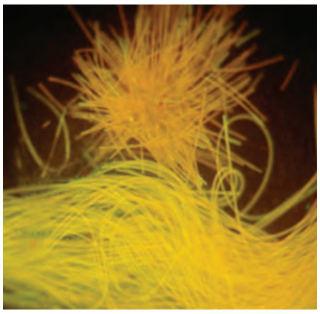
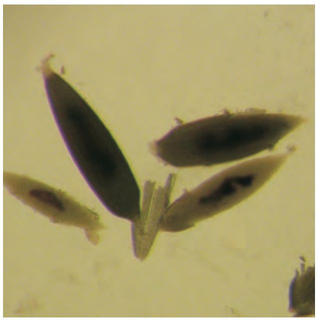
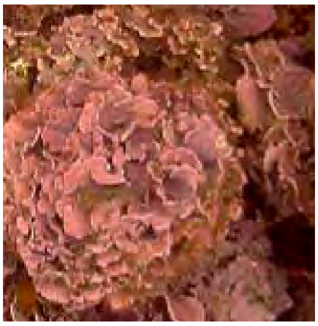
OCEAN Challenge

The Challenger Society for Marine Science

A deep-sea lab in the Med • Little auks link land and sea
Diazotrophs: small but mighty • Fast-sinking Acantharia
Geoengineering challenges: putting theory into practice
Ocean acidification and marine life

Volume 18, Winter 2011 (Double Issue)

The maps and diagrams were drawn by The ArtWorks.

The cover was designed by Ann Aldred Associates.

Cover photograph

CONTENTS

Message from the Editor

Welcome to the latest issue of Ocean Challenge*, which is a double issue. You may have noticed that it is the first part of Volume 18, rather than the second part of Volume 17, as you might have expected. This change has been made to enable Volume Nos to correspond to a particular year. The aim is still to publish three issues (or one single issue and one double issue) per year.*

In the first part of this issue we have feature articles about a deep-sea laboratory in the Mediterranean, the role of little auks in maintaining the Svalbard tundra, and fascinating planktonic organisms – essential diazotrophs and fast-sinking acantharians. The articles in the second half of the issue all address the increasingly pressing problems of rising CO_2 *and ocean acidification.*

News updates

Marine Conservation Zones on track – but there is one more chance to have an input

Marine Conservation Zones (MCZs) are a new form of marine protection for England and Wales that will be designated under the 2009 *Marine and Coastal Access* Act. They will protect nationally important marine wildlife, habitats, geology and geomorphology, with sites selected to encompass a range of marine wildlife, not just the rare or threatened animals and plants.

Four Regional MCZ projects have been set up to obtain guidance from people who use, value or make their living from the sea, as part of the development of recommendations for future MCZs (see 'The MPA jigsaw' in the last issue). Through meetings, group interviews, individual interviews and questionnaires, the four Regional MCZ projects have now collected feedback and information from over one million people and have published a second set of regional progress reports; there has been input from a wide range of interests, both as groups and organisations, and as individuals. Stakeholders who have been consulted include commercial fishermen, divers, shore anglers, recreational sea-users and wildlife enthusiasts. This latest set of reports, representing broad areas of interest for consideration, rather than concrete proposals, has been delivered to the Science Advisory Panel – an independent body made up of expert marine scientists, set up to support the four regional projects in the MCZ selection process by offering objective scientific assessment of site proposals, and to offer independent advice to government Ministers.

The progress reports can be viewed on the relevant websites:
South-east (Balanced Seas): www.balancedseas.org
South-west (Finding Sanctuary): www.finding-sanctuary.org
Irish Sea (Irish Sea Conservation Zones): www.irishseaconservation.org.uk
North Sea (Net Gain): www.netgainmcz.org

The Regional MCZ Projects are publishing a third set of progress reports in March, a**nd there will be one final opportunity for people to feed back on the information by contacting their Regional Stakeholder Representative**. On receiving feedback from the Science Advisory Panel, the Regional MCZ Projects must deliver draft final proposals, including site boundaries and conservation objectives. The final MCZ recommendations must be delivered to the Science Advisory Panel and the Statutory Nature Conservation Bodies (i.e. the Joint Nature Conservation Committee and Natural England} at the end of August; regional and cumulative impact assessments must be compieted by the end of September. The Statutory Nature Conservation Bodies must deliver their final advice to government at the end of November, to enable designation of MCZs by 2012, thus playing a key role in fulfilling the UK Government's commitment to establishing an ecologically coherent network of Marine Protected Areas (MPAs) by 2012.

The MCZ Project's informative interactive website is: www.mczmapping.org

Limitations of the GITEWS tsunami-warning system

If you read the article 'New early warning system for Indian Ocean tsunamis' in the last *Ocean Challenge,* you may have been surprised to learn of the enormous loss of life caused by a tsunami that struck off the coast of Indonesia in October last year. The tsunami, triggered by an earthquake of magnitude 7.8, hit the Mentawi islands, about 150 km off the west coast of Sumatra, devastating villages, and displacing 20 000 people; hundreds of people were killed, with many being swept out to sea.

Reports that the GITEWS buoys had been vandalised proved not to be true, but the Head of the Indonesian Meteorology and Geophysic Agency said that the buoy network had been in need of maintenance since 2009 and that as it was being operated by inexperienced workers it was not working properly.

It transpired that although the system was working *in theory*, financial constraints had meant that only ten of the instrumented buoys had been installed, and were positioned so as to provide a warning to inhabitants of the most densely populated areas. This did not include the the Mentawi islands, whose population of about 35 000 live in scattered villages.

As it happened, the epicentre was so close to the Mentawi Islands that the tsunami would have reached them in minutes, so a warning would have been useless. Even if there had been more time, the passing on any warning would have been problematic, as few villages on the islands have electricity and mobile phones are rare. These circumstances highlight the intrinsic difficulty of operating a disaster prevention and response system in poor and underdeveloped countries.

SCOR: supporting oceanography worldwide

Ed Urban

At the Challenger Society AGM in September 2010, members endorsed Council's proposal for the Society to take over the Royal Society's role as the UK adhering organisation for the Scientific Committee on Oceanic Research (SCOR). This means that the Challenger Society will now be the main link between UK marine scientists and SCOR.

SCOR is the primary organization of the International Council for Science (ICSU) responsible for ocean sciences. It provides a mechanism for oceanographers from different countries, cultures and disciplines to identify cutting-edge research topics; to plan and conduct large-scale multi-disciplinary research programmes; and to build scientific research capacity for ocean science in developing countries. It is envisaged that the Challenger Society's new role will lead to better interaction between SCOR and the UK marine science community.

SCOR was formed by ICSU in 1957 and since that time has been involved in the development of most large-scale international ocean research projects, including the first one, the International Indian Ocean Expedition in the late 1950s to early 1960s. Currently, SCOR sponsors the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) programme, the GEOTRACES project, the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, and the Surface Ocean–Lower Atmosphere Study (SOLAS).

SCOR is also known for its working groups, which cover the entire range of ocean research and observation topics. Currently, SCOR working groups include activities on the microbial carbon pump, the influence of mid-ocean ridges on the global carbon cycle, technology for automated plankton identification, the influence of the Benguela current system on global climate, the oceanography of deep-ocean exchanges with continental shelves, the equation of state of seawater, global time-series of phytoplankton and zooplankton, compilation of data from iron-enrichment experiments, and enhanced instrumentation of volunteer observing ships for oceanographic measurements.

www.scor-int.org

SCOR relies on the ideas and energy of members of the global ocean science community, who volunteer their time; approximately 250 scientists are involved in SCOR activities at any given time. SCOR maintains an international Secretariat at the University of Delaware (USA) with a small staff. Several countries, including the UK, have supported international project offices for SCOR-sponsored projects.

Although SCOR conducts some of its activities as a sole sponsor, many other activities are co-sponsored by other ICSU bodies. These include the International Geosphere–Biosphere Programme (IGBP), World Climate Research Programme, International Association for the Physical Sciences of the Ocean, IGBP projects (Land–Ocean Interactions in the Coastal Zone and International Marine Global Changes project), and other projects (InterRidge). SCOR also works closely with the Intergovernmental Oceanographic Commission and several of its programmes on issues of shared interest.

The UK has a national SCOR committee, currently chaired by Prof. Peter Burkill (SAFHOS), one of 33 such committees that support international SCOR. UK scientists (notably George Deacon) played an important role in SCOR's early development and subsequent history. Other UK scientists currently leading SCOR activities include Gideon Henderson (Oxford, co-chair of the GEOTRACES Scientific Steering Committee), John Johnson (UEA, co-chair of WG 129 on Deep Ocean Exchanges with the Shelf), Phil Culverhouse (University of Plymouth, co-chair of WG 130 on Automatic Visual Plankton Identification), and Dorothee Bakker (UEA, co-chair of WG 131 on The Legacy of *in situ* Iron Enrichment: Data Compilation and Modelling). The titles of these groups give an idea of the breadth of SCOR activities.

An important aspect of SCOR's work is in the area of developing capacity for ocean science worldwide, and helping scientists from developed and developing countries to work together. SCOR provides travel support for scientists from developing countries to attend major ocean science meetings, and has in the past two years sent three individuals to teach and mentor in developing countries. SCOR is also leading efforts to stimulate interactions among several different organizations with important roles in ocean science capacity-building.

SCOR depends on strong involvement of national committees in international SCOR. The new role of the Challenger Society in UK SCOR offers opportunities for both SCOR and the Challenger Society and we look forward to discussion of how to optimize our new partnership.

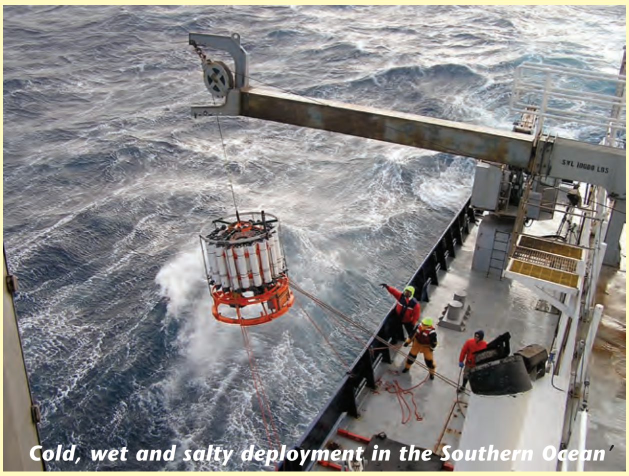
Ed Urban SCOR Executive Director

Southampton Conference Awards and Prizes

As usual, the biennial Challenger Society Conference was an occasion when the Society recognised excellent work in the marine sciences by Society members. In 2010, the Society's most prestigious award, the Challenger Medal, was presented to Professor Patrick Holligan. Challenger fellowships were awarded to Claire Hughes (UEA), Dave Suggett (University of Essex), Alberto Naveira-Garabato (National Oceanography Centre, NOCS) and Laura Robinson (Woods Hole Oceanographic Institution, USA). The Challenger/IMarEST/SUT undergraduate dissertation prize was won by Anna Belcher of the University of Southampton.

The Cath Allen Prize for the best poster at the conference was won by John Prytherch, NOCS. The Norman Heaps prize for the best presentation was awarded to Loic Jullion, NOCS. Loic also won the President's Photographic Competition, for which the topic was 'Marine scientists at work'; Loic's photo can be seen here.

For more details see Challenger Wave, *September 2010.*



Cold, wet and salty deployment in the Southern Ocean

Jobs for the buoys

Kelvin Boot and Tim Smyth

Scientists have been sampling the English Channel for more than a century, investigating its biology and chemistry, and monitoring its tides and currents. The Channel is a complex environment, yet in many ways is representative of coastal seas around the UK. The western Channel, off Plymouth, is especially interesting as it is here that oceanic and coastal waters meet: an ideal area to monitor long-term changes brought about by rising sea temperatures, for example, or shorter term changes as the seasons come and go. But getting the information has never been straightforward. Now Plymouth Marine Laboratory (PML) scientists are using modern technology to continue and broaden the collection of data.

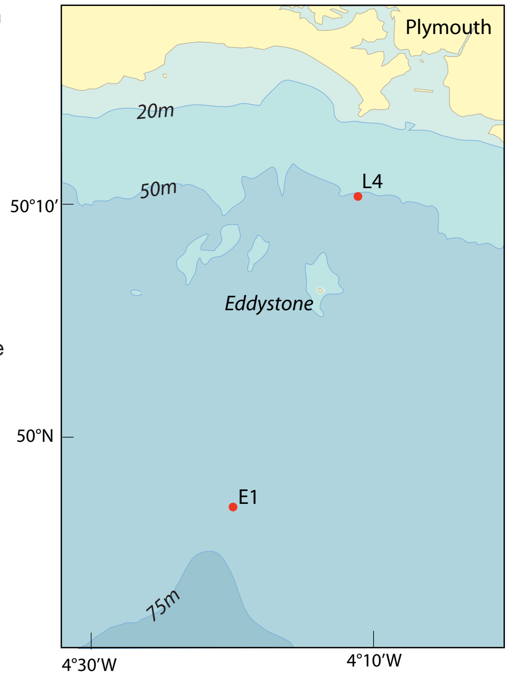
Until recently, the only way we could collect data was to visit the sampling sites on our research vessel to take a range of physical measurements, such as temperature, salinity and optics, or obtain biological samples directly from the water for analysis back at the laboratory. At best, we managed this on a weekly basis, but it's a highly weather-dependent activity so there were no guarantees. And while such long-term data have proved invaluable in helping us understand longer-term trends and therefore large-scale changes in the Channel, there was a serious gap in our understanding of what was going on a daily or even hourly time-frame.

The deployment in 2009 of our two shiny new buoys marked a significant advance in both the quality of the information and the ease with which we could get it. The buoys are autonomous – they send us their data automatically almost as soon as it's recorded, enabling us to 'fill in the gaps' between the weekly boat-collected samples.

The buoys are part of the Western Channel Observatory, which combines routine *in situ* sampling with modelling and remote sensing. Between them, the buoys cover a range of conditions. (*see map, right*). At around 7 nautical miles off Plymouth, L4 is close enough to shore to tell us about inputs from the local estuaries. E1 is sampling in very different conditions, 25 nautical miles offshore on the open continental shelf, where there is more of an oceanic character, and the two datasets thus provide a comparison of the impact and timings of any changes taking place.

Tim carrying out final checks to instrumentation and support iequipment on buoy L4. Solar and wind generators provide the power for the array of data and navigation transmitters, while a weather station collects meteorological data. In addition, a range of environmental sensors can be lowered through the 'moon pool' that penetrates the 3.1 m float.

So apart from being new, what makes these buoys so special? They carry an impressive array of equipment powered by a combination of solar and wind energy. This variety of instrumentation and their flexibility make the buoys unique. But their other star quality is their ruggedness. This is crucial because conditions in the English Channel are harsh, with waves up to 6 m,



strong winds and a high volume of boat traffic. In short it's hostile and busy, causing serious logistical problems for long-term buoy deployments.

Standard environmental monitoring buoys used around the world would simply not be up to it, so we went back to the drawing board to create something new. We worked with Plymouth company Hippo Marine to design and build the new buoys to withstand the Channel's tough conditions while enabling the equipment to take the sensitive measurements needed. Integral to the design is a 'moon pool' – an enclosed column of water at the centre of the buoy which enables the instruments to be lowered into the sea and remain submerged and working, while being completely protected.

Each of the buoys weighs around 3.5 tonnes and requires 6 tonnes of anchorage to keep it in place. To add to the challenge, they also have to be kept on station and facing in a constant direction, to ensure the solar panels are oriented efficiently and the optics equipment is unshaded.

It hasn't all been plain sailing. We really were at the mercy of the elements when it came to getting the buoys to their stations, and on more than one occasion the deployment mission had to be aborted as the weather deteriorated. Tethering the buoys was also quite a challenge – the possibility of a 7 m buoy running amok in one of the world's busiest shipping lanes was not to be contemplated lightly, as we'd learned from experience. Even with all its heavy-duty tethering, the L4 buoy decided to make a break for a nearby beach during a test run in 2008. As a consequence of this incident, the entire system was refined and improved, so our buoys can hopefully stand up to anything the Channel will throw at them in the years to come.

Down to the detail

We can use the long-term data collected by boat to establish a baseline for studying how humans are affecting the oceans and the planet through climate change, as temperature regimes are altered, ocean chemistry is affected and the make-up of the biota varies. With the buoys now fully operational, we also have high-frequency, small-scale data, which enable us to look at short-term changes and see how they in turn affect the longer term trends. All this gives us a much greater understanding of our coastal waters.

Take plankton blooms, for example, which can appear within hours and spread and die within days. We need to understand what drives these blooms and why a particular species appears one year and maybe not the next. Plankton blooms may result in concentrations of commercially valuable fish – a boon to fishermen – or perhaps concentrate toxins (as in 'red tides') – a threat to shellfisheries. Small changes in the physics or chemistry of the sea may hold some of the answers but it is likely to be a complex combination of factors. Our sensors are measuring temperature, salinity, nitrate levels, sediment concentrations, coloured dissolved organic material (which can interfere with satellite readings), and chlorophyll; there's even a weather station and camera on board. By studying these factors we can begin to understand how changes in the environment – temperature and nutrient availability for example – affect the marine ecosystem on an hourly basis, giving us the potential for predicting the onset of phytoplankton blooms.

The L4 buoy has already given us information on the influence on phytoplankton of freshwater surges resulting from flood conditions in the River Tamar. These 'freshening' events coincided with algal blooms, a function of an increase in nitrate being made available from river run-off, at a time when conditions were otherwise unsuitable for accelerated plankton growth. We'd had our suspicions about this for many years but until now had not been able to recover any evidence on our weekly sampling visits.

Put this small-scale detail together with PML's expertise in ecosystem modelling, remote sensing, and our existing weekly *in situ* observations, and some very useful insights into what is happening in the English Channel are emerging. This level of detail will directly support decisions about the sustainable management of our coastal and shelf waters. Not only that, but as different questions about the chemistry and physics of the sea arise and new methods of study are developed, our buoys are flexible enough to accommodate new instruments to provide the data needed to respond.

One could be forgiven for thinking that the data buoys' hourly readings, combined with broad-scale satellite observations, which give information on sea-surface temperature and chlorophyll (phytoplankton) concentration would make boat visits redundant. This is far from the case, we still need other readings and water samples for analysis in the lab, because the deeper water column still eludes the satellites and the data buoys' instruments. Before we had only part of the story, now we have boat, buoy and satellite working together to give us the complete picture.

Further information

The buoys were funded through NERC's Oceans 2025 initiative, which is implemented through seven leading UK marine centres: www.oceans2025.org

Kelvin Boot is the PML Science Communicator: kelota@pml.ac.uk

Tim Smyth is manager of the data buoy project at PML: tjsm@pml.ac.uk.

Western Channel Observatory: www.westernchannelobservatory.org.uk

Professor Peter Lockwood MA, Ph.D, FRSA, FRSE (1931–2011)

The death of Peter (A.P.M.) Lockwood breaks another link with the apparent golden age of investment in science, technology and the universities during the 1950s and '60s. Peter was educated at St Paul's, Westminster and, after National Service in the Royal Artillery, went up to Cambridge to read Natural Sciences. After graduating in 1954 he began postgraduate research on marine osmoregulation under the supervision of J.A. Ramsey, and pioneered the use of radiotracers, developing techniques that are still the definitive means of quantifying ion and water fluxes in aquatic animals.

After the award of his doctorate Peter took up an assistant lectureship in Edinburgh and then in 1962 he moved to Southampton to join John Raymont in setting up the multidisciplinary Department of Oceanography. Later, as head of department, he bore the responsibility of guiding the department through several years of dramatic change in the 1980s, that saw the department emerge from the review of university oceanography and change from a postgraduate-only teaching unit to a much larger body with its own undergraduate degrees. Despite administrative pressures, Peter was active outside the department, working on behalf of the Biological Council and UNESCO and also continuing with his own research. Peter's books and many scientific papers covered the physiology and ultrastructure of estuarine animals and the distribution of relict isopod populations, as well the construction of artificial reefs in the Cayman Islands and Poole Bay, taking in diving physiology, the haemolymph (circulatory fluid) of *Peripetus* and the impact of alien species carried in ballast water.

Those of us who knew Peter will remember him as unfailingly courteous with a dry sense of humour and possessed of a sharp intellect coupled with an immense breadth of knowledge within and without the bounds of marine biology.

Peter died peacefully on 2 January and is survived by his wife Kathleen and their three children.

Lawrence Hawkins

A DEEP-SEA LABORATORY IN THE MED –

infrastructure by courtesy of astrophysicists!

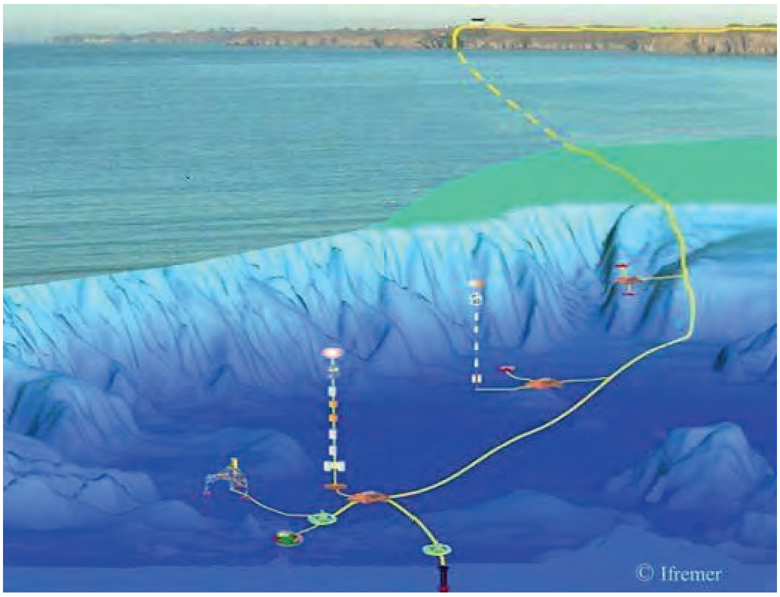
Anne Holford on behalf of the KM3Net Consortium

Our knowledge of the universe is mainly derived from observations of the electromagnetic emanations of stars and galaxies, from radio waves, through the infrared to X-rays and gamma rays. In addition, charged cosmic rays and, more recently, neutrinos,* have been used. Neutrinos are particularly useful as they are weakly interacting particles, which are unaffected by the gas, dust, and swirling magnetic fields they pass through on their journey to Earth: they enter our atmosphere unhindered, straight from their sources, travelling at very close to the speed of light. However, neutrinos are very difficult to detect, and it was realised during the 1970s that a detector for high-energy cosmic neutrinos would need to consist of vast amounts of target material. The proposed solution was to instrument a large volume of seawater in the deep sea to produce a 'neutrino telescope'. This is good news for oceanographers as the network infrastructure of a neutrino telescope can easily support a deep-sea marine observatory, allowing different scientific communities to share and maintain a common infrastructure as well as to share data. In 2005, the European Union agreed to fund the design and preparatory phase of a neutrino telescope and multidisciplinary deep-sea observatory in the Mediterranean Sea.

Sea-bed observatories transmitting data in real time via fibre-optic cables are being developed in various projects around the world

Figure 1 *An artist's impression of a cabled deep-sea observatory showing the electro-optical link to the shore station, with three junction boxes distributed along the sea-bed, each with an assortment of instruments, lander-type platforms and mooring strings. Power is supplied from the shore station via the cable and down-converted at the junction box providing the appropriate voltage to the instrumentation. Data are sampled and returned in real time via the junction box and cable to the data dissemination system at the shore station.*

(By courtesy of Ifremer)



The case for deep-sea observatories

There is a growing recognition among politicians and scientists alike that research addressing international scientific questions, such as the potential impacts of climate change and geo-hazards like earthquakes and tsunamis, should be conducted within a multidisciplinary framework. Our current understanding of such global-scale problems is fragmented and lacks data from coherent long-term monitoring. Datasets from the deep sea are particularly rare; long-term datasets are available from only a few locations worldwide, and the longest of these only covers a period of approximately three decades.

Key questions requiring a comprehensive inter-disciplinary approach include:

- How can constant monitoring of seismic activity, pore-water chemistry and pressure be used to improve prediction and modelling of earthquakes, slope-failure and tsunamis?
- To what extent do sea-bed processes influence ocean physics, ocean biogeochemistry and marine ecosystems?

