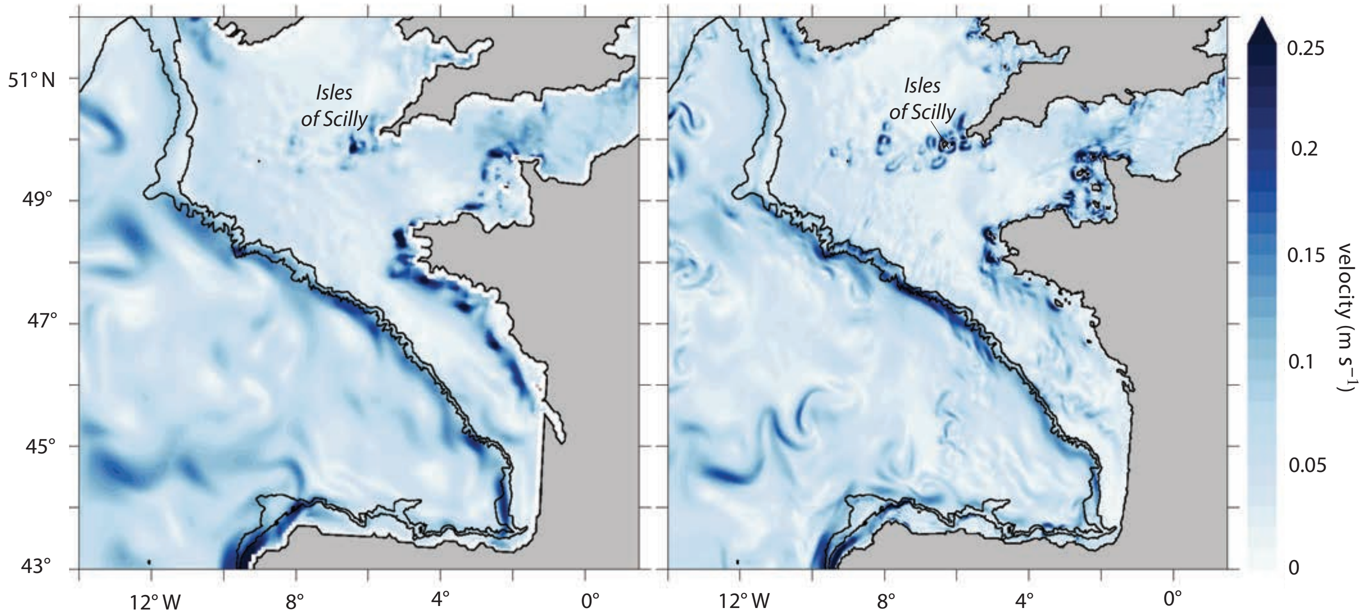

Figure 2 *Velocity fields (m s^{-1}) averaged over 5 days for the upper 10 m in the Celtic Sea and Bay of Biscay. The 200 m and 1000 m isobaths are shown in black (cf. Figure 1).* ***Left*** *The 1/12th degree configuration (NNA).* ***Right*** *The 1/60th configuration (AMM60). The AMM60 velocity field shows eddies in finer detail, and clear onshore flow up submarine canyons onto the Celtic Sea shelf; the slope current off northern Spain also appears more continuous.*

The value of high resolution

Developed as part of the FASTNEt project, AMM60 (Atlantic Margin Model at 1/60th of a degree) is a new, higher resolution configuration of the UK Met Office operational Atlantic Margin configuration, at 1/60th degree resolution in the horizontal (~1.8 km, compared with ~7 km previously). It extends from 40.1° N to 64.9° N, and from 24.9° W to 17.3° E, encompassing the whole Atlantic margin, from Spain to Norway (Figure 1). It is based on the NEMO code (http://www.nemo-ocean.eu) and is intended to reproduce complex, relatively small-scale processes such as currents resulting from internal tides, slope-current meanders and eddies, on the shelf as well as along the slope. As it reproduces more small-scale features than basin-scale configurations, AMM60 is better suited to data–model intercomparisons and quantification of the cross-shelf exchange.

In order to simulate realistic velocity fields in line with recent observations, it is necessary to provide the model with atmospheric forcing (wind, humidity, temperature etc. plus solar flux) as well as oceanic boundary forcing: tidal forcing at the lateral boundaries is derived from a remote sensing product (Topex/Poseidon altimeter); water masses and oceanic velocities come from a 1/12th model (the Northern North Atlantic configuration, NNA), which has been run on a basin scale and for a longer period than AMM60. NNA is based on the same numerical code as AMM60 (NEMO), and aims at reproducing the general long-term circulation in the basin. In the context of FASTNEt, this configuration will be used to track water particles to gain insight into distant water mass origins, transport across the shelf, and inter-annual variability.

Figure 2 shows the velocity fields averaged over 5 days and 10 m for the 1/12th degree NNA configuration (left) and AMM60 (right), for 3 March 2010. Both simulations reproduce a warm and saline poleward current, flowing along the 1000 m isobath (i.e. along the continental slope). This current is stronger in the high-resolution simulation, with speeds up to 0.3 m s^{-1}. It is also more unstable, having generated strong mesoscale activity: filaments, eddies – cyclonic and anticyclonic – can be observed off the shelf, mainly in the Bay of Biscay. Such activity can also be observed in NNA (left), but the resolution of the configuration is too limited to fully resolve the eddies. The fine-scale processes linked to high-resolution patterns in the bathymetry are also better resolved in AMM60. For instance, on the Celtic Sea shelf, there is an on-shelf flow towards the coast along submarine canyons (e.g. around 48° N, 8° W), and eddies can be seen forming around banks off the Isles of Scilly (south-west of the tip of Cornwall). This comparison demonstrates the capacity of the high-resolution configuration to reproduce similar general patterns but more energetic processes, such as eddies and internal tides, due to its finer grid.

Such numerical simulations, thanks to their large spatio-temporal coverage, can also improve our knowledge of seasonal and interannual variability of the ocean, and help identify the controlling processes in shelf-sea exchange. It can also help identify regions of special interest where, for example, persistent eddy or high internal tide activity is present, and where intensive observations could be conducted.

However, it is important not to overlook that, whatever their resolution, models must be validated against observations. In this project the modellers and observationalists are working closely together to mutual benefit.

The FASTNEt project will be completed by the end of 2015, but study of ocean–shelf exchange and exploitation of numerical simulations will continue, as insights learnt through – and information provided by – these models are applied to new and exciting challenges to help us better understand our seas.

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‘Dead zones’ in the open ocean

The concentration of dissolved oxygen in seawater is of critical importance to almost all marine life, and plays a role in biogeochemical cycling in the ocean. Dissolved oxygen levels <10 μmol kg^{-1} (‘severe hypoxia’) can cause mass mortality of fish; bacteria begin to convert nitrite and ammonia to nitrogen gas, which results in a loss of fixed nitrogen from the water, so limiting primary productivity. Below about 5 μmol kg^{-1}, bacteria begin to use nitrate in anaerobic respiration. Finally, below 2 μmol kg^{-1} (‘anoxia’) only specially adapted bacteria can survive.

Locally, the concentration of dissolved oxygen is the result of a delicate balance between oxygen supply and consumption. Areas of extremely low oxygen concentrations may occur on the microscale at particle boundaries, at the mesoscale (e.g. in coastal dead zones resulting from excess nutrient run-off), or at the large scale as in oxygen minimum zones resulting from high productivity associated with upwelling along eastern boundaries and/or limited ocean ventilation (cf. Figure 6, p. 41).

A recent paper in the open access journal *Biogeosciences* describes for the first time areas of severely hypoxic, even anoxic water, in the open ocean of the eastern tropical North Atlantic, a region where oxygen concentration typically does not fall below 40 μmol kg^{-1}. The most extreme results were recorded in 2010 at the Cape Verde Ocean Observatory mooring, 800 km from the coast of West Africa (Figure 1). Other examples were found using profiling floats equipped with oxygen sensors.

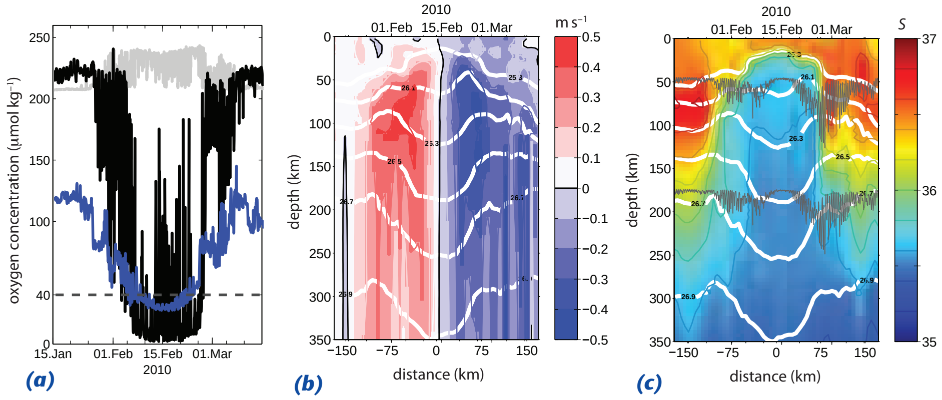


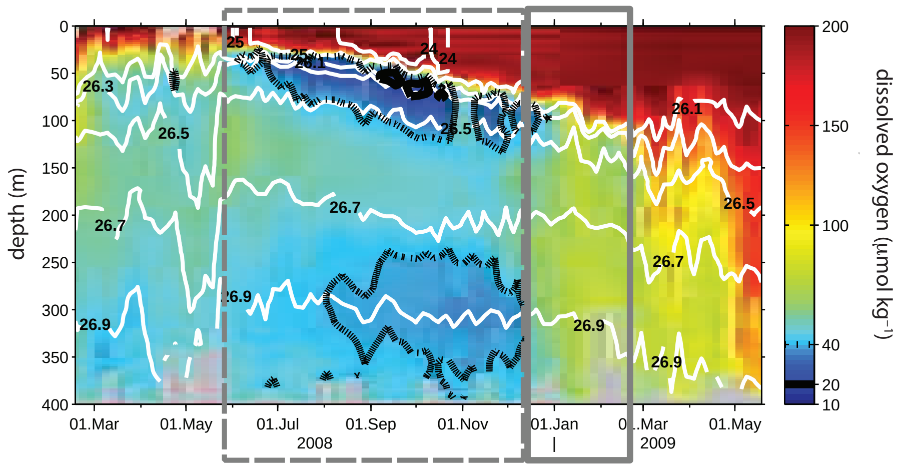
Figure 1 ***(a)*** *Time-series of dissolved oxygen from the two sensors (42 m black line; 170 m blue line) at the Cape Verde Ocean Observatory mooring during the passing of a ‘dead zone’ eddy in February 2010. The horizontal dashed line corresponds to 40 μmol kg^{-1}, the lowest oxygen concentration so far reported in North Atlantic open waters.* ***(b)*** *Corresponding time-series of velocity in the eddy (pink out of the paper, blue into the paper) and* ***(c)*** *corresponding time-series of salinity. In (b) and (c) the white contours are selected density (σ_θ) surfaces, and in (c) the grey lines show the varying depths of the two oxygen sensors during installation. (From Karstensen* et al.*, 2015)*

In all these cases, the columns of low-oxygen water were within mesoscale eddies formed from instabilities in coastal currents off West Africa. They started off with non-critical oxygen levels but soon a low-oxygen core developed, and then persisted over the course of many months while the eddies propagated into the open waters of the Atlantic (Figure 2).

The increasing flow velocity towards the outer edges of such eddies (e.g. 0.5 m s^{-1} for the Cape Verde eddy, Figure 1(b)), limits the exchange of properties across their boundaries. High productivity within the eddies, the associated high respiration, and the bacterial decomposition of sinking organic material, creates low levels of oxygen in the eddy cores. As the eddies’ rotation rate slows, and they lose integrity, they begin to mix with surrounding water, and the low-oxygen core disappears (Figure 2). This process of oxygen depletion through enhanced productivity resembles the creation of ‘dead zones’ so far only reported for coastal areas or lakes.

The eddies in question were large (about 100 km across), and the low-oxygen cores occupied a depth range from ~ 40 m to ~ 100 m. That they were affecting the marine ecosystem could be seem from the fact that diurnal migration of zooplankton was being suppressed within them.

Figure 2 *Time-series of oxygen from profiling float data, collected in 2008. The lowest oxygen concentrations (< 20 μmol kg^{-1}) are indicated by the areas enclosed by the black contour. The white contours show potential density (σ_θ). The two grey boxes indicate the time that the float was in a cyclonic eddy; the dashed box (left) corresponds to the period when the water in the eddy was completely isolated, and the solid box to the period when it was beginning to mix with the surrounding water. (From Karstensen* et al.*, 2015)*



Dead-zone eddies are considered completely natural phenomena, which have probably been overlooked in the past. The rapid oxygen depletion within them makes them ideal natural laboratories for studying the impact of decreasing oxygen levels on ecosystems.

Further Reading

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Karstensen and 9 others (2015) Open ocean dead zones in the tropical North Atlantic Ocean. *Biogeosciences* **12**, 2597–605. doi: 10.5194/bg-12-2597-2015

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Many thanks to Johannes Karstensen for his assistance with this article. Ed

The Ocean Colour Climate Change Initiative

Merging ocean colour observations seamlessly

Sam Lavender, Tom Jackson and Shubha Sathyendranath

Remote sensing of the ocean has transformed many areas of marine science, by making visible complex flow patterns, and distributions of phytoplankton and sediment carried in surface waters. Ocean colour remote-sensing from space began in 1978, with the launch of NASA's Coastal Zone Color Scanner (CZCS) aboard the Nimbus 7 *satellite. Intended as a proof-of-concept, it was expected to operate for one year, but in fact remained in service until 1986. CZCS has been followed by sensors such as SeaWiFS, MERIS and MODIS which have increased the time-series of data available. So millions of pixels have been collected, but on any one day, areas of sea are obscured by cloud, dust or water in the atmosphere, and even 10 years' worth of images for a given month may have gaps. This problem can be addressed by combining data from several sensors, but is not straightforward. There may be systematic differences between sensors themselves, and further differences may be introduced through the application of algorithms to remove the influence of the atmosphere on a satellite sensor. Here, members of the Ocean Colour Climate Change Initiative (CCI) project team explain how work led by Plymouth Marine Laboratory, and funded by the European Space Agency, is tackling this challenge. Ed*

Ocean colour for climate studies

Ocean Colour CCI generates ocean colour products specifically designed for climate studies. The project runs in parallel with 12 others in the European Space Agency's (ESA's) CCI programme (http://www.esa-cci.org/), all of which are developing Essential Climate Variables (ECVs), i.e. key environmental variables that are economically and technically feasible to measure, and are useful for monitoring various components of the Earth system. The Ocean Colour CCI project aims to produce a long-term multi-sensor time-series of satellite ocean-colour data with specific information on errors and uncertainties; it is the only marine ECV targeting the biological field.

Ocean colour is influenced by many factors, including both suspended and dissolved components. However, it is largely determined by phytoplankton abundance, which can be indexed as chlorophyll concentration, and is a key factor in the ocean carbon cycle and hence important in all discussions dealing with pathways of carbon in the Earth System. Also, since phytoplankton are at the base of the pelagic food web, they are fundamental to understanding how the marine ecosystem responds to climate variability and climate change. Nevertheless, the role of phytoplankton and ocean colour in climate studies is still not fully understood, not least because other factors such as sediment load often complicate the picture.

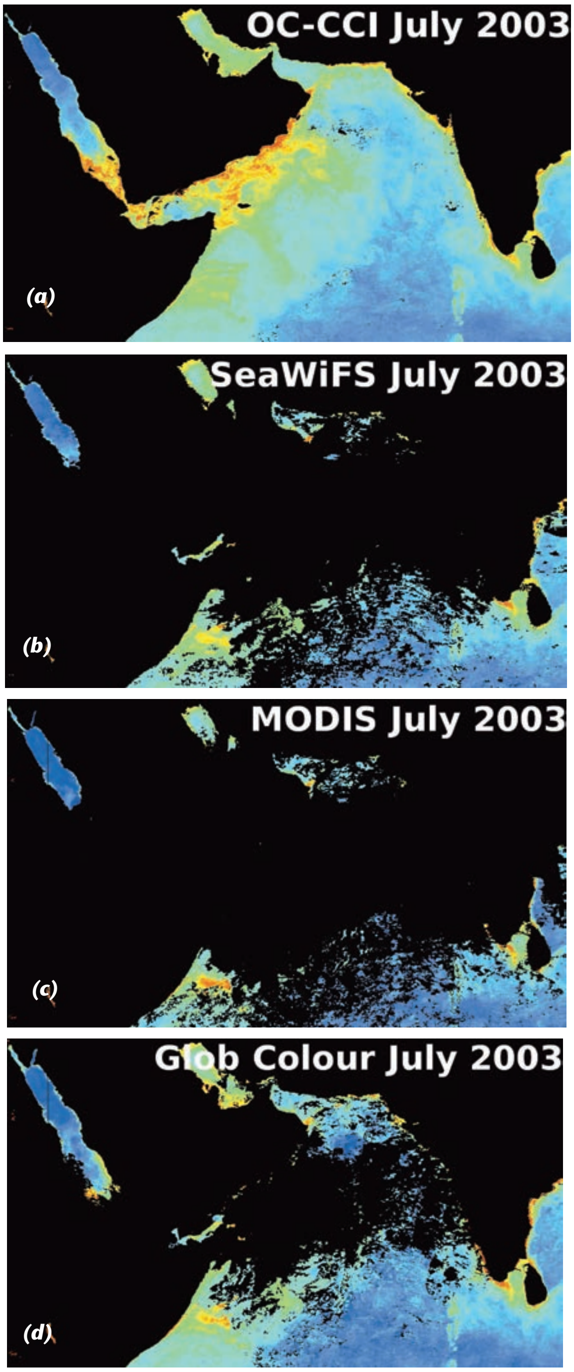


Figure 1 *Ocean colour images of the Arabian Sea/northern Indian Ocean, for July 2003, generated using:*

(a) *the ocean colour Essential Climate Variable, produced by the Ocean Colour CCI;*

(b) *SeaWiFS and* ***(c)*** *MODIS, the previous states of the art using unmerged data;*

(d) *the ESA GlobColour project, the previous state of the art using merged data.*

Ocean Colour CCI uses an improved atmospheric correction for the MERIS data and so can fill gaps that have previously existed in both single sensor and merged datasets. The image shows a marked improvement in coverage of the Arabian Sea, especially the region of high chlorophyll (red) resulting from coastal upwelling off Oman.

At the end of Phase 1, the project's activity had resulted in a 15-year merged ocean colour time-series of a quality that could reliably be used in climate change research. Phase 2, which started in 2014, aims to follow a cyclical update process with release of a revised dataset in 2015. Near-term updates included processing up to the end of 2014 (the current dataset extends until 2012) with longer term goals including the incorporation of data from future missions such as the EU Copernicus Ocean and Land Colour Instrument (OLCI) on board the *Sentinel-3* satellites.

Producing an ocean colour Essential Climate Variable has required a number of intermediate steps.