*A significant proportion of all elementary particles in the universe are neutrinos. They are similar to electrons, have a very small but non-zero mass and do not carry an electric charge. Neutrinos are able to pass through ordinary matter almost undisturbed, and are extremely difficult to detect. They are created as a result of certain types of radioactive decay or nuclear reactions such as those that take place in the Sun, in nuclear reactors, or when cosmic rays strike atoms.

• To what extent might physical and biogeochemical processes occuring at different scales be related?

• What aspects of ocean physics and biogeochemical cycling will be most sensitive to climate change?

• What important feedbacks of ecological change will influence biogeochemical cycles?

• What factors control the distribution and abundance of marine life, and what will the influence of anthropogenic change be?

The development of ocean observatories (Figure 1) provides an opportunity for marine science in Europe to evolve, with the collection of standardised data capable of bridging various measurement systems/scales across a dispersed network in European waters. Furthermore, these systems can be developed taking into account the requirements of the modelling community, and such standardised datasets should improve the design of our models, making predictions more accurate.

Until now, research in the deep sea has been limited by power and data communications constraints. In general, observations have been made by autonomous measuring systems, which are deployed for up to a year and which need to be recovered for the data to be retrieved. Data-storage and battery capacity have limited data-sampling to intervals of minutes or longer, with the inevitable breaks in data-collection. By contrast, a cabled deep-sea observatory can use a continuous and steady power supply, allowing data-acquisition in real time. Real-time data acquisition will also allow the implementation of intelligent systems which can react dynamically to events by changing sampling rates, and monitoring additional parameters as and when required.

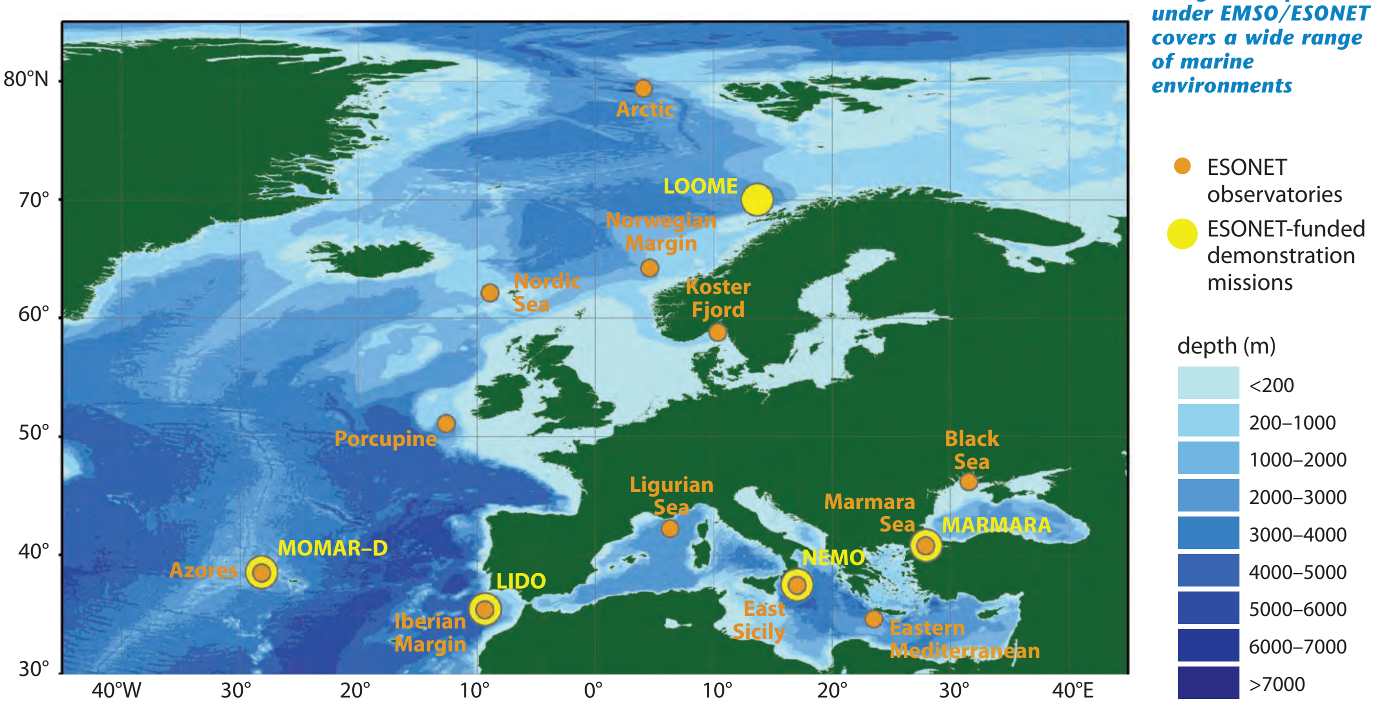
ESONET

Efforts now underway to establish a network of deep-sea observatories in European seas include the European large-scale research Infrastructure programme EMSO (European Multidisciplinary Seafloor Observatory) being developed as part of the European Seas Observatory NETwork Network of Excellence (ESONET NoE).

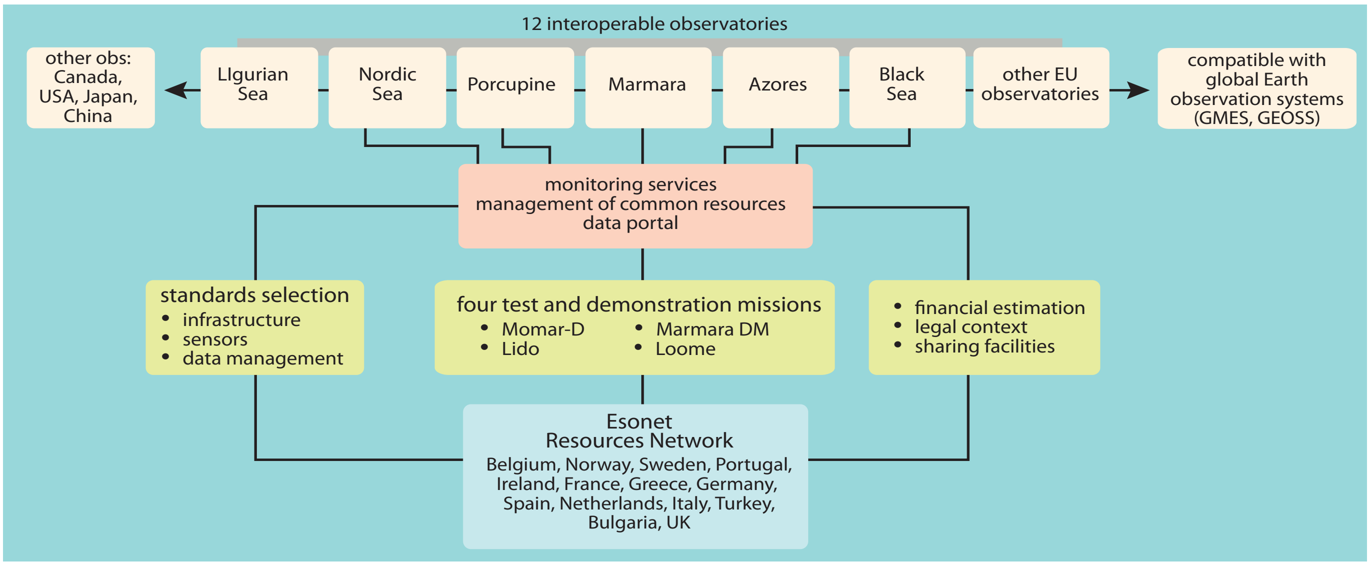
The proposed network of ocean observatories will feed into larger global environmental monitoring systems, including GOOS (Global Ocean Observing System), GEOSS (Global Earth Observation System of Systems) and GMES (Global Monitoring for Environment and Security). The chosen sites span a wide range of marine environments, including the polar and sub-Arctic regions, gyres, the continental shelf, and the Mediterranean (Figure 2). To prove the technology and viability of the core services (see below), a series of demonstration missions (highlighted in yellow in Figure 2) have been funded and are currently being designed and implemented.

A generic sensor package is being developed for ESONET; it is based on standard oceanographic sensors and is being assembled from commercially off-the-shelf instruments. The aim is for it to be used on all ESONET/EMSO observatories to continuously measure parameters of interest to a large part of the marine community includ-

Figure 2 *The proposed network of deep-sea observatories around Europe. The five highlighted in yellow are the first ESONET-funded demonstration missions.*



The network of observatories being developed under EMSO/ESONET covers a wide range of marine environments



ESONET brings together ~300 scientists, engineers and technicians from 14 European countries

Figure 3 *Interaction/flow of data products and services that are provided to the stakeholders and users by the ESONET Network of Excellence.*

ing temperature, conductivity (salinity), pressure (depth), turbidity, chlorophyll fluorescence, dissolved oxygen, current speed and direction, and ambient sound (passive acoustics). The variables measured with this package include Essential Climate Variables (ECVs) that are important in the context of climate system monitoring, supporting the work of the UN Framework Convention on Climate Change (UNFCCC) and the IPCC. In addition, depending on the location and the scientific objectives of the researchers, there will be instrumentation to allow the study of seismic activity, biogeochemical fluxes, and faunal abundances. Provision of a variety of tools allows investigators to make connections between processes that are usually observed in disparate ways. ESONET data products and services will be openly available, along with information about quality and provenance of the data.

In December 2009 the Neptune Canada cabled observatory began live operations with data being broadcast in real time on the internet. Several ESONET partner institutions are also involved in Neptune Canada, ensuring that knowledge gained from this experience is shared, and international contacts are maintained, thus maximising resources and effort.

Neutrino telescopes in the ocean

The interaction of neutrinos with seawater or the rock beneath releases secondary particles, known as muons, which fly a long distance (in the same direction as the neutrino) before stopping. These charged particles produce a short flash of Cherenkov radiation – light detectable by photomultipliers in clear water at distances of tens of metres. Cherenkov radiation is produced when particles exceed the velocity of light in the medium and is the electromagnetic version of a sonic boom. With a sufficient number of 'hits' detected in photomultipliers along the muon trajectory, the detector reconstructs the direction of the incoming neutrino and its energy can be estimated. Accumulations of tracks pointing in a given direction will establish the co-ordinates and characteristics of this neutrino source (Figure 4, *opposite*).

Neutrino telescope and observatory in the Med

The proposed neutrino telescope and multidisciplinary deep-sea cabled observatory, mentioned at the start of the article, is being devoped by KM3NeT – a consortium comprising forty institutes and university groupings from Cyprus, France, Germany, Greece, Ireland, Italy, Netherlands, Romania, Spain and the UK.

The geographic location in the Mediterranean is perfect since the area of the sky covered includes the centre of our Galaxy. In addition, the Mediterranean deep sea is of prime interest to the marine and Earth science communities. Indeed, at a workshop in 2008, the Mediterranean Science Commission characterised the Mediterranean Sea as a miniature ocean; it can be regarded as an ideal model to study oceanic processes and land–ocean–atmosphere interaction. Geological records have shown that the Mediterranean ecosystem amplifies climatic signals, making it an ideal test-bed for climate studies. Furthermore, recent observations have shown large-scale changes in deep ocean circulation within the Mediterranean and in the regional climate.

The KM3NeT neutrino telescope will be composed of a number of vertical structures known as 'detection units', each anchored to the sea-bed and kept vertically upright with buoys. Each detection unit consists of a series of mechanical structures called storeys supporting the necessary sensors and electronic components, along with power and data line interfaces (cf. Figure 5). The detection of Cherenkov light is achieved using light detectors in the form of photomultipliers (housed in glass spheres known as optical modules) which measure the time of arrival and the amount of the Cherenkov light (Figure 4). Knowing the arrival time and the position of the optical modules allows the reconstruction of the muon track to a precision of within a few tenths of a degree.

Because the attenuation length of light in the deep sea is of the order of 50–60 m for wavelengths around 470 nm, the sensor matrix can be spread out over a large volume of clear Mediterranean water. Simulations have demonstrated that the horizontal distance between detection units can be 130–180 m, and the vertical distance between the storeys 30–40 m. When complete, the KM3NeT detector array will occupy a volume of several cubic kilometres. Accurate knowledge of the position of each photomultiplier is essential, and to this end an acoustic triangulation system of hydrophones and transponders, along with oceanographic sensors such as acoustic Doppler current profilers and conductivity–temperature–depth probes will be positioned strategically throughout the array. These data will be shared with the marine science community and will complement the data obtained from the marine and Earth science nodes positioned around the detector (*see overleaf*). This will be the first opportunity to monitor in detail a volume of deep seawater and investigate phenomena such as internal waves and short time-scale oscillations in the water column in real time.

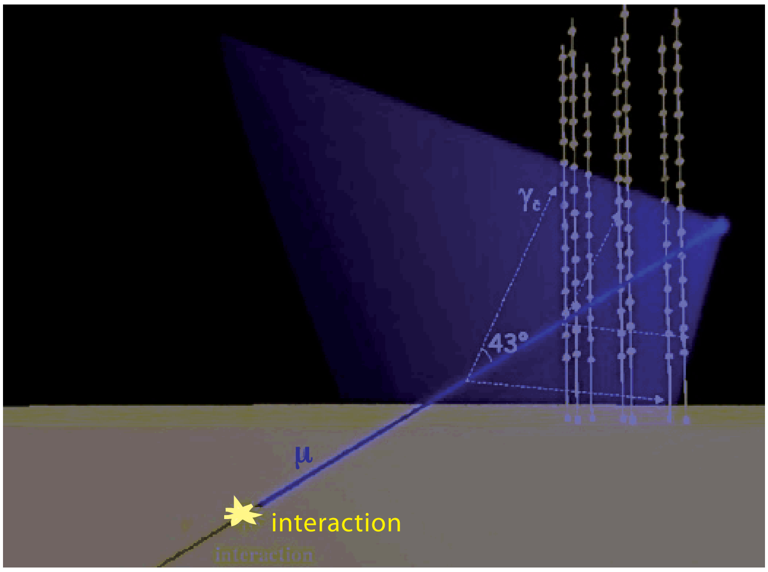
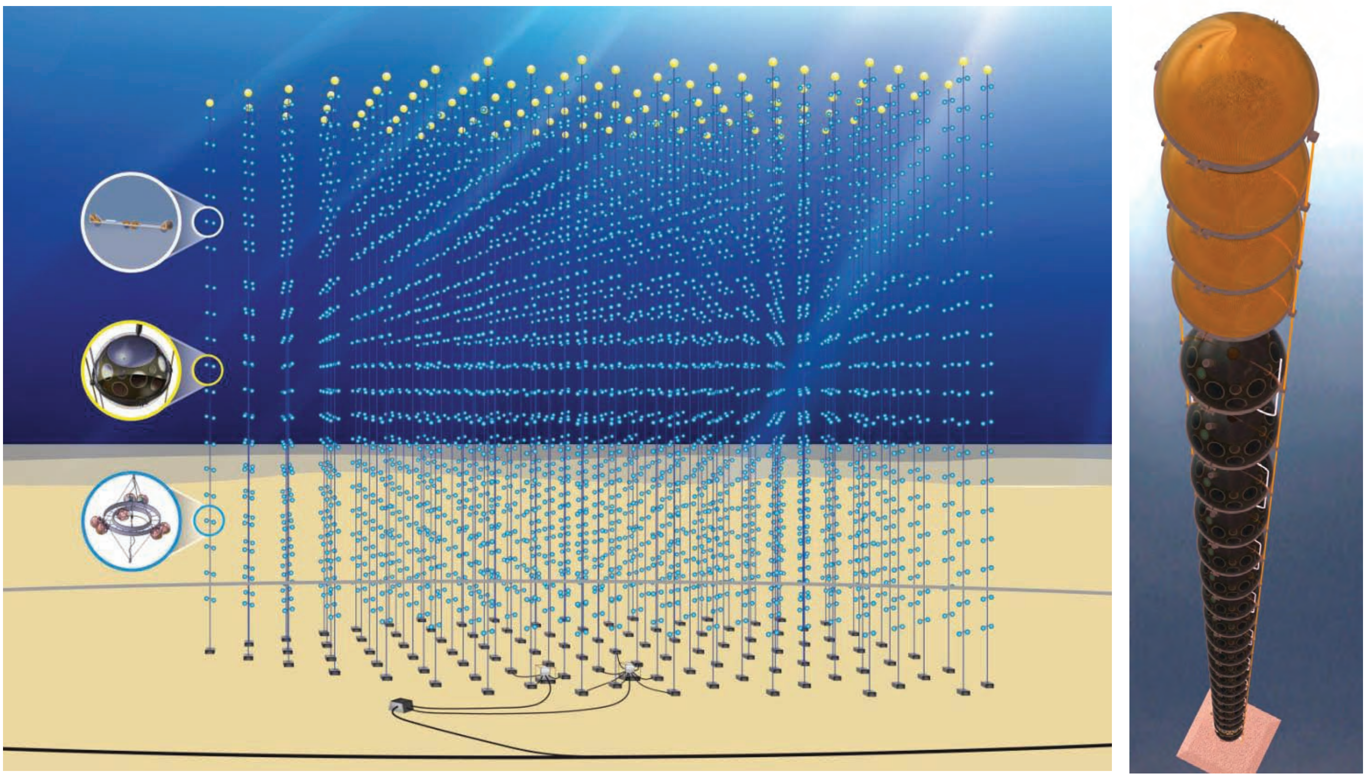


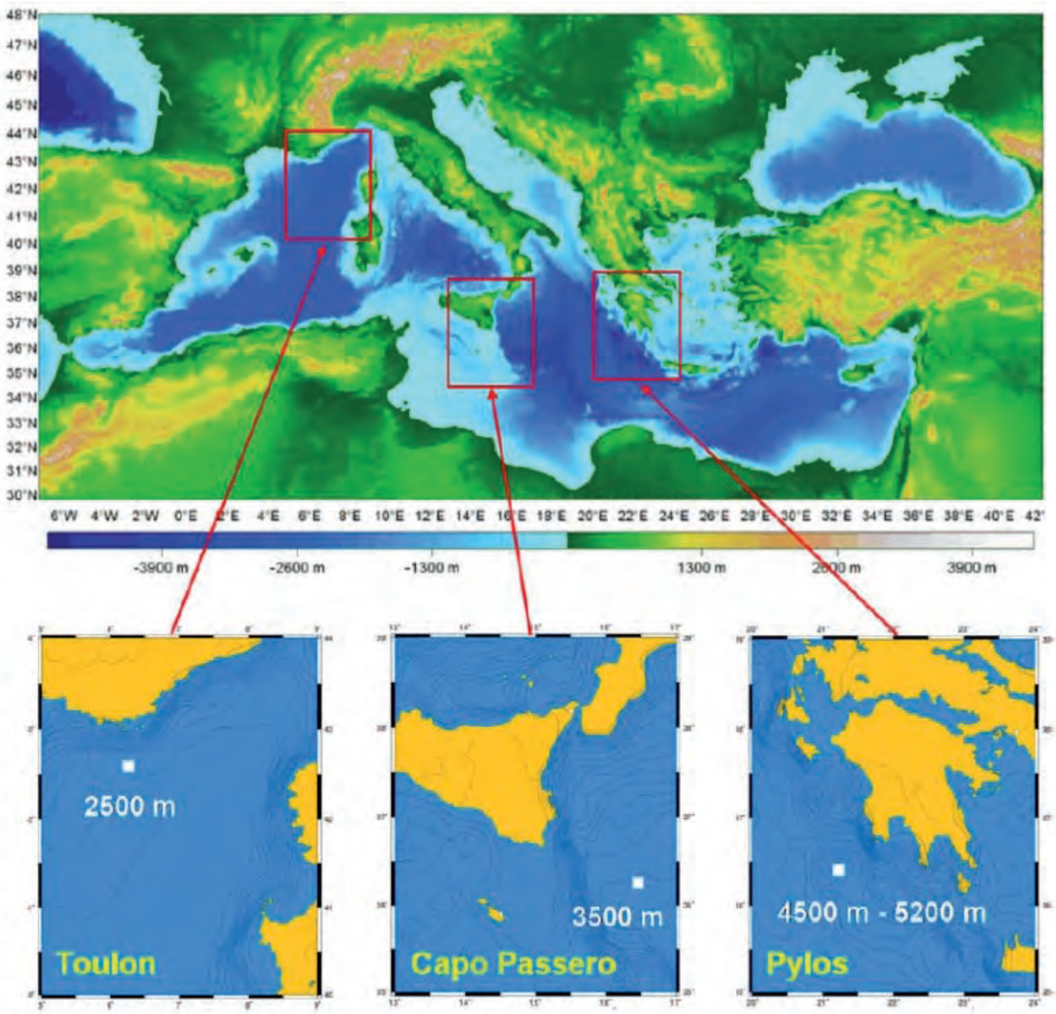
Figure 4 *Principle of detection of high energy neutrinos in an underwater neutrino telescope; μ is a muon, γ_c is the opening angle for the cone of Cherenkov light and 43° is the angle of refraction for Cherenkov light in seawater.*

The spectrum of Cherenkov radiation coincides with the typical spectrum of bioluminescent light, centred around 470–480 nm. Relatively little is known about bioluminescence generated by organisms in the deep sea, so this is of great interest to both marine biologists and the KM3NeT telescope community.

A neutrino telescope is a 3D matrix of sensors sensitive to Cherenkov light in the visible spectrum

Figure 5 Left *Artist's impression of the KM3NeT neutrino telescope on the sea floor, showing the detector lines, the sea-bed interlinks cables, the junction box and the cable to the shore. For clarity, in this illustration the number of storeys per line is reduced and items are not drawn to scale.*
Right *Schematic layout of a proposed KM3NeT detection unit: the black spheres are optical modules and the orange ones are buoys.*





There are three neutrino telescope pilot projects in the Mediterranean; one, off Toulon, is fully operational

Figure 6 *Locations of the Mediterranean neutrino telescope projects: ANTARES off Toulon (France), NEMO off Capo Passero Sicily (Italy) and NESTOR off Pylos (Greece).*

The KM3NeT concept

The KM3NeT concept is based on the design and technology developed for the three pilot projects in the Mediterranean Sea, sited at the locations shown in Figure 6. ANTARES, off Toulon on the French coast, is fully operational and has been gathering data for several years.

The common infrastructure, consisting of the electro-optical cable, primary junction boxes and shore station, will be managed jointly by both the astrophysical and the Earth/marine science communities. The primary objective of the Earth/marine science contribution to the KM3NeT programme is to establish a network of observatory nodes. This network will incorporate a number of secondary junction boxes strategically positioned around the footprint of the neutrino telescope and connected to a primary junction box. Each secondary junction box will service a suite of sensors connected to it and will deliver continuous real-time data to shore. The instrumentation will consist of combinations of the following:

- Autonomous sensors such as seismographs.
- Moorings containing suites of instruments, as described above.
- Fixed structures with removable modules containing instruments such as video cameras, acoustic devices and chemical analysers along with suites of oceanographic sensors such as the proposed ESONET standard instrumentation module.

The data will be gathered at the shore station and transferred via internet services to the relevant data centres and outreach sites, in a similar way to that used by ESONET (cf. Figure 3).

It is hoped that eventually there will be an 'integrated Mediterranean Marine Observatory', incorporating instrumentation placed on satellites, buoys, moorings, ships, drifters, profilers, gliders and coastal systems including arrays of weather stations. Such a permanent infrastructure will extend our knowledge of physical processes and their effect on the distribution of suspended geological, chemical and biological materials. It will enable real-time tracking of vertical migrations of organisms and, by implementing elements of the new Ocean Tracking Network, will allow the tracking of fish and marine mammals equipped with implanted transmitters. In addition, such a system can provide continuous observations for investigating transitory hazardous events such as earthquakes and failures of the continental slope.

Multipurpose observatories represent the way forward, and combining scientific data with economical, environmental and social parameters will allow an integrated approach to marine management. Sustainable development will depend more and more on intelligent management of the marine environment, with formulation of policies based on informed decisions relying on intelligent support systems, depending on a supply of real-time data and using numerical modelling.

The future for KM3NeT

It is anticipated that construction of the KM3NeT observatory will begin some time in 2013, and it will take approximately five years to complete. Data-collection will start during the construction phase with the first scientific data available in late 2014. The design studies have indicated that the current scientific objectives can be met within a budget of approximately 250 million Euros.

The structure is intended to remain *in situ* for a period of approximately twenty years, with minimal maintenance on the telescope array and yearly maintenance on the marine science nodes. Biofouling could prove to be a major problem and investigations are currently being undertaken with a view to mitigating the problem. Environmental impact assessments are being carried out with respect to the array's construction, commissioning, operation and maintenance, as well as decommissioning and the legacy post decommissioning. As part of these studies, the consortium is looking into the possibility of the observatory providing its own renewable power source using either solar or wind technology.

It is anticipated that the data and all relevant core services will be made available to the scientific community as a whole under the legal framework that will have been established before operations begin. It is envisaged that access to the system will be granted to the following users and stakeholders:

- Scientists from KM3MeT member institutes
- Other scientists from within the EU
- Scientific institutions outside the EU
- EU government departments and organisations
- Non-governmental organisations

Different levels of secure access will be implemented and operational data relevant to civil protection will be streamed directly to the relevant national agencies. KM3NeT will maintain a dedicated outreach website containing two sections, one for the layperson and one for scientists. Real-time data will be displayed on the site and one of the main aims is to attract young people to all aspects of the KM3NeT scientific output, and allow the general public to understand how funds are being used to enhance scientific and technical knowledge.

The decision to build the KM3NeT array and sea-bed observatory in the Mediterranean Sea, and the precise site chosen, were determined by the requirements of neutrino astronomy, but the challenge for the deep-sea marine community is to make the best use of this opportunity to intensively instrument part of the Mediterranean Sea.

Further Reading

Bagley *et al.* (2008) *KM3Net: Conceptual Design for a deep-sea research infrasturture incorporating a very large volume neutrino telescope in the Mediterranean Sea.* ISBN: 978-90-5488-031-5. http://www.km3net.org/CDR/CDR-KM3NeT.pdf

Bagley *et al.* (2010) *KM3NeT: Technical Design for a deep-sea research infrastructure incorporating a very large volume neutrino telescope in the Mediterranean Sea.* ISBN: 978-90-6488-033-9.

Briand. F (Ed.) (2008) *CIESM Workshop Monographs* 34.

http://www.ciesm.org/index.htm

http://www.km3net.org/

http://www.neptunecanada.ca

http://www.mbari.org/topics/technology/tech-observatories.htm#mars

http://www.jamstec.go.jp/jamstec-e/maritec/donet/project/measurement.html

http://www.esonet-emso.org/

http://www.eurosites.info/

Ann Holford works at Oceanlab, University of Aberdeen. She has been instrumental in providing and co-ordinating the technical input to the Earth and Sea Science work package for the KM3NeT project. She was a member of the editorial team which produced the Conceptual Design Report and the Technical Design Report.

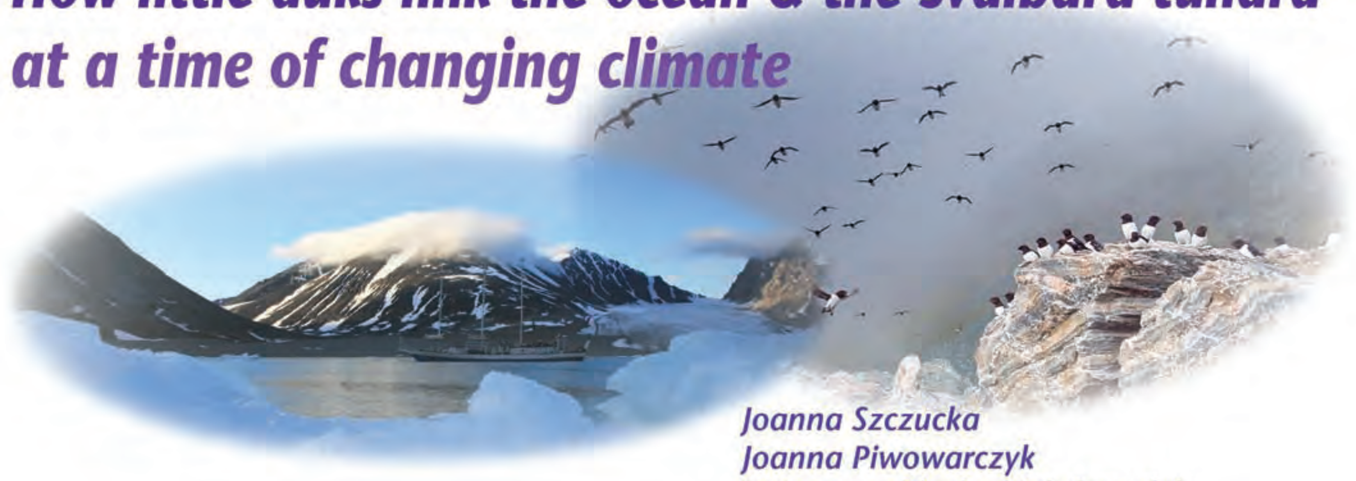
a.holford@abdn.ac.uk

The Significance of Marine Science and Marine Scientists in Present-day Europe

A conference on this topic was held by the European Federation of Marine Science and Technology Societies (EFMS) in October 2010. Powerpoint presentations from the conference are on the EFMS website **http://www.efmsts.eu/** and the keynote lectures have been put together in a special 12-page issue of *Mesopelaga*, published by the Hellenic Oceanographers' Association. For more information contact Angela Colling on **AngelaMColling@gmail.com**.

The Federation aims to integrate experiences from different countries, connect marine science societies, and stimulate politicians and public opinion to appreciate that the oceans are still largely unexplored and that enormous benefits can be gained through investing in improving our knowledge and understanding of the sea.

How little auks link the ocean & the Svalbard tundra at a time of changing climate



Joanna Szczucka
Joanna Piwowarczyk
Katarzyna Błachowiak-Samołyk
and Lech Stempniewicz

Spectacular climate change has been observed in the Arctic during the last decade. Over that time, the temperature of Atlantic Water in the Nordic seas has risen by 0.3 °C – a huge increase in comparison with a rise of 0.06 °C over the last 50 years for the ocean as a whole. An excellent site for researching the change is the Svalbard archipelago, whose waters are strongly influenced by the cold Arctic Sørkapp Current and the warm West Spitsbergen Current. These currents not only differ with regard to their temperature and salinity, but also in the compositions of their zooplankton populations. Comparison of the marine organisms that inhabit areas with distinctive hydrological regimes is allowing us to draw conclusions about the impact of climate change on the planktonic crustaceans, the planktivorous little auks, and the Arctic tundra that is fertilised by these colonially breeding marine birds.

About our project

Long-term multidisciplinary studies of Arctic ecosystems are scarce. Since the 1970s, Norwegian and Polish scientists have been collaborating in the investigation of the fjords and coastal areas of Svalbard (which is Norwegian). Our knowledge of this region is now substantial, but is still fragmentary.

The Institute of Oceanology of the Polish Academy of Sciences in Sopot, the University of Gdansk (Poland) and the Norwegian Polar Institute in Tromsø (Norway) have a long and well established collaboration on Arctic marine ecology. As a result of this cooperation, Polish and Norwegian scientists submitted a joint proposal to the Polish-Norwegian Research Fund, to investigate how climate change is affecting a keystone species of the Svalbard ecosystem – the little auk or, in Norwegian, Alkekonge. 2008 saw the beginning of the project 'Response of marine and terrestrial ecosystems to climate changes in Arctic – links between physical environment, biodiversity of zooplankton and seabird populations'.

The photo of the vessel Oceania *in the Arctic, used in the title image, was taken by Marcin Wichoroski.*

The main objective of the project is to estimate the impact of climate warming on Arctic zooplankton communities (particularly copepods, *Calanus* spp.), little auks (*Alle alle*) and their physical environment. We are studying the interactions between water masses, marine life and terrestrial ecosystems using both direct and innovative remote sensing methods. Our goal is to obtain data on:

1. Water circulation, heat and salt transport by the West Spitsbergen Current, distribution and properties of water masses, and exchanges between fjords and the deep sea;

2. Optical parameters relating to the living conditions of phytoplankton and zooplankton;

3. The structure of the plankton community;

4. The breeding acitivity, feeding ecology and behaviour of little auks, as well as the characteristics of the various colonies.

Investigations are carried out in areas adjacent to four Spitsbergen fjords representing different climatic (hydrological) regimes and biota (Figure 1). The most southerly study area is adjacent to Hornsund fjord in south-west Spitsbergen, where there is a large little auk breeding population. This area is mainly influenced by the Arctic Sørkapp Current and to a lesser extent by the West Spitsbergen Current, which carries water from the Atlantic. In the other three sites, Atlantic water masses dominate. In the central region of western Spitsbergen there are small scattered little auk colonies (study sites, Isfjord and Kongsfjord), whereas in north-western Spitsbergen (study site, Magdalenefjord) a large little auk breeding population is maintained. The differences in the sizes of the various colonies are assumed to be related to the distances to the nearest good feeding grounds.

The 'ocean climate' in a given region depends on how flow rates of currents are influencing the hydrological structure and properties of the local water column. In the vicinity of Spitsbergen, the ocean climate is influenced by Atlantic waters that flow from the south and are relatively warm and saline, and by waters that flow from the Arctic and are colder and less saline. The West Spitsbergen Current transports Atlantic waters throughout the region where our studies are being conducted. Both the temperature of these waters and the intensity of their flow have increased significantly in recent years. Small volumes of Atlantic water have begun to enter the fjords, and change the climatic conditions in Spitsbergen as well as the hydrology and ice cover in the fjords. These changes are having a significant impact on the local ecosystems.

As will be discussed later, light is also an important factor controlling the living conditions of plankton throughout the water column. There is a strong correlation between the availability of light at various depths and the spatial distribution, species composition and biomass of phytoplankton populations and of the zooplankton that feed on them. Underwater visibility also determines the feeding conditions for predators, including the planktivorous little auks.

What little auks really like to eat

The zooplankton – a diverse group of animals that drift passively in the water column, and range in size from microscopic flagellates and minute crustaceans, to giant jellyfish – play a significant role in the food web of the whole Arctic ecosystem linking producers and consumers. The large zooplankton crustaceans that dominate Arctic waters are rich in calories and make an excellent food source for planktivorous seabirds such as the little auk. Off Svalbard, there has in recent years been an increase in the abundance of Atlantic crustaceans, which has been expected to stimulate a shift in the food web towards increasing populations of planktivorous fish and, consequently, of piscivorous birds, such as guillemots and kittiwakes.

The little auk is the most abundant seabird in the Northern Hemisphere. It is considered a keystone species in Arctic ecosystems, with a total population estimated at several tens of million pairs. It is

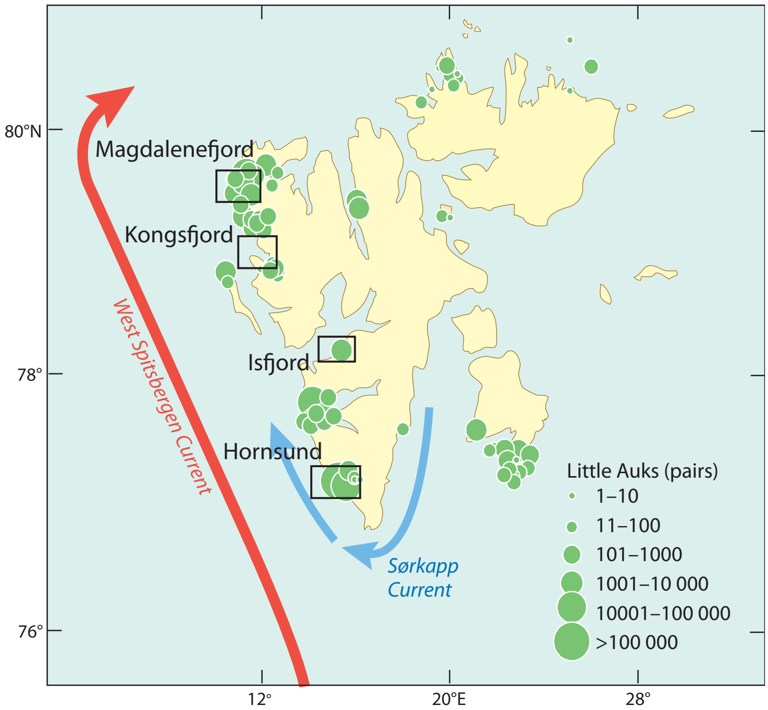


Figure 1 *Map of Svalbard showing the main currents, the positions of little auk colonies and the four fjords investigated within the Alkekonge project.*

Sizes of little auk colonies reflect distances to the nearest good feeding grounds

Figure 2 ***Left*** *A little auk consuming a large euphausid.* ***Right*** *A little auk about to enter its nest and feed a chick with the contents of Its gular pouch. A little auk's gular pouch can contain as many as 3800 small crustaceans, weighing as much as 10g. (Photos by courtesy of Cornelius Nelo)*

Little auks feed voraciously during the breeding season

a small, dove-sized bird that nests principally on Greenland and the Svalbard Archipelago. After the breeding season, the little auks overwinter along the coasts of southern Greenland, Newfoundland, and northern Europe.

The little auk is a specialized planktivore that mainly consumes tiny crustaceans. Its preferred prey are copepods of the genus *Calanus*, which the birds catch one at a time during their dives to depths as great as 30 m. As they forage, the parent birds accumulate prey in their gular pouches (Figure 2), then carry it back to their chicks waiting in the breeding colonies.

Little auk nests are usually situated under boulders on mountain slopes covered with rock debris. The breeding period lasts about three months, from June to August, during the Arctic summer. Like many other seabirds, the little auk is monogamous. Each nesting season a female lays a single egg, which is then incubated by both parents for 29 days. After hatching, the chick remains in the nest for about a month, requires intense care from its parents and initially needs to be brooded. Food is delivered to the chick five to eight times a day. About one week before fledging the female abandons the chick, and the young bird eventually leaves the colony and flies out to sea, guided by the male parent.

The Arctic ecosystem is most dynamic within the transitional zone where water from rivers and glaciers, carrying abundant mineral and organic material, mixes with coastal water. The physical characteristics of marine waters determine the productivity of the phytoplankton, and hence also the distribution and species of zooplankton, which in turn determine the quality and quantity of the food available to the planktivorous birds. The cold Arctic waters are inhabited by two large species of copepod: *Calanus glacialis* and *Calanus hyperboreus*, which are the preferred food of the little auk. The Atlantic water mass is predominantly inhabited by smaller copepod species such as *Calanus finmarchicus*, which are of lower nutritional value to the birds. Because the little auk is a specialized planktivore, it is a sensitive indicator of change in the marine environment. During the warming period (1870–1930) which followed the Little Ice Age (1650–1850), the cold Arctic currents shifted away from the coasts of Iceland and southern Greenland, and the little auks deserted these areas.

Large breeding colonies of little auks have a substantial positive impact on impoverished Arctic terrestrial ecosystems. The little auks consume large quantities of food, and at the peak of their foraging activity, they can remove up to 24% of the copepod standing stock of the feeding ground. The droppings of the masses of seabirds that feed at sea and nest on land, enrich the tundra around the breeding colonies. The minerals in their guano, discarded prey, eggs, dead chicks and adult birds all contribute to the fertilisation of the soil. Little auks nest in enormous colonies, and these are often significant distances from the coast, so as they fly in, they fertilise extensive areas of tundra that would otherwise revert to barren, rocky deserts (Figure 3).

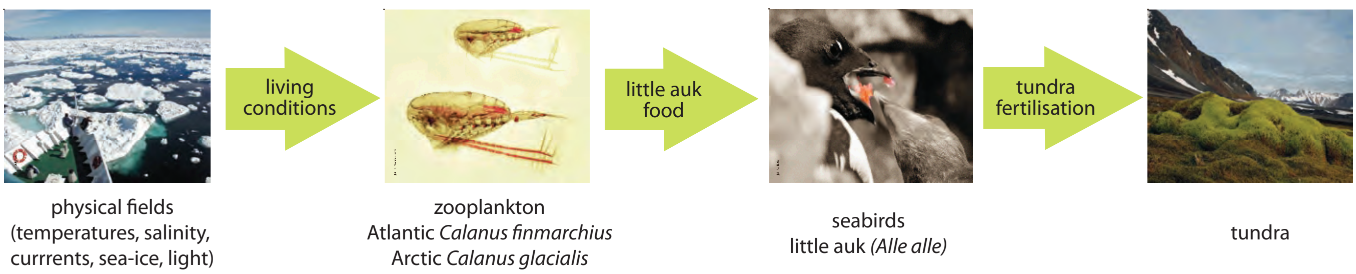
Alkekonge – the observations

Profiles of temperature, salinity and current flow are recorded from the surface to the sea-bed at depths down to 4000 m. Each deep profile takes several hours to be completed, and the data are transmitted via a conducting cable to a shipboard computer, where they are archived and analysed. During a typical month-long oceanic cruise, about 200 profiles, are collected. The data are analysed to identify the structure and properties of the water masses, the current structure and the locations of oceanic fronts and gyres. Probes towed behind the ship take measurements at various depths over the shelves and in the fjords, providing a detailed picture of the exchange and mixing processes of water masses. Since 2004, a substantial warming of the West Spitsbergen Current has been observed and the summer isotherm of 5 °C at 100 m depth has moved northwards by 4.5°. Warm water has extended in over the shelf and has been advected into the Svalbard fjords. In summer 2006, the temperature of Atlantic Water at the core of the West Spitsbergen Current reached a record high value. This warming influenced the weather conditions in the Svalbard area, and reduced the ice-cover within the fjords and in the adjacent sea

Conditions in the nearby ocean indirectly affect the productivity of the Svalbard tundra

Figure 3 *The relationship between oceanographic conditions off Svalbard, zooplankton, little auk populations and the Arctic tundra. The tundra ecosystem is not self-sufficient in nutrients, but during the little auk breeding season, nutrients from the ocean are transferred to the land, allowing it to become green and productive.*

(Photos by courtesy of Dariusz Jakubas, Sławomir Kwaśniewski, Cornelius Nelo and Mateusz Ciechanowski)



areas. Consequently, during the following two winters there was little or no ice within the West Spitsbergen fjords. Similar warming occurred again in 2009. Figure 4 shows the properties of Atlantic Water carried by the West Spitsbergen Current between 1996 and 2009, as measured across the line of latitude 76° 30' N. Mean volume and heat transports fluctuate from year to year, but the general trend is increasing in both cases.

in glaciated fjords, optical properties of the water are governed by stratification and circulation patterns. Changes in the intensity of sunlight down the water column are determined by the water transparency which, in turn, is determined by the concentrations of suspended organic particles (phytoplankton), mineral particles and dissolved organic matter. Suspended material accumulates at depths where there are strong temperature and salinity (i.e. density) gradients, and these more turbid layers attenuate the light, limiting the range of underwater visibility. There might be a two-fold link between water optical properties (here observed in terms of transparency) and little auks' feeding patterns. As lower transparency is an indication of the presence of organic and/or inorganic substances, less transparent waters might be potential feeding areas. On the other hand, less transparent water means poorer visibility, which may hamper the birds' ability to locate prey.

Marine spectro-radiometers are being used to take measurements of the intensity of sunlight penetrating to various depths in the water column. The euphotic zone is the depth over which the solar radiation available for photosynthesis falls to 1% of its value at the surface of the water. In other words, the depth of the euphotic zone is a measure of water clarity and is an important parameter affecting physical and biological processes in marine ecosystems. The depth of the euphotic zone can be measured from space, and Figure 5 shows euphotic zone depths for Spitsbergen waters as retrieved from remote sensing of ocean colour via the satellite-borne instrument, MODIS. The range of observed euphotic zone depth varies from above 60 m in Atlantic waters (darker blue in Figure 5) to just a few metres in the fjords in the vicinity of glaciers. Actually in the area very close to glaciers it can be less than 1 m, but this is not visible on the map, due to satellite pixel resolution.

Investigation of zooplankton populations

Observations of zooplankton distribution are conducted by three different methods: the traditional plankton net (WP2 and Multi Plankton Sampler), the Laser Optical Plankton Counter (LOPC) and acoustic backscatter methods (echo-sounding).

Conventional zooplankton sampling using nets requires time-consuming, labour-intensive analyses in the laboratory to identify and enumerate the zooplankton species present and provide detailed information on the composition of the zooplankton

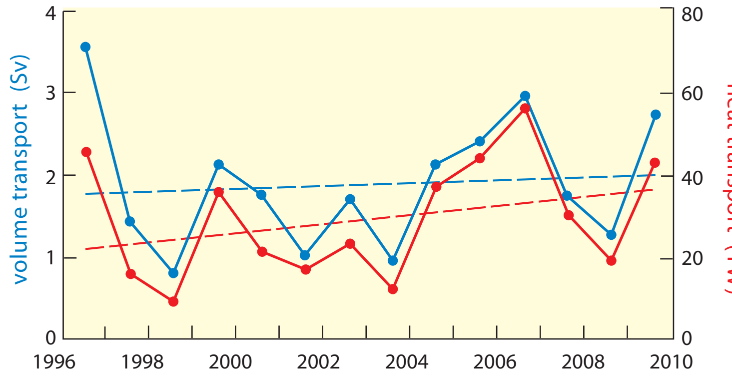


Figure 4 *Mean volume transport and heat transport of Atlantic Water in the West Spitsbergen Current. (1 Sv (sverdrup) = 10^6 m^3 s^{-1}; 1 TW (terawatt) = 10^{12} watts.)*

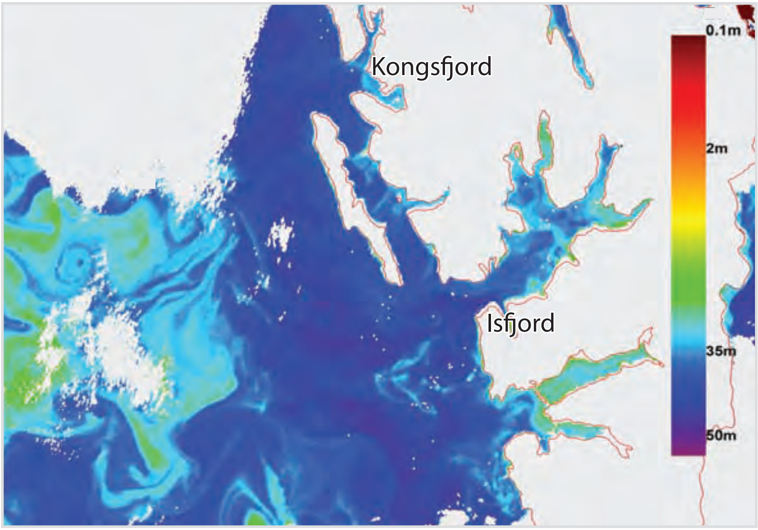
The mean volume and heat transports of Atlantic Water fluctuate from year to year, but the trend is upwards

populations. Each zooplankton sample is thoroughly scanned to generate counts of the larger (total size > 0.5 cm) zooplankters, which are the potential prey of the little auks. Using this method it is possible to calculate precisely the proportion of the little auks' main food – *C. glacialis* (mostly pre-adult and adult organisms) – relative to the other zooplankters, which are smaller or less caloric (including *C. finmarchicus*). A third *Calanus* species – *C. hyperboreus* – is also favoured by little auks, but it is rather rare in the surface waters over the Spitsbergen shelf studied in our project, as it is a deep-water species, typical of the Arctic.

The innovative LOPC technique has a number of advantages over traditional sampling, and its high spatial and temporal resolution compensates for the lack of taxonomic information. The LOPC measures the cross-sectional area of each plankton

Figure 5 *The depth of the euphotic zone for the waters off central western Spitsbergen, retrieved from remote-sensing ocean colour via MODIS satellite data. It can be seen that the euphotic zone is shallower not only in the fiords in the vicinity of glaciers but also along the West Spitsbergen Current where phytoplankton blooms occur.*

Seawater transparency may be important in determining where seabirds choose to feed



More zooplankton in the water does not mean a better feeding ground for little auks

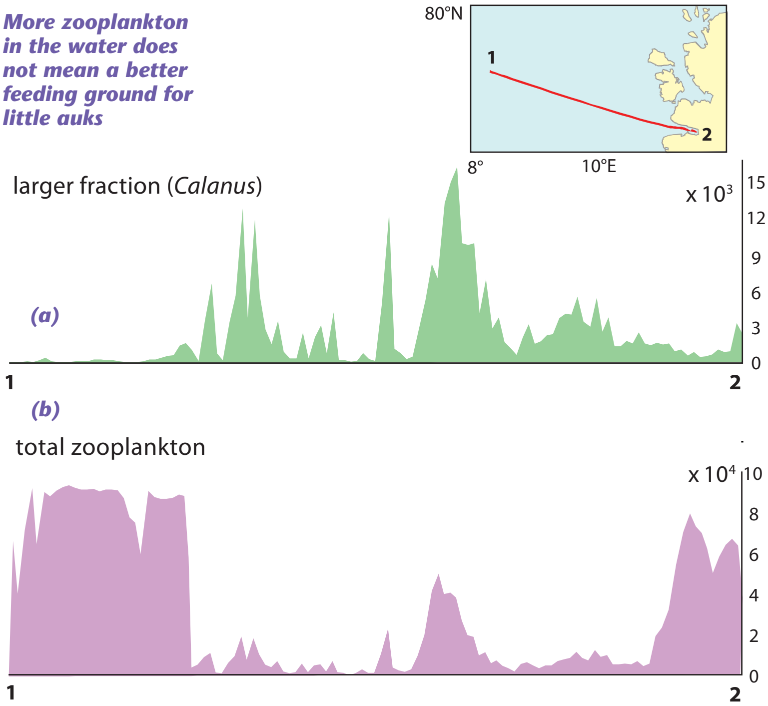


Figure 6 *Abundances of* ***(a)*** *larger zooplankton, mainly older copepodid stages of* Calanus *spp. (i.e. potential little auk prey) and* ***(b)*** *total zooplankton. Little auks need to find patches of high-quality food (the larger zooplankton fraction) which are generally not well correlated with the peaks of total zooplankton abundance. The diagram is based on continuous LOPC measurements at 10 m depth out from Magdalenefjord (35 nautical miles) in summer 2009.*

'particle' that interrupts the path of the laser beam in the sampling tunnel, and provides continuous data in real time on the abundance, size, bio-volume and shape of particles drifting in the water column. Therefore, the LOPC has the potential to map the distribution of the selected zooplankton size classes at high resolution, and so characterize foraging grounds for planktivores such as little auks.