User requirements

User requirements underpin all Ocean Colour CCI activities; in Phase 1, a survey and consultation were undertaken at the beginning of the project, in order to incorporate the views of modellers and observational scientists alike. These results, along with requirements from the Global Climate Observing System (GCOS), form the design basis.

Ocean colour data products include remote-sensing reflectance in the visible domain, and derived chlorophyll concentration, in addition to a number of other optical properties computed from the radiances, including various inherent (absorption and scattering) optical properties of the upper ocean, and the diffuse attenuation coefficient for downwelling irradiance. They utilise data from ESA's MERIS and NASA's SeaWiFS and Aqua-MODIS archives.

Algorithm selection

The selection of algorithms is a key part of the development: firstly, to correct for atmospheric effects that mask the signal from the ocean (atmospheric correction); and secondly to convert the retrieved ocean-colour signal into biogeochemically relevant variables such as the chlorophyll-*a* concentration.

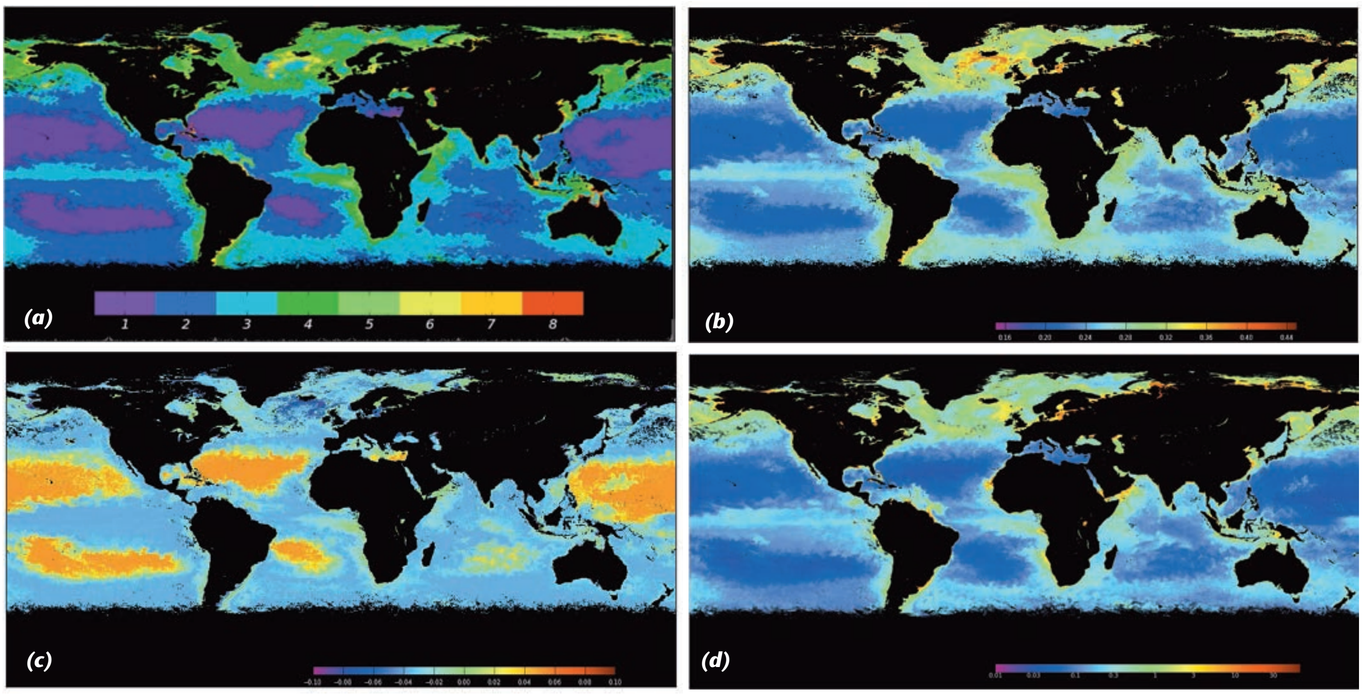
Many algorithms are available – each with its own limitations and advantages. To select the best one, a suite of algorithm-selection criteria was developed that includes qualitative considerations such as the robustness of the algorithms in the event of modifications in the marine ecosystem in a changing climate. The quantitative performance of the algorithms was also evaluated using a suite of statistical tests on satellite products matched with *in situ* observations. This process led to a significant improvement in the spatial coverage of data from the MERIS sensor (see Further Reading), as shown by its contribution to the Ocean Colour CCI image in Figure 1. The algorithm selection procedures have the potential to be routinely implemented, such that the performance of emerging algorithms can be compared with existing algorithms as they become available (see Further Reading).

Achieving climate-quality data

The Global Climate Observing System (GCOS) requirements identify time-series data of spectrally resolved remote-sensing reflectance and chlorophyll-*a* as a priority. However, since the three ocean colour sensors used in the project (SeaWiFS, MERIS and Aqua-MODIS) each had different sets of spectral bands, a reference sensor had to be selected and the remote-sensing reflectance wavebands of the other sensors shifted to that of the reference sensor (chosen to be SeaWiFS), ensuring a merged product at the same wavelengths throughout the time-series. This 'band-shifting' was also essential to determine inter-sensor biases, which had to be corrected, to avoid spurious trends in time-series data.

*There are various different ways of classifying ocean and coastal waters on the basis of their optical characteristics. For example, the terms Case 1/Case 2 are used when the dominant contributors are either chlorophyll-*a* (Case 1) or suspended inorganic sediment, detrital and dissolved material (Case 2). The system used in Figure 2(a) is based on the approach of Moore *et al.* (2009) (see Further Reading).

Figure 2 ***(a)*** *Example of a distribution of optical water classes* across the oceans for July 2003 (i.e. the class most commonly applicable during that month), ranging from clearest ocean water (class 1, purple) to waters that are highly productive and/or dominated by a high sediment load (class 8, red). These classications are used to assign corresponding uncertainties in chlorophyll-*a *generated on a pixel-by-pixel basis. These include* ***(b)*** *root-mean square difference error ($\log_{10}$chl-*a*) and* ***(c)*** *bias values ($\log_{10}$chl-*a*).* ***(d)*** *The resulting Ocean Colour CCI product for mean chlorophyll-*a* (mg m^{-3}) in July 2003. Note that root mean square difference errors are greatest (red) in highly productive areas and least in the low-nutrient centres of gyres, where bias values with reference to* in situ *data are highest.*



Ocean Colour Products

Spatial coverage: Global level 3 binned multi-sensor merged data as sinusoidal and geographic products at 4 km resolution
Temporal resolution: daily, 8-daily, monthly
Temporal coverage: 1997–2013 (Version 2); 1997–2012 (Version 1)

Main Ocean Colour products (ECVs)

Phytoplankton chlorophyll-*a* concentration (chlor_*a*) (mg m^{-3})
Remote-sensing reflectance (R_{rs}) at six wavelengths (sr^{-1})
Uncertainty layers are included

Other Ocean Colour products

Total absorption (a_{tot}) (m^{-1}) and **backscattering coefficients (b_{bp})** (m^{-1})
No uncertainty layers for either as a_{tot} is a combined product and there are insufficient data for b_{bp}

Phytoplankton absorption coefficient (a_{ph}) (m^{-1})
and **absorption coefficients for dissolved and detrital material (a_{dg})** (m^{-1})
Uncertainty layers are included

Diffuse attenuation coefficient for downwelling irradiance (K_d for light of wavelength 490 nm)
Uncertainty layers are included

A major achievement for the project was devising a method to provide pixel-by-pixel error characterisation for the merged product. The uncertainties provided include root mean square error and bias, based on validation with *in situ* data (cf. Figure 2(b) and (c)). This was achieved through the use of optical classification of pixels (Figure 2(a)), and optical-class-based uncertainty characterisation. A number of optical water classes were defined by spectral reflectance values. Uncertainties were computed for each optical water class, for each product (see Box). The uncertainty for a product at any given pixel can then be estimated using the optical classification of the pixel and the class-specific product uncertainties.

A new integrated database of *in situ* observations was set up from a number of available sources such as MERMAID, NOMAD and SeaBASS, and matched up with satellite data to help establish the uncertainty characteristics. The database also provides the basis for the validation exercises; in addition, a number of comparison exercises have been undertaken to evaluate the consistency of the data products.

Version 1 of the Ocean Colour CCI dataset has provided improved coverage, error characterisation and bias correction, whilst meeting the GCOS requirements for temporal resolution and accuracy. Version 1 has recently been assessed by ocean colour and ecosystem modelling experts within the project, and their feedback is being taken into consideration for Version 3 of the product (see below).

Version 2 uses updated input datasets and extends the time-series to the end of 2013. It also optimises the uncertainty generation, incorporates an improved bias correction and improved MERIS cloud mask (the cloud mask removes any pixels that are not seawater, primarily cloud pixels). There have also been some minor changes to the format, and so scripts and code may need updating. Ongoing feedback is encouraged from all users; please email: help@esa-oceancolour-cci.org

The aim of Version 3 is to include new sensors, such as the NOAA/NASA Visible Infrared Imaging Radiometer Suite (VIIRS), to ensure long-term evolution of the ECV products while also focussing on reducing the uncertainties in Case 2 (primarily coastal) waters, which are high in sediment and/or dissolved organic material.

Ocean Colour CCI products

The data can be directly downloaded via FTP (ftp://oc-cci-data:ELaiWai8ae@oceancolour.org/) or viewed/ downloaded via an interactive website at http://www.oceancolour.org/ which also includes a Composite Browser, Web GIS Portal and OPeNDAP access details. The tools for handling the data include plugin readers for BEAM and SeaDAS. For further details please consult the Product User Guide (http://www.esa-oceancolour-cci.org/?q=webfm_send/496) or website FAQ (http://www.esa-oceancolour-cci.org/?q=faq). A summary of the products is given in the Box above.

We gratefully acknowledge the support we have received from ESA, NASA and the community at large in developing the new merged time-series product.

All data products are freely available online, and all documentation is accessible on the project website (http://www.esa-oceancolour-cci.org/).

Further Reading

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Moore, T.S., J.W. Campbell and M.D. Dowell (2009) A class-based approach to characterizing and mapping the uncertainty of the MODIS ocean chlorophyll product. *Remote Sensing of Environment*, **113**, 2424–30.

Müller and 15 others (2015) A methodology for assessing atmospheric correction processors based on in-situ measurements, *Remote Sensing of Environment* (in press).

For more on ocean optics, including optical water classes, see the Ocean Optics Web Book http://www.oceanopticsbook.info/view/overview_of_optical_oceanography

More technical information can be found in a series of reports on the IOCCG website: http://www.ioccg.org/reports_ioccg.html

Sam Lavender, **Tom Jackson** and **Shubha Sathyendranath** are members of the OC-CCI project. To contact the team, visit help@esa-oceancolour-cci.org

The Western Channel Observatory

Collecting rare and precious time-series – from photons to fish

Tim Smyth, James Fishwick, Tom Bell and Steve Widdicombe

The marine environment has been routinely monitored off the coast of Plymouth since the latter decades of the 19th century. The resulting wealth of observations, covering phenomena ranging from photons to fish, gives marine scientists the ideal opportunity to carry out contextualised studies of marine processes, and develop and validate ecosystem models, as well as to quantify the extent and impact of climatic and environmental change. The Western Channel Observatory (WCO), established in 2005, essentially brought under one umbrella the time-series stations L4 (50°15' N, 4° 13.2' W; 50 m depth) which is situated 4 nautical miles (n.m.) off the coast, and E1 (50°02' N, 4°23' W; 80 m depth) situated 20 n.m. offshore, together with modelling and remote sensing expertise.

Station L4 has been routinely sampled by the Plymouth Marine Laboratory (PML) on a weekly basis since 1988, building on earlier time-series maintained by the Marine Biological Association (MBA). The early elements of the time-series were dominated by vertical net tows for zooplankton (Figure 2) and basic ancillary measurements of surface temperature. These were quickly augmented in the early 1990s by phytoplankton taxonomy and a unique series on copepod egg production.

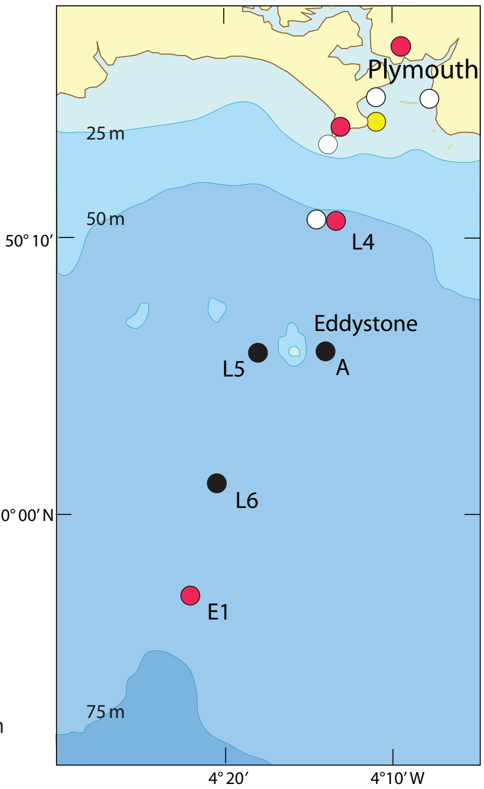
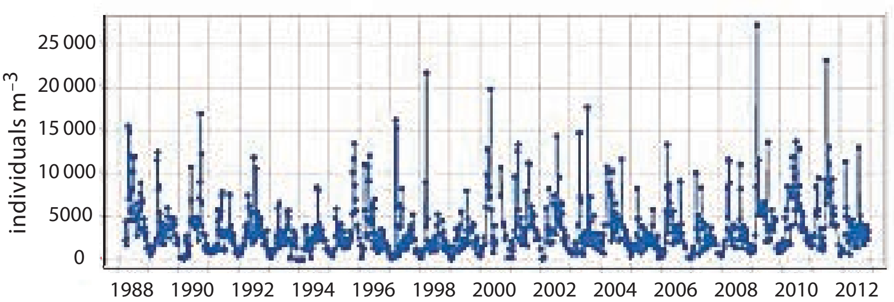


Figure 1 *Map showing the location of the principle sampling stations of the Western Channel Observatory. Red dots are principle locations: PML, Rame Head, L4 and E1; black dots are historical stations; white circles are benthic sampling stations and the yellow circle is the Penlee Point Atmospheric Observatory.*

Technological advances later on in the decade meant that temperature and salinity profiles could be measured on a consistent basis with reliable instrumentation. During the last 10–15 years, the core measurements of the WCO have expanded to cover inorganic nutrients (nitrate, nitrite, phosphate, silicate and ammonia), phytoplankton pigments including chlorophyll, flow cytometry, primary production, carbonate chemistry (e.g. pH) and various bio-optical measurements. These core measurements, funded by the Natural Environmental Research Council, together with the necessary infrastructure of small research vessels (RVs *Plymouth Quest* and *MBA Sepia*), provide the background against which short-term seasonal or opportunistic process studies can take place. These have included investigations into the cycling of volatile climatically important gases and the growing impact of microscopic particles of plastic in the marine environment. The long-term maintenance of the time-series, rare and precious in their own right, over multiple annual cycles, provides the essential contextual



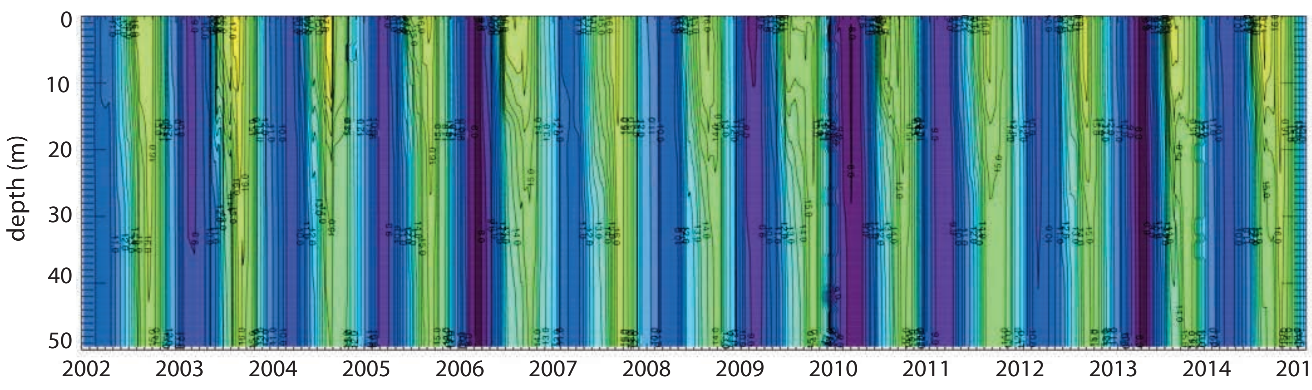


Figure 2 Upper *Variability in total zooplankton counts at station L4 since 1988. Zooplankton are sampled using a vertical net haul (mesh size 200 µm) and are taxonomically identified at PML. (Plot by courtesy Rachel Harmer)*

Lower *The variation of temperature with depth at station L4 since 2002. Coldest winters (< 8 °C) show in deep purple and warmest summers (>17 °C) in bright yellow.*

Figure 3 Upper *L4 buoy on station showing the atmospheric instrument array around the top ring, including solar irradiance, wind speed and meteorological sensors as well as communication aerials. Wind generators and solar panels are clearly seen, along with the instrument control boxes just above the 'No Mooring' sign. Battery boxes are situated just above the surface of the 3.1 m diameter float.*

Lower *The instruments are sheathed in copper to prevent excess biofouling.*

information against which these studies can be set. The series also lends itself to validating ecosystem models, which have been developed by the Plymouth Marine Laboratory over the past 20 years, across the range of essential variables of physics, chemistry and biology.

Station E1, started in 1903 by the MBA and restarted by PML in 2002 using funding from the Marine Environmental Change Network, was originally the first station in a transect running from Plymouth to just west of Ushant (E5), north-west France. This is one of the longest hydrographic series in the world, with temperature and salinity profiles available for nearly a century. Although there are gaps in the record due to the world wars and funding hiatuses, these time-series rival the globally well-known series at Hawaii (HOT) and Bermuda (BATS). Most of the core measurements highlighted above for L4 are now collected by PML on a fortnightly basis at E1, although sampling is more restricted given the constraints of the weather and distance from shore.

In 2008, the scope of the WCO was expanded to include an element often missing from many other observatories: the benthos. Funding provided through the NERC Oceans 2025 programme allowed PML to initiate the WCO Benthic Survey in which four contrasting local sub-tidal benthic habitats (including the sea-bed at L4) were sampled every other month from July 2008 until July 2011. This multidisciplinary survey brought together biogeochemists, microbiologists and ecologists to conduct a fully integrated study of environmental and biological seasonal dynamics in benthic ecosystems. Once these benthic data were coupled to those pelagic data already being routinely collected through the WCO, it was possible to explore the interconnections and interdependencies which exist between the different biological components of a complete ecosystem.

At the end of 2011 the Benthic Survey was scaled back with regular sampling largely concentrated around L4. However, more intensive and frequent sampling does still occur (Figure 4), especially in response to interesting environmental anomalies, such as the huge plankton bloom in 2012 and the severe storms of February 2014 (cf. Figure 5 overleaf). The WCO Benthic Survey now represents a significant benthic time-series and is increasingly being used by visiting researchers and students as the backdrop against which to conduct shorter-term process-based studies.