One of the very first attempts to re-code the data from the LOPC by inter-calibrating its measurements with data derived from traditional examination of net samples from the same station, depth and time, showed good agreement in identifying larger zooplankton species such as those mentioned above, the older copepodid stages of the three *Calanus* species – the main food of little auks.

The composition of the little auk diet is determined on the basis of samples taken from the gular pouches of parent birds returning to feed their chicks (cf. Figures 2 and 7). Little auk behaviour at breeding colonies is observed continuously for several days in order to establish the mean number of times the chicks are fed within a 24-hour

Figure 7 ***Below*** *During the breeding season parent little auks fly non-stop to the zooplankton-rich foraging grounds and back to the colony (cf. Figure 8) to feed their chicks (****Left****).*

(Photo below by courtesy of Cornelius Nelo)

Little auk parents feed their single chick 5–8 times a day

period. Some of the birds are tagged with miniature temperature and pressure loggers and with GPS modules that provide data about the range of their foraging flights and the depths to which they dive. In Figure 8, tracks of two birds equipped with GPS-loggers show that little auks foraged at distances of about 120 km from the colony. These are the first direct measurements of distances of little auk foraging flights that have been documented.

When little auks dive to feed on zooplankton, their dive is powered by wing beats, and they can be detected underwater acoustically by the air bubbles that are released from among their feathers during the dive.. The Autonomous Hydroacoustic System (AHS) is a buoy consisting of an active section (an upward-looking echo-sounder working at a frequency of 130 kHz) and a passive (noise) section (two external omnidirectional hydrophones), both of which detect the air bubbles. Interpretation of the patterns of acoustic back-scattered echoes makes it possible to follow the trails of bubbles released from the birds' wings during diving, and to determine the depth of diving and the speed of their ascent. Analysis of the echo-sounder records showed that the birds were diving as deep as 34 m. A histogram of dive-depths obtained in this way is shown in Figure 9. Over half of the recorded events were limited to a depth of 5 m, but many deeper dives were also detected. This observation agrees quite well with data obtained in another part of the same project by Harald Steen from the Norwegian Polar Institute, using pressure loggers attached to individual birds. Figure 10 shows a 10-hour record of the position of a little auk in relation to the sea-surface, from which it is possible to deduce what the bird was doing at various times – diving, flying, floating, etc.

The effect on the tundra

The impact the little auks are having on the tundra structure is being investigated using the stable isotope ratios ^{12}C /^{13}C and ^{14}C/^{15}C. These allow an evaluation of the degree to which the tundra ecosystem is enriched with organic material that has been transported from the ocean to the land. We compare the isotopic signal of successive links in the food web, i.e. seabirds' tissues, their food items and faeces, as well as soil invertebrates, tundra plants, herbivores and predators collected both in the vicinity of little auk colonies and away from them. On the basis of our data, we conclude that Arctic ornithogenic (bird-generated) tundra structure depends significantly on local climatic regimes as well as the intensity of fertilisation by seabirds. Plant communities in areas of ornithogenic tundra influenced by warm climatic conditions differ from those influenced by cold climatic conditions.

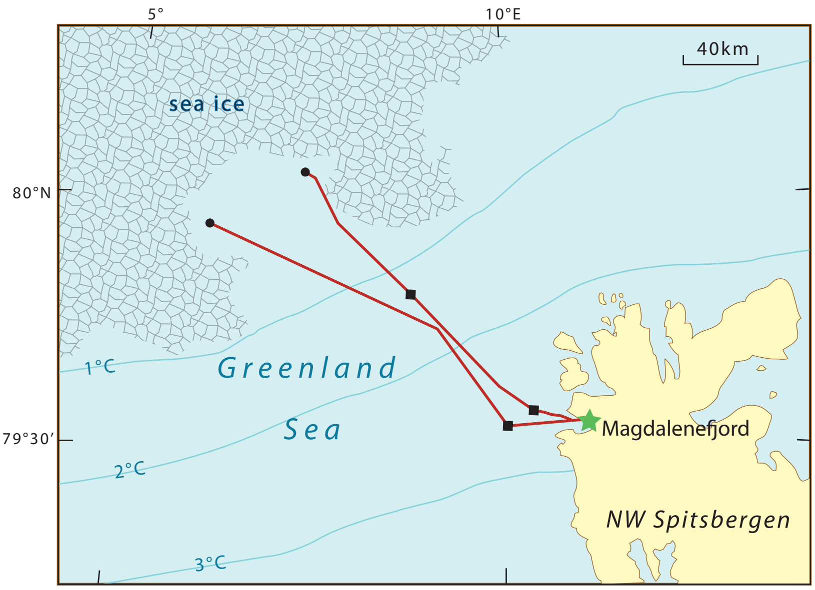


Figure 8 Tracks of two little auks equipped with GPS (July 2009). ★ = little auk colony in Magdalenefjord; isotherms: data for July 2009 from the database Reyn_Smith Olv2; sea-ice extent: data for 28 July 2009 according to the ice map from Meteorologisk Institutt, Norway.

Little auks may forage as much as 120 km from the colony

Figure 9 Distribution of the depths of little auks' dives, obtained using acoustic measurement of the bubble trails produced by little auks when they dived (cf. Figure 10).

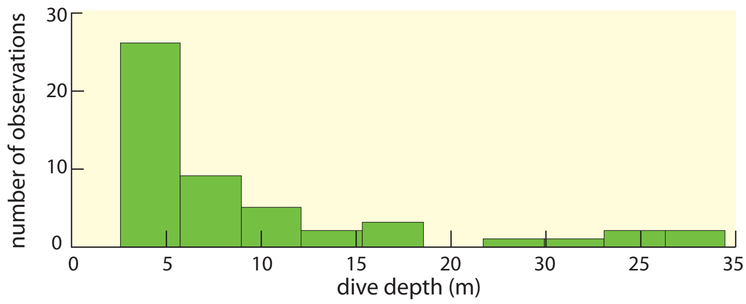
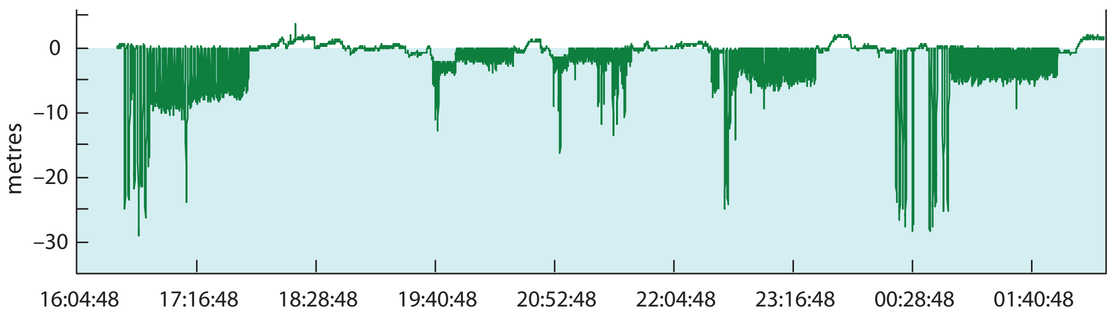


Figure 10 10-hour pressure logger record of the position of a little auk relative to the sea-surface (0).



Both methods for determining dive-depths showed that about half of little auks' dives are quite shallow, but half are down to 20–30 m

Future changes

As a result of climate warming causing a decline in planktivorous seabird populations, we can expect that large areas of ornithogenic tundra associated with little auk colonies may eventually disappear. This may lead to habitat fragmentation with negative consequences for tundra-dependent birds and mammals, and a substantial decrease in biodiversity of tundra plant and animal communities.

Our project therefore highlights the importance of studying the relationship between Arctic Water characteristics and marine organisms in achieving a better understanding of the whole Arctic system, including the physical environment, phyto- and zooplankton populations, seabirds and tundra communities. As a final result of our project, we expect to make predictions about how the European Arctic will change in the future.

Acknowledgements

We would like to thank all of the Project participants and acknowledge those who do not appear in the author list. We are particularly indebted to Emilia Trudnowska and Marta Głuchowska for their special contribution in editing this article and Martin Angel for critical reading of the manuscript. The project is supported by a grant from Norway through the Norwegian Financial Mechanism.

Further Reading

Karnovsky, N.J., S. Kwasniewski, J.M. Wesławski, W. Walkusz and A. Beszczynska-Möller (2003) Foraging behaviour of little auks in a heterogeneous environment. *Marine Ecology Progress Series*, **253**, 289–303.

Kwaśniewski S., M. Głuchowska, D. Jakubas, K. Wojczulanis-Jakubas, W. Walkusz, N. Karnovsky, K. Błachowiak-Samołyk and M. Cisek (2010) The impact of different hydrographic conditions and zooplankton communities on provisioning Little Auks along the West coast of Spitsbergen. *Progress in Oceanography,* **87**, 72–82.

Piechura, J. and W. Walczowski (2009) Warming of the West Spitsbergen Current and sea ice north of Svalbard. *Oceanologia,* **51**, 147–64.

Steen, H., D. Vogedes, F. Broms, S. Falk-Petersen and J. Berge (2007) Little auks (*Alle alle*) breeding in a High Arctic fjord system: bimodal foraging strategies as a response to poor food quality? *Polar Research,* **26**, 118–25.

Stempniewicz, L. (2001) *Alle alle*. Little Auk, *The Journal of the Birds of the Western Palearctic*. Oxford University Press. BWP Update 3, 175–201.

Stempniewicz, L., K. Błachowiak-Samołyk and J.M. Wesławski (2007) Impact of climate change on zooplankton communities, seabird populations and arctic terrestrial ecosystem – A scenario. *Deep-Sea Research II,* **54**, 2934–45.

Wojczulanis-Jakubas, K., D. Jakubas, N. Karnovsky, and W. Walkusz (2009) Little auks (*Alle alle*) utilize the bimodal foraging strategy under divergent foraging conditions, *Polar Research,* **29**, 22–9.

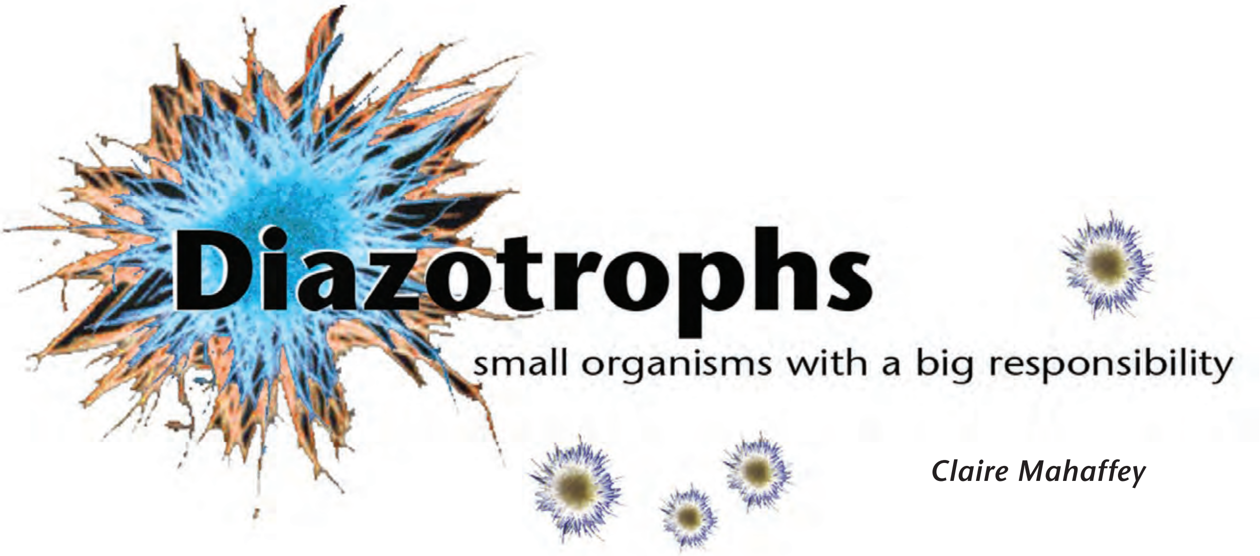
Joanna Szczucka is an Associate Professor in the Department of Marine Physics, Institute of Oceanology, Polish Academy of Science, Sopot. She is an underwater acoustician dealing with fish and zooplankton distributions, sea-bottom properties and Arctic noise interpretation. She is currently the Alkekonge Project Coordinator.
szczucka@iopan.gda.pl

Joanna Piwowarczyk is a junior scientist in the Department of Marine Ecology, Institute of Oceanology, Polish Academy of Science. She is an economist with a special interest in environmental valuation methods for policies and projects. She is currently the Alkekonge Project Secretary.
joanna_p@iopan.gda.pl

Katarzyna Błachowiak-Samołyk is currently an Associate Professor in the Department of Marine Ecology, Institute of Oceanology, Polish Academy of Science, where her research is focussing on Arctic zooplankton, which is proving to be complementary to her earlier studies on Southern Ocean pelagic fauna. kasiab@iopan.gda.pl

Lech Stempniewicz is a Professor and Head of Department of the Vertebrate Ecology and Zoology University of Gdansk. His main scientific interests are the functioning of polar ecosystems, ecology and the behaviour of birds and mammals.
biols@univ.gda.pl

(Photo by courtesy of Cornelius Nelo)



Diazotrophs

small organisms with a big responsibility

Claire Mahaffey

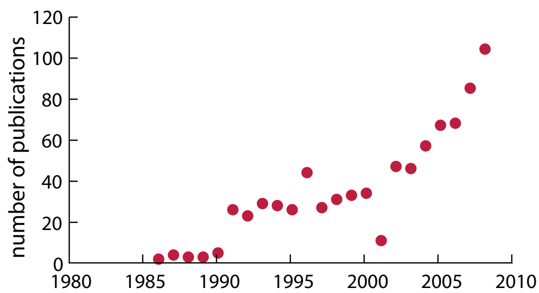
Our planet would be an inhospitable place without cyanobacteria, also known as blue–green algae. Millions of years ago, they were the first organisms to release oxygen as a metabolic by-product, and so dramatically altered the atmosphere and the biodiversity of organisms on Earth. Some cyanobacteria, known as diazotrophs, have evolved the ability to fix the most abundant source of nitrogen on Earth, dinitrogen gas (N_2), and thus are responsible for fertilising both terrestrial and aquatic ecosystems with a form of nitrogen available to plants and bacteria. They also play an important role in regulating atmospheric carbon dioxide in the Earth system. With such a responsibility, you wonder why cyanobacteria don't make headline news!

What is nitrogen-fixation?

Nitrogen-fixation is the biological transformation of atmospheric dinitrogen gas (N_2) to a form of dissolved nitrogen that can be used by bacteria and phytoplankton (e.g. ammonium, NH_4^+), and is the global source of nitrogen to the oceans over geological time-scales. The process of nitrogen-fixation, and its importance as a source of nitrogen to plants in both the terrestrial and marine environment, has been recognised since before the 1800s. However, it was not until the early 1900s, when systematic studies on the different forms of nitrogen began, that the role of marine nitrogen-fixation as a major control on marine productivity was realised. The growing need to understand this important process is perhaps best reflected by the rapid increase in the number of peer-reviewed scientific papers focussed specifically on marine nitrogen-fixation, published annually over the past two decades (Figure 1).

As marine diazotrophs have evolved to assimilate the most abundant form of nitrogen in the marine environment, they are able to occupy a niche in low-nutrient subtropical gyres where the growth of other phytoplankton is limited by the availability of fixed nitrogen (Figure 2). Like all marine microbes, diazotrophs require other elements to grow, the two most essential (and perhaps best studied) being iron and phosphorus. The enzyme responsible for the process of nitrogen-fixation, nitrogenase, is iron-rich, and thus the iron requirements of diazotrophs are typically 5 to 8 times greater than those of non-diazotrophic phytoplankton. To maintain growth, diazotrophs require phosphorus at a ratio of 1 : 16 relative to nitrogen. However, diazotrophs are poor competitors for the most accessible form of phosphorus, phosphate (PO_4^{3-}), having 30 times less affinity for phosphate than non-diazotrophic phytoplankton. Instead, diazotrophs are able to satisfy some of their phosphorus requirements by producing a hydrolytic enzyme, such as alkaline phosphatase, which removes phosphate bound to dissolved organic matter. Different nutritional strategies by diazotrophs relieve phosphorus-limitation and mean that many species, both diazotrophs and non-diazotrophs, can co-exist in phosphorus-depleted regions of the ocean.

Figure 1 *The number of papers containing 'marine nitrogen fixation' in the title or list of keywords, published per year since 1986.*
(Source: Web of Science)



Increasing numbers of research papers are addressing marine nitrogen-fixation

Diazotrophs thrive in the low-nutrient subtropical gyres

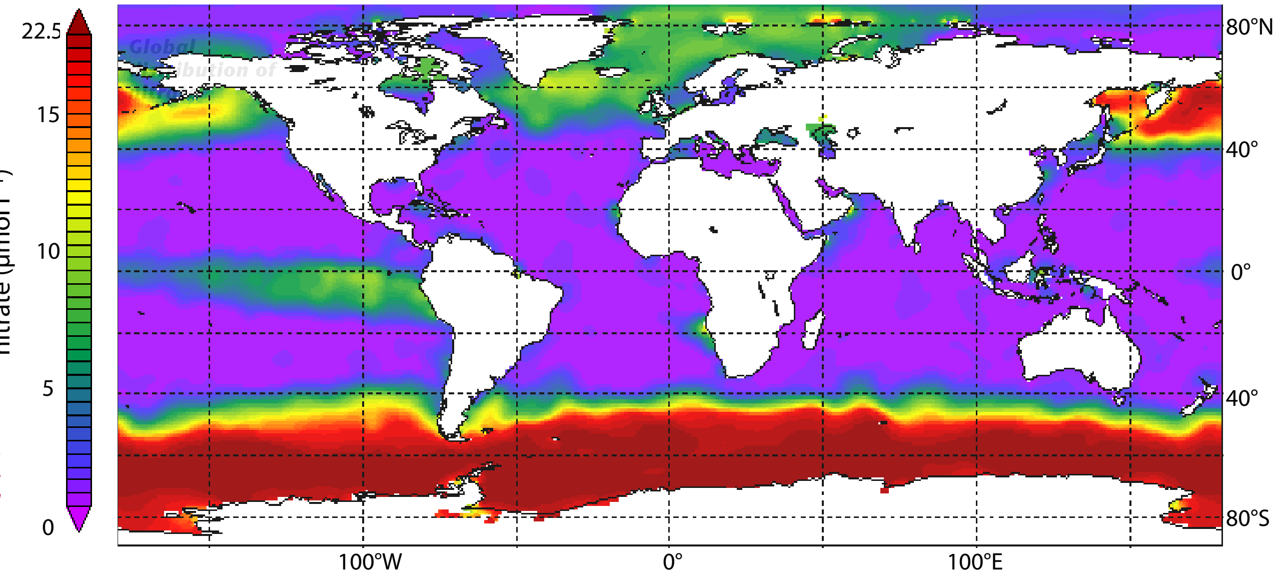


Figure 2 *Distribution of nitrate (NO_3^-, µmol l^{-1}) in the surface ocean, with the oligotrophic areas, where low nitrate concentrations limit primary production, in purple. Diazotrophs are typically found in the warm waters of the low-nitrate subtropical gyres. (Source: www.pmel.naoo.gov)*

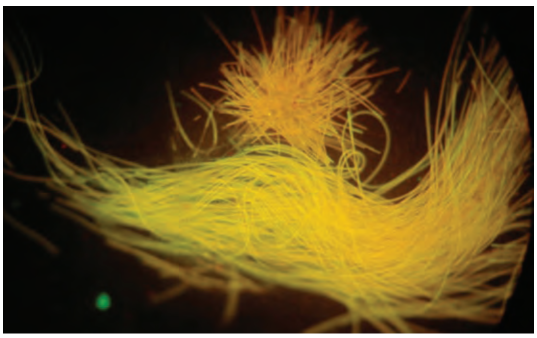
Diazotrophs are a diverse group of single-celled prokaryotic organisms (including cyanobacteria) that range in size and form from unicells of less than 10 µm (or 0.01 mm) to filamentous colonial diazotrophs greater than 100 µm (0.1 mm) across. They are typically found in low-nutrient or oligotrophic subtropical gyres in surface waters where temperatures exceed 22 °C.

At present, at least three distinct ecological groups of diazotrophs are recognised: unicellular, filamentous colonial, and symbiotic. Although different kinds of diazotrophs can and do co-exist, in many ocean regions the diazotroph community is dominated by unicellular diazotrophs (e.g. *Crocosphaera*) which at any one time can be responsible for more than 80% of the nitrogen-fixing activity. The importance of these unicellular diazotrophs in the marine nitrogen cycle was only discovered within the past decade as a result of advances in molecular sequencing techniques which allowed identification by their DNA.

Figure 3 *The colonial diazotroph* Trichodesmium *in puff **(above)** and tuff **(below)** morphologies.* Trichodesmium *colonies can consist of 10 to 375 filaments, and filament diameters range from 10 to 500 µm.*

(By courtesy of Rachel Foster, MPI for Marine Microbiology, Germany)

Trichodesmium colonies may be in the form of puffs or tuffs



Two of the most commonly observed unicellular diazotrophs, termed group A and group B, are yet to be cultured in the laboratory and therefore little is known about their physiology, elemental requirements and fate. In contrast, the most thoroughly studied genus of diazotroph, both in the laboratory and in the field, is *Trichodesmium*, a filamentous, non-heterocyst*-forming cyanobacterium whose colonies are found in either 'puff' or 'tuff' morphology (Figure 3). There are various theories about why *Trichodesmium* filaments clump together – for example, clumping would protect their nitrogen-fixing apparatus from oxygen, which would deactivate the enzyme nitrogenase. It is not known why there are two different morphologies, which can occur even for the same species.

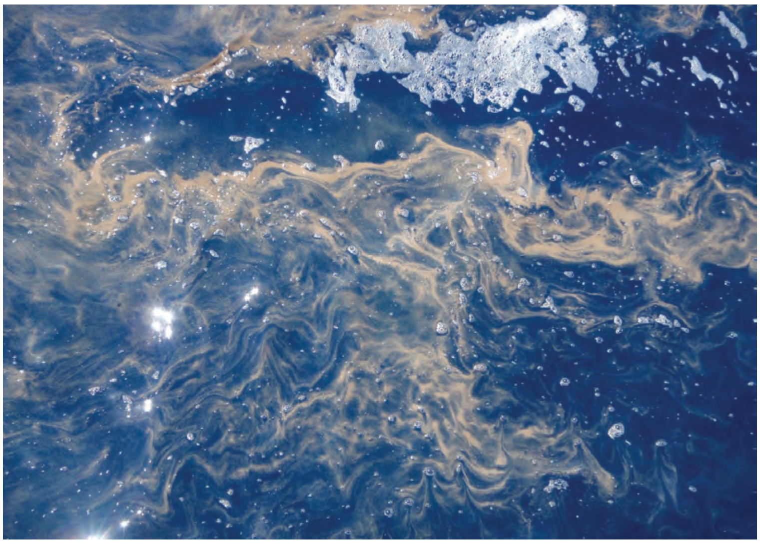
Trichodesmium spp. alone are responsible for approximately 50% of global nitrogen-fixation and are thus considered to be amongst the most important diazotrophs globally. *Trichodesmium* colonies can be large (up to 0.2 mm) and dramatic surface bloom formations are visible from ships (Figure 4(a) and from Earth-orbiting satellites (Figure 4(b)). In 1768, Captain Cook described an accumulation of *Trichodesmium* as 'sea sawdust'. In 1845, while on the *Beagle*, Charles Darwin observed a 'reddish-brown appearance in the sea' and using a weak lens described the organisms as 'chopped bits of hay, with their ends jagged' (see Box *opposite*). Darwin was also describing surface slicks of *Trichodesmium* in tuff form.