Both L4 and E1 can now boast hourly automated measurements of surface variables such as meteorological parameters, sea-surface temperature, salinity, solar irradiance, oxygen, nitrate, chlorophyll and suspended sediments. These are measured using systems developed by PML, and in the case of E1, in partnership with the UK Met Office. These high

Figure 4 (a) *Regular benthic dredging is part of the WCO's long-term Benthic Survey.* ***(b)*** *The starfishes* Marthasterias glacialis *and* Astropecten irregularis *and shelly gravel form a backdrop for other benthic organisms such as hermit crabs. (Both photos by courtesy of Kelvin Boot/PML)* frequency measurements have given us insights into short duration events such as algal blooms or intrusions of riverine discharge following heavy rain, which would not have been resolved by the traditional weekly sampling. The buoys have also provided the opportunity for development and testing of instruments and devices for commercial partners. Plans are already in place for the next generation of automated buoys to have a profiling capability, in order to resolve changes in the vertical structure of the water column over the tidal cycle.

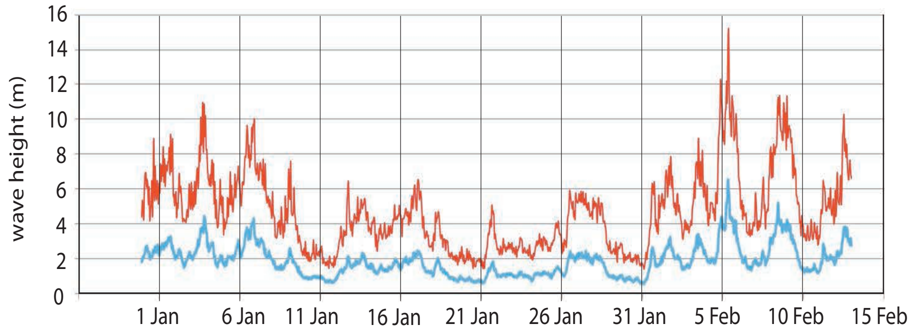


Figure 5 *Variation of maximum and average wave height measured by the E1 buoy during the 2014 winter storms. This buoy is a collaborative effort between PML and the UK Met Office. (Plot by courtesy of James Fishwick)*

Future developments of the Observatory and its associated science will embrace the concept of Earth Systems Science. Integral to this discipline are the interactions between the atmosphere and ocean and also between the ocean and the sea-floor. Recent developments at the WCO have included the establishment of an atmospheric station at Penlee Point, situated at the mouth of Plymouth Sound (Figure 1). Measurements of carbon dioxide, methane, sulphur dioxide, ozone and aerosols will allow complex linkages between the marine and atmospheric environments to be elucidated as never before. At the other end of the water column, the linkages between the ocean and sea-floor are being uncovered by PML's benthic ecologists. Again, working against a backdrop of long-term time-series, restarted by PML in 2008 but with a heritage going back to the 1950s, sampling over multiple annual cycles has given fresh insights into the seasonality and interannual variability of these waters. The greatest rewards in this area in the coming years are likely to come from pulling these processes and measurements into the framework of ecosystem models.

In summary, despite elements of the WCO being established for more than a century, the western English Channel never ceases to surprise marine scientists by its variability and complexity. This provides a challenge for the latest ecosystem models, remote sensing science and our understanding of the marine system in general, which is likely to last for several decades to come.

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Tom Bell is a senior scientist at PML and set up the Penlee Point Atmospheric Observatory. **James Fishwick** is the operations and technical manager of the WCO. **Steve Widdicombe** heads up the ecological and benthic work of the WCO.

Figure 6 Plymouth Quest *and* MBA Sepia *rendezvous at the L4 buoy*

Is there a down-side to MPAs?

Understanding their impacts on population health and disease

Charlotte Eve Davies

It is no longer news that much of the world's oceans are overfished. Stocks of fish and invertebrate have been over-exploited for our ever-hungry, growing human population, leaving some species in dangerous decline. The establishment of marine protected areas (MPAs) across the globe has been hailed as the silver bullet for conservation, with reports of increased catch, and spillover of recovered populations into adjacent fisheries, helping to replenish overfished stocks. But there may be unintended consequences if these areas are left unmonitored. As populations of certain species are restored, disease can increase too.

Lundy Island, off the north coast of Devon, was the UK's first MPA. It was established as a marine nature reserve in 1986, incorporated a no-take zone in 2003, and was designated a marine conservation zone in 2010. Four years of monitoring, from 2003 to 2007, saw a marked increase in commonly fished species, such as lobster, inside the no-take zone in comparison with fished areas. But in 2010, a study off Lundy (see Further Reading) called for a cost–benefit review of marine reserves after it was found that shell disease in European lobsters may be increasing inside the protected area, possibly as a result of the high population density.

To investigate further, we returned to Lundy the following year to monitor the populations of European lobster. When we compared the no-take zone, which had not been fished for 8 years, to a fished area, we found that the no-take zone had more abundant, larger lobsters. This phenomenon is a well-known result of establishing MPAs and one of the reasons they are celebrated. Local fishermen agreed that since the no-take zone was implemented, there had been an increase in catch around the area.

But in the same survey, we found that there was a higher probability of lobsters being injured inside the Lundy no-take zone. European lobsters have a solitary and aggressive nature, so in areas of high density, such as the no-take zone, we expected to find a lot of injury. Still, injury is known to be a precursor to disease. The shell of a lobster is its first line of defence and once it is breached, pathogens may gain entry. This is significant because other studies have shown that pathogens in marine ecosystems are on the rise, a phenomenon which may be exacerbated by climate change. It is important to monitor disease and understand the effects on populations elsewhere in the world, especially those species which are commercially exploited. In the past, disease in American lobsters is thought to have contributed to the collapse of a lobster fishery off southern Massachusetts (see Whale *et al*. in http://www.vims.edu/research/departments/eaah/programs/crustacean/research/lobster_shell_disease/Lobster-Project-Resources/Publications/Lobster-pdf-files/).

Our study is interesting in that it introduces the idea that unfished populations in marine parks may eventually reach a threshold at which conditions become unhealthy. This in turn could open up the possibility of controlled fishing in long-standing no-take zones. Allowing fishing could be a controversial move but studies have shown that high abundance in marine reserves may render animals vulnerable to disease particularly because infections can no longer be 'fished out'. A total ban on fishing is certainly positive in allowing recovery of populations back to unexploited densities, but no-take areas may have a finite period of success.

There is no doubt that fishery closures and marine protected areas do help contribute to the conservation of species, but the important message here is that we must monitor them more closely. In November 2013, the UK designated 27 new MPA sites. Monitoring species richness,

An example of shell disease on the claws of a lobster from the Lundy island reserve

abundance and disease in these areas will be crucial to avoiding any unwanted side-effects such as increased incidence of disease.

Further Reading

Wootton E.C., A.P. Woolmer, C.L. Vogan, E.C. Pope, K.M. Hamilton and A.F. Rowley (2012) Increased disease calls for a cost–benefits review of marine reserves. *PLoS ONE* **7** (12): e51615. doi:10.1371/journal.pone.0051615 http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0051615

See also http://mpanews.org/MPA141.pdf

Charlotte Eve Davies is a researcher in crustacean disease and recently completed her Ph.D at the Dept of Bioscience, Swansea University, investigating the health status of the European lobster. She is passionate about the integration of fishermen and marine scientists for the betterment of fisheries management. cedavies72@gmail.com

Training fishermen in surveying techniques in waters around Lundy Island

To read more about the study, see: Davies, C.E., A.F. Johnson, E.C. Wootton, S.J. Greenwood, K.F Clark, C.L. Vogan and A.F. Rowley (2015) Effects of population density and body size on disease ecology of the European lobster in a temperate marine conservation zone. ICES Journal of Marine Science (special issue) doi: 10.1093/icesjms/fsu237

Is climate change being taken seriously at last?

In July, a large international conference 'Our Common Future under Climate Change' (http://www.commonfuture) met in Paris – with close to 2000 participants from almost 100 countries. Its stated aim was to send a clear message to the 2015 UN Paris Climate Conference in December (COP21), which will be focussing on producing a cooperation framework among governments 'for a steady increase of individual and collective ambitions for addressing the challenge of climate change'. The 'Outcome statement', headed 'The Science Offers Robust Foundations for Ambitious Outcomes at COP21 and Beyond' somehow manages to have an upbeat flavour, giving more prominence to what it calls 'The Solution Space' than to 'The Problem Space'. Perhaps the aim was to prevent governments just giving up in the face of what seems an insurmountable problem.

Around the same time, the media picked up on a paper in *Science*,* evaluating changes to the ocean and its ecosystems, as well as to the goods and services they provide, under two contrasting CO_2 scenarios: the current high-emissions scenario (Representative Concentration Pathway 8.5, RCP8.5) and a stringent emissions scenario (RCP2.6) which might keep the mean increase in global temperature below 2°C in the 21st century.

*Gattuso *et al.* Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science,* **349,** No. 6243. doi: 10.1126/science.aac4722

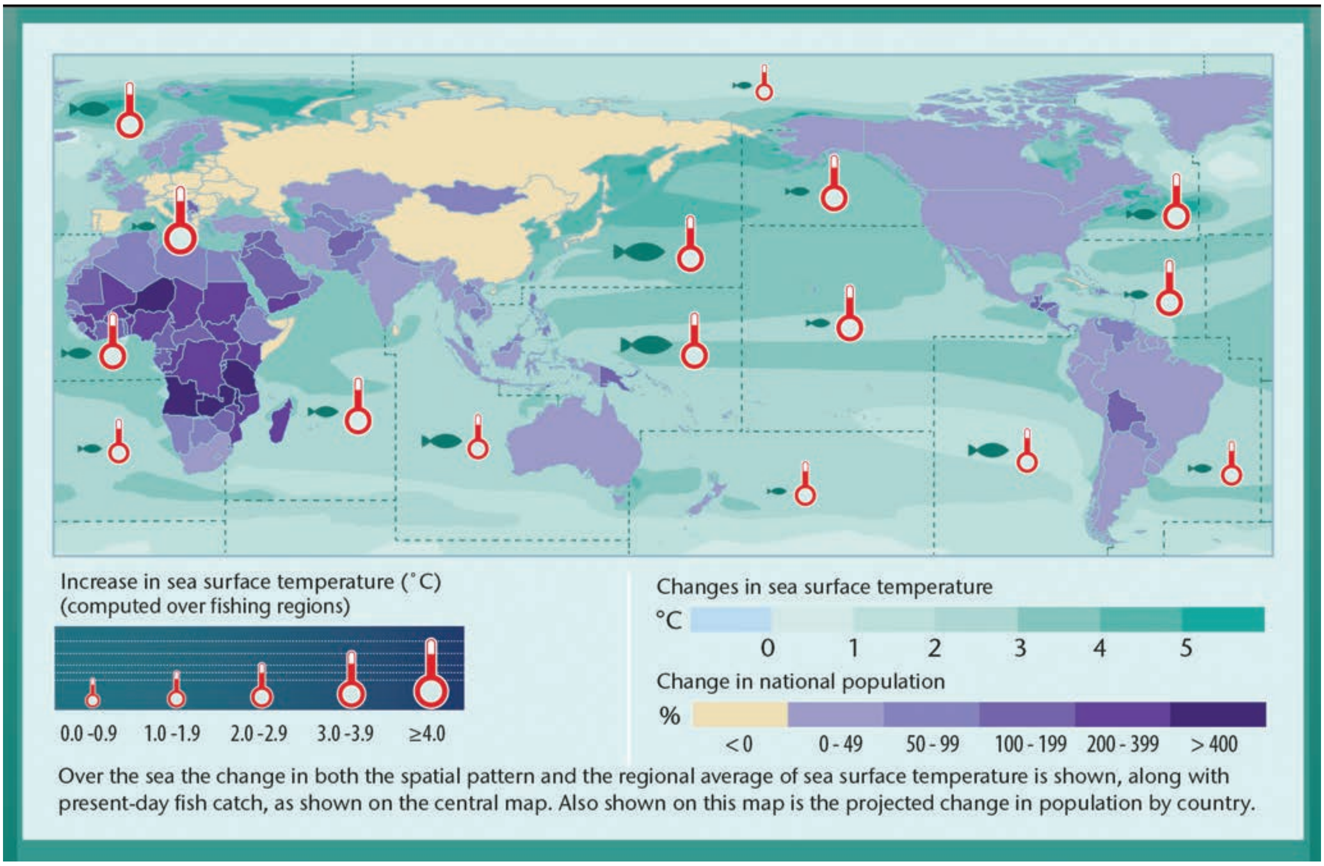
The *Science* website offers useful Powerpoint versions of the diagrams in the paper, for education puposes. In a similar move, in September 2014 the UK Met Office produced a group of maps which show the potential long-term influence of climate change on human activity. The climate projections shown do not include any assumptions about adaptation or adaptive capacity. They show a 'business as usual' greenhouse gas concentration scenario (i.e. RCP8.5) with no explicit mitigation of greenhouse gas emissions, and a 'middle of the road' socio-economic scenario (SSP2) for population change. The map that most directly relates to the oceans is reproduced below. Again, these maps are a great educational resource, which should perhaps be more widely known.

But education alone doesn't seem to be enough. For decades, at least in the UK, school children have been urging their parents to recycle more, and climate change has been part of university syllabuses for at least as long. Why hasn't all this education translated into real changes in attitude at govenment level before now?

An intervention that may strongly influence the choices made by large numbers of people, and hence how certain elected governments behave, is the Pope's 184-page encyclical, issued in May. This called for a radical transformation of politics, economics and individual lifestyles and for swift and unified global action to tackle environmental degradation and climate change. The Pope blamed apathy, the reckless pursuit of profits, excessive faith in technology and political shortsightedness, combined with a disregard for the world's poorest people.

Brazil (which has a large Catholic population) is amongst the major emitter countries whose governments have yet to present plans for consideration at COP21 in December. Others include China (now investing heavily in renewable energy) and India (currently pushing increased coal production). The United States (now at peak oil production) has pledged reductions of 26–28% below 2005 CO_2 emissions by 2025; the EU has the most ambitious target for reduction in emissions, of 40% below 1990 levels by 2030. Let's hope this isn't all too little, too late. Ed

Future change in sea-surface temperature and population change by country. By courtesy of the Met Office. More information is available at www.metoffice.gov.uk/climate-guide/climate-change/human-dynamics © Crown Copyright



OCEAN ACIDIFICATION

IN A CHANGING WORLD

Jason M. Hall-Spencer

Victorian scientists of the HMS *Challenger* era would no doubt be shocked by the ways in which humanity, and our use of fossil fuels, is altering the physical, chemical and biological nature of the oceans. Since the 1950s, coastal ecosystems have been radically transformed by human activity – the world population now stands at 7.2 billion and is rising fast. Our use of finite natural resources is accelerating and this, coupled with poor management of renewable resources, means the planet has entered a phase of mass extinction with widespread biodiversity loss. The oceans are no exception; within a generation, fishing using fossil fuels has removed large fish from ecosystems and homogenised continental shelf habitats, with extensive damage now occurring all along shelf-break regions and even on remote seamounts. Here I attempt to set a problem of which we have only recently become aware – ocean acidification – into the context of other threats faced by the ocean. The good news is that we have the scientific evidence and social capital needed to address these problems. Governments are at last getting serious about cutting carbon dioxide emissions and enforcing restrictions on destructive practices, but it will need the Victorians' prowess in leadership and their political will to turn things around.

This article is a personal perspective, based on the author's keynote presentation at the 2014 Challenger Conference in Plymouth

John Murray and the early marine biology stations

After the return of HMS *Challenger* from her two-year circumnaviation of the globe, John Murray FRS (1841–1914) oversaw the publication of results from the expedition in 50 volumes brimming with information about life in the oceans. The surge in interest created by these discoveries built up momentum which led to the establishment of both the Marine Biological Association of the United Kingdom and the Scottish Marine Biological Association.

in 1883, John Murray was instrumental in setting up a floating marine station, called the 'Ark' (Figure 1), which was moved from Granton in East Scotland to the Isle of Cumbrae in the Firth of Clyde, leading to the foundation of Millport Marine Biological Station in 1885. Little over a hundred years later, this is where I had a wonderful time doing a Ph.D on seaweed zonation which led on to postdoctoral work assessing the relative impacts of fishing gears, dredging and aquaculture. This instilled in me a love of marine biology stations; their seawater smell makes me feel at home, and I enjoy the constant turn-over of visitors with a passion for marine science and fascinating insights into often obscure aspects of marine life.

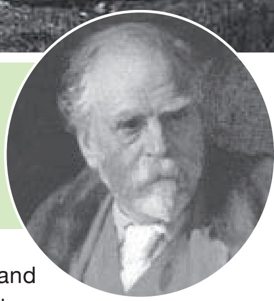


Figure 1 *The Ark floating marine station, which was wrecked by a storm in January 1900.*
Right *Its founder, John Murray.*
(Photo of the Ark by courtesy of North Ayrshire Council Heritage Service)

The Ark was the forerunner to Millport Marine Station, opened by John Murray in 1897

If we consider the major environmental issues facing marine science today, the Firth of Clyde is like the global ocean in miniature since it exemplifies what we have put coastal ecosystems through the world over. Back in the 1880s the Clyde, Thames, Mersey and other industrialised estuaries stank of untreated sewage which posed a risk to human health. Pollution had turned the mudflats anoxic, degrading migratory bird feeding sites and preventing salmon migration. Around 1900, things began to improve in the Clyde estuary, as Glasgow began dumping sewage farther offshore. In the 1990s the sewage vessel *Gardyloo* offered strangely popular free trips for pensioners; today, sewage dumping is no longer permitted, and the wastes are incinerated on land, so thankfully the grim joke that swimming off Millport was 'just going through the motions' is no longer true. However, pollution from rivers continues, along with the addition of contaminants from the atmosphere.

Overfishing and habitat destruction

Hopefully, we can learn from the Victorians' proactive approach to tackling sewage pollution and apply it to other marine environmental issues, including overfishing. Action on this particular issue got off to a poor start because influential Victorian scientists could not foresee how fossil-fuel use would transform the efficiency with which we can catch fish. Indeed, in 1883 Thomas Huxley FRS, later President of the Marine Biological Association of the UK, stated:

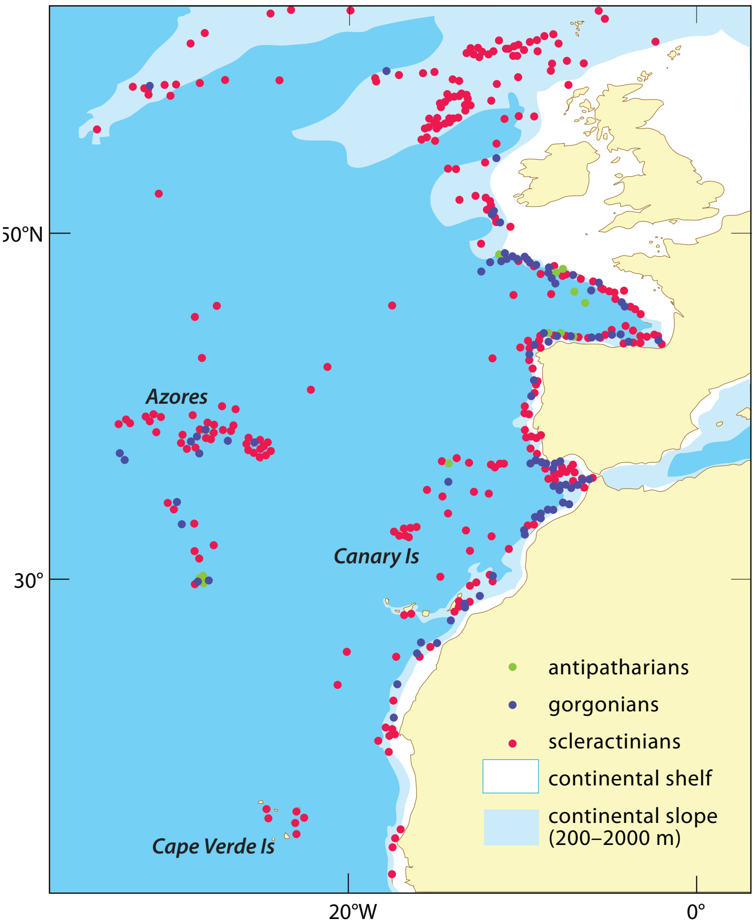
'I believe then that the cod fishery, the herring fishery, pilchard fishery, the mackerel fishery and probably all the great sea fisheries are inexhaustible: that is to say that nothing we do seriously affects the number of fish, and any attempt to regulate these fisheries seems consequently from the nature of the case to be useless.'

Huxley wasn't to blame – there were no internal combustion engines then, and he went around by horse-drawn carriage.

HMS *Challenger* was a sailing vessel, but she had a steam engine to operate winches for deep-sea sampling. Steam power from burning coal ushered in a renaissance of oceanic discovery, and the libraries of Millport and Plymouth marine stations house cruise reports which capture the excitement of the time – reports from *Lightening* (1868), *Josephine* (1869), *Porcupine* (1869–70), *Challenger* (1873), *Valorous* (1875), *Travailleur* (1880–82) and *Talisman* (1883).

The pioneer scientists of the 1870s discovered life in the deep sea, and showed that diversity of groups such as corals (Figure 2) actually increased with depth because conditions on the continental shelf are too variable for organisms that need the more constant conditions of the deep. Around the UK there are eight species of hard coral (scleractinians) at depths < 200 m, but 32 deeper than 200 m. Similarly, there are just two gorgonian species in shallow waters but 25 species from depths > 200 m along the continental shelf break. Sadly, many of the areas sampled by the Victorians have been damaged by fishing. Powerful diesel trawlers equipped with 'canyon busters' and 'rockhopper gear' are homogenising the sea-bed at continental shelf-break depths just as steam-powered trawlers did on the continental shelf a century ago. Fortunately European member states have been quick to react, with a network of no-trawl areas now in place to protect vulnerable deep-sea habitats. That was clearly the sensible course of action: north-east Atlantic coral habitats take millennia to form, provide areas for the feeding and breeding of commercially important fish, yet can easily be bulldozed with one passage of a trawl.

Damaging fishing practices also occur inshore; we have seen the extirpation of large fish and progressively 'fished down the food webs' of UK waters. High trophic level organisms, such as sharks and cod, have been selectively removed, which has allowed lower trophic level organisms to proliferate. So nowadays much of the fishing industry relies on invertebrates like prawns, cuttlefish and scallops rather than fish. These



The Victorians found that corals were diverse and widespread in the cold, dark waters of the north-east Altantic

Figure 2 *Collection sites of deep-water (>200 m) corals from the continental slope, seamounts >1000 m in height, and oceanic islands off Africa and Europe and in mid-ocean, compiled from late 19th century research reports. The corals are antipatharians (black corals), scleractinians (hard corals) and gorgonians (sea fans).*

Figure 3 ***Upper left*** *A juvenile scallop (*Pecten maximus*, shell 1 cm across) living on a bed of pink twig-like maerl (*Lithothamnion corallioides*) at a protected site on St Mawes Bank in the Fal Estuary, England.* ***Lower left*** *A flame-shell (*Limaria hians*, shell 2.5 cm long) near Otter Spit in Loch Fyne, Scotland, in 1998. This beautiful mollusc formed extensive reefs that have recently been destroyed as the area was not protected from destructive towed gear.* ***Upper right*** *The 10-cm-long teeth of a commercial dredge about to be deployed; these teeth are dragged through surface sediments to capture scallops.* ***Lower right*** *Scallop dredge track with a dislodged adult scallop (arrow, shell width 12 cm) and muddy sediment brought to the maerl surface (centre of photograph) in the Firth of Clyde (see Hall-Spencer and Moore, 2002).*

Dredging for scallops can kill individual organisms and cause long-term damage to sea-bed habitats

have been described as the 'cockroaches of the sea', so resilient are they to trawling, but even these fisheries are scuppered if disease takes hold, such as prawn-wasting disease which is prevalent in the Clyde. There are welcome signs that society is beginning to grapple with destructive fishing – hats off to the Community of Arran Seabed Trust who persuaded government of the need to set aside areas that are off limits to scallop dredges and trawls (www.arrancoast.com). This is not before time, given the raft of scientific information available about destruction of seagrass beds and coastal reefs formed by oysters and horse mussels. There are reports that the wonderful maerl and flame-shell reefs (Figure 3) I documented in Loch Fyne in the 1990s have since been obliterated by scallop dredging, and this pains me deeply.

Recent public consultations on UK marine management revealed widespread support for a network of sea-bed regeneration zones that, most agree, should be off-limits to the more destructive forms of fishing, and such sites are starting to crop up around the UK. Understandably, some of those that trawl, dredge or electrocute the sea bed were against such restrictions. Still, there is a wide body of folk who are all for restricting damage, like the anglers who want spawning areas protected or fishermen who want sustainable livelihoods and so use low-impact gear. Carbon footprints must also be considered – it seems bonkers that we export seafood we can dredge or trawl using powerful vessels, and import seafood that we are culturally accustomed to eating but can no longer catch in sufficient amounts to meet demand (like Icelandic cod and whiting).

Planetary change and ocean acidification

The last 60 years have without doubt seen the most profound transformation of humanity's relationship with the natural world in the history of humankind. Since 1950, the human population has trebled, water use is up from 1800 to 5800 $km^3 yr^{-1}$, the number of rivers dammed has risen from 4000 to 28000, fertiliser consumption has jumped from 40 to 280 million tonnes a year, quadrupling inputs of nitrogen to the coastal zone (Figure 4), and we've lost 65% of the atmospheric ozone. Motor vehicle use is up from 30 million to 750 million vehicles on the road, and international tourism has really boomed, rising from <1 million international arrivals per year in the 1950s to 600 million today. With all this frenetic movement, by air, land and sea, it's little wonder that the rockpools on Plymouth Hoe are now jam-packed with invasive species – all new arrivals since the *Plymouth Marine Fauna*

Planetary changes which began during the industrial revolution have accelerated since the 1950s

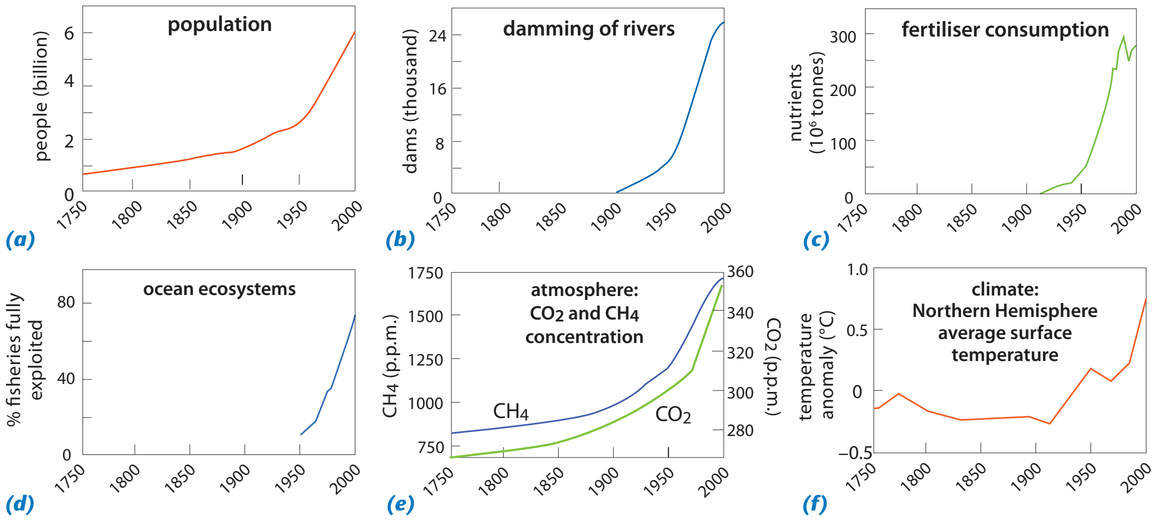


***Figure 4** The effects of the accelerating anthropogenic changes are now clearly discernible at the Earth system level. The increasing human population **(a)** is having global effects on coastal systems through the rising use of water **(b)** and fertilisers **(c)**, and through overexploitation of fisheries **(d)**. Increasing concentrations of carbon dioxide and methane in the atmosphere **(e)** are causing rising sea-surface temperatures **(f)**. (Adapted from Steffen* et al. *2004)*

was published in 1957. Since then there has clearly been a great acceleration in our use of the Earth's resources; atmospheric methane concentrations are up from 1250 to 1750 p.p.b.v. (parts per billion by volume) and atmospheric CO_2 concentrations up from 300 to 360 p.p.m.v., causing seawater temperatures to rise (Figure 4). We know from ice-core data that these warming gases are at much higher levels than at any time in the past 800 000 years, including a sequence of glacial periods and warm periods (see Further Reading). We have entered unknown territory as the excess CO_2 in the atmosphere is acidifying the surface oceans.

Over the next 100 years, ocean acidity and pH could change by considerably more than they have changed over the last 100 years

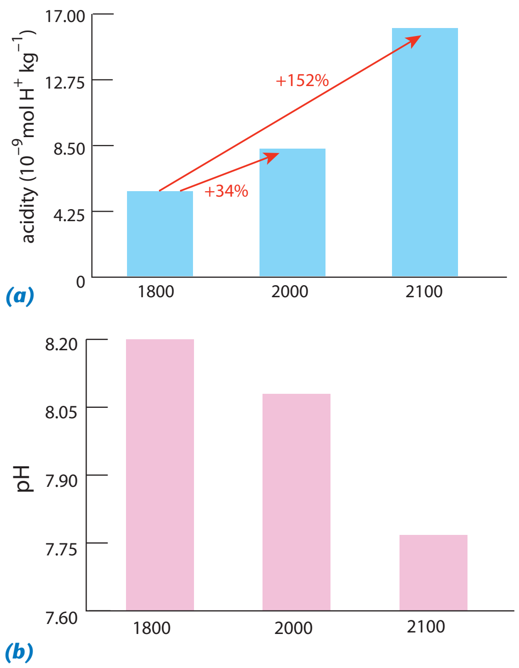


***Figure 5** **(a)** Average surface ocean acidity and **(b)** pH, in 1800 and 2000, and projected for 2100.*

Ocean acidification is an issue that wasn't even thought of in the era of the *Challenger* Expedition. It wasn't until 2006 that it dawned on most marine biologists, myself included, that a third of CO_2 emissions (increasing by 1% a year in the 1990s and 3.5% a year in the 2000s) are dissolving into, and acidifying, the sea. Today we add around 10 PgC yr^{-1} to the atmosphere, of which around 9.1 PgC yr^{-1} is from burning fossil fuels (1 PgC = 1 petagram = 10^{15} g of carbon). A quarter of CO_2 emissions to date have been taken up by the oceans; this equates to every reader of this article – and everyone else on Earth – throwing a bowling ball's weight of carbon into the sea every day.

Monitoring of surface seawater off Hawaii, and on both sides of the North Atlantic, clearly shows increases in CO_2 levels that are tracking atmospheric increases. Carbon dioxide forms carbonic acid when it dissolves in water, and has caused a 34% increase in seawater acidity (i.e. the concentration of H^+ ions) since 1800, and will have caused about a 150% increase in surface ocean acidity by 2100 (Figure 5). This is the fastest rate of chemical ocean change for millions of years, and perhaps in all time, since the rate at which fossil fuels are being burnt is geologically unique.

Clearly ocean acidification is not acting in isolation. Rising CO_2 levels are also causing ocean warming which is damaging tropical coral reefs, melting Arctic ice, thawing tundra and leading to poleward shifts in the distributions of many marine species. In low-latitude areas, warming waters are becoming depleted in oxygen as warm waters can't hold as much oxygen as cold (darker blue areas in Figure 6), and low productivity areas in the centres of mid-ocean gyres

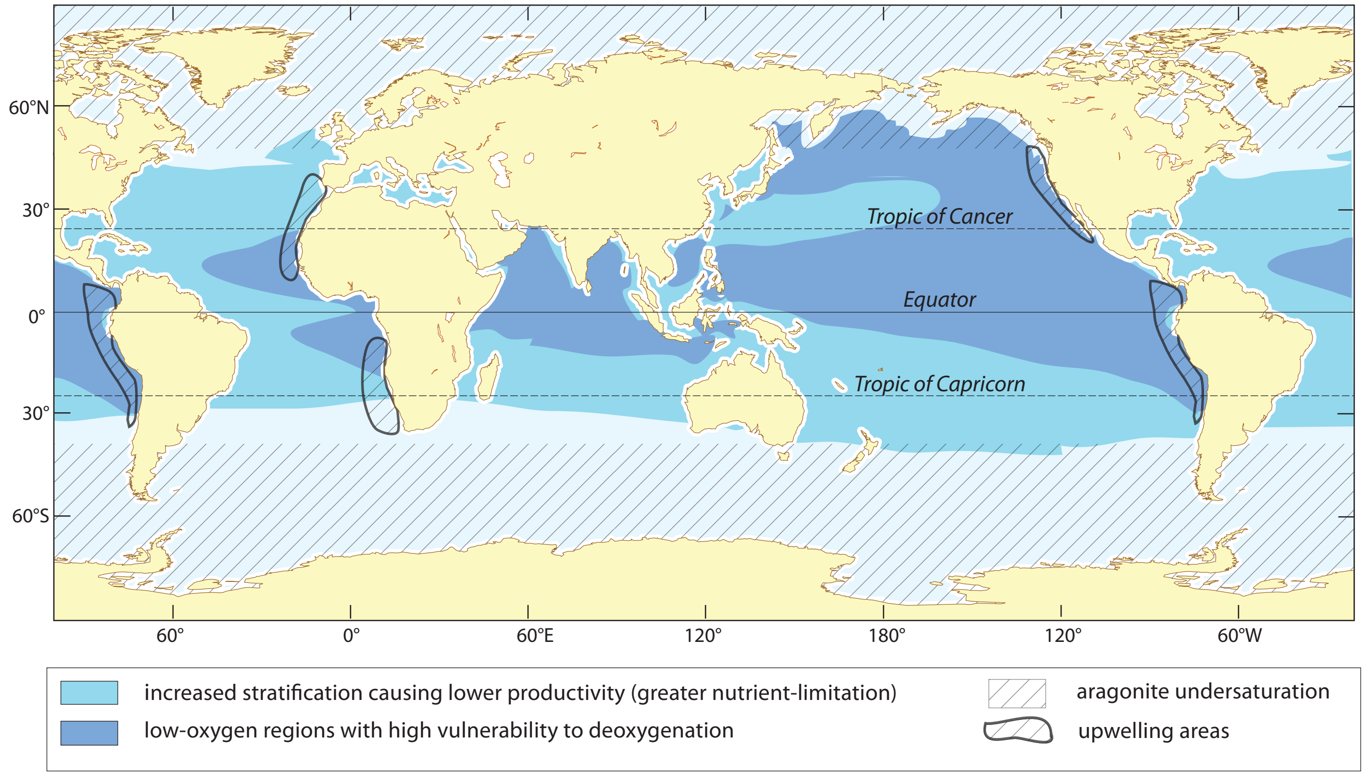
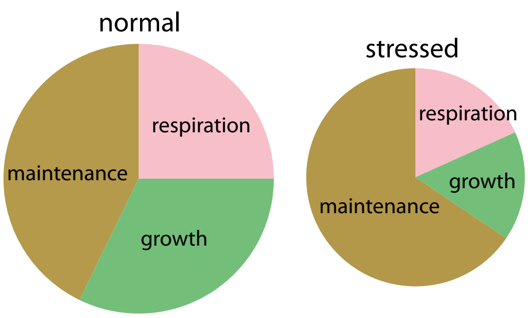


Figure 6 *Surface water regions of particular vulnerability to ocean warming, acidification and de-oxygenation. Aragonite is the form of calcium carbonate used by hard corals and many other organisms to build their skeletons; waters in high latitudes and upwelling regions are corrosive to aragonite (see Gruber 2011).*

Surface waters across the globe are subject to three main stressors

are expanding in size due to increased thermal stratification which suppresses mixing and so starves the surface waters of the nutrients that underpin food web productivity.

Ocean acidification research is the 'new kid on the block' amongst planetary environmental issues, but as evidence rolls in from across the globe it is clear that many organisms are likely to be affected because ocean acidification not only increases the amount of carbon available for photosynthesis and so is a resource for primary production, but also lowers the amount of carbonate in the water, so that it can become corrosive to exposed skeletons and shells (*see later*). Ocean acidification has myriad biological ramifications because H^+ concentrations can influence the transport of materials across cell membranes and so can affect reproduction, behaviour, respiration and growth (Figure 7). This effect of ocean acidification is thought to explain why the fossil shells laid down after high-CO_2 mass extinction events are dwarf forms, since smaller animals are better able to cope with the stress of ocean acidification (see Further Reading).



Ways of studying ocean acidification

One of the earliest studies of the biological effects of ocean acidification was carried out in aquaria in which corals switched from calcification to dissolution as CO_2 levels rose (see Figure 8, overleaf). This study was followed by a slew of high-profile papers pointing out that unless we get a grip on CO_2 emissions tropical coral reefs will disappear.