*A heterocyst is a specialized cell formed by some nitrogen-fixers. Nitrogenase, the enzyme that drives fixation of N_2, is irreversibly inhibited by oxygen. Formation of a heterocyst creates an anoxic environment that prevents deactivation of the nitrogenase. *Trichodesmium* does not have a heterocyst and thus uses other means to protect the nitrogenase enzyme.

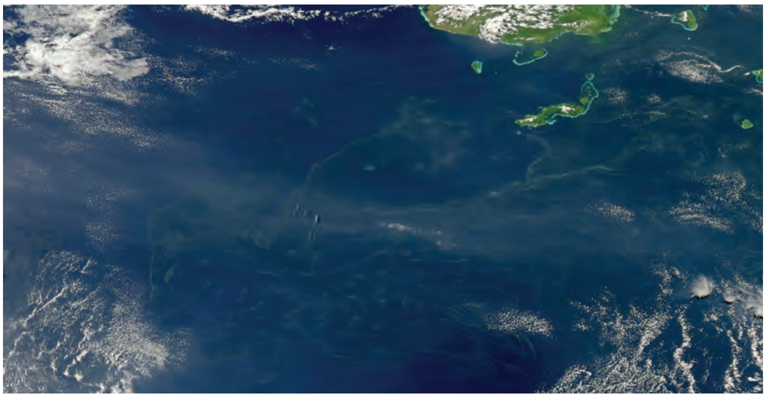
Darwin's observations of 'sea sawdust'

March 18th. – We sailed from Bahia. A few days afterwards, when not far distant from the Abrolhos Islets, my attention was called to a reddish-brown appearance in the sea. The whole surface of the water, as it appeared under a weak lens, seemed as if covered by chopped bits of hay, with their ends jagged. These are minute cylindrical confervæ, in bundles or rafts of from twenty to sixty in each. Mr. Berkeley informs me that they are the same species (Trichodesmium erythrœum) with that found over large spaces in the Red Sea, and whence its name of Red Sea is derived. Their numbers must be infinite: the ship passed through several bands of them, one of which was about ten yards wide, and, judging from the mud-like colour of the water, at least two and a half miles long. In almost every long voyage some account is given of these confervæ. They appear especially common in the sea near Australia; and off Cape Leeuwin I found an allied, but smaller and apparently different species. Captain Cook, in his third voyage, remarks, that the sailors gave to this appearance the name of sea-sawdust.

Source: Darwin, C.R. (1845). Journal of researches into the natural history and geology of the countries visited during the voyage of H.M.S. Beagle round the world, under the Command of Capt. Fitz Roy, R.N. 2nd edition. London: John Murray.



(a)



(b)

Figure 4 **(a)** *A* Trichodesmium *bloom off the coast of eastern Australia in November 2010 (field of view is ~ 1 m across).* **(b)** *Aqua MODIS satellite image of the ocean south of Fiji in October 2010. Although partly obscured by cloud, large-scale swirls of* Trichodesmium *can be seen over much of the area shown (field of view is ~ 600 km across).*

((a) by courtesy of Mark Brown, University of Sydney, Australia; (b) See http://modis.gsfc.nasa.gov/)

Blooms of* Trichodesmium *– the 'sea sawdust', observed by Cook and Darwin – can cover huge areas of ocean

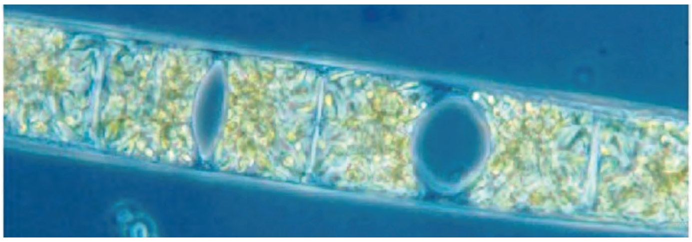
Due to its size and ease of identification, the phosphorus and iron requirements of *Trichodesmium* are well known, and its physiological properties are often used in models as representing a typical marine diazotroph.

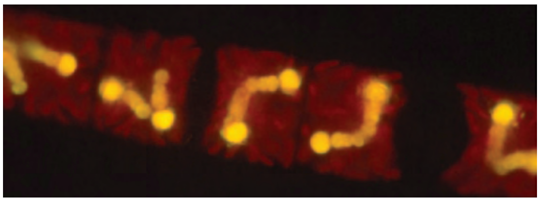
An interesting and important diazotroph group in terms of the carbon cycle (see later) are the symbiotic heterocystous cyanobacteria, *Richelia* spp., which live on or within large diatom hosts such as *Hemialus* and *Rhizosolenia* (Figure 5). The symbiosis between *Richelia* and its host allows diatoms to exist in an open ocean environment where they would otherwise be excluded by nutrient-limitation. *Richelia* supply fixed nitrogen to the diatom and, in return, the diatom ensures the symbionts gain sufficient light by maintaining its position in the sunlit upper surface ocean. However, the diatom host requires silicate, so such symbiotic relationships can only exist where silicate concentrations are sufficiently high to support growth of the diatoms' protective silicate shells, or frustules.

There have been numerous field campaigns to study the various diazotrophic groups in the world's oceans but the relatively short duration of a typical research cruise means that we only get snapshots of how these organisms live in the

Figure 5 *The symbiotic diazotroph* Richelia *living on/inside a diatom host,* Hemialus, *viewed under a light microscope (***Upper***) and viewed under an epifluorescence microscope (***Lower***). The yellow strands (each about 5 μm long) are the* Richelia.

(By courtesy of Professor D. Caron, USC)





The diazotroph* Richelia *lives on or within the diatom* Hemialus *to their mutual benefit

In the North Atlantic large communities of diazotrophs deplete surface concentrations of phosphate and DOP

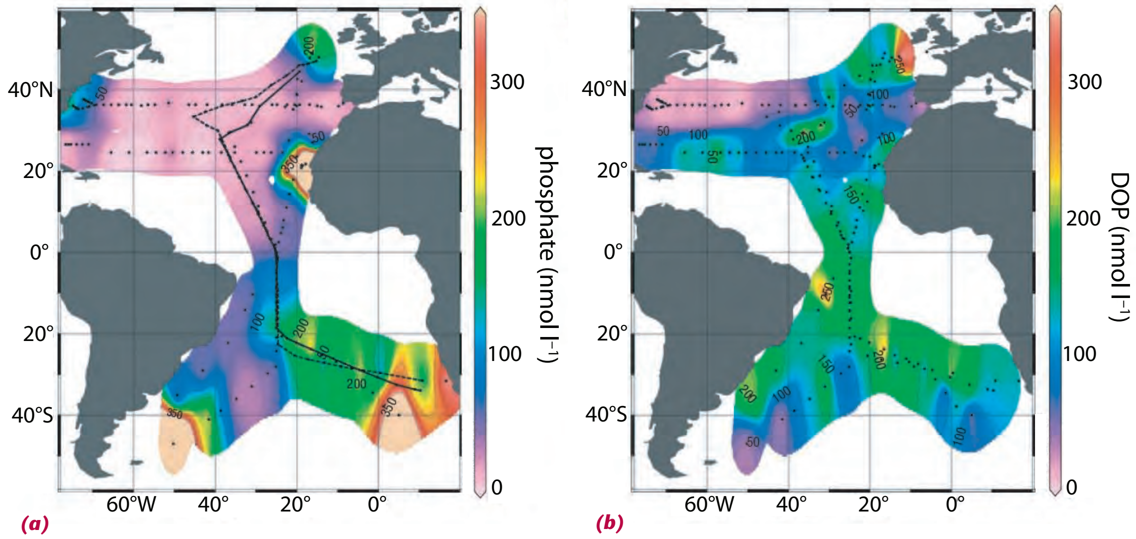


Figure 6 *Concentration of **(a)** phosphate and **(b)** dissolved organic phosphorus (DOP) at 25 m in the Atlantic Ocean. Note the difference in phosphorus concentrations between the North and South Atlantic, reflecting contrasting abundances of diazotrophs, resulting from dust being supplied in abundance to the North Atlantic but not to the South Atlantic. Stations sampled (dots) and cruise tracks (solid and dashed lines) are from various AMT cruises between April 2000 and November 2005, plus cruises D279 (April 2004) and CD171 (May 2005).*

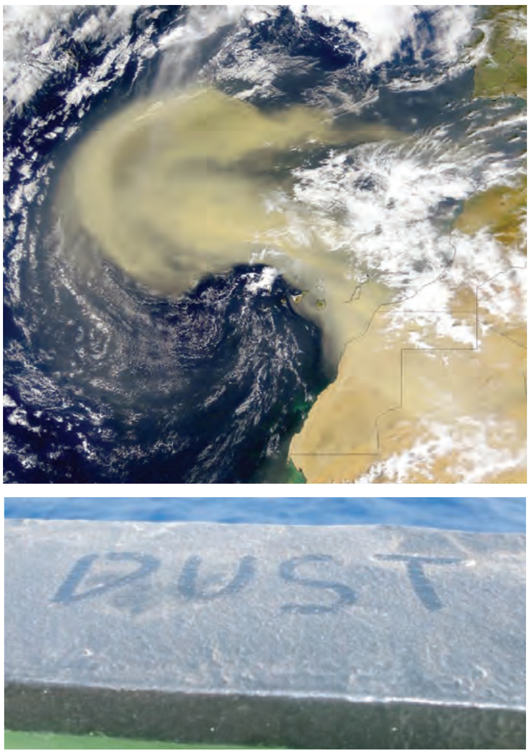
(Data originally published by Mather et al.*, 2008)*

ocean. However, three years of near-monthly observations of diazotrophic community structure and activity from the Hawaii Ocean Time-series in the North Pacific subtropical gyre have provided a measure of both the seasonal and interannual variability in nitrogen-fixation, and we do know that their relative abundance and activity change seasonally. Using molecular techniques and measurements of rates of nitrogen-fixation for different sizes of diazotroph, these time-series observations show that the abundance and activity of unicellular diazotrophs is relatively constant throughout the year. However, in late summer and early autumn, there are recurring blooms of *Trichodesmium* and *Richelia* associated with diatoms, which 'overprint' on the background unicellular diazotrophs. Satellite measurements of sea-surface height (reflecting fine-scale circulation patterns) show that these blooms may be stimulated by subtle yet important changes in water column structure. It is postulated that the fine-scale changes in circulation cause the diazotroph communities to be supplied with limiting nutrients in amounts that, although small, are enough to relieve their phosphorus and iron stress.

Figure 7 ***Upper*** *Satellite-derived image of a dust storm over the Atlantic Ocean in January 2000.* ***Lower*** *Dust deposited on the rails of RRS* Discovery.

((a) SeaWiFS/NASA; (b) by courtesy of Ross Holland, NOCS)

Saharan dust over the North Atlantic and on the rails of RRS **Discovery**



Dust and nitrogen-fixation

Availability of the nutrients iron and phosphorus is considered to temporally and spatially constrain the distribution of diazotrophs in the world's oceans. Field observations and model studies show a strong relationship between regions of iron input and diazotroph abundance. Trade winds over the Sahara desert suspend large quantities of iron-rich dust into the atmosphere and transport it over the North Atlantic (Figure 7), and Saharan dust deposition is considered the principal source of iron to the North Atlantic. Through both dry and wet deposition (settling out of the atmosphere, and being washed out in rain), the dust fertilizes the surface

In the North Atlantic large communities of diazotrophs deplete surface concentrations of phosphate and DOP

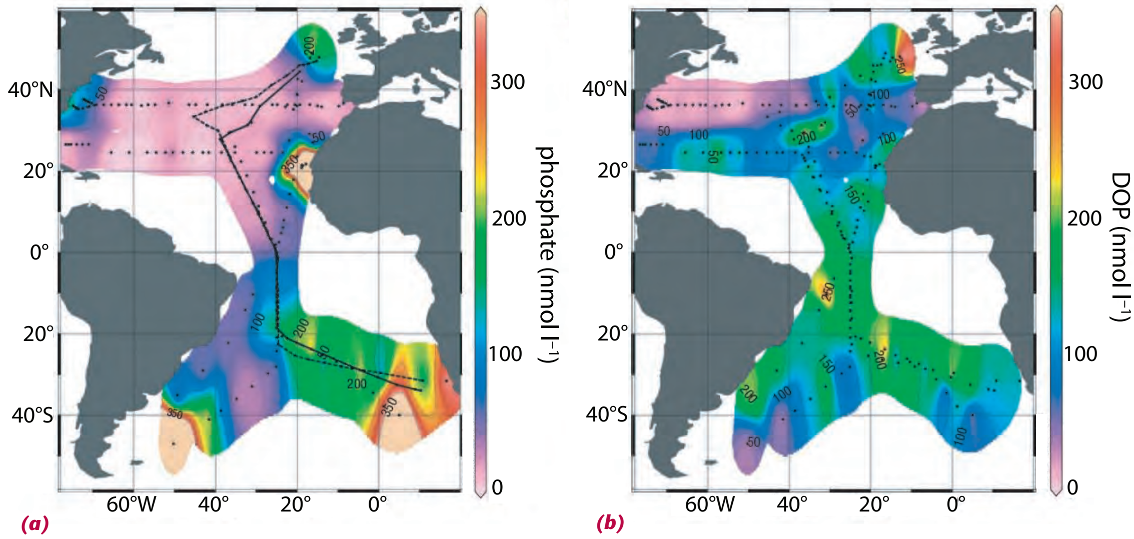


Figure 6 *Concentration of* ***(a)*** *phosphate and* ***(b)*** *dissolved organic phosphorus (DOP) at 25 m in the Atlantic Ocean. Note the difference in phosphorus concentrations between the North and South Atlantic, reflecting contrasting abundances of diazotrophs, resulting from dust being supplied in abundance to the North Atlantic but not to the South Atlantic. Stations sampled (dots) and cruise tracks (solid and dashed lines) are from various AMT cruises between April 2000 and November 2005, plus cruises D279 (April 2004) and CD171 (May 2005).*

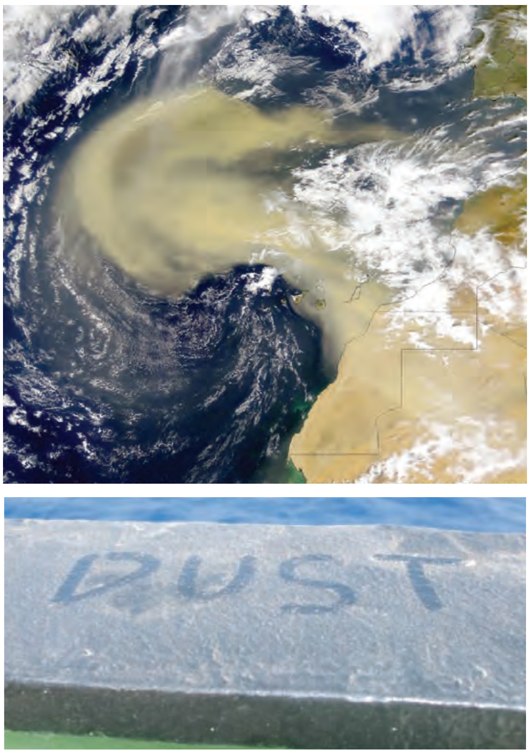
(Data originally published by Mather et al.*, 2008)*

ocean. However, three years of near-monthly observations of diazotrophic community structure and activity from the Hawaii Ocean Time-series in the North Pacific subtropical gyre have provided a measure of both the seasonal and interannual variability in nitrogen-fixation, and we do know that their relative abundance and activity change seasonally. Using molecular techniques and measurements of rates of nitrogen-fixation for different sizes of diazotroph, these time-series observations show that the abundance and activity of unicellular diazotrophs is relatively constant throughout the year. However, in late summer and early autumn, there are recurring blooms of *Trichodesmium* and *Richelia* associated with diatoms, which 'overprint' on the background unicellular diazotrophs. Satellite measurements of sea-surface height (reflecting fine-scale circulation patterns) show that these blooms may be stimulated by subtle yet important changes in water column structure. It is postulated that the fine-scale changes in circulation cause the diazotroph communities to be supplied with limiting nutrients in amounts that, although small, are enough to relieve their phosphorus and iron stress.

Figure 7 ***Upper*** *Satellite-derived image of a dust storm over the Atlantic Ocean in January 2000.* ***Lower*** *Dust deposited on the rails of RRS* Discovery.

((a) SeaWiFS/NASA; (b) by courtesy of Ross Holland, NOCS)

Saharan dust over the North Atlantic and on the rails of RRS Discovery



Dust and nitrogen-fixation

Availability of the nutrients iron and phosphorus is considered to temporally and spatially constrain the distribution of diazotrophs in the world's oceans. Field observations and model studies show a strong relationship between regions of iron input and diazotroph abundance. Trade winds over the Sahara desert suspend large quantities of iron-rich dust into the atmosphere and transport it over the North Atlantic (Figure 7), and Saharan dust deposition is considered the principal source of iron to the North Atlantic. Through both dry and wet deposition (settling out of the atmosphere, and being washed out in rain), the dust fertilizes the surface ocean with iron, creating a niche for diazotrophs. This supply of dust-derived iron is episodic and confined to the (sub-)tropical North Atlantic, with the South Atlantic receiving negligible inputs of iron-rich dust. This north/south divide in iron supply has a dramatic impact on the abundance of diazotrophs and the distribution of surface phosphorus. Direct observations and modelling of nutrient ratios show that rates of nitrogen-fixation are orders of magnitude higher in the North Atlantic compared to the South Atlantic. The phosphorus demand associated with nitrogen-fixation results in phosphate concentrations being 1 to 2 orders of magnitude lower in the North Atlantic compared with the South Atlantic (Figure 6(a)). In fact, the North Atlantic exhibits the lowest phosphate concentrations in the world's oceans. Complete assimilation of phosphate in the North Atlantic causes diazotrophs to be phosphate-limited. However, as previously mentioned, diazotrophs have the ability to adapt to phosphorus-limitation by producing the enzyme alkaline phosphatase which detaches phosphorus from organic matter. A study published by researchers at the University of Liverpool showed that alkaline phosphatase activity was 3 to 4 times higher in the North Atlantic relative to the South Atlantic. This difference in assimilation of organic-bound phosphorus is manifested in the strong latitudinal gradients in surface ocean dissolved organic phosphorus, DOP (Figure 6(b)), with concentrations being 50% lower in the North Atlantic relative to the South Atlantic.

In January 2008, a research campaign in the eastern tropical Atlantic Ocean, led by Professor Eric Achterberg (University of Southampton) as part of the Surface Ocean–Lower Atmosphere Study (SOLAS), was fortunate to capture the direct impact of Saharan dust on the surface ocean biogeochemistry. Almost three weeks into a six-week cruise, a cloud of dust appeared on MODIS satellite images, and within days, a layer of Saharan dust coated the ship's rails (Figure 7). The abundance and activity of diazotrophs were monitored before and during the dust event, providing valuable information on the response of diazotrophs to inputs of iron-rich dust.

To date, few studies have observed diazotrophs, or indeed found measureable rates of nitrogen-fixation, in the South Atlantic. One study found diazotrophs in the Gulf of Guinea but their abundance and significant nitrogen-fixing activity have been attributed to inputs of iron and phosphorus from the River Congo. Indeed, there is emerging evidence to suggest that tropical rivers have a significant impact on diazotroph distributions, the best studied example being the River Amazon.

Diazotrophs and tropical rivers

The Amazon is the largest river in the world by volume and accounts for 18% of all the riverine input to the oceans. Between May and September, the Amazon plume covers up to 20% of the western tropical North Atlantic, and its fresh-water influence is observed up to 500 km out to sea (Figure 8).

As well as delivering fresh water, the Amazon is responsible for supplying iron, phosphorus and silicate to the western Atlantic. However, nitrogen is stripped out of the water upstream in the estuary by the biologically mediated process of denitrification, so the waters of the Amazonian plume are relatively nitrogen-poor. Along the salinity gradient from the river water (salinity < 30), to mesohaline waters (salinity between 30 and 35) to oceanic waters (salinity > 35), there is a transition in nutrient concentration that causes a succession of phytoplankton and diazotrophs. In riverine waters, high nutrient concentrations support the growth of coastal diatom species, and nitrogen-fixing activity is close to the limits of detection. In the mesohaline waters, relatively high concentrations of phosphate, iron and silicate enhance the growth of *Richelia* associated with the diatom hosts *Hemialus* and *Rhizosolenia*. Indeed, a recent study found that rates of nitrogen-fixation were six times higher in mesohaline waters than in the surrounding oceanic waters, which were dominated by *Trichodesmium*.

During peak flow (May–August), the Richelia-rich Amazon plume covers an area of 1.2 x 10^{12} km^2

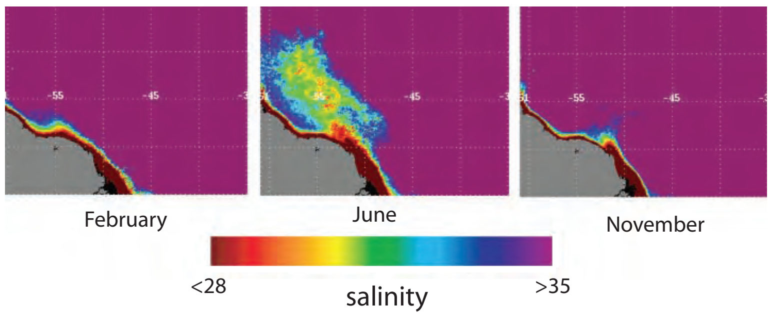


Figure 8 *Freshwater inputs from the Amazon river to the western tropical Atlantic in February, June and November. The extensive plume is carried northwards along the coast by the Guyana Current (the map covers an area from the Equator to 10°N, and from 30° to 65°W), and the gradient in salinity is accompanied by a nutrient gradient and by changing planktonic communities. Diazotrophs are relatively rare in riverine waters (red); the symbiotic diazotroph* Richelia *flourishes in mesohaline waters (yellow–indigo); and* Trichodesmium *dominates truly oceanic waters (purple).*

(By courtesy of Ajit Subramaniam, LDEO, Columbia University, USA)

Fate of fixed nitrogen

There is still great uncertainty about the fate of nitrogen fixed by diazotrophs. Data from laboratory culture studies of *Trichodesmium* suggest that between 50 and 100% of the nitrogen fixed is exuded as ammonium or dissolved organic nitrogen compounds such as amino acids. These forms of nitrogen are readily available to bacteria and phytoplankton and thus will benefit the co-existing community by relieving nitrogen-limitation.

Time-series observations from the North Pacific subtropical gyre show that there has been a 9% increase in surface integrated dissolved organic nitrogen (DON) concentrations between 1989 and 1999. Together with other biogeochemical data, the decadal increase in DON has been attributed to an increase in marine nitrogen-fixation driven by changing water column conditions, thus supporting laboratory findings on the exudation of DON by diazotrophs, However, in contrast to both these findings, recent molecular and stable-isotope studies have yet to find a biological signature or marker representative of nitrogen-fixers in the large and complex DON pool in the subtropical ocean, casting some doubt over the fate of fixed nitrogen.