As I specialise in temperate systems, this work on tropical coral reefs set me wondering about what ocean acidification might do to the organisms that live off Plymouth and the corals that form deep north-east Atlantic reefs. One way to approach this question is to visit places that are like what we expect the future to be like;

Figure 7 *Hypothetical energy budget for normal and stressed organisms. In stressed conditions maintenance costs can increase, leaving less energy available for growth or reproduction. Ocean acidification can depress metabolic rates, hence the smaller pie size for the energy budget of the stressed organism.*

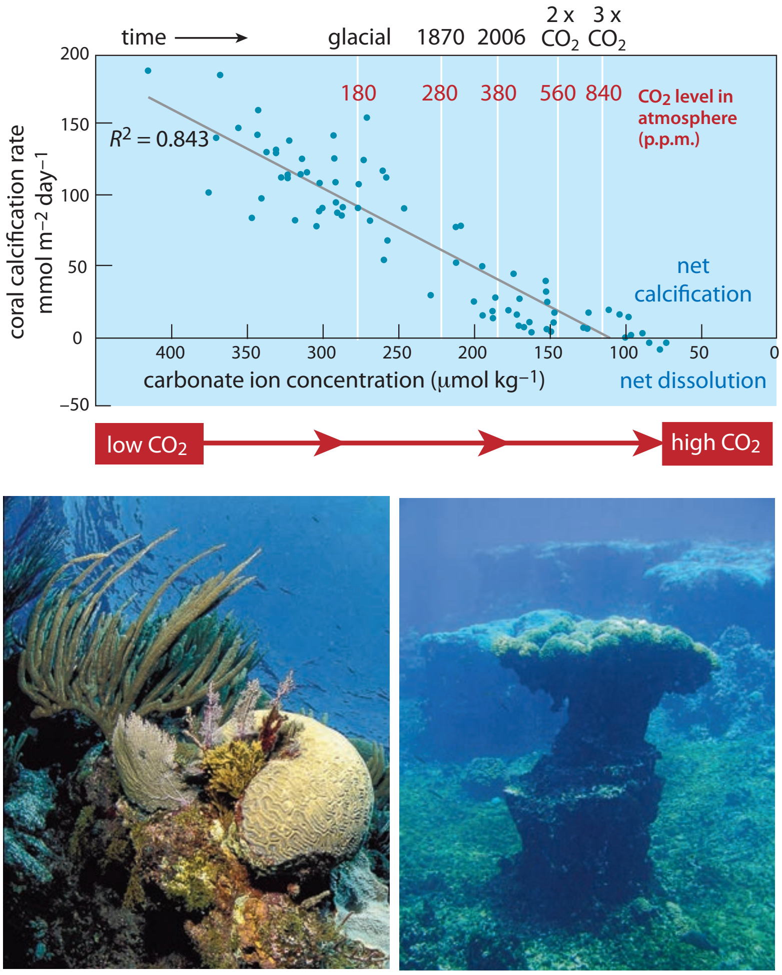


Figure 8* *Upper *Work in aquaria has shown that as CO_2 levels in the atmosphere rise, carbonate ion concentrations in seawater fall, which slows down tropical coral calcification rates until eventually the reef begins to dissolve (see Langdon and Atkinson, 2005).*

Lower left *Robust coral reefs occur around the Bahamas where seawater carbonate levels are high.* ***Lower right*** *Coral reefs are eroded and crumble away where carbonate levels are low, such as in upwelling waters of the eastern Pacific Ocean (cf. Figure 6)*

(Photos by courtesy of Alex Venn, Centre Scientifique de Monaco, and Mark Eakin, NOAA)

As CO_2 levels rise, coral reefs begin to dissolve

a comparison of coral reefs of the Bahamas (photo on left, Figure 8) with those off Panama (photo on right) shows that coral reefs begin to crumble as carbonate saturation states fall. So today we find robust reefs in the Caribbean but eroded reefs in the low carbonate waters of the tropical easten Pacific. Studying places that already experience the lower carbonate conditions of a high-CO_2 world allows us to find out about the ecological effects of ocean acidification.

CO_2 seeps

Volcanic activity causes CO_2 to bubble up from the sea floor, acidifying large areas for hundreds of years. Research has begun in coastal areas that are acidified by CO_2 in this way, showing which organisms thrive and which are most vulnerable. The tricky bit is finding areas without the confounding effects of sulphur or toxic metals, but it can be done. This approach augments laboratory work which is usually short-term and on organisms that are isolated from competitors, parasites and grazers.

We have found that chronic exposure to increases in CO_2 around seeps alters food webs and causes marine biodiversity loss in the Mediterranean (Figure 9), the Sea of Cortez and off Papua New Guinea. Key groups, like sea urchins and coralline algae, are consistently compromised and fish reproduction is disrupted. However, it is not all doom and gloom; higher CO_2 levels stimulate the growth of certain diatoms, macroalgae and seagrasses (Figure 10). If temperatures remain low enough then the symbiotic algae of corals and anemones do well, as do numerous invasive species of seaweed. Some organisms adapt to long-term acidification, and species with protective tissues – including some corals in the tropics and mussels in temperate areas – often tolerate acidified seawater. Unfortunately, the combination of acidification and rising temperatures is often deadly as the fall in carbonate saturation causes coral skeleton dissolution, and increased CO_2 levels stimulate the growth of fleshy algae that smother reefs (Figure 11).

There is now an opportunity, an 'ocean challenge' if you will, to show which organisms, habitats and coastal ecosystem services will be resilient to ocean acidification, and which are vulnerable.

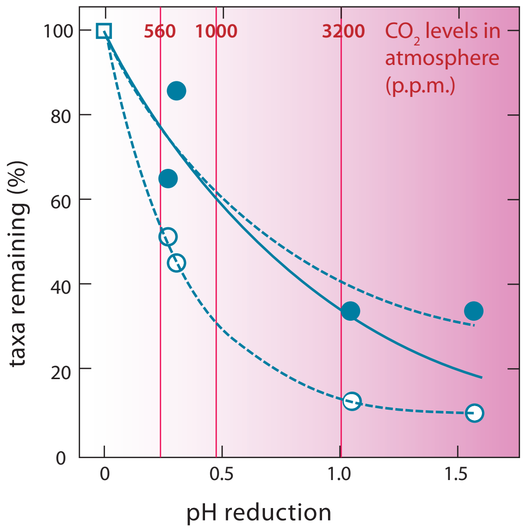


Figure 9 *The diversity of calcified (open circles) and non-calcified (filled circles) taxa falls as rising CO_2 levels cause pH to fall at volcanic vents off Ischia (Italy). Red vertical lines show atmospheric CO_2 levels required to cause the seawater pH changes observed and the solid blue curve shows the loss for all taxa, with around a 30% fall in diversity at levels of ocean acidification expected by 2100.*

(Data from Hall-Spencer et al.*, 2008)*

Figure 10 *Seagrass and fleshy algae flourish at at a shallow CO_2 seep off the island of Ischia (Italy) but calcified organisms die out in these low carbonate waters. (Photo by courtesy of David Liittschwager)*

I hope we can learn from the ways in which Victorian marine scientists met environmental challenges of their day, such as the drive to clean up estuaries. We must combine forces to better understand how CO_2 emissions will shape coastal ecosystems in order to inform the people that this will affect the most, including those who rely on aquaculture, fisheries and coastal tourism.

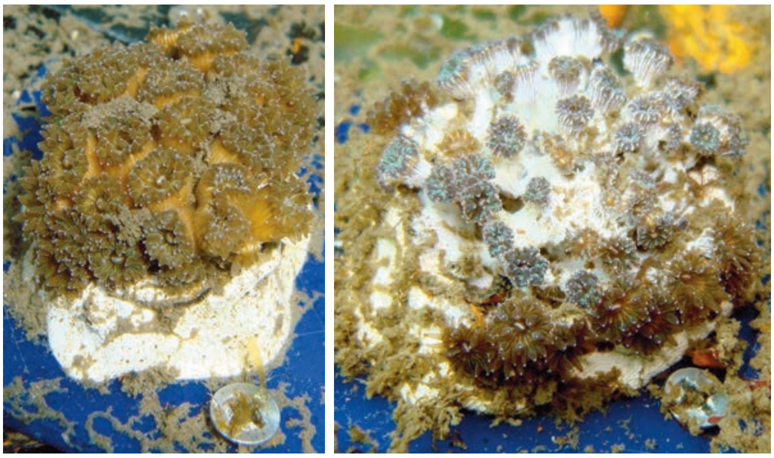


Figure 11 ***Left*** *The scleractinian coral* Cladocora caespitosa *grows well at high CO_2 levels.*
Right *When ocean acidification combines with unusually high summer temperatures these corals are killed (see* Rodolfo-Metalpa et al. *2011).*

While seagrass and algae may flourish in high-CO_2 conditions, many corals suffer, especially when stressed by high temperatures

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Jason Hall-Spencer pioneered the use of natural analogues to study the effects of rising CO_2 levels on marine ecosystems. He is Professor of Marine Biology at Plymouth University, Editor-in-Chief of Regional Studies in Marine Science, a UK Government Scientific Advisor on Marine Conservation Zones and serves on the Ocean Acidification International Reference User Group.
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Why the eastern Mediterranean can be a dangerous place to live

Beverly Goodman-Tchernov

The Mediterranean is the largest and deepest marginal sea on Earth. It is connected through the Straits of Gibraltar to the Atlantic Ocean in the west and via the Dardanelles to the Black Sea in the east. The basin itself is divided into western and eastern basins by a relatively shallow ridge (~ 500 m) at the Straits of Sicily. The subject of this review is the larger eastern basin, which includes the Adriatic, Ionian, Aegean and Levantine Seas. The basin was formed as the last stage of the closing of the Tethys Ocean. It has a series of small plates with tectonically active boundaries, which were formed by the collision of Africa with Eurasia (Figure 1). It has diverse complex bathymetric features, both deep and shallow, and is semi-enclosed. Due to its unique features, it represents a natural laboratory for a variety of globally important geohazard processes. (It is also the setting for unusual nutrient cycling in the water column, as discussed in the following article. Ed)

Geohazards in the Eastern Mediterranean

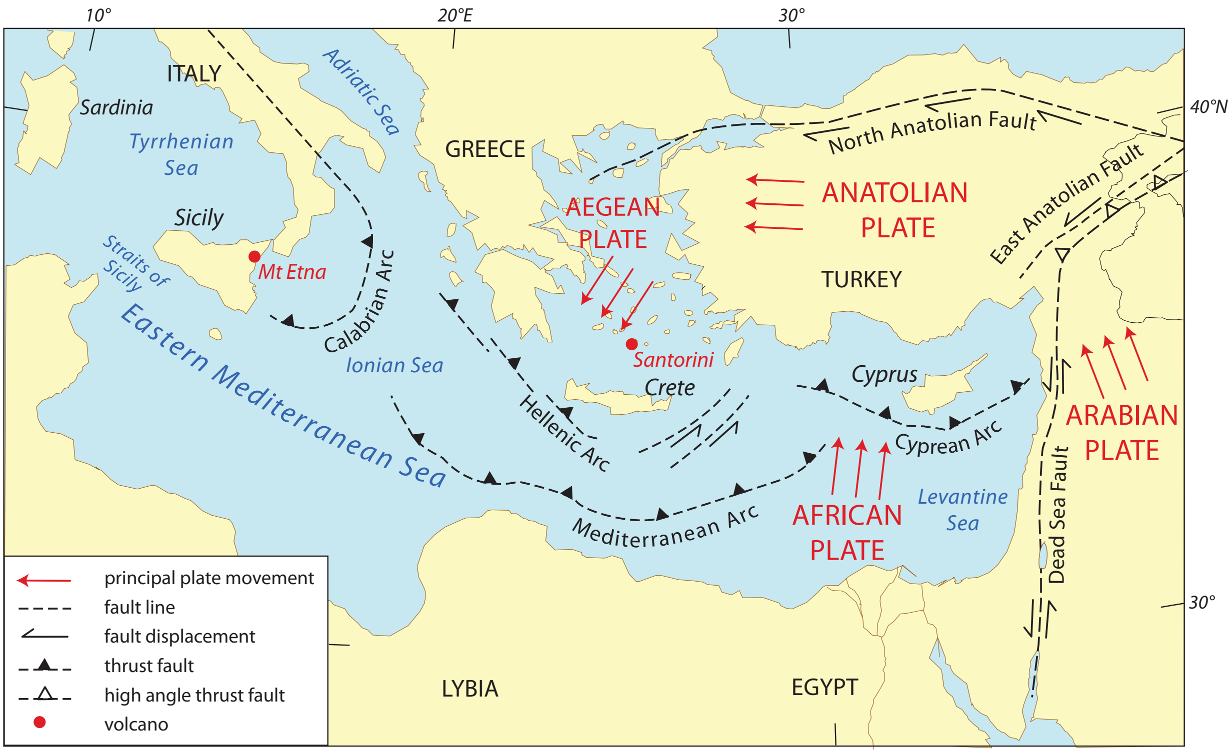
Because it has a number of active plate boundaries, the Eastern Mediterranean Sea is particularly vulnerable to seismically generated hazards.

Earthquakes

In the relatively uneventful year of 2014, 30 earthquakes were recorded in the Eastern Mediterranean. The largest (Magnitude 5.1) was measured at Ierápetra, Lasithi, Greece, an area with frequent large earthquakes due to its position on the active Hellenic Arc. Other areas in the eastern Mediterranean that are also seismically active include the Cyprean Arc, and especially the Northern Anatolian Fault Zone where the 1999 Izmit Magnitude 7.4 earthquake resulted in the deaths of over 17 000 people. To the south, the Eastern Anatolian Fault runs along the contact between the Anatolian and Arabian Plates and is another area with high seismic potential.

Destructive earthquakes are known from many parts of the eastern Mediterranean. The largest instrumentally recorded earthquakes are the 1903 Kythera earthquake (Magnitude 8.2) and the 1926 Rhodes earthquake (Magnitude 7.8, recorded by the USGS). Historical records of earthquake events help to lengthen the time period of known events, and the descriptions sometimes provide enough detail to reconstruct the magnitudes of the events. Together these records, used with extreme caution, can be helpful for deducing minimum recurrence rates over longer time-frames. While these values should be considered with extreme caution, generally speaking there are records of earthquakes of Magnitude 7.5 and higher occurring every 100 years or so, with large earthquakes (Magnitudes 5.5–7.5) occurring around every 40 years, and events of up to Magnitude 5.5 occurring annually.

Figure 1 *Map of the Eastern Mediterranean showing the major plates and plate boundaries and the associated plate movements. The subduction of the African Plate beneath the Aegean Plate results in an arc-shaped accretionary complex (a body of faulted and folded sedimentary rocks) between the Mediterranean and Hellenic Arcs. To the north of this there is a 'volcanic arc', including the volcano of Santorini (Thera). South of Cyprus, the Cyprean Arc is formed from the interaction of the African and Anatolian Plates. These plate boundaries, together with the volcanoes, represent the potential sources of geohazards in the basin.*



Volcanic eruptions

Volcanic eruptions are rare. Perhaps the most damaging and well known was the massive plinian* eruption on the island of Thera (Santorini) in approximately 1600 BC. It produced a caldera collapse† (cf. Figure 2) and resulted in a major tsunami which affected the whole eastern Mediterranean. The Theran eruption may have altered the climate significantly for a period of time and impacted civilizations throughout the region. While what actually happened is widely debated, some have linked this event to societal changes such as the decline of the Minoan civilization on nearby Crete or even the biblical story of the parting of the Red Sea.

Figure 2 *The Santorini archipelago, the islands of which are the above-water part of a volcanic caldera. During the mega-eruption of 1600 BC, the island of Thera exploded, causing a tsunami which some believe contributed to the end of the Minoan civilisation on Crete.*

Mt Etna, located on the eastern side of Sicily, is another active volcano. Eruptions occur regularly and are of varying intensity; some have impacted the eastern Mediterranean through the ash projected into the atmosphere.

*Plinian eruptions produce powerful convecting plumes of ash which ascend up into the stratosphere. They are named after Pliny the Younger, a Roman statesman who wrote a remarkably objective account of the eruption of Mt Vesuvius in 79 AD.

†A caldera is a cauldron-like feature formed by the collapse of land following a large volcanic eruption, triggered by the emptying of the magma chamber beneath the volcano.

Tsunamis

Like the Theran eruption of 1600 BC, the eruption of Mt Etna 7000–8000 years ago is suspected of triggering a mega-tsunami which impacted the entire eastern Mediterranean as a result of a collapse or landslide event.

Tsunamis are devastating side-effects of earthquakes and volcanic eruptions. In the case of the Eastern Mediterranean, the enclosed nature of the basin influences the way in which tsunamis propagate from their source and interact with the coastline, and increases the potential for resonance and for reflections, which can increase wave heights or result in repeated wave arrivals after the initial event.

Mediterranean tsunamis account for about 10% of all tsunamis worldwide, and a large portion of those are in the tectonically active eastern Mediterranean (data from NOAA, National Geophysical Data Center NGDC). Recent instrumentally recorded tsunamis in the eastern Mediterranean include events in 1999, 1956 and 1908.

In about 440 BC the Greek historian Herodotus wrote a description of an intervention by Poseidon against the invading Persians in 479 BC, involving a great sea wave. While Herodotus' identification of the cause of the wave may have been flawed, his description was quite accurate and fits the phases of a tsunami as they are identified today. Later, the historian Thucydides produced a similar account of a 426 BC event impacting the Malian and Euboean Gulfs, which extend from the Aegean Sea into central Greece.

In addition to the catalogues of written records, there are also a growing number of field studies, which are improving our understanding of the magnitude, significance and impact of these events as well as identifying undocumented instances. Sedimentological studies of modern deposits following recent mega-tsunamis (e.g. the 2004 Boxing Day tsunami) have also greatly contributed to our ability to discover, identify and understand such events.

However, unlike the mega-tsunamis of the past decade, Mediterranean tsunamis are generally the result of offshore slumping events triggered by earthquakes rather than major displacements on oceanic subduction zones. Typically, tsunamis resulting from landslides or slumping tend to be more localised, and do not propagate that far from their origin. However, this does not mean they are less significant, as the areas that are affected can experience major damage comparable to that caused by events generated from earthquakes along underwater plate boundaries, which propagate more widely. The geographic area affected will be less, but the destruction at any individual site affected will be similar.

Also, there are events known to have affected the whole Eastern Mediterranean Sea (such as the earthquake of. 365 AD, or the 1600 BC Theran eruption), which – whatever the immediate cause (earthquake or volcanic eruption) – were accompanied by a collapse of submerged rocks and sediments.

Coastal and offshore areas of today's Eastern Mediterranean Sea contain structures such as pipelines, gas platforms and telecommunication networks, and coastal areas are heavily populated and house significant critical infrastructure (power stations, desalination plants, etc.). The tsunamis generated from the eruptions of Mt Etna (7000–8000 years ago), Thera (1600 BC), and the 365 AD earthquake, were probably on a par in intensity with the 2004 Boxing Day tsunami which killed 250 000 people. Given the number of people living along those same coastlines today, any events of similar magnitude will have catastrophic consequences.

Further reading

Goodman-Tchernov, B.N., H.W. Dey, E.G. Reinhardt, F. McCoy and Y. Mart (2009) Tsunami waves generated by the Santorini eruption reached Eastern Mediterranean shores. *Geology*, **37**, 943–6.

Poulos, S., G. Alexandrakis, T. Paranama and A. Karditsa (2005) Tsunamis affecting Greece in ancient and modern times. *Ocean Challenge,* **15** (1), 32–7.

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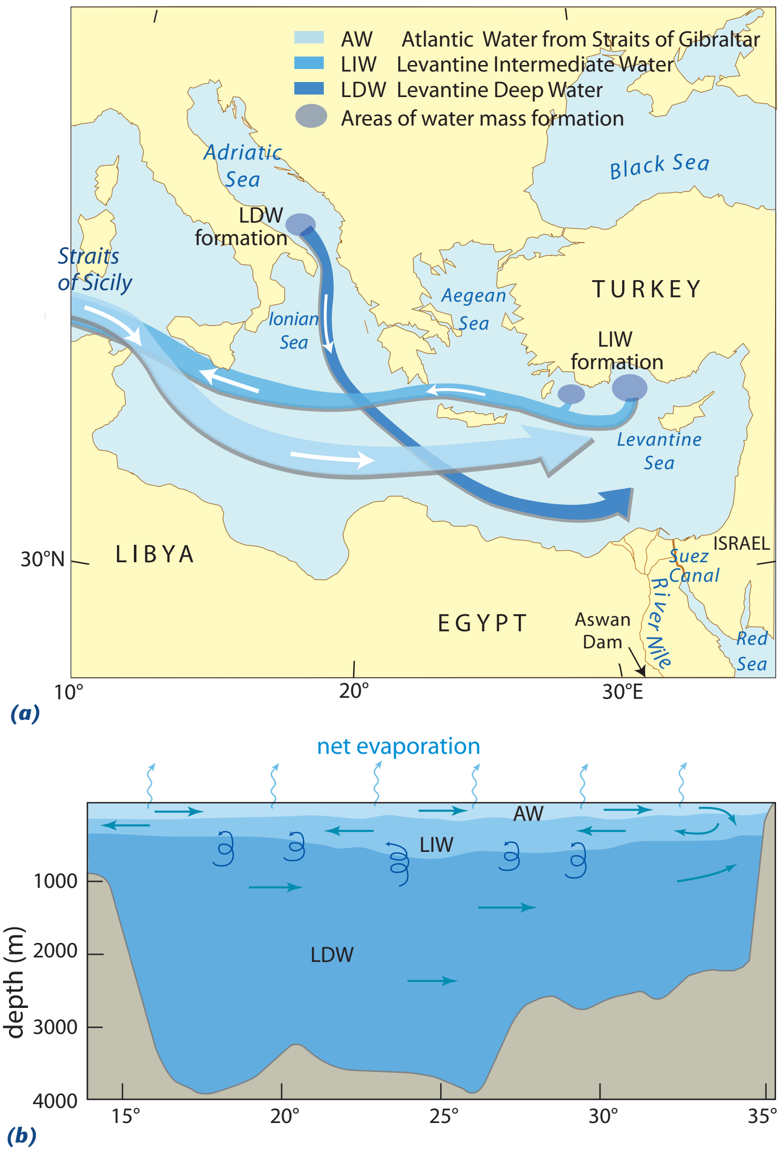
THE EASTERN MEDITERRANEAN SEA

A natural laboratory for studying marine biogeochemical processes

Michael D. Krom and Yair Suari

The Eastern Mediterranean Sea is an unusual part of the global ocean, with biogeochemical characteristics that make it an ideal natural laboratory for studying the cycling of nutrients. Despite the fact that it has high inputs of pollutant nutrients from the large population in its catchment, it is as much a desert as the Sahara to the south. It has a highly unusual nitrogen : phosphorus (N : P) ratio which results in it being the largest body of water in the world whose major annual phytoplankton bloom is P-limited. It is also uniquely vulnerable to both climate and environmental change, and is the only area of the world for which the recent IPCC confidently predicted that the climate will get hotter and drier. It has also been directly affected by the end of the Nile flood on completion of the Aswan dam in 1965. These changes are affecting the physical circulation, and will continue to do so, and in turn will control the nutrient cycling. In this review we explain the reasons for some of the unusual biogeochemical features which make the Eastern Mediterranean Sea such an interesting place to study.



Physical circulation

The Mediterranean is one of only two large basins in the world with anti-estuarine* circulation (the other is the Red Sea). Atlantic surface water of normal salinity (35) flows into the Mediterranean at the Straits of Gibraltar. This Atlantic Water (AW) flows eastward, mainly along the southern half of the western basin to the Straits of Sicily. There, the upper 200 m of the water flows over the sill into the Eastern Mediterranean basin. This water flows along the southern side of the basin past Libya and Egypt to the Israeli–Lebanese coast and thence to an area off southern Turkey. During this time it becomes progressively saltier because of the unusual excess of evaporation over precipitation in this semi-enclosed basin – it is after all, immediately adjacent to the Sahara, the largest desert in the world. In winter, cooling increases its density further, and it sinks to form Levantine Intermediate Water (LIW), which then flows west at a depth of 200–500 m, eventually leaving the Eastern Mediterranean Sea via the Straits of Sicily. The residence times for these two water masses in the Eastern Mediterranean are very short: AW

*In an estuary, fresh river water flows out to sea above incoming saline seawater. In the case of the Mediterranean, less saline AW water flows in at the Straits of Gibraltar above more saline intermediate water flowing out to the Atlantic. In the context of the article, the important point is that incoming water flows above outgoing water.

Figure 1 ***(a)*** *Map of the Eastern Mediterranean Sea showing the areas of formation of the main water masses, and greatly simplified flow paths.*
(b) *A west–east cross-section of the Eastern Mediterranean showing approximate vertical extents of the water masses.*

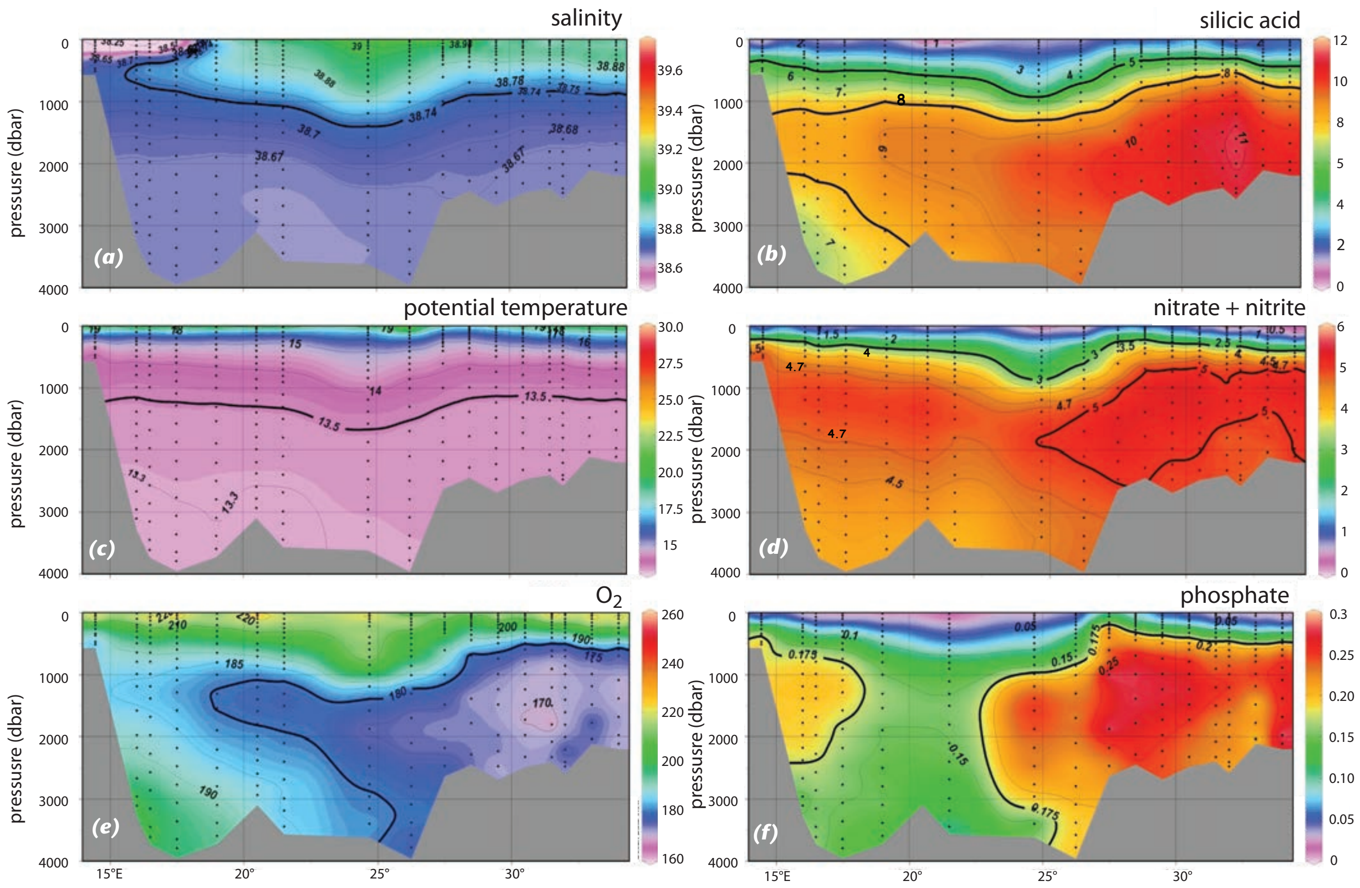


Figure 2 *Sections along a west–east transect of the Eastern Mediterranean in 1987. Data points are indicated by dots.* ***Left side (a)*** *Salinity,* ***(c)*** *potential temperature (°C) and* ***(e)*** *dissolved oxygen (µmol kg^{-1}).* ***Right-side*** *Nutrients:* ***(b)*** *Silicic acid, $Si(OH)_4$,* ***(d)*** *nitrate + nitrite, $NO_3^- + NO_2^-$ (µmol kg^{-1}) and* ***(f)*** *phosphate, PO_4^{3-} (µmol kg^{-1}). The anti-estuarine circulation can clearly be seen in (a), where a tongue of AW of relatively low salinity flows in through the Straits of Sicily above westward-flowing LIW of higher salinity. The nitrate and phosphate concentrations in the deep water increase towards the east as organic matter, mainly dead phytoplankton, sinks down from above and decomposes. Silicic acid is added from the pore waters of the sediments below.*

The anti-estuarine circulation in the Eastern Mediterranean has a profound effect on the vertical distribution of nutrients and dissolved oxygen

has a residence time of ~7 years while LIW has a residence time of ~8 years. These short residence times are crucial to the observed biogeochemical patterns in the basin.

Flowing beneath these two upper water masses is Levantine Deep Water (LDW), which is formed in the southern Adriatic in winter. It flows into the Ionian Sea and from there fills the deep basin of the Eastern Mediterranean Sea (>500 m) by flowing east. The residence time of LDW in the basin is 120–150 years – longer than the surface waters but still much shorter than residence times of water in the major ocean basins.

The Eastern Mediterranean Sea is one of the few locations in the world's oceans in which the circulation pattern has dramatically changed in recent decades. During the late 1980s and early 1990s the site of deep-water formation switched temporarily from the southern Adriatic to the Aegean. This resulted in a new body of deep water, known as the East Mediterranean Transient. Subsequently there has been a switch back to deep water being formed in the southern Adriatic. The reason for this switch is still under debate, but it is likely to have been caused, or at least facilitated, by anthropogenic climate and/or environmental change, possibly including the effect of the completion of the Aswan Dam in 1965 (see below).

This is not the only major change in circulation in the Eastern Mediterranean that has happened in geologically recent times. Between 9500 and 5500 years ago these waters switched from their present ultra-oligotrophic (very low-nutrient) state to a situation in which organic-rich sediment known as sapropel was deposited. In a recent modelling study, Grimm and co-workers have suggested this was mainly because of a drastic change in the deep water circulation. Their model indicates that there was a marked slowing of the formation of deep water between 500 and 1500 m, while the water deeper than 1500 m became completely stagnant. Decomposition of organic matter dropping from the photic zone would have used up most if not all of the oxygen in the 500–1500 m oxygen-minimum depth zone, while the water below 1500 m became completely oxygen-depleted and sulphide-rich, similar to the deep waters of the Black Sea today. In addition, there may have been changes in the surface water circulation caused by the wetter climate at that time which could have resulted in some increase in productivity in the photic zone. As a result, large amounts of organic matter survived to accumulate in the sediment.

Cycling of N and P

Our understanding of the unusual N and P cycling in the Eastern Mediterranean has developed dramatically in the two decades since 'The oceanography of the Eastern Mediterranean Sea' was published in *Ocean Challenge* (see Further Reading). At that time it was already known that although the Eastern Mediterranean Sea is nearly completely surrounded by land, with significant associated nutrient inputs, it was ultra-oligotrophic with annual primary productivity of only 60–80 gC m^{-2} yr^{-1}. This is even lower than that measured in the low productivity areas of the north-western Sargasso Sea. By comparison, the Baltic Sea, which has similar nutrient input per unit area, has high primary productivity and other characteristics associated with being eutrophic (high-nutrient).

The unusually low productivity in the Eastern Mediterranean Sea is a result of its anti-estuarine circulation. Nutrient-depleted surface waters flow in from the Western Mediterranean, while intermediate waters, which contain nutrients released by the decomposition of plankton dropping from the photic zone, flow out of the basin. In addition, nutrients added to the surface waters directly from the atmosphere and/or from rivers only remain in the Eastern Mediterranean for a few years before they are washed out through the Straits of Sicily. Concentrations of nutrients in surface and intermediate water are thus very low (Figure 2(b),(d),(f)), while deep-water concentrations are far lower than those measured in other areas of the global ocean (Table 1) because of both the circulation pattern which efficiently removes nutrients from the basin, and the relatively short residence time of the deep water. One of the consequences of the low nutrient concentrations in the Eastern Mediterranean is that chemical analysis of nutrients is especially challenging, requiring nanomolar technology and analysis of fresh (unfrozen) samples of dissolved inorganic nutrients, from the photic zone especially.

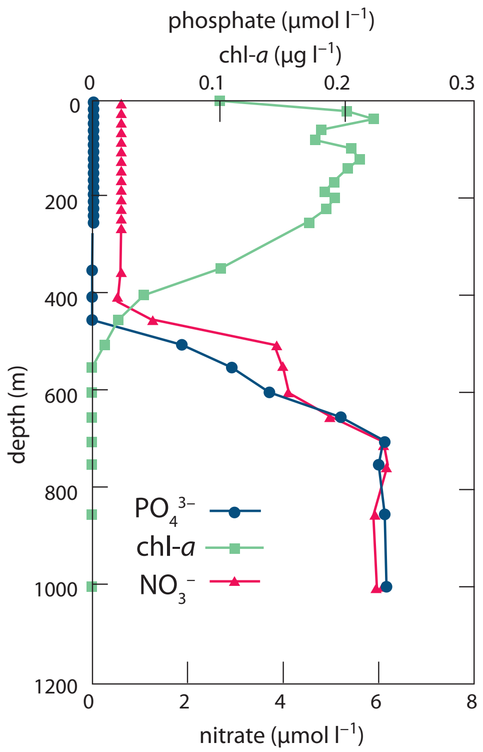
Table 1 *Nutrient and dissolved oxygen concentrations in deep water in the Eastern Mediterranean compared with deep water elsewhere in the global ocean*

Chemical species (concentrations in µmol l^{-1})	**Eastern Med**	**North Atlantic**	**North Pacific**
nitrate (NO_3^-)	6	16	50
phosphate (PO_4^{3-})	0.25	1	3
silicic acid	6–11.5	20	160
degree of saturation of dissolved oxygen	> 80%	0–100%	0–100%
N : P ratio	28.1	16.1	16.1

In 1991, it was shown that the deep water had an unusual nitrate : phosphate ratio of 28:1 (see Further Reading). Subsequently, it was shown that for nitrogen and phosphorus in material of organic origin, both dissolved and particulate, N : P ratios are much higher than the Redfield ratio of 16 : 1 (i.e. much higher than the commonly used molar ratio of nitrogen and phosphorus in marine organic matter). Thus the high N : P ratio was caused by a regional shortage of P relative to N. A high N : P ratio suggested that primary productivity in the Eastern Mediterranean Sea is P-limited, i.e. phytoplankton grow until they run out of phosphorus, while excess nitrate remains in the water column. Indeed this is what happens in the Eastern Mediterranean during the major annual phytoplankton bloom, which unusually occurs in winter (Figure 3), when warm sunny days are interspersed with short periods of colder, cloudy and blustery weather when nutrients are mixed up into the surface water.

Zero P and residual N in the upper water column following a plankton bloom is characteristic of a P-limited system

Figure 3 *Profiles of dissolved nutrients (phosphate and nitrate) and chlorophyll-a (a measure of phytoplankton biomass) during the winter phytoplankton bloom in the Levantine Basin.*



The obvious question was: Why does the Eastern Mediterranean suffer from a shortage of P relative to N? Initially it was thought this might be due to Saharan dust scavenging phosphate (but not nitrate) as it sinks through the water column. It is known that dust has a high content of iron oxides and that iron oxides can adsorb phosphate but do not react with nitrate. However, when this idea was tested in the Eastern Mediterranean, it was found that the iron oxides in Saharan dust do not react with phosphate, because desert weathering causes iron oxides to be chemically unreactive.

A possible explanation for the relatively high N concentrations was that there might be regionally high rates of N_2-fixation.* Recent measurements carried out by labs in Italy, Israel and France showed this idea was also wrong because there are unusually *low* rates of N_2-fixation in the Eastern Mediterranean. Subsequently, a new hypothesis was developed by Krom and co-workers based initially on a detailed nutrient budget for the Eastern Mediterranean Sea. They found that all of the external sources of nutrients had a higher than Redfieldian N : P ratio (> 16 : 1), with atmospheric sources mainly from polluted air masses from southern Europe having a particularly high ratio of >100 : 1. They proposed that the high N : P ratio in the contributing external sources remained in the water column because there was very little nitrate reduction occurring to remove the extra nitrate from the water column. This is because nitrate reduction requires anoxic conditions in the sediment or water column and these do not occur in the present Eastern Mediterranean Sea as there is such low primary productivity and hence only a small flux of organic matter from the surface waters. Anoxic conditions require an excess of organic matter (as occurred 9500–5500 years ago).

In spring 2002, the CYCLOPS (CYCLing Of Phosphorus in the eastern Mediterranean) Lagrangian 'addition experiment'* was carried out in the south-eastern Levantine basin. This experiment – one of only two addition experiments in which phosphate (rather than iron) has been added to a patch of surface water – was designed to improve understanding about the nature of N and P cycling in the Eastern Mediterranean. We expected the system to show P-limitation of productivity, but to our surprise this was not what we found. In fact, the phytoplankton productivity in May when the experiment was carried out was limited by both N and P. It was concluded that the change in nutrient limitation since the winter P-limited bloom (cf. Figure 3) was a result of subsequent phytoplankton growth converting the left-over nitrate to dissolved organic nitrogen (e.g. amino acids), which was bioavailable for heterotrophic bacteria, but not directly available for phytoplankton growth.

***** In N_2-fixation, atmospheric nitrogen is converted to forms of nitrogen suitable for the construction of organic material; in the sea, this involves cyanobacteria.

†An addition experiment is one in which a fertilising substance is added to surface seawater and increases in primary productivity are measured. The first such experiment was IronEx in 1993.

Recently a 1D mass-balance N and P model was developed to describe nutrient cycling in the Eastern Mediterranean (see Further Reading). The model uses known flow rates for surface, intermediate and deep water and the latest chemical measurements for all the relevant chemical nutrient species. It is able to reproduce all of the major unusual nutrient cycling processes described in this article. It also shows that although there have been major increases in the input of nutrients due to pollution (24% in P and 62% in N) since 1950, the increase in primary productivity has only been 16%. That is due to the rapid flushing out of nutrients caused by the unusual circulation. In the future the model will be used to predict the effect of climate change on nutrient cycling in the basin.