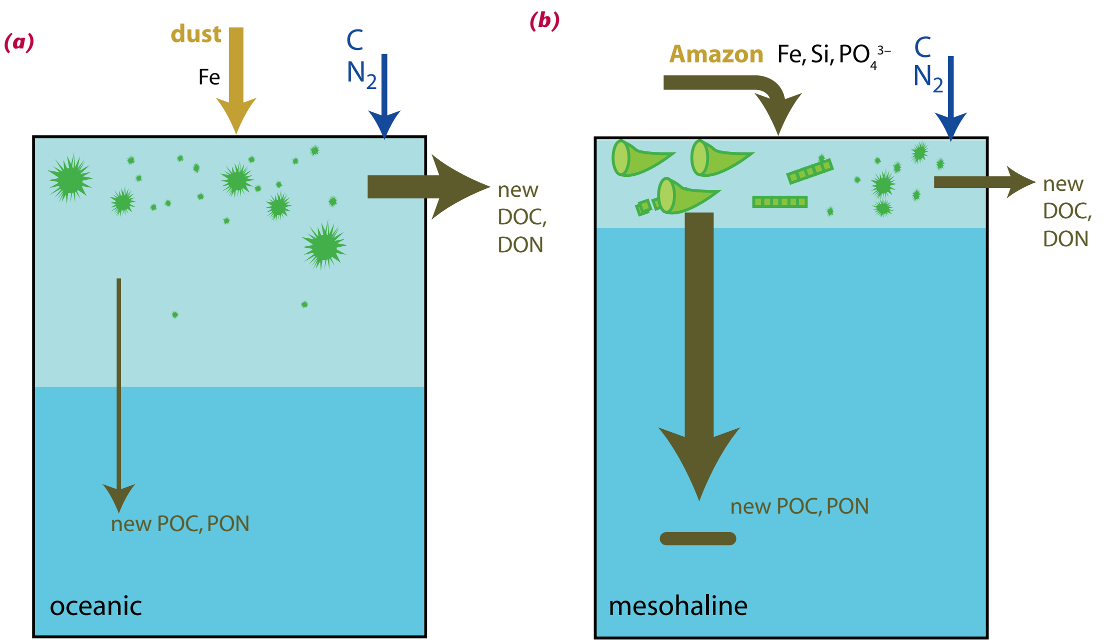
In addition to uncertainty about the fate of fixed nitrogen, there is still a question about what happens to diazotrophs when they die. There are at least two potential pathways. The first is that diazotrophs may simply sink out of the surface ocean into the deep ocean as intact cells, fragments or aggregates, and thus contribute to the flux of particulate organic carbon (POC) from the surface to the deep ocean, known as 'export production'. Alternatively, diazotrophs may be retained in the surface ocean and be rapidly remineralized by bacteria and therefore add to the dissolved nutrient pool in the surface ocean.

Accumulating evidence suggests that the fate of diazotrophs is dependent on the diazotroph group involved (Figure 9). Sediment traps, used to collect sinking particulate organic matter and measure export production, reveal that *Richelia* is effectively removed from the surface ocean via sinking of their relatively large and heavy diatom host cells (Figure 9(b)). In the region influenced by the Amazon, the drawdown of carbon dioxide, and the flux of particles out of the surface ocean, are two to four times higher in waters dominated by *Richelia* associated with diatoms than in waters dominated by *Trichodesmium*. Indeed, intact cells of *Richelia* with the diatom *Hemialus* have been found at 4000 m in the oligotrophic North Pacific subtropical gyre, supporting the idea that this diazotroph–diatom symbiosis plays an important role in the sequestration of carbon in these open ocean regions. In contrast, the fate of unicellular diazotrophs and *Trichodesmium* is still unknown.

Figure 9 *Schematic diagram illustrating the contrasting fates of* ***(a)*** Trichodesmium *in an oceanic environment and* ***(b)*** *diazotrophs within diatom hosts (e.g.* Richelia *with* Hemialus*) associated with nutrient inputs via the Amazon river. Note the different sizes of the arrows representing the fates of carbon (C) and nitrogen (N) in dissolved and particulate form (DOC and DON, and POC and PON, respectively).*

(By courtesy of Ajit Subramaniam, LDEO, Columbia University, USA)

Trichodesmium remains are remineralised in surface waters, but Richelia sink into the deep ocean with their diatom hosts



Diazotrophs in a changing climate

Increased concentrations of atmospheric carbon dioxide are changing the Earth's climate system and affecting the terrestrial and marine environments. Over the past decade, increased carbon dioxide concentrations have led to concerns over decreased pH of ocean waters, and the potential decline in the efficiency of the ocean in absorbing greenhouse gases. However, a handful of studies have found that under higher carbon dioxide concentrations, rates of nitrogen-fixation and carbon-fixation by *Trichodesmium* spp. would actually increase by 35–100% and 15–128%, respectively. Such studies provide evidence of a potential positive feedback system in ocean ecosystems. However, limitation of nitrogen-fixation by other factors, such as availability of phosphorus and iron, would most likely restrict the effectiveness of diazotrophs in altering atmospheric carbon dioxide concentrations.

Climate models predict that sea-surface temperature will increase by up to 3 °C in subtropical gyres by 2090. This climate-induced warming is predicted to cause a poleward expansion of these already vast regions, which may have both a direct and an indirect impact on nitrogen-fixation. Increased sea-surface temperatures are predicted to enhance stratification, and hence the stability of the water column, and so reduce the flux of inorganic nutrients to the surface ocean via upward mixing, causing an expansion of the nutrient-poor surface waters in which diazotrophs thrive. The combined effects of both increased stratification and reduced nutrient inputs are predicted to increase nitrogen-fixation by 27%. Time-series observations from the North Pacific subtropical gyre support this idea, and indeed, a climate-induced decadal increase in nitrogen-fixation has already been reported. However, temperature has an impact on the physiology of diazotrophs. Laboratory studies show that *Trichodesmium* fixes nitrogen at temperatures between 20 and 34 °C, with optimal rates measured to occur between 24 and 30 °C. As the warm subtropical waters expand polewards, the potential region of *Trichodesmium* growth is predicted to increase by 11%. However, beyond 30 °C, there is an overall decrease in the rate at which *Trichodesmium* fixes nitrogen, so increased sea-surface temperatures may actually decrease nitrogen-fixation in some regions. Thus, the net effect of increased sea-surface temperature on nitrogen-fixation remains uncertain.

One thing that *is* certain about diazotrophs, is that this fascinating group of organisms still holds many secrets, not least because of their diversity and their complex environmental and metabolic requirements. The race is on to understand how diazotrophs live in the present ocean before we can tackle the question of how they may survive in the future ocean.

Further Reading

Breitbarth, E., A. Oschilies and J. LaRoche (2007) Physiological constraints on the global distribution of *Trichodesmium* – effect of temperature on diazotrophy. *Biogeosciences*, **4**, 53–61.

Church, M.J., C. Mahaffey, R.M. Letelier, R. Lukas, J.P. Zehr and D. M. Karl (2009) Physical forcing of nitrogen fixation and diazotroph community structure in the North Pacific subtropical gyre. *Global Biogeochemical Cycles*, **23**, GB2020, doi:10.1029/2008GB003418.

Mahaffey, C., A.F. Michaels and D.G. Capone (2005) The conundrum of marine N_2 fixation. *American Journal of Science*, **305**, 546–95.

Moore, C.M., M.M. Mills, E.P. Achterberg, R.J. Geider, J. LaRoche, M.I. Lucas, E.L. McDonagh, X. Pan, A.J.Poulton, M.J.A. Rijkenberg, D.J. Suggett, S.J. Ussher and E.M.S. Woodword (2009) Large-scale distribution of Atlantic nitrogen fixation controlled by iron availability. *Nature Geoscience,* **2**, 867–71.

Subramaniam, A., P.L. Yager, E. J. Carpenter, C. Mahaffey, K. Björkman, S. Cooley, A.B. Kustka, J.P. Montoya, S.A. Sañudo-Wilhelmy, R. Shipe, and D.G. Capone (2008) Amazon River enhances diazotrophy and carbon sequestration in the tropical North Atlantic Ocean. *Proceedings of the National Academy of Sciences*, **105**, 30, 10460–65.

Claire Mahaffey is a Lecturer in Marine Sciences at the School of Environmental Sciences, University of Liverpool. She studies the supply, cycling and fate of nitrogen and phosphorus in the subtropical open ocean and the temperate coastal ocean, and is particularly interested in marine nitrogen-fixation, mesoscale physical processes and the cycling of dissolved organic matter.

mahaffey@liv.ac.uk

Challenger Society for Marine Science, Institute of Marine Engineering, Science and Technology and Society for Underwater Technology Undergraduate Prize

The Challenger Society for Marine Science (CSMS), the Institute of Marine Engineering, Science and Technology (IMarEST) and the Society for Underwater Technology (SUT) organise a competitive award scheme to support students studying for a Bachelor's degree in Marine Science or Technology at a UK University or College. The scheme is based on a single payment of up to £500 to the successful student. It is envisaged that one award will be presented each year.

Details of the Award

Title The Marine Science and Technology Tripartite Award

Award One award of up to £500 will be awarded each year.

Eligibility Final Year students enrolled on UK University or College Marine Science or Technology courses. Applicants must be student members of the CSMS, IMarEST or SUT. An individual will only be eligible for one undergraduate dissertation award from the awards schemes of any of these three societies.

Procedure

Each academic year, CSMS, IMarEST and SUT will circulate details of the scheme to the Heads of Department at all Universities and Colleges with appropriate courses, inviting them to submit applications from students in their departments. The applicants and their sponsors will be required to complete an application form setting out details of their course and an abstract written by the applicant about his/her final year dissertation. A recommendation by his/her sponsor is also required. Shortlisted candidates will then be required to submit their full dissertation by the end of June of that same year (the candidates' final year).

Assessment

The application forms will be assessed against predetermined criteria by a scholarships subcommittee made up of members representing each of CSMS, IMarEST and SUT who will then shortlist candidates for the award. The subcommittee will then have sole responsibility for awarding the scholarship from the submitted dissertations.

Application Forms

Application forms may be obtained from the Head of Department or direct from the CSMS, IMarEST or SUT websites

Where to send the form

All forms to be submitted to Ben Saunders (**ben.saunders@imarest.org**) by the end of May. The scholarships sub-committee will undertake the selection of the shortlisted applicants and duly inform them of the requirement to submit their full dissertation by the end of June. Submission of the full dissertation by shortlisted candidates will be the responsibility of the individual student. The scholarships subcommittee will undertake the selection of the successful applicant for the award and will promulgate the results by the last working day of August. The award will be presented at an AGM of the awarding society.

Sinking to get ahead?

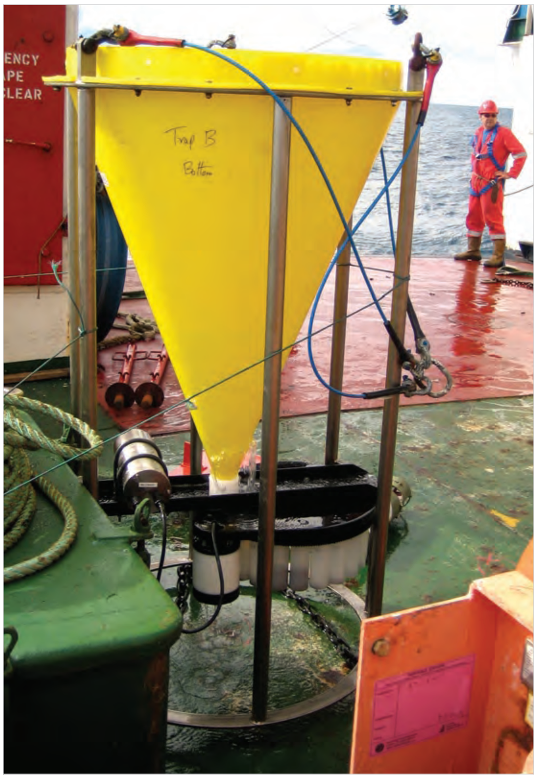
Acantharia in the North Atlantic particle flux

Patrick Martin

Throughout the oceans, a continuous rain of organic particles sinks into the deep ocean from the sunlit surface waters, where photosynthesis produces new biomass. This process – the Biological Carbon Pump – removes about ten gigatons of carbon from the surface ocean each year. The sinking particles are very diverse, and include algal cells, protozoans, faeces and remains of animals, and aggregates of all or any of these. However, the particle flux can at times be heavily dominated by specific organisms. This article discusses the recording of a flux event in the Iceland Basin consisting mainly of single-celled organisms known as Acantharia. Previous studies had suggested that acantharian shells invariably dissolve within the first few hundred metres, and that they thus fail to sink much further, but very unusually the Iceland Basin Acantharia sank to at least 2000 m depth. This discovery has interesting implications for the reproductive strategy of these organisms.

Catching sinking particles

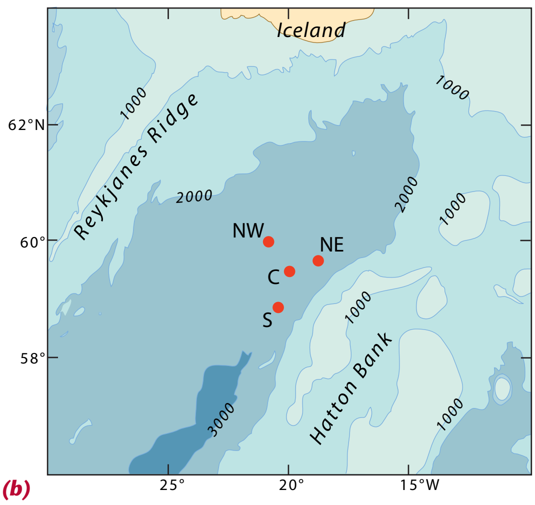
One of the main methods of studying the Biological Carbon Pump is by deploying sediment traps: essentially, a sediment trap is a large funnel leading down to a set of sample-collection cups that are automatically rotated under the funnel on pre-determined dates (Figure 1(a)). Traps are generally attached to a mooring line anchored to the sea floor, but depending on the length of the mooring a trap can be located kilometres above the sea floor. Any particles that sink into the funnel will roll down into the cups, which are usually filled with a preservative solution, and the trap thus collects a time-series of the particle flux. Given the known area of the funnel's opening, the collection period for each sample cup, and the abundance of material in that cup, one can calculate the magnitude of the particle flux.



(a)

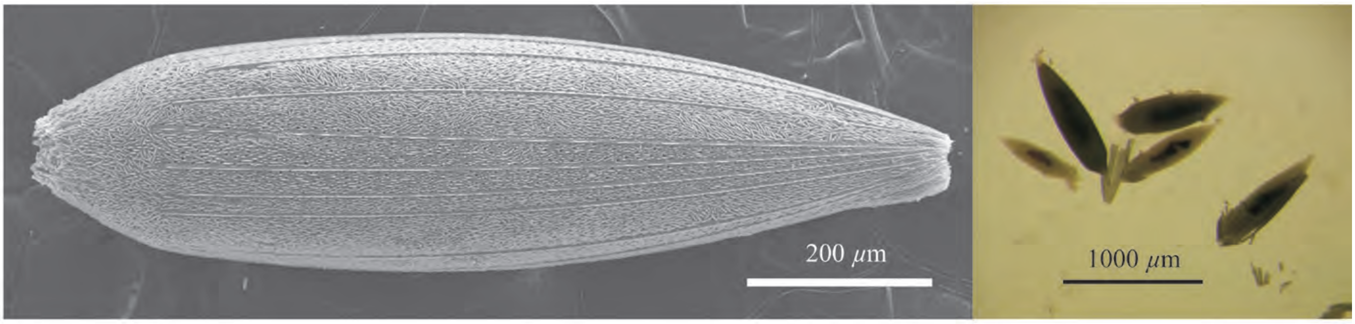
Figure 1 **(a)** *A sediment trap after recovery. Some of the collection cups have clearly caught a large volume of material.*

(b) *Map of the trap deployment area in the Iceland Basin. The four traps are labelled by their positions relative to each other, e.g. 'NW' is the north-western trap, while 'C' is the central trap. Contour depths are in metres. The traps were at a depth of 2000 m.*



(b)

Sediment traps provide valuable information about the Biological Carbon Pump



The celestite shells of Acantharian cysts have a streamlined torpedo shape

Figure 2 ***(a)*** *Scanning electron micrograph, and* ***(b)*** *light micrograph of acantharian cysts found in our samples. (a) shows a fully intact individual, and (b) some shell fragments; only the two topmost shells are completely intact. Shell breakage is almost certainly a result of sample-handling.*

Four such traps were deployed at 2000 m depth in the Iceland Basin from autumn 2006 to late summer 2007, rotating their collection cups synchronously (Figure 1(b)). The traps were recovered during a cruise aboard RRS *Discovery,* and to the delight of all involved, all four traps had worked while underwater.

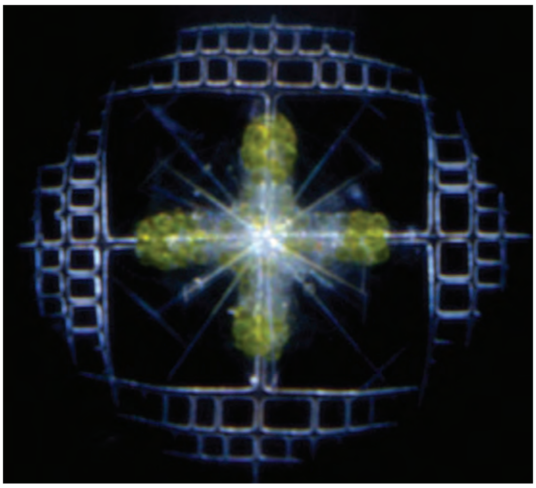
Back on land, delight turned into surprise, with the discovery that three cups on each trap, collecting between April and May, contained thousands of rather nondescript, shelled, spindle-form organisms up to 1 mm in length (Figure 2). In several samples these organisms clearly dominated the particle flux, but nobody quite knew what they were. The answer came from analysing the elemental composition of their shells with an X-ray probe, which revealed that the shells contained primarily strontium (Sr) and sulphur (S). The only organisms known to precipitate these elements are Acantharia, which form shells and skeletons of celestite, i.e. strontium sulphate.

Acantharia are single-celled planktonic animals (protozoans) most closely related to the Radiolaria (whose shells/skeletons are made of opal, i.e. silica), and more distantly to the Foraminifera (whose shells/skeletons are made of calcite). Their relative obscurity notwithstanding, Acantharia are globally distributed and generally encountered in the ocean at abundances equal to those of Radiolaria and Foraminifera, which are the other major protists in their size-class. Acantharians not having been a major research priority of late, one of the most authoritative texts on their biology and taxonomy is still a lengthy monograph by Wladimir Schewiakoff, published in 1926 in German.

Figure 3 *Adult acantharian of the species* Lithoptera mulleri, *about 0.12 mm in diameter. This species has 20 celestite spicules, of which four are more elaborate; green areas are the sites of the symbiotic algae.*

(By courtesy of Johan Decelle, Station Biologique de Roscoff)

Acantharians strongly resemble their close relatives, the radiolarians



The adults' intricate celestite skeletons are composed of spicules radiating outwards from the centre of the cell (Figure 3). What we had collected were Acantharian cysts (explained below), which have no spicules, but instead a celestite shell. The use of celestite is also one reason why acantharians are rarely studied, and hence poorly known: strontium is very undersaturated in seawater, and within days of sampling their shells and skeletons dissolve in preservative solutions, which are usually mixtures of seawater and formaldehyde. Undersaturation of strontium in seawater means that the shells and skeletons are not preserved in sea-floor sediments either.

We used a seawater/formaldehyde mixture as a preservative in our traps. The preservative thus contained some strontium from the seawater, but a substantial amount of the celestite from the cysts nevertheless dissolved into the preservative. By measuring the dissolved strontium concentration in each cup after recovering the traps, and subtracting the amount of strontium contained in the preservative before deployment, dissolution could be corrected for. In some cups, celestite dissolution had increased the strontium concentration 8-fold, to 60 μg Sr g^{-1}. This is close to the saturation point, and explains why many cysts in these cups had not dissolved – they presumably fell into the cup after the preservative had already become near-saturated from the dissolution of cysts collected earlier.

It is not known how acantharians manage to precipitate and maintain their shells and skeletons in seawater, although organic coatings around the celestite are probably important. Why acantharians should use celestite is not clear, although a recent study of strontium isotopes has shown that 90–95 million years ago the seawater strontium concentration was at least 4–5 times higher than today. It is possible that these conditions may have led to Acantharia evolving to use strontium in their shells, but as there is no acantharian fossil record this hypothesis cannot be tested easily.

Life as an acantharian

Acantharia have a complex life-cycle with several stages, though many of its details are still unknown. Adult Acantharia dwell in surface waters, and are rarely found below two or three hundred metres. A sophisticated system for buoyancy regulation allows them to adjust their position in the water column: contractile filaments, the myonemes, are used to inflate a fibrous envelope surrounding the cell, increasing buoyancy so that the individual ascends, or deflate it so that it descends. Adults of most species commonly contain symbiotic algae capable of photosynthesis (zooxanthellae), thus contributing to primary productivity, which may be particularly significant in tropical and subtropical areas of low overall productivity. However, they also capture and feed off algae, small protists, and even small copepods, which they capture with long projections (pseudopodia).

Many species of Acantharia form reproductive cysts, and it was such cysts (rather than adult cells) that were found in the samples collected in the Iceland Basin. Adults encyst themselves by dissolving their skeleton and reprecipitating the celestite as an outer shell, and this signals the end of their life-cycle. Meanwhile, flagellated gametes* (unfertilized cells each containing one set of chromosomes) are formed within the cell, and the cyst starts to sink. Celestite being the densest oceanic biomineral (4 g cm^{-3}), they sink rapidly (in a laboratory test, cysts from the Iceland Sea samples sank the equivalent of 500 m per day). The gametes are then released at depth, exiting through pores in the shell. After the release of the gametes the remains of the cyst presumably continue to sink rapidly until all celestite has dissolved.

Once two gametes have fused, the resulting zygote (a fertilized cell with two sets of chromosomes) undergoes most of its juvenile development at depth. Schewiakoff believed that the zygotes even sink as far as the sea floor, as they lose the flagellae of the gametes, but his observations were in waters no deeper than 1000 m. The acantharians ascend to the surface again as young adults, presumably using their buoyancy control system.

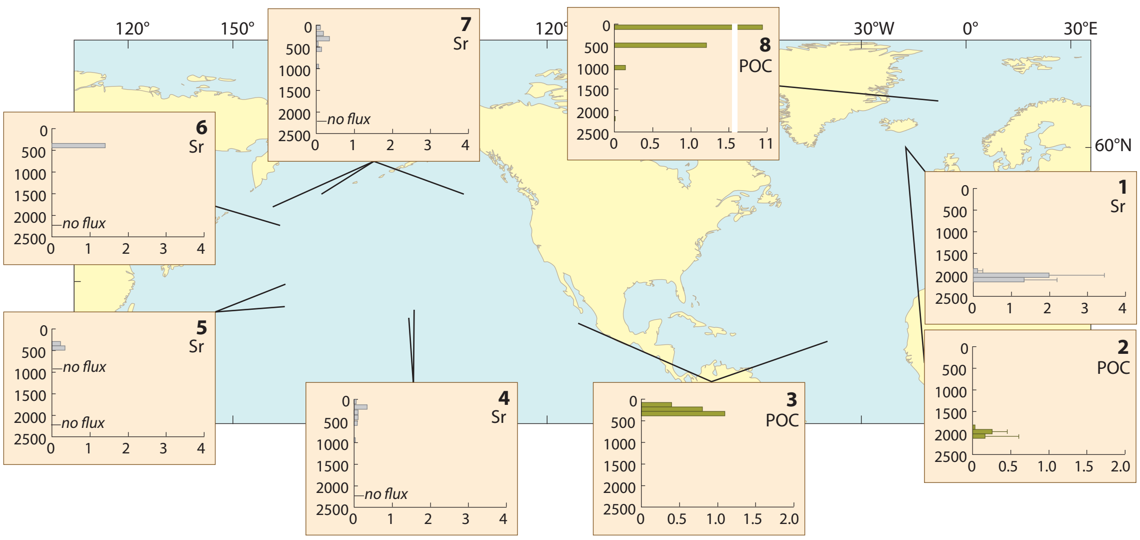
Acantharia and biogeochemistry

Recent research has focussed largely on the role of Acantharia in biogeochemical cycles, particularly on the cycles of strontium and carbon. Strontium is largely conservative in seawater, i.e. its concentration is governed mainly by abiotic factors such as evaporation. However, differences of up to 5% are often found between the (salinity-normalised) strontium concentration at the surface and that below several hundred metres, and are ascribed to the sinking of dead or encysted Acantharia, whose dissolution creates a local maximum in strontium concentration.

Several studies have used sediment traps to study the downward flux of Acantharia. In contrast to our results, these found at most sporadic individuals at or below 1000 m, a sparsity which they attributed to rapid celestite dissolution. As Figure 4 shows, our traps at 2000 m (plot 1) recorded strontium fluxes at least twice those previously reported anywhere else in the water column (up to 3 mg Sr m^{-2} day^{-1} compared to at most 1.5 mg Sr m^{-2} day^{-1}). As far as

*Gametes are reproductive cells that unite during sexual reproduction to form a new cell called a zygote. The flagellae (whip-like appendages) of acantharian gametes allow them to 'swim'.

Figure 4 *Distribution and magnitude of acantharian fluxes reported in the literature and in the present study. Plots show either strontium flux (grey bars) or acantharian particulate organic carbon flux (POC, green bars), both in mg m^{-2} day^{-1}, plotted against sampling depth. (1) and (2) show the particulate organic carbon (POC) and strontium (Sr) fluxes I measured, as a mean across the four traps for each of the three collection cups containing Acantharia. (3) is a composite plot of acantharian flux from Michaels (1991) and Michaels* et al. *(1995). (4)–(7) are from Bernstein* et al. *(1987) and Lamborg* et al. *(2008). (8) is from Antia* et al. *(1993).*



The Iceland Basin observations are the first to show large concentrations of acantharian POC and strontium at 2000 m depth

acantharian carbon is concerned, our traps (plot 2) recorded fluxes up to two-fold higher than had been recorded at or below 1000 m. These were even comparable to acantharian carbon fluxes recorded at just 100 m in some studies (e.g. plot 3 in Figure 4).

Interestingly, for the southern trap, none of the sample cups contained more than a few acantharian cysts, and hence the mean flux across the four traps for each period was substantially lower than the two highest fluxes (traps NW and NE). It is possible that this difference between traps is linked to the northward decrease in sea-surface temperature over the trap deployment area, in which case the high fluxes measured in the two northern traps would be more characteristic of the basin has a whole – but this needs further investigation.

Overall then, the 2000 m acantharian flux in the Iceland Basin study was comparable with fluxes measured between 100 m and 500 m in other studies, and by far the highest ever recorded below 1000 m (cf. Figure 4). How important are these results for the Biological Carbon Pump in the North Atlantic? The carbon flux contributed to individual cups by Acantharia was up to 50% of the total carbon flux showing that they can contribute very significantly during specific periods – but most Acantharia were in the samples taken during the two weeks before the arrival of phytodetritus from the spring bloom – which contributes the year's greatest pulse of carbon flux in the high-latitude North Atlantic. Thus, the importance of Acantharia for the annual deep-sea carbon flux in the region is minor.

Deep sinking as a reproductive adaptation

A more interesting way of thinking about this result is to ask why Acantharia in the Iceland Basin should sink so much deeper than elsewhere. The proximate explanation undoubtedly lies in their size: the cysts were 2–3-fold larger than those caught in other sediment trap studies, and correspondingly sank several times faster. Although they would still dissolve eventually, the distance they would be able to sink before dissolving completely would be greater than for more slowly sinking cysts, and thus so many were caught at 2000 m. Taking an evolutionary viewpoint, it is very tempting to speculate that large, very deep-sinking cysts could be an adaptation to high-latitude environments with substantial seasonal variation in the strength of the Biological Carbon Pump. The North Atlantic spring bloom leads to sudden and rapid sedimentation of a large quantity of relatively fresh organic matter, which can carpet the sea floor at several kilometres depth. The Acantharia in the Iceland Basin traps were presumably living as adults in the surface before and during the bloom, and it is possible that rapid and deep sinking of cysts might be a strategy to release gametes sufficiently deep to allow developing juveniles to feed off the subsequent fall of phytodetritus.

If correct, this hypothesis could at least partly explain why other studies found such low acantharian fluxes at depth, as they were conducted either at much lower latitudes (where productivity and particle flux tend to be much lower and less seasonal), or in the summer. However, this explanation would only make sense if gametes really were released very deep, and if juveniles actually feed while at depth. To really make use of the phytodetritus, juveniles would probably need to dwell on, or close to, the sea floor, as suggested by Schewiakoff.

Clearly, much remains to be discovered about acantharian biology and ecology, and thus about their biogeochemistry. One way of building up a clearer picture of acantharian fluxes and their seasonal variability would be to make more use of long-term sediment-trap samples, as these are able to collect throughout an annual cycle – before the Iceland basin study, projects had used only short-term trap deployments, typically for several days. Long-term studies would either require new deployments with strontium chloride added to the preservative solution, or – as in our study – measurement of dissolved strontium in the preservative after recovering the samples, to correct for the substantial celestite dissolution that occurs after collection.

Further Reading

Bernstein, R.E., R.A. Feely, R.H. Byrne, M.F. Lamb, and A.F. Michaels (1987) Acantharian fluxes and strontium to chlorinity ratios in the north Pacific Ocean. *Science* **237,** 1490–94.

Coogan, L.A. (2009) Altered oceanic crust as an inorganic record of paleoseawater Sr concentration. *Geochemistry, Geophysics, Geosystems,* **10**, Q04001, doi:10.1029/2008GC002341.

Conte, M.H., N. Ralph, E.H. Ross (2001). Seasonal and interannual variability in deep ocean particle fluxes at the Oceanic Flux Program (OFP)/Bermuda Atlantic Time Series (BATS) site in the western Sargasso Sea near Bermuda. *Deep-Sea Research II,* **48**, 1471–1505.

Febvre, J., and C. Febvre-Chevalier (2001) Acantharia. In *Encyclopedia of Life Sciences*. John Wiley & Sons Ltd, Chichester. http://www.els.net

Michaels, A.F., D.A. Caron, N.R. Swanberg, F.A. Howse, and C.M. Michaels (1995). Planktonic sarcodines (Acantharia, Radiolaria, Foraminifera) in surface waters near Bermuda – abundance, biomass and vertical flux. *Journal of Plankton Research,* **17**, 131–63.

Martin, P., J.T. Allen, M.J. Cooper, D.G. Johns, R.S. Lampitt, R. Sanders, and D.A.H. Teagle (2010) Sedimentation of acantharian cysts in the Iceland Basin: Strontium as a ballast for deep ocean particle flux, and implications for acantharian reproductive strategies. *Limnology & Oceanography,* **55**, 604–14.

Schewiakoff, W.T. (1926) Die Acantharia. *Fauna e Flora del Golfo di Napoli,* **37**, 1–755.

Patrick Martin is a Ph.D student at the National Oceanography Centre in Southampton, and works on the factors affecting downward particle flux in the oceans.

patrick.martin@noc.soton.ac.uk

Climate geoengineering using the ocean

Nem Vaughan

Climate geoengineering – deliberate large-scale intervention in the Earth system to moderate global warming – has attracted significant attention in the last few years. Ideas about geoengineering the ocean have a long history. One of the earliest papers on the subject, 'On geoengineering and the CO_2 problem', published in 1977, suggested injecting CO_2 into suitable sinking thermohaline currents. In the intervening years, much of the ocean-based geoengineering interest has focussed on enhancing the Biological Carbon Pump, for example by fertilising the iron-limited surface waters of the Southern Ocean. With the recent resurgence of interest in geoengineering, there is now a greater range of ideas that centre on manipulation of, or on, the ocean. Using three different ocean-based geoengineering interventions, I will briefly discuss matters of commercial and media interest and the challenge of transferring theory to practice, and then introduce a more recently developed idea.

The 2009 Royal Society report on geoengineering provides an excellent overview of the current state of research on geoengineering – a field very much in its infancy on a range of fronts. The renewed interest in geoengineering is emerging as a result of increasing rates of carbon dioxide (CO_2) emissions, particularly from fossil-fuel burning, and negligible global efforts to reduce these emissions. These trends in emissions are occurring against a backdrop of concern about what level of atmospheric CO_2 equates to 'avoiding dangerous climate change' (ranging from 350 to 550 p.p.m.) and what the scale of the challenge not to exceed these different levels of atmospheric CO_2 might be.

Commercial and media interest

Given these concerns, geoengineering understandably attracts significant media and commercial attention. Commercial interest is largely motivated by the development of carbon markets, the public face of which is the ability to 'offset' certain activities, such as a flight or a train journey. The media attention arises from the interest in climate change in general, and more specifically in what climate change 'solutions' there may be – although to call any geoengineering idea a 'solution' is misleading, as no form of geoengineering will remove the need to reduce emissions.

The likely cost of a geoengineering scheme would be a key factor in its potential use in present or future carbon markets. However, costs are difficult to establish as a lot of research remains to be done. For example, the current estimated cost of carbon sequestration by ocean iron fertilisation varies by over two orders of magnitude, from less than 10 $US to more than 300 $US per tonne of carbon sequestered. Critically, carbon markets require verification that the carbon has been removed from the system on a long-term basis, without any counteracting release of other greenhouse gases (such as nitrous oxide or methane). Establishing and robustly demonstrating this necessary verification may be a significantly larger expense than the deployment of the geoengineering intervention itself.

Public perception and the media portrayal of science can have a significant impact, as experienced by those participating in the LOHAFEX* iron fertilisation experiment in February 2009. Several iron fertilisation experiments have taken place since the mid-1990s, yet LOHAFEX attracted particular public and media attention because it was in apparent contravention of guidance by the *Convention on Biological Diversity*, which restricted further fertilisation studies in the open ocean until an internationally agreed legal framework was in place.

*LOHAFEX is an Indo-German iron fertilisation experiment in the Southern Ocean; LOHA is Hindi for iron, FEX stands for Fertilization EXperiment.

The media play a significant role in forming and informing public perceptions of potentially contentious areas of science. Geoengineering has a particular appeal, inspiring futuristic artists' renditions of interventions, more often of the solar radiation management type of geoengineering. This appeal in terms of popular science media has a number of drawbacks; for example, significant differences between various types of geoengineering are rarely made clear; furthermore, oversimplification of the science, or enthusiasm for the potential, often cause the known and unknown possible side-effects to be overlooked, whilst giving a misleading impression of how far developed the research is.

Enhancing the Biological Carbon Pump

Fertilisation of surface waters

So far, commercial interest in geoengineering has focussed on the possibility of fertilisation of surface water to earn carbon offset credits. The aim of ocean fertilisation is to stimulate phytoplankton blooms in nutrient-limited areas with the expectation that the increased productivity will result in a net increase in carbon export to deep waters. There are a number of ventures, with a range of approaches, despite a consensus by scientific experts that ocean fertilisation as a geoengineering technique is likely to be relatively ineffective, potentially deleterious, and inappropriate as a strategy for carbon dioxide removal (see for example the SOLAS position statement, available at http://www.szxolas-int.org/). Such ventures include the Ocean Nourishment Corporation (ONC), whose planned field experiment in the Sulu Sea, off the coast of the Philippines, attracted a 52-author criticism in the *Marine Pollution Bulletin*. In a recent paper, Margaret Leinen provides a more positive perspective on how commercial interest, carbon offset markets and scientific research may be able to work together (see Further Reading).

Bringing up nutrient-rich waters from below

The idea of bringing nutrient-rich water from depth to the sunlit surface layer in order to increase productivity, and in turn carbon export to depth, has been repeatedly suggested. This is similar in principle to the idea of nutrient addition to nutrient-limited surface waters, and therefore has similar limitations, such as variability in bloom response, and detection of any increased export production. In addition, an oft-voiced concern is that bringing cooler, deeper water to the surface will cause an outgassing of CO_2 due to warming and decreasing pressure. The idea of pumping deep nutrient-rich water up 'ocean pipes' has been tested in computer models but many of the concerns can only be addressed by deployment of a real pump in the open ocean.

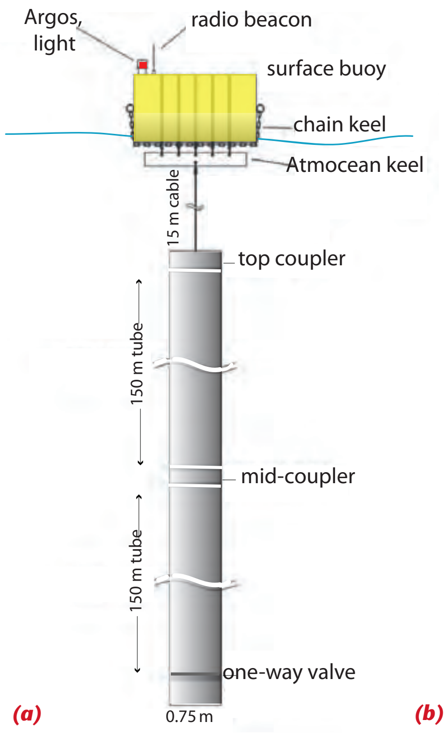
Transferring theory into practice

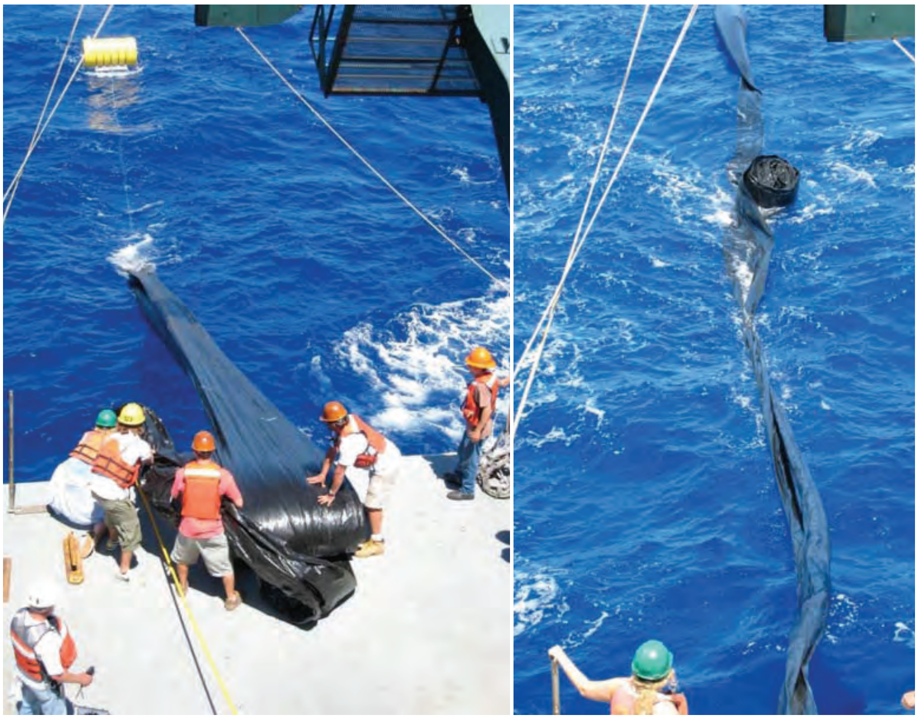
A commercial company, Atmocean (www.atmocean.com), has developed a wave-driven pump design, the underlying principle of which was conceived of in the late seventies by John Issacs. The wave-driven pumps consist of a foam surface float attached by 15 m extension cable to two sections of 150 m polyethylene

Pumping up deep water to fertilise the surface ocean may be one way of increasing carbon export to depth

Figure 1 (a) *The components and configuration of the wave pumps used in the 2010 study by researchers from Oregon State University and the University of Hawaii.* ***(b)*** *Deployment of one of the pumps while the vessel moved slowly forward. The forward motion of the ship caused the tube to unwind to its full length; after it had fully opened, the valve and recovery line were deployed.*

(From White et al. *(2010); see Further Reading)*





'tubing' surrounding vinyl-coated cabling, with a one-way valve at the bottom (Figure 1(a)). A group from Oregon State University and the University of Hawaii tested one of Atmocean's pumps in June 2008 in the waters north of Oahu, Hawaii (Figure 1(b)). The resulting paper, published in the *Journal of Oceanic and Atmospheric Technology,* provides a fascinating account of the attempts to see if the pump would stand up to the rigours of the open ocean. It also describes the experimental set-up and the monitoring that would be needed in future attempts to see if drawn-up water can generate and sustain phytoplankton blooms.

Suffice it to say, the pipe did not weather the open ocean well, succumbing to the dynamic environment relatively rapidly. Whilst working, the wave-driven pumps took less than 2 hours to transport water vertically from a depth of 300 m to the surface. However, the pump failed after about 17 hours, by which time about 765 m^3 of nutrient-rich water had been delivered to the surface. Calculations indicated that this volume of water would be insufficient to generate a detectable biological response, and as a result the detailed long-term biological response to a sustained period of upwelling could not to be investigated. Ultimately, knowing the fate of the phytoplankton bloom is vital in any attempt to achieve (and verify) increased carbon export, and success depends on being able to track and monitor biochemically evolving water masses. In their paper, the researchers show how this aspect poses a significant challenge, and they provide an in-depth discussion of the unique biological constraints of this geoengineering idea.

The 'ocean pipes' case study illustrates that ideas that work in theory or in controlled environments may not necessarily work in the natural environment. This is of course by no means a revelation, but it is important to reiterate these lessons with respect to discussions of geoengineering ideas, specifically when considering the magnitude and time-scale of cooling potential. Geoengineering is at *very* early stages, particularly in terms of actual engineering structures.

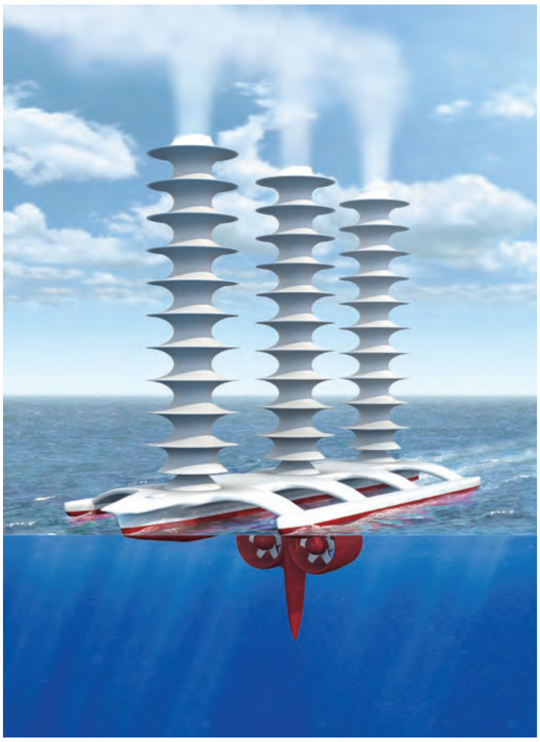
Solar radiation management at sea

The two geoengineering ideas discussed above are based on CO_2 removal, where the purpose of the intervention is to remove CO_2 from the atmosphere for a significant period of time. The other approach to geoengineering is solar radiation management, aiming to cool the planet by increasing the proportion of sunlight reflected back to space.

A proposed ocean-based solar radiation management technique would enhance the albedo (reflectivity) of marine stratocumulus clouds, using specially designed vessels to mechanically increase the atmospheric abundance of sea-salt aerosols which act as cloud condensation nuclei. The increase in cloud condensation nuclei would enable the clouds to be made of more, smaller particles thus causing the clouds to appear brighter – a phenomenon known as the Twomey effect. More sunlight would be reflected back to space, resulting in cooling. Modelling work suggests that the effectiveness of such a geoengineering intervention is likely to be greatest in regions off the coast of California (North Pacific), Chile (South Pacific), Namibia (South Atlantic) and western Australia (Indian Ocean). In order for this method to work, the air mass in question needs

Figure 2 ***Above*** *Flettner's first rotor ship, the* Baden-Baden, *which crossed the Atlantic in 1926. 'Flettner rotors' are vertical spinning cylinders, by that produce forces perpendicular to the wind direction.* ***Right*** *Stephen Salter's spray vessel, with three 20 m high Flettner rotors. The proposal is that a number of automated spray vessels would sail back and forth across targeted ocean regions. (See overleaf.)*

((a) By courtesy of Stephen Salter; (b) © John MacNeill)



Sending sea salt into the atmosphere may encourage formation of brighter clouds, reflecting more solar radiation back to space

to be relatively free of other aerosols (e.g. dust), hence the suitability of more remote marine areas.

Research in this area is progressing on two fronts. On the theoretical side, modellers have used global circulation models to see if increasing cloud albedo might bring the global mean temperature down to, for example, pre-industrial levels, from a starting point of double the pre-industrial CO_2 concentration (560 pp.m.). The latest developments are the use of global aerosol transport models that incorporate detailed aerosol interactions and can simulate the impact of a sea-spray particle flux on the formation of cloud condensation nuclei. Korhonen and colleagues found that, compared to earlier models, these more detailed models predicted that significantly more sea spray would be required to produce a given change in the properties of clouds affecting their reflectivity.

Progress on the practical front involves the development of mechanisms that would spray the seawater up into the atmosphere. Stephen Salter from the University of Edinburgh has developed a design for a sailing vessel that uses Flettner rotors instead of sails and has a pump that sprays a fine mist of seawater from the top of these rotors (Figure 2). It is envisaged that a flotilla of these unmanned vessels would be monitored and controlled from land.

A scale-model version of this vessel design has already been constructed. A full scale prototype has not yet been built as it requires a significant investment. If these vessels do prove seaworthy and able to perform as anticipated, the next step in the science would be to see if a detectable change in cloud albedo is measurable and attributable to the sea spray from the vessels.

A major concern with this geoengineering idea is that because the intervention is highly regionally focussed, it has the potential to alter regional weather patterns, monsoon systems and/or large scale interannual modes, such as El Niño–Southern Oscillation. The heterogeneous nature of possible foreseen and unforeseen impacts of *any* solar radiation management geoengineering idea raises the issue of governance, encompassing social, ethical and legal considerations. For example, if a region experiences floods or droughts, and sea-spraying has occurred off its coast that year, the local inhabitants might have a strong inclination to attribute one to the other and to seek compensation (despite the link being extremely difficult to prove). Social, ethical and legal issues will likely be dominant factors in the demise of certain geoengineering proposals.

What future for geoengineering?

There are many more concerns and issues relating to geoengineering, but hopefully I have managed to give a flavour of some of the challenges, illustrated using examples of ocean-based geoengineering ideas. The interest in geoengineering is not likely to subside any time soon given the climate change challenge. However, enthusiasm for geoengineering must be tempered by an appreciation that this area of research is still in its infancy, and much of it is still very theoretical.

Science has a long history of making significant breakthroughs in understanding when motivated by the need to tackle particular world problems. Even if no geoengineering idea is ever implemented, perhaps the legacy of the present-day interest in geoengineering will be a better understanding of certain components of the Earth system. What is important, given the magnitude of the concern about climate change, is that geoengineering does not distract from the principal means of ameliorating climate change, which is to reduce our emissions of CO_2 by transitioning to a zero-carbon global economy.

Further Reading

Glibert, P. M. and 20 others (2008) Ocean urea fertilization for carbon credits poses high ecological risks. *Marine Pollution Bulletin,* **56**,1049.

Korhonen, H., K.S. Carslaw and S. Romakkaniemi (2010) Enhancement of marine cloud albedo via controlled sea spray injections: a global model study of the influence of emission rates, microphysics and transport. *Atmospheric Chemistry and Physics,* **10**, 4133.

Latham, J., P. Rasch, C.-C. Chen, L. Kettles, A. Gadian, A. Gettelman, H. Morrison, K. Bower and T. Choularton (2008) Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Phil. Trans. Roy. Soc., A* **366**, 3969.

Leinen, M. (2008) Building relationships between scientists and business in ocean iron fertilization. *Marine Ecology Progress Series,* **364**, 251.

Marchetti, C. (1977) On geoengineering and the CO_2 problem. *Climatic Change,* **1**, 59.

Salter, S., G. Sortino and J. Latham (2008) Sea-going hardware for the cloud albedo method of reversing global warming. *Phil. Trans. Roy. Soc. A* **366**, 3989

White, A., K. Bjorkman, E. Grabowski, R. Letelier, S. Poulos, B. Watkins, and D. Karl (2010) An open ocean trial of controlled upwelling using wave pump technology. *Journal of Atmospheric and Oceanic Technology,* **27**, 385.

For more about the Royal Society Report, *Geo-engineering the Climate: Science, Governance and Uncertainty,* see the article by John Shepherd in *Ocean Challenge,* Vol.17, No.1. The Report itself can be downloaded from the Royal Society's website: www.royalsociety.org

Nem Vaughan is a Tyndall Centre for Climate Change Research Fellow working on climate change mitigation and geoengineering, and is part of the EPSRC Integrated Assessment of Geo-engineering Proposals project. www.iagp.ac.uk

n.vaughan@uea.ac.uk

Atmospheric CO_2, ocean acidification and calcification

A reminder of the basics ...

For those for whom chemistry is not a 'core activity' here is a very brief overview of the basic science relating to atmospheric CO_2 and ocean acidification.

CO_2 and other inorganic carbon in the ocean

Molecules of CO_2 are continually entering and leaving the ocean, with the net direction of the flux varying locally: e.g. water rising from depth at low latitudes will release CO_2 as a result of warming and a decrease in pressure; cold surface water sinking at high latitudes will take down CO_2. On the global scale, however, the amount of CO_2 diffusing into the ocean depends on the concentration of CO_2 in the atmosphere: the higher the atmospheric concentration, the greater the flux into the ocean.