Silica cycling

Although silicic acid** has been routinely measured in the Eastern Mediterranean Sea over the past 50 years, there have been few attempts to understand the controls on silica cycling. In a recently published (2014) study, Krom and colleagues reviewed the unusual features of the silica distribution in the water column of the Eastern Mediterranean Sea (see Further Reading). As shown in Figure 2(b), there is an almost constant surface concentration of ~1 µmol l^{-1} of silicic acid in the photic zone, and there is no evidence of seasonal change. Silicic acid increases with depth across a well-defined silica-cline from 200 m to ~1000 m. As mentioned earlier, the maximum concentration in the deep waters of the Eastern Mediterranean (<11.5 µmol l^{-1}) is much lower than values typically observed elsewhere (Table 1). Such vertical distributions of silicic acid in other areas of the ocean are typically due to uptake by diatoms in the photic zone and dissolution of diatom frustules at depth. However, this cannot be the explanation for the Eastern Mediterranean because diatoms – which are typically found in high nutrient waters – are very scarce because of the unusually low concentrations of N and P in the surface waters.

The low but constant silicic acid concentration of ~1 µmol l^{-1} in surface waters is explained as the concentration in surface water flowing in from the Western Mediterranean Sea remaining unchanged because of negligible diatom growth. As far as deep water is concerned, the concentration of silicic acid in the deep Ionian Sea is due to the sum of silicic acid and opaline silica

**The most common form of dissolved silicon in seawater is as the anion SiO_4^{4+}. This can form a variety of hydroxyl anions depending on the pH of the water (usually as sodium salts). It is usually analysed in very acid solution and thus measured as silicic acid. Plankton such as diatoms grow their skeletons from opaline silica (SiO_2) which they make by extracting silicate anions (SiO_4^{4+}) from seawater. When they die and decompose this opaline silica can dissolve back to re-form SiO_4^{4+}

(i.e. biogenic silica) in the deep water formed in the South Adriatic in winter, during the main phytoplankton bloom. The observed increase in the deep water across the basin (Figure 2(b)) is due to silicic acid fluxing out from the underlying sediments. As with N and P, the low concentrations in the deep water are due in part to the relatively short residence time of deep water (100–150 years) and in part to the rapid exchange of surface and intermediate water, which results in a large export flux of silicic acid from the Eastern Mediterranean Sea.

The silica cycle in the Eastern Mediterranean Sea has also been recently described by a nutrient budget (see Further Reading). Previous attempts at a silica budget have been grossly out of balance (indicating a net export of $150–250 \times 10^9$ mol Si yr^{-1}) as they have been calculated from the simple difference between silicic acid fluxing into the Eastern Mediterranean Sea in nutrient-depleted surface waters and that exported with the intermediate waters. To close the budget requires major and previously unaccounted-for sources of silicic acid being supplied to the Eastern Mediterranean basin. The new budget includes biogenic silica brought in by rivers, and diatoms which grow in the turbulent waters of the Straits of Sicily. These sources are particularly important because of the degree of undersaturation of silicic acid in deep water and the relatively high temperature (~13 °C) of deep water, which cause the opaline silica to dissolve rapidly. However, even with these inputs the budget is not closed.

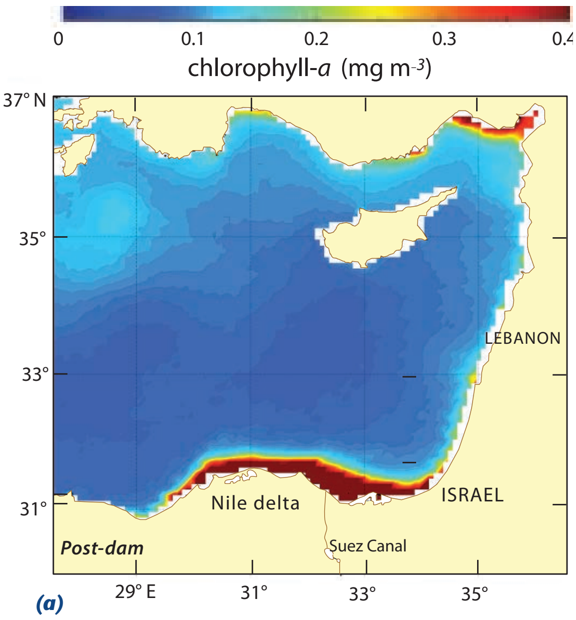
It has been suggested that the *in situ* breakdown of aluminosilicates (clays) in terrestrial sediments might be an important general source of silicic acid to the ocean. At present, this phase (lithogenic silica) is generally only quantified as a correction for estimates of opaline (i.e. biogenic) silica. In the new budget for the Eastern Mediterranean Sea, the benthic silicic acid efflux is estimated as 57×10^9 moles Si yr^{-1}, or 25% of the total reactive Si input to the basin. However, this estimate was based on pore-water silicic acid profiles collected in 1975 at only three sites in the central Eastern Mediterranean and it was assumed that all of the silicic acid fluxing out of the sediment was due to aluminosilicate decomposition. Recent preliminary data from two cores in the Levantine basin indicated that 70–90% of the silicic acid could be formed through decomposition of lithogenic silica, i.e. this new and previously unconsidered source of silicic acid is indeed very important in the Eastern Mediterranean Sea. Further measurements are clearly needed to refine these estimates.

The effect of the 1965 'turn-off' of the Nile on coastal processes

One of the most important global environmental changes caused by human being is the effect of damming major rivers on nutrient cycling in the adjacent coastal waters. Until 1964, the annual Nile water discharge into the Mediterranean was $43 \times 10^9\ m^3\ yr^{-1}$, most of which reached the coast between August and October, having fallen as monsoon rain on the Ethiopian highlands. This Biblically famous Nile flood led to a massive seasonal phytoplankton bloom off the Nile delta, increasing counts by two orders of magnitude. from $10–15 \times 10^4$ cells l^{-1} to $200–2000 \times 10^4$ cells l^{-1}. After the Aswan Dam was completed in 1965, the flood was 'controlled' and there was no discharge of water directly into coastal waters. Indeed the distributaries of the Nile delta have been sealed by dams to prevent seawater encroaching into the delta. Prior to 1965, during the flood the Nile plume extended to the Lebanese/Israeli coast and reduced the salinity of coastal waters by up to 6. A layer of 'brown water', carried by the flood water, and which almost certainly was a diatom bloom, has been described by onlookers.

Damming caused a shift in the phytoplankton community structure. There was a major drop in fish landings shortly after the damming, then a gradual increase to values higher than those pre-1965. The observed increase in fish catches might be partly due to increased fishing effort and to problems in record-keeping, but there has also been a major increase in waste water discharge into the Mediterranean, resulting from population growth. This waste water was more nutrient-rich than previously, due to the Egyptian diet becoming more protein-based, and adoption of chemical fertilizers in Egyptian agriculture. Furthermore, sewage drainage systems now help to disperse nutrients into coastal lagoons in the delta and from there, via adjacent wetlands, into offshore waters (Figure 4(a)). The main differences from the pre-1965 situation are that the nutrient supply to the Levantine Sea no longer has a major summer peak, and the river plume is no longer dispersed during the flood.

Recently a new model – developed by combining a biogeochemical flux model with the Princeton ocean model – has simulated the nutrient distribution and subsequent productivity in the south-eastern Levantine basin prior to the damming of the Nile, and allowed comparison with the same region in modern times. The model showed that pre-1965, nutrients provided by the flood caused higher chlorophyll concentrations that were mainly advected towards the Lebanese/Israeli coast, with only a moderate increase at the Nile delta itself (Figure 4(b)). (NB Chlorophyll scales in (a) and (b) are different.) The increased phytoplankton biomass was followed by extensive



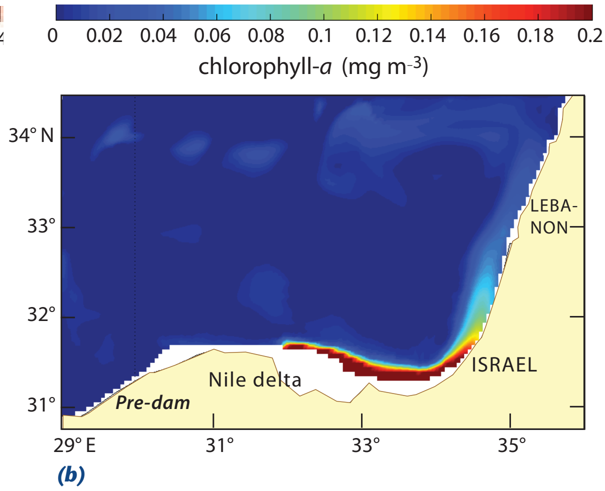


Figure 4 *Comparison of post-1965 and pre-1965 chlorophyll-a concentrations in surface waters of the Levantine Sea (note the different chlorophyll scales).* ***(a)*** *Mean chlorophyll-a concentration for the years 1997–2010, as determined by remote sensing (SeaWiFS).* ***(b)*** *Modelled chlorophyll-a concentration for September due to nutrients added by the River Nile flood.*

A new combined model confirms that prior to 1965 the bloom caused by the seasonal nutrient plume from the Nile spread towards the eastern coast of the Levantine Sea

increased grazing. In addition, the model showed that there was a lengthening of the spring bloom into June – the normal winter bloom in the Eastern Mediterranean Sea finishes in March. The model also showed that in the post-damming period there have been lower chlorophyll concentrations away from the immediate area of the delta, while the largest change is an increase in chlorophyll close to the delta, especially in the summer period; there was no 'advected' phytoplankton bloom off the Lebanese/Israeli coast after the Aswan Dam was completed. Modelled present-day chlorophyll concentrations are consistent with observations from SeaWiFS satellite data (Figure 4(a)).

Exotic species in the Levantine Sea

The largest and most widespread invasion of exotic species anywhere in the world has occurred in the south-eastern Levantine Basin. By 2009, 66% of the fish, 74% of the crustaceans and 87% of the molluscs were of Indo-Pacific origin. The Suez Canal was opened in 1869, and ever since invasive species, referred to as Lessepsian migrants after Ferdinand de Lesseps, the French engineer who led the canal construction, have invaded from the Red Sea. The reasons for the exceptionally high rate of invader success are yet to be fully determined, but the fact that the Mediterranean ecological community is derived from temperate species suited to relatively cold seawater of normal salinity (35), which spread from the Atlantic after the end of the Messinian salinity crisis, while the Eastern Mediterranean is subtropical with higher temperatures and more saline waters (38–39) similar to values in the northern Red Sea, is probably important.

The rate of Lessepsian migration increased dramatically after the 1970s. This increase was probably caused by the expansion of the Suez Canal, which removed the salinity block at the Bitter Lakes near the southern end of the Canal. The temporary cessation of fishing off North Sinai between 1967 and 1982, due to the occupation of the Sinai Peninsula after the 1967 war, might also have allowed invasive species to become established.

Questions still needing answers

Close to 450 million people currently live within the drainage basin of the Mediterranean. Rapid population growth and economic development since the 1950s has caused a major increase in nutrient supply to the Eastern Mediterranean Sea. Although significant impacts have been observed locally in near-shore coastal areas such as the northern Adriatic, there is little evidence of a major change in the trophic state of the open waters of the Eastern Mediterranean Sea. However, the extent to which the Eastern Mediterranean will be able to cope with future anthropogenic nutrient inputs is unknown. Population in the Mediterranean basin is projected to grow an additional 20% during the first quarter of the 21st century, while climate change unequivocally predicted by the 5th IPCC may profoundly modify the thermohaline circulation of the Eastern Mediterranean Sea. A better understanding of basin-scale nutrient cycling will therefore help us not only to interpret present and past biogeochemical conditions in the Sea, but also to forecast its response to ongoing and future anthropogenic pressures.

There are a number of open questions still to be answered regarding the unusual features of the Eastern Mediterranean Sea. For example what is the natural state of the biogeochemical system? Has it always been P-limited or is the current unusual high N : P ratio simply a result of anthropogenic change? Waters in the Eastern Mediterranean have flipped from ultra-oligotrophic to eutrophic and back again many times in the last millennia as a result of natural climate change. What will be the consequence of the present rapidly increasing anthropogenic climate change? Is it possible that it might cause a flip back to eutrophic conditions? Or maybe it will result in even less productivity and, as a result, reduced fish production. Can we determine how the switching off of the Nile River in 1965 has changed the Eastern Mediterranean Sea ecosystem? How has this influenced the nature and magnitude of the Red Sea invasion? Might this also have affected other ecosystems such as the deep-sea ecosystem and/or that associated with the many cold vents in the region?

Further Reading

The N : P ratio and nutrient cycling

Krom, M.D., N. Kress and S. Brenner (1991) Phosphorus limitation of primary productivity in the Eastern Mediterranean Sea. *Limnol. Oceanogr.* **36**, 424–32.

Nutrient cycling of the Eastern Mediterranean has been described in more detail in a paper on the nitrate and phosphate cycles:

Krom, M.D., K.-C. Emeis and P. van-Cappellan (2010) Why is the Eastern Mediterranean P limited? *Progress in Oceanography* **85**, 236–44.

and more recently on the silica cycle:

Krom, M.D., N. Kress and K. Fanning (2014) Silica cycling in the ultra-oligotrophic Eastern Mediterranean Sea. *Biogeosciences* **11**, 15, 4211–23.

Mike Krom's original article in this publication::

Krom, Michael D. (1994) The oceanography of the Eastern Mediterranean Sea, *Ocean Challenge* **5**, No. 3, 22–8.

The turn-off of the Nile

The classic paper describing the effect of the Nile turnoff on coastal processes is by Scott Nixon:

Nixon, S.W. (2003) Replacing the Nile: are anthropogenic nutrients providing the fertility once brought to the Mediterranean by a great river? *AMBIO: A Journal of the Human Environment* **32**, 30–39.

Acknowledments

MDK would like to thank his many colleagues at the Leeds School of Earth and Environment in general, and the Cohen group in particular, for their help and inspiration over the past many years. This review is dedicated to his mentor, Bob Berner, who passed away in early 2015. He was an inspiration to all who were privileged to work with him. MDK also wishes to thank Uri Schattner, Michael Lazar and Danny Tchernov for welcoming him to Haifa University.

Michael Krom is moving back to Israel after 24 years at the School of Earth and Environment of Leeds University where he has worked on the unusual properties and processes in the Eastern Mediterranean. He plans to continue this research with new colleagues including **Yair Suari**, who works at the School of Marine Sciences and Marine Environment, Ruppin Academic Centre, Michmoret, and Beverley Goodman-Tchernov at Haifa University, with the aim of inspiring a new generation of marine scientists with his passion for this unique and vulnerable sea – the sea that was central in the development of western civilisation.

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Book Reviews

Inventing the Weather Forecast

The Weather Experiment: the pioneers who sought to see the future by Peter Moore (2015), Chatto and Windus (Penguin Random House) 395 pp. £13.60 (hard cover, ISBN 13: 978-0-701-18799-6).

The first 70 years of the 19th century saw meteorology transformed from a nascent subject into a true science, with a consequence being the development of a new field of weather forecasting on both sides of the North Atlantic. The experiences of naval officers at sea were central to this transformation. In a very readable book, Peter Moore takes us on a voyage through the tortuous development and controversies of 19th century meteorology, driven by a range of key figures in contemporary science, art and mathematics, principally centred in Britain or the United States. However, the two central characters in Peter Moore's narrative are both linked to the ocean – Admiral Francis Beaufort, famous for the development of the Beaufort wind scale, and Admiral Robert Fitzroy, normally known for being the captain of the *Beagle* during the famous journey of Charles Darwin that led to *The Origin of Species,* but who should be better known as the inventor of weather forecasting and so father of the UK Meteorological Office.

We follow the careers of both men from early times experiencing and observing the weather at sea, often in extreme circumstances, to eminent positions within the Hydrographic Office in Beaufort's case, and the Board of Trade for Fitzroy. However, *The Weather Experiment* is not just a biography of these two key characters, but takes us through the often controversial development of 19th century meteorology. We see the opposed and entrenched scientific positions taken by those attempting to explain storms – Espy's heating and convection view versus Redfield and Reid's cyclonic whirling winds. At the time, cyclonic theory received wider support, as it was not only more compatible with both land and ocean observations of hurricanes, but was also aided by the poor press generated by Espy's ill-advised divergence into the possibilities of rainmaking raised by his theory. Of course, the truth is a combination of both theories, an idea we see crystallising with Francis Galton's discovery of the anticyclone through mapping weather on a European scale.

Another crucial moment developed by Peter Moore is Matthew Maury persuading the international community to start the development of global maps of ocean winds and temperatures in 1853. Maury was a Lieutenant in the US Navy, who had been responsible for converting weather data into sailing charts. This was the beginning of the climate time-series we use today in the study of global warming; furthermore, as the time saved by sailing *with* prevailing winds rather than against them would have economic rewards, the 1853 Brussels Conference led indirectly to Fitzroy's innovations. Britain's Board of Trade set up a group under Fitzroy's command to begin development of such sailing charts for British trade interests but – particularly following the tragic wreck of the *Royal Charter* on the Anglesey coast in 1859 – Fitzroy expanded his remit to cover the issue of storm warnings to British ports and, later, weather forecasts to the general public.

Despite a temporary hiatus in the forecasts as a result of controversies after Fitzroy's suicide in 1865, their publication can be seen as the beginning of the modern science of weather forecasting. *The Weather Experiment* leaves us on the verge of the Norwegian frontal model, bringing alive the science as understood in the late 19th century, on which Bjerknes built his theory. Despite the tragedies and controversies in Fitzroy's life, which led him to suicide, ultimately his belief in the possibility and utility of weather forecasting has been proven correct, for which all at sea, and on land, are thankful. Peter Moore has brought this development thoroughly to life in *The Weather Experiment*.

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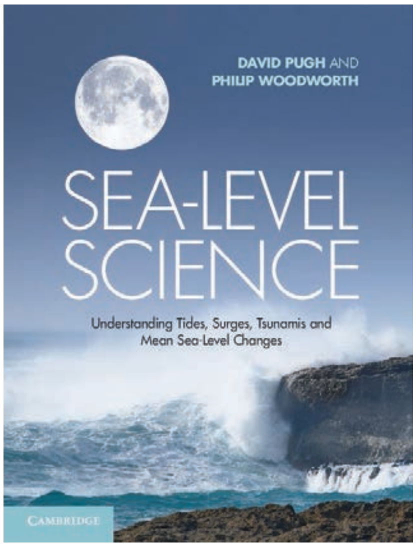
The rise and fall of the oceans

Sea-level science: understanding tides, surges, tsunamis and mean sea-level changes by David Pugh and Philip Woodworth (2014) Cambridge University Press, 396pp., £45 (hard cover, ISBN 13: 978-1-107-02819-7).



Sea level keeps changing around the world at a number of scales in both time and space. Storms generate rapid changes which are hard to predict, the tides introduce predictable variations of several metres on time-scales of hours to days to weeks, and changes due to climate change take years to millennia to be noticed. Variations in sea level are important to us because knowing how the surface of the ocean moves is crucial to preventing flooding and erosion, extracting energy from the ocean, and ensuring safe navigation.