After a CO_2 molecule crosses the sea-surface from the atmosphere into the ocean, it does not necessarily remain as a disssolved gaseous CO_2 molecule (CO_2(aq)) ('aq' = aqueous). Instead it may react with water to produce carbonic acid (H_2CO_3):

$$H_2O + CO_2(aq) \rightarrow H_2CO_3(aq) \;...... (1)$$

Only a very small proportion of dissolved inorganic carbon exists in the ocean as carbonic acid. Most is in the forms of gaseous carbon dioxide, CO_2(gas), bicarbonate (hydrogen carbonate) ions HCO_3^-(aq), and carbonate ions, CO_3^{2-}(aq). The relative proportions of these forms changes with the acidity of the ocean.

Ocean acidification

Whether a solution is acidic or alkaline (basic) depends on the availability of H^+ ions. pH, a measure of how acid or alkaline a solution is, is calculated as:

$$pH = \log10\,(1/[H^+] = -\log_{10}[H^+] \;...... (2)$$

where square brackets indicate concentration in moles per litre. Pure water, H_2O, is regarded as neutral: a small proportion of water molecules split up into (equal numbers of) H^+ and OH^- ions, each at a concentration of 10^{-7} moles l^{-1}; this means that a neutral solution has a pH of 7 (eqn 2). An acid solution has an excess of H^+ and a pH less than 7 (Figure 1).

On formation (eqn 1), carbonic acid breaks down rapidly to produce H^+ and bicarbonate ions:

$$H_2CO_3(aq) \rightarrow H^+(aq) + HCO_3^-(aq) \;... (3)$$

The increase in H^+ results in some carbonate ion reacting with it to form (more) bicarbonate:

$$H^+(aq) + CO_3^{2-}(aq) \rightarrow HCO_3^-(aq) \;... (4)$$

Thus addition of CO_2 to the ocean results in an increase in the concentration of HCO_3^- ions and H_2CO_3, a decrease in the concentration of CO_3^{2-} ions, and an increase in the concentration of H^+ ions (i.e. an increase in acidity).

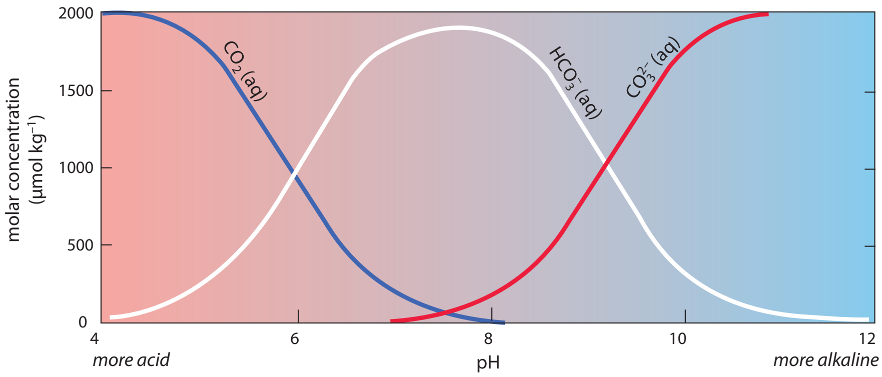


Figure 1 *Changes with changing pH in the concentration of the three forms of dissolved inorganic carbon in the ocean (for a water temperature of 15 °C and a salinity of 35). Pure water (neutral) has a pH of 7. The pH of seawater is around 8 (slightly alkaline). The more acid the ocean, the more of its carbon is pushed into CO_2, and less into HCO_3^- and CO_3^{2-}.*

Since the mid-18th century (the beginning of industrialisation) the burning of fossil fuels has been releasing CO_2 into the atmosphere. As the proportion of CO_2 in the atmosphere has increased, so more and more has been dissolving in the ocean, increasing the acidity. It has been estimated that from 1751 to 1994, the pH of surface ocean waters decreased from ~8.18 to ~8.10, an increase of H^+ ion concentration of 18.9%. By the first decade of the 21st century, the change in ocean pH relative to pre-industrial levels was about −0.11, representing an increase of some 30% in H^+ ion concentration.

Calcification and dissolution

Marine calcification occurs when calcium carbonate is precipitated in surface or shallow waters according to the reaction

$$Ca^{2+}(aq) + 2HCO_3^-(aq) \rightarrow CaCO_3(s) + H_2O + CO_2\,(gas) \;.... (5)$$

where (s) indicates solid. Note that this process produces CO_2 gas, which means that marine calcification indirectly adds to the CO_2 in the atmosphere.

Calcium carbonate exists in two main crystalline forms, calcite and aragonite. The calcium carbonate shells and skeletons of marine organisms may be of calcite or of aragonite or, sometimes, of both. Of the two forms, aragonite is by far the more soluble/less stable.

The addition of CO_2 to seawater, and the resulting decrease in pH, means that calcium carbonate shells in seawater are less stable, and eventually they disolve. The solubility of $CaCO_3$ increases with decreasing temperature and increasing pressure. When planktonic organisms with calcium carbonate shells/skeletons die and sink out of surface waters, the calcium carbonate initally remains intact, but will tend to dissolve when the surrounding seawater becomes understaurated with CO_3^{2-} ions; aragonite shells will start to dissolve at shallower depths than calcite shells. Calcium carbonate remains only survive to reach the deep sea-bed, and to accumulate there, if they are being supplied in large amounts. (The carbon released in the deep sea takes 100s–1000s of years to get back to the surface.)

The carbonate buffer and seawater pH

As mentioned earlier, addition of CO_2 to the ocean increases the H^+ concentration (eqns 1 and 3), but some of the added H^+ reacts with CO_3^{2-} to convert it to bicarbonate (eqn 4). Initially, most of the added H^+ is 'mopped up' in this way and the change in pH is much less than it would otherwise be; this phenomenon, whereby the pH of seawater changes very little despite a considerable addition of H^+, is known as the carbonate buffer. This process also consumes some CO_3^{2-} ion, so the pH buffering effect diminishes as CO_2 concentrations increase. More worryingly, the rate at which CO_2 is currently being added to the ocean is too great for the carbonate buffer to keep pace with.

On longer time-scales (thousands of years) interaction with $CaCO_3$-rich sediments tends to buffer the chemistry of seawater. For example, if the deep ocean were to become more acidic, CO_3^{2-} ion would dissolve out of carbonate sediments.

This overview drew on *Ocean acidification due to increasing atmospheric carbon dioxide,* Royal Society, 2005, amongst other sources. A user-friendly graphic about ocean pH may be found in *Oceanus* (online) 8 January 2010. See also 'Calcium carbonate and climate' by Toby Tyrrell and John Wright, *Ocean Challenge*, Vol.11, No.1.

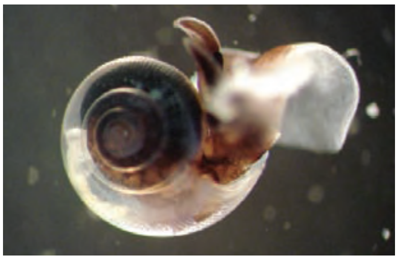
Acidification in the Arctic Ocean

Helen Findlay

The Arctic Ocean is an important part of Earth's climate system, but for researchers it is a hostile environment. This means that real-time information on how the Arctic Ocean is changing is a step behind other areas of ocean. It is only in the last few years that datasets relating to carbon cycling have begun to be collected from the Arctic. There are longer time-series datasets from the sub-Arctic regions, which indicate that the rate of ocean acidification is much faster in these colder waters. This is not surprising: simple physics tells us that colder waters have a greater capacity to hold dissolved gases, which means that more CO_2 can be taken up from the atmosphere into the Arctic Ocean. We also know that the natural levels of carbonate ions in the Arctic Ocean are much lower than they are elsewhere in the world's oceans, which means that Arctic waters are unable to buffer changes in pH as well as other waters in other oceans (cf. explanation of buffering on p.35). Together, these facts mean that the Arctic Ocean is highly vulnerable to ocean acidification, and model projections suggest that the Arctic could become corrosive to calcium carbonate minerals (aragonite and calcite) in the next 20–50 years.

A complex puzzle

There is still some uncertainty around the model projections for the Arctic Ocean, arising from a number of factors. First, the small amount of real data with which the models can be validated and parameterized. Rather worryingly, the data that have been collected show that aragonite undersaturation is already occurring seasonally in some areas of the Arctic. Secondly, there is the complex and poorly understood interaction between sea-ice and the exchange of CO_2 between the atmosphere and the ocean. It was thought that sea-ice acts as 'lid' on the ocean, essentially preventing any flow of CO_2, so that in spring when the sea-ice melts and exposes the cold seawater to the atmosphere there is a net flow of CO_2 into the ocean. However, recent studies suggest that the interaction is not quite so straightforward. As sea-ice forms, the salt in the seawater is ejected as brine which flows through the ice creating small channels. The highly concentrated brine waters have high levels of CO_2 and buffering compounds, so when they flow into the surface ocean they could cause a net loss of CO_2 from the ocean into the atmosphere, although this would be reversed during melting of sea-ice. Thirdly, there remains some uncertainty around the rate of sea-ice melting and projections of global CO_2 emissions. Assuming the rate of emissions remains at the 'business-as-usual' level, sea-ice in the Arctic is predicted to disappear in the summertime in the next 20–30 years, potentially exposing the summer ice-free ocean to higher concentrations of atmospheric CO_2 and increasing the rate of ocean acidification.



The 'sea butterfly' Limacina helicina
Pteropods play an important role in the marine food web, particularly at high latitudes Their decline would seriously affect marine ecosystems, and the fishery resources that they support.
(By courtesy of Steeve Comeau, EPOCA)

Consequences for Arctic life

So what does this mean for the Arctic ecosystem? For organisms that have structures made of calcium carbonate, this really will be the 'acid test'. If organisms living in the Arctic have time to adapt to these corrosive levels of carbonate ions then we will know that there is hope for other organisms around the world too. However, research to-date on calcifying organisms from around the rest of the world is not encouraging. A meta-analysis of ocean acidification studies (i.e. a systematic review of what those studies show) indicates that net calcification rate (the rate organisms calcify minus the rate of dissolution of their structures) decreased with decreasing pH across all major taxa – organims were unable to increase calcification sufficiently to overcome increasing rates of dissolution.

But we need to study the Arctic organisms themselves to get a better understanding of whether they already have coping mechanisms in place. If they already live in a relatively low carbonate ion environment perhaps they already have some mechanisms that allow them to survive. Furthermore, if the surface waters under the sea-ice do have a large variability in CO_2, alkalinity and pH, then perhaps these organisms are already 'used to' large fluctuations in the chemistry of their environment. As in all ecosystems, however, any disruption to the bottom of the food web will have implications further up the chain, even if the larger organisms are themselves less vulnerable. For example, pteropods, commonly known as 'sea butterflies', are free-swimming snails with a calcified shell (*see photo*), and are important prey for many larger Arctic predators, such as Arctic cod. Clams are also important shellfish in the Arctic and are the main food source for walruses. Laboratory studies have shown that both pteropods and clams are detrimentally impacted by ocean acidification.

With the Arctic potentially ice-free in summer within just a few decades, industry and commercial organisations are already turning their heads northwards. The oil and gas industries will seek to exploit new hydrocarbon reserves, fisheries industries will look to exploit new fish stocks, and shipping industries will adopt shorter shipping routes. New exploitation of the Arctic Ocean will create additional stresses on this vulnerable environment, adding to the difficulties faced by organisms living in a warming, acidifying ocean.

International research efforts

While the International Polar Year (IPY) has now come to an end, it has provided the framework for the international collaboration that is necessary to carry out important research in the Arctic Ocean. International research projects aiming to answer some of these questions include the Scottish Association for Marine Science (SAMS) Ice Chaser Expedition in 2008, the European Project on Ocean Acidification (EPOCA) Arctic campaigns (benthic in 2009 and pelagic in 2010) and the Catlin Arctic Survey 2010, to name just a few European projects. These various projects investigate different aspects of the bigger picture of carbon cycling in the Arctic Ocean and how changes in chemistry might affect the ecosystem. More information can be found at the project websites:
http://www.sams.ac.uk/research/research-themes/arctic-cruise-2008
www.epocaarcic2009.wordpress.com
www.epocaartic2010.wordpress.com
www.catlinarcticsurvey.com

Helen Findlay is the Lord Kingsland Fellow at Plymouth Marine Laboratory researching ocean acidification in the temperate and polar oceans.
hefi@pml.ac.uk

Predicting the long-term effects of ocean acidification

A challenge for experimental science

Steve Widdicombe

There is a general expectation by policy-makers that scientists should be able to provide the knowledge needed to guide them as they address the big environmental issues of the day. Often the overriding political and societal needs are for scientists to predict the impacts of an environmental stressor (e.g. pollution, fishing, aquaculture) on important species, populations and communities, and to determine how these impacts will affect marine ecosystems. Such knowledge has traditionally been generated using controlled manipulation and observation of biological systems. However, in the case of ocean acidification these traditional approaches may not be appropriate. Whilst the acidification of the world's oceans is happening at an alarming rate, this process is still too slow to be accurately reproduced in laboratory and mesocosm experiments. Even experiments that run for many months are often accused of representing a relatively sudden change in conditions, with the results observed being more akin to a temporary, 'shock' response. Consequently, such short-term experiments may not be appropriate for direct prediction of the long-term effects of ocean acidification on the survival of individual organisms, the distribution of populations, and the structure and diversity of communities So, until long-term exposure experiments (i.e. ones that last several years) have been conducted, an alternative approach is needed. The approach currently being used is to identify the physiological and behavioural mechanisms by which marine organisms respond to elevated levels of CO_2. This can be achieved through short-term exposure experiments and, although the approach is not without its difficulties, data from such experiments are allowing scientists to build a greater conceptual understanding of how ocean acidification will affect the many fundamental physiological and ecological processes that underpin the performance and functioning of marine organisms and ecosystems.

Over recent years there has been a rapid increase in the number of experiments identifying and quantifying the effects of ocean acidification on many physiological processes in both benthic and pelagic organisms. These include calcification, acid–base balance within organisms, metabolic rate, protein synthesis and the functioning of the immune system. There have also been a few studies exploring the impacts on organisms' behavioural responses, e.g. predator avoidance. However, although these experiments provide some insight, the challenge still remains to amalgamate all these different elements to generate a holistic appreciation of how ocean acidification will affect the long-term sustainability of populations and the structure of communities. Whilst doing so it should be borne in mind that ocean acidification can simultaneously affect a large number of interdependent physiological and ecological processes operating within an individual, with effects acting synergistically (with), or antagonistically (against), each other. For example, a recent study of the periwinkle *Littorina littorea* demonstrated the potential for changes in an animal's behaviour to compensate for a negative impact of CO_2 on a key physiological process. The study showed that exposure to high CO_2 prevented periwinkles from thickening their shells in response to the presence of their main predator, the green shore crab *Carcinus meanus,* leaving them potentially more vulnerable to being eaten. However, exposure to high CO_2 also stimulated *L. littorea* to increase its avoidance activity, thus reducing its chances of being encountered by the crab.

Under high CO_2, vulnerable periwinkles avoid predators more actively
(By courtesy of Sarah Dashfield, PML)

In addition to the complexity of numerous interdependent impacts, predicting the fate of species in a high-CO_2 future is further complicated in that the nature and severity of any acidification impact is likely to vary even within a single species. First, high-CO_2 impacts are predicted to differ between the various stages of an organism's life cycle, and there are indications that juvenile stages could be more vulnerable than adults. Secondly, individuals from populations situated at the edges of a species' biogeographical range could respond differently from those individuals from the middle of this range. Range-edge populations could turn out to be more vulnerable because they are already at their physiological limits or, alternatively, these populations may actually be shown to possess a greater ability to use mechanisms designed to deal with increased environmental variability, such as phenotypic plasticity (i.e.the ability to change body shape or behaviour in response to an environmental cue) than mid-range populations from more stable environments. Data are not yet available to identify which of these possibilities is true.

Finally, experiments are still needed to determine whether animals will be able to change their physiology or their behaviour in response to ocean acidification. Such changes would initially come at an energetic cost to the individual organism concerned. Then, given sufficient time and a sufficient number of generations, species may be able to adapt genetically to the environmental changes associated with ocean acidification. However, for multicellular animals these environmental changes are occurring very rapidly when compared with currently accepted rates of evolution. Consequently, short-term changes in organism physiology and behaviour may only be sustainable in the short-term, and long-term reductions in individual and population fitness could result in species extinctions before adaptation has chance to occur.

The drivers and responses associated with ocean acidification are obviously operating over time-scales that can not be repeated in controlled exposure experiments. However, as long as short-term studies are conducted with the specific intentions of unravelling the physiological and ecological responses of marine organisms to elevated CO_2, and do not falsely claim to be a true representation of how ecosystems will look and function 100 years from now, they are, and will continue to be, of enormous value to those working to predict the effects future environmental change.

Further Reading

Widdicombe, S. and J.I. Spicer (2008) Predicting the impact of ocean acidification on benthic biodiversity: What can physiology tell us? *Journal of Experimental Marine Biology and Ecology* **366***,* 187–97.

Widdicombe, S., S. Dupont and M. Thorndyke (2010) Laboratory experiments and benthic mesocosm studies. In: *Guide to best practices in ocean acidification research and data reporting.* Edited by U. Riebesell, V. Fabry, L. Hansson and J.-P. Gattuso. Luxemburg: Office for the Official Publications of the European Communities. pp.99–108.

Steve Widdicombe is Head of Science for Biodiversity and Ecosystem Function at Plymouth Marine Laboratory.
swi@pml.ac.uk

OCEAN ACIDIFICATION AND FISHERIES: FISH FRY OR FRIED FISH?

Will Le Quesne

Emissions of CO_2 from human activities are acidifying the oceans. Animals and plants living in the oceans are being exposed to a reduction in ocean pH at a rate and extent not seen in tens of millions of years. This has led to concerns that ocean acidification could have negative impacts on marine life, and therefore also on fishing which has long been an important source of economic activity in many coastal regions (Figure 1).

The direct biological impacts of ocean acidification occur at the cellular level, but it is the expression of these effects at the population and ecosystem level, and the resulting effects on fishing communities, that is of societal concern. The productivity of commercial stocks depends upon both the physiological status of target species and the ecological setting within which they occur. Thus scaling up from physiological experiments to predicting effects at the level of population and ecosystem requires explicit consideration of ecology as well as physiology. Determining the resulting impact on fishing businesses and communities requires further assessments of the economic status of fisheries and the capacity for adaptation to changes in resource productivity within fisheries and markets.

Fishing for organisms with calcified shells has long been an important economic activity

Figure 1 *Oyster dredgers off Cockenzie in the Firth of Forth, from James Bertram's* The Harvest of the Sea, *published in 1865.*

From an ecological perspective, there are two key and distinct questions that can be asked about the potential impacts of ocean acidification on fisheries. First, will the relative composition of species making up a marine community be altered? Secondly, will the overall productivity of the system be altered? The mechanisms which can drive these changes may be either direct or indirect. Direct effects are caused by the action of ocean acidification on the physiological condition of an organism. Indirect effects are due to changes in ecological interactions induced by ocean acidification, such as reduced availability of food where a prey organism is directly affected.

Scientific understanding of the physiological effects of ocean acidification is still limited – let alone understanding of potential effects at the level of populations and ecosystems. For this reason, discussion of the potential impacts of ocean acidification on fisheries is currently limited to identifying possible trends rather than predictions of the response of specific populations. However the situation may become clearer over the next three to five years as a number of national and international research programmes are underway, or being established, globally.

Direct effects

A range of direct physiological impacts of ocean acidification have been suggested. Some of these impacts could be common across many species and types of organisms, whilst others are specific to individual species or limited groups of species. Although notable work on physiological impacts has been conducted, knowledge is still limited to a few species and often on the basis of only short-term experiments. Some studies have reported seemingly contradictory results; it is not yet clear whether these represent methodological differences or whether they reflect true features of the biology.

The physiological impacts of acidification can be roughly grouped into three categories: general impacts on physiology due to changes in internal acid–base balance; impacts on reproduction and early development; and impacts on calcification, i.e. the development of hard calcified structures such as shells.

As far as organisms' internal acid–base balance is concerned, some species are able to regulate their internal ionic balance in response to changes in seawater chemistry, whereas for other species the internal ionic balance follows any changes in the external seawater. An emerging theory of the general sensitivity of species to changes in acid–base balance predicts that active organisms, and species with large amounts of extra-cellular fluid, such as blood, will be less sensitive to ocean acidification. Active animals, such as fish, squid and some crabs, may be pre-adapted to cope with ocean acidification because CO_2 tends to build up in their bodies during exercise and they possess specialised structures to control and maintain internal CO_2 levels. For example, the internal concentration of CO_2 in an active fish may reach 10 000 p.p.m. (parts per million); this should be viewed in the context of a current atmospheric CO_2 concentration of 380 p.p.m., and a predicted rise to more than 750 p.p.m. by the end of the century.

For species capable of internal ionic regulation, the additional energetic cost of ionic regulation is uncertain. A significant increase in the basic metabolic costs of life would reduce the amount of energy available for growth per unit of food consumed. This would reduce the efficiency of biomass transfer up food webs and thereby reduce system productivity at higher trophic levels. In the case of species unable to regulate their internal ionic balance, elevated CO_2 levels may reduce metabolic rates which could reduce feeding and growth rates. Not only would this have a direct impact on affected species it could also alter predator–prey relationships.

The onset of ocean acidification will occur over a period of decades and will proceed alongside changes in global temperatures, thus impacts of ocean acidification need to be considered in the light of simultaneously developing climate change. Increasing water temperatures have led to an observed shift in the geographic range of some species, including commercially targeted fish. Typically, species retreat to cooler water towards the poles in response to warming. Experiments have indicated that the upper thermal limit of the spider crab (*Hyas araneus*) is reduced by at least 1.5 °C under the CO_2 conditions expected by 2100. This indicates that ocean acidification can reduce the thermal tolerance window within which species can survive, and could increase the rate of the pole-ward retreat of species in response to warming.

Reproduction and early life stages are expected to be particularly sensitive to the direct impacts of ocean acidification. Early life stages do not possess the more specialised buffering mechanisms of fully developed organisms, and are known to be most susceptible to environmental toxicants. Furthermore, sperm and eggs of broadcast spawners (organisms that release their numerous eggs into the water column) are directly exposed to changes in seawater chemistry. Experimental results so far show a range of sensitivities of reproduction and early development to ocean acidification. Amongst invertebrates there is an almost complete spectrum of sensitivities, from brittlestars that undergo complete mortality under minor changes in pH (cf. Figure 2), to urchins that show abnormal development under moderate levels of CO_2-enrichment, through to tunicates, which have no hard parts and which show improved development under CO_2-enriched conditions. In the case of fish, only very limited work has been conducted on the sensitivity to ocean acidification of reproduction and early development. Initial results indicate that fish will not suffer mortality as a direct result of acidification at levels that can be realisti-

Figure 2 *Larvae of the common brittlestar* Ophiothrix fragilis *at the stage of developing calcified 'arms', reared in seawater under varying CO_2 concentrations (viewed under polarised light).* ***(a)*** *pH 8.1 (typical of seawater at the present time) and* ***(b)*** *pH 7.9 (corresponding to atmospheric CO_2 at 600 p.p.m.): the larvae are Note the shorter 'arms' and loss of symmetry under pH 7.9.* ***(c)*** *pH 7.7 (corresponding to atmospheric CO_2 at 980 p.p.m.); here, larval development has failed. In (a) and (b), the body length is 200–300 µm, and in (c) the scale bar is 10 µm.*

Brittlestars are amongst those organisms whose larvae could be badly affected by ocean acidification

(a) *(b)* *(c)*

(Photos by courtesy of Sam Dupont).

Shellfish are an important resource for UK fisheries

Figure 3 *Shellfish such as scallops typically account for 30–45% of the value of annual landings for UK vessels.*

(© Crown copyright 2009. Reproduced by permission of Cefas, Lowestoft)

cally expected, although some work has found that fish larvae reared under acidified conditions may be less capable of avoiding predators, and may have larger otoliths (small 'ear bones' related to balance and orientation).

Many marine invertebrates form shells that are hardened by calcium carbonate. These include the shells of bivalves (e.g. oysters and scallops), gastropods (e.g. whelks and winkles) and crustaceans (e.g. crabs and lobsters). The process of calcification is particularly sensitive to the acidity of seawater, as the degree of carbonate saturation decreases with increasing acidity (decreasing pH) which means that forming calcium carbonate structures becomes increasingly expensive energy-wise as pH