In this book, two sea-level science giants, Professors David Pugh and Phil Woodworth, provide a very comprehensive treatment of all aspects of sea level and sea-level change. In an easy-to-follow way, and using a large amount of illustration, they guide the reader through the diverse aspects of the subject. Especially nice is the way they introduce and explain the mathematical descriptions of the subject to ensure the reader can follow and understand what each equation means physically.

The book kicks off with how we measure sea level. The first chapter starts with a section on 'The science of measurement', after which the authors go on to describe the various methods we have and have had to measure sea-level. We are also briefed on the problems we may encounter when doing the measurements, and how we can get hold of the data from various sources.

The four chapters which follows all deal with various aspects of the tide, beginning with why there is a tide to start with (Tidal forces), and a description of the methods we use to produce tide tables (Tidal analysis and prediction). The next two chapters deal with the dynamics and energetics of tides and why tides at our coasts are so different from those in deeper and open water.

Sea-level variations produced by tides are by their very nature highly predictable. Chapter 7 looks at the opposite end of the spectra: how our weather can generate rapid large variations in sea level which are quite difficult to forecast. The authors focus a lot of attention on storm surges, which are often responsible for flooding events at the coast.

'Tsunami' became a household expression after the events on 26 December 2004, and the authors rightfully dedicate a whole chapter to this incredibly destructive phenomenon. This includes their generation, how they travel across the ocean at great speeds, why they can become so large near the coast, and how the existing tsunami-warning systems operate.

The following three chapters deal with large-scale changes in mean sea level in space and time, including changes due to vertical land movement. We are again given a nice introduction to the subject, an overview of how we obtain the signals we see, and their implications. This is especially true for the part about future sea-level rise, which is a very good introduction to the subject.

The book's final two chapters deal with applications of sea level change (coastal defences, tidal power generation etc.) and how sea level affects life on planet Earth. They form a good rounding-off to the core of the book and put sea-level science into a larger scale context.

There are four appendices dealing with the mathematical theory behind the processes described. Keeping them out of the book proper is a great way of keeping the average reader hooked, whilst providing information for those who want (or need) it still in one source.

Overall, this is a very good textbook and well worth the price. Students at undergraduate and postgraduate level, and from a range of disciplines, now have a core textbook covering much of the subject of sea-level and sea-level change. It will certainly be sitting within easy reach on my shelf, and it will most certainly form a new basis for my own teaching on tides and waves.

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Managing the challenge to our coasts from climate change

Coastal risk management in a changing climate edited by Barbara Zanuttigh, Robert Nicholls, Jean-Paul Vanderlinden, Hans F. Burcharth and Richard C. Thompson (2015) Butterworth–Heinemann, Elsevier, 638pp. flexicover £85.50 (ISBN 13: 978-0-12-397310-8); Kindle £81.22.

Considering the growing pressures on the coast from climate change, sea-level rise, storms, sediment depletion, population change, resource scarcity, ecosystem degradation, energy efficiency etc., this is a very timely volume. It is an output from the EU-funded THESEUS project (www.theseusproject.eu), which examined the development of a transdisciplinary framework for flood-risk assessment for safer, more resilient coasts for human use and healthy coastal habitats.

Following a short introductory chapter, the first substantive chapter by Nicholls *et al.* (Chapter 2: Developing a holistic approach to assessing and managing coastal flood risk) plays a very important role within the book, setting the foundations for considering flooding from an array of disciplinary and interdisciplinary perspectives: the socio-economic and political contexts in which flooding takes place; the abiotic and biotic properties and processes that determine flooding; the operational definitions of risk, vulnerability and resilience; and frameworks for assessing and addressing flood risk – in particular the Source–Pathway–Receptor–Consequence model that frames the coastal flooding system for risk assessment, management and mitigation. Rather than being a mechanistic review of the various considerations that need to be brought to bear to address coastal flooding in a coherent way, the chapter provides the reader with a holistic view of a problem that spans social, physical and biological sciences, engineering and economics, planning and policy, evidence and modelling, and handling uncertainty within decision-making. It therefore speaks to a wide range of stakeholders engaged in building a shared understanding of coastal flooding.

Burcharth *et al.* (Chapter 3: Innovative engineering solutions and best practices to mitigate coastal risk) appear to take more of an engineering approach in their review of various solutions to flooding, examining an incredible array of interventions which extend from floating, submerged and land-based devices and structures, to sediments, landforms and natural environments. Their examination of design principles, environmental dynamics and properties that must be considered, and the economics and suitability of different engineering options, presents a handbook for engineers, spanning approaches from modifying the environment to working with nature. It doesn't seek to challenge the interdisciplinary tone of the preceding chapter, it simply gives a more traditional view of dealing with coastal flooding as an environmental problem for which there are various engineering solutions.

In contrast, Chapter 4 by Hoggart *et al.* (Ecological approaches to coastal risk mitigation) is firmly rooted in the ecosystem approach to resource assessment and management, including the economic valuation of coastal ecosystem goods and services as the cornerstone for informed decision-making which promotes healthy, functioning ecosystems and minimises ecological/environmental impacts. The chapter focusses largely on coastal environmental management techniques for beaches, sand dunes, saltmarshes, reefs and seagrass meadows. Further, it examines the ecohydrology and biogeomorphology of coastal ecosystems, i.e. the interaction between plants, sediments and hydraulics, and shows how this understanding provides the foundation for flood mitigation measures such as managed realignment, wetland restoration and beach recharge – as well as embedding ecological design in hard engineering structure. This chapter is closely aligned to current priorities in environmental and flood risk management that more effectively addresses the wider implications of local interventions.

Vanderlinden *et al*. (Chapter 5: Nonstructural approaches to coastal risk mitigations) take forward the underlying themes of holism and inclusive decision-making, and further develop many of the issues covered in Chapter 2 by Nicholls *et al.* The central focus here is the governance of coastal flood mitigation – particularly with respect to climate change, although the sections on insurance and business recovery planning perhaps over-emphasise the economics of flooding. The chapter offers a very different perspective from that of Burcharth *et al*. in that flood risk is not situated in the physical sciences and engineering solutions but is framed very much in building resilience through spatial and economic planning, resource allocation, knowledge exchange, and stakeholder engagement. This exploration includes: governmental instruments; business operations and strategic investment; institutional and individual actions before, during and after flooding; and communication of risk and uncertainty in relation to present and future conditions. The 'inclusive', 'interdisciplinary' and 'innovation' trajectory of the book, and indeed of the THESEUS project, culminates in Chapter 6 by Koundouri *et al.* (Toward sustainable decision making). The subject matter streams from time-scales for decision-making, from short-term operation to long-term strategic, through to tools for decision support that aim to bring together a variety of information within prevailing legislative structures. Various decision-support tools are examined: multi-criteria analysis for assessing the degree of flood risk and the most appropriate mitigation option; embedding environmental, economic and social perspectives in risk assessment; and cost–benefit analysis. An impressive illustration of the THESEUS decision-support system (DSS) is provided, demonstrating its effectiveness as a tool for exploring scenarios of changing flood risk and the consequences of alternative management strategies and interventions.

Chapter 7 is divided into case studies which are offered as illustrations of how a holistic approach enables risk-assessment, identification of further research and data needs, and selection of appropriate mitigation measures. All examples are examined using the same Source–Pathway–Receptor–Consequence model to explore the extent of hazard in relation to climate change, the impact of flooding and erosion on coastal environments and infrastructure, and the most suitable intervention given prevailing policy limitations. Examination of the critical balance between water and sediment budgets for coastal system 'health', and how this may be impacted by climate change and human activity, is undertaken for the Scheldt (Netherlands), the Yangtze (China) and the Elbe (Germany). The maintenance of beaches for flood mitigation, a thriving tourist economy and aesthetic value is examined for Varna (Bulgaria), Cesenatico, (Italy), Cancun (Mexico) and Hel (Poland), and the vulnerability of the dune coastline as a natural flood defence is investigated for the Gironde, France. Santander Bay (Spain) is presented as an example of flood and erosion risk analysis, and the Teign estuary (UK) provides an illustration of flood mitigation that has been taken forward through inclusive decision-making.

Whilst this book is clearly the published output of an EU-funded research consortium aiming to develop safer, more resilient coastlines, the exemplar case studies are given essential coherence by the material presented in Chapters 2 to 6. Complementing the disciplinary focus of the chapter on innovative engineering solutions, the main body of the edited volume is a strong proponent of interdisciplinary research and its essential role in addressing coastal flood risk. It is certainly an excellent textbook for both undergraduate and taught postgraduate audiences, and is a very good point of reference for numerous researchers and experts who find themselves becoming engaged more and more in interdisciplinary, problem-orientated research. This is also an important resource for a wide range of stakeholders who are currently meeting the challenges of present and future climate change in the coastal zone.

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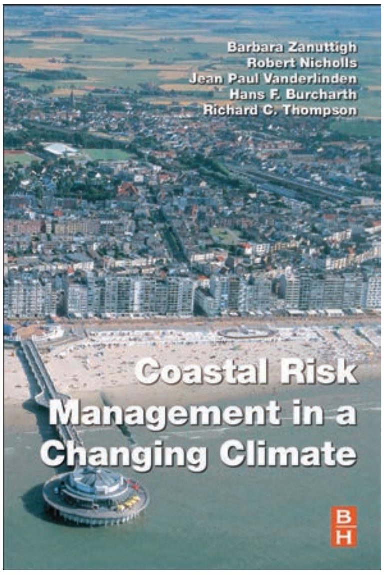

Staircases in the oceans

Double-diffusive convection by Timour Radko (2013) Cambridge University Press, 342pp. £75 (hard cover, ISBN 13: 978-0-521-88074-9).

This is a well-written and engaging account of a relatively new branch of fluid mechanics which was developed primarily by oceanographers. Until the 1950s, the large difference in molecular diffusivity between heat and salt was considered to be unimportant in the ocean where transport was thought to be invariably dominated by turbulence, with equal eddy coefficients for heat and salt. Then in 1956, Henry Stommel, Arnold Arons and Duncan Blanchard described the concept of 'the perpetual salt fountain', the idea of which was to raise nutrient-rich water through the tropical thermocline via a long copper pipe which allowed the transfer of heat between the contents of the pipe and its surroundings. As the tropical thermocline is also a halocline, with salinity increasing with height, an upward flow in the pipe, once started, continues since heat, but not salt, is transferred to the rising water making it less dense. Four years later, Melvin Stern made the crucial realisation that because of the differences in the molecular diffusivities of salt and heat, by two orders of magnitude, instability and convection could occur in the ocean without the copper pipe.

Timour Radko, who came into the subject as a student with Stern, provides a full account of the early history of double diffusive convection (DDC) and then goes on to give a clear and illuminating description of the physical mechanisms involved in the two DDC regimes. In the 'salt finger' regime, warm salty water overlies cooler fresher water in a column which is stable overall, although the salt profile contains potential energy which may be released to drive convection. In the 'diffusive' regime (cold fresh water over warm salty), the heat profile furnishes the potential energy to drive convection. In both cases, it is the difference in molecular diffusivities which allows the different rates of transport of heat and salt which are crucial in promoting convection. In contrast to conventional mixing, which reduces water column stability, DDC tends to increase stratification, making the bottom water denser or the overlying less dense through a counter-gradient flux of mass.

Stern's theoretical analysis of DDC was complemented by an extensive series of laboratory experiments, many by Stuart Turner in Cambridge, which clarified the mechanisms involved in both DDC regimes and showed that DDC could produce 'staircase' profiles in which thin salt finger or diffusive interfaces separated thick turbulent layers driven by the buoyancy flux through the interfaces. The suspicion that such structures might occur in the ocean was confirmed in the mid-1960s when Bob Tait and Malcolm Howe observed extensive staircase structures under the Mediterranean outflow in the Gulf of Cadiz with layers of thickness ~ 20 m separated by finger interfaces ~ 1 m thick. Other examples from the western tropical Atlantic and the Tyrrhenian Sea soon followed and the operation of salt fingers within the finger interfaces was confirmed by optical imaging.

Following his account of the physical mechanisms of DDC, Radko devotes several chapters to the theory of DDC, starting with the linear instability problem before discussing attempts to deduce the flux laws for DDC convection from first principles and establish the conditions which limit the growth of double diffusive interfaces. He also deals with the role of DDC in the formation and evolution of thermohaline intrusions. There is much heavy, non-linear theory in this section of the book but the author is a good guide in such difficult areas and provides an illuminating text and some nice examples of direct numerical simulations of DDC to illustrate the analysis.

For an oceanographer, one of the most interesting chapters is that which considers the intriguing questions raised by staircase structures. The vertical extent (hundreds of metres) of these features was the first indication that differences in molecular properties could have impacts on the large-scale structure of the ocean. Subsequent observations in salt finger regimes have shown that DDC layers may remain coherent over scales > 100 km and may persist for many months or even years.

Staircases are apparently restricted to a relatively small number of regions of the ocean but Radko argues, on the basis of the *T–S* structure, that the action of DDC is much more pervasive and contributes extensively to mixing even when staircase structures are not evident. Certainly it now appears that DDC is a major contributor to mixing in the Arctic Ocean where staircases with diffusive interfaces are widely observed. Combined with the warming inflow from the Atlantic, DDC may thus be responsible for the recent acceleration in the summer retreat of ice cover. In regard to this and other aspects of ocean mixing, the book is very timely. Radko wants us to consider more fully the relevance of DDC to modern oceanography and also to other areas of science including astrophysics, geophysics and chemistry. He makes a strong case for the importance of his subject and is a worthy champion and advocate for the community of what he calls 'Double Diffusers'.

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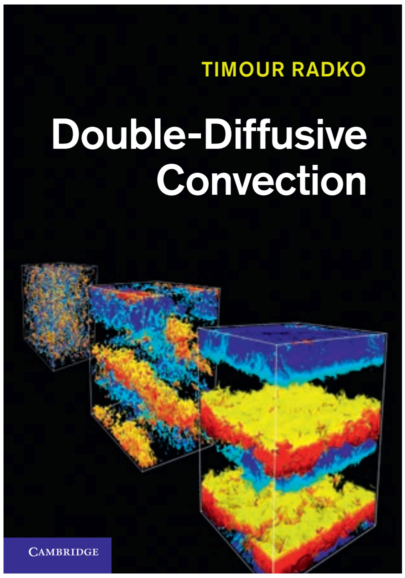
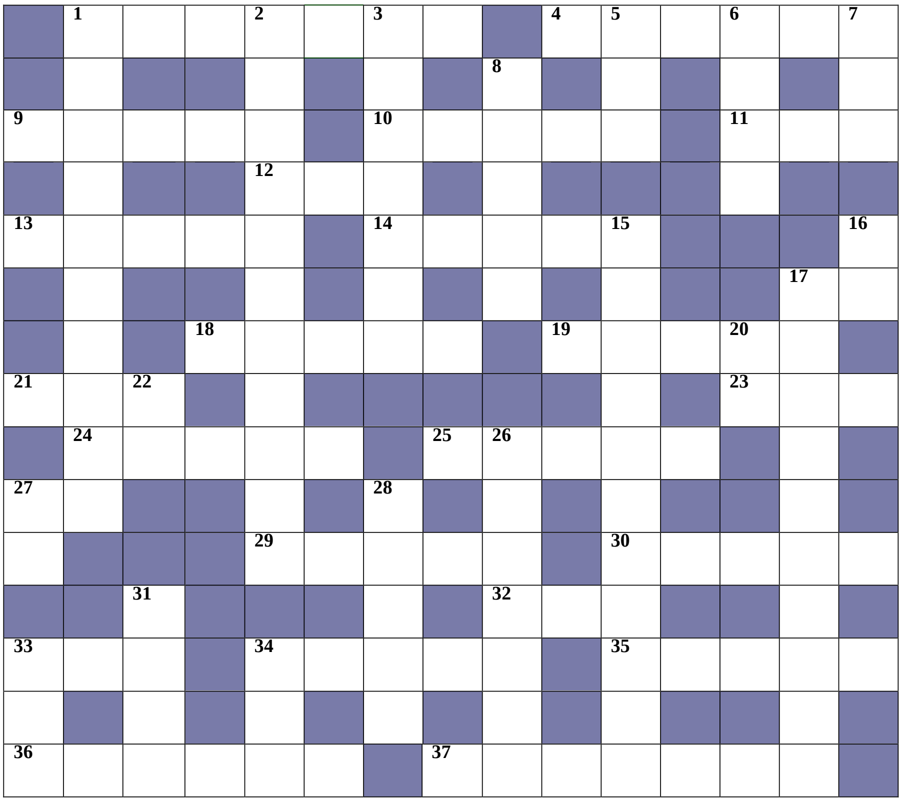


The Maritime Crossword Challenge

We hope you will enjoy our maritime crossword. Some of the clues are semi-cryptic, and all have a flavour of the ocean and/or marine science. If you are a regular reader of *Ocean Challenge*, you may have an advantage for some clues. The first correct solution to be received by the Editor (address on inside back cover) will earn the sender a cheque for £40.



ACROSS

1 and 4 Locations referred to in connection with these are given in 3 Down (7,6)

9 Sailing boat with a fore-and-aft rig (5)

10 A scruffy steamer (5)

11 See 8 Down

12 The Nemesis of many a Homarus (3)

13 Prefix meaning 'same' or 'similar' (5)

14 This occurs when a wave or tsunami meets the shore (3-2)

17 Greek letter with a Life of its own (2)

18 Part of both a coral polyp and a flower (5)

19 A typical vessel of opportunity (5)

21 Commonly found in seawater along with POM, and includes DOC (3)

23 Used to stun fish illegally to collect them for aquaria (3)

24 Freshwater fish with tolerance for brackish and salty water (5)

25 Port of ancient Rome (5)

27 Nautical abbreviation with several meanings (2)

29 Like an old photo of a shell-less mollusc (5)

30 A cod-like fish (5)

32 Association of commercial (mainly S&T) companies involved with the sea, ships and ports (3)

33 The Silver ––– is a misnamed feature in the southern North Sea (3)

34 This whale knows the best route (5)

35 Owner of a shaving implement which might help explain some of your research results? (5)

36 Seas where much of North Atlantic Deep Water forms (6)

37 Fish with thick lips, including the best-known cleaner fish (7)

DOWN

1 One of the Canaries, but partly encompassed by the Thames? (4,2,4)

2 A brainy little fish? (11)

3 ------ Head is between Cape Wrath and Berwick-upon-Tweed (7)

5 You can now use one of these to check tide times (3)

6 The smallest of these are glass (4)

7 and 33 A literary kind of coral? (3,3)

8 and 11 Across Where CO_2 has been monitored since 1956 (5,3)

15 and 11 What modellers hope their models will produce (11)

16 Fathoms and knots are not this (2)

17 Thick layers of well-mixed water (10)

20 Platinum-group element, particularly hard to detect in seawater (2)

22 A microscopic amount of dynamic viscosity (2)

26 Its alternative name suggests that it has fins (3,4)

27 Lunar element? (2)

28 Beautiful objects ultimately made from very old diatoms (5)

31 What the winds do to the upper ocean (4)

34 Used for potential, including the tidal kind (3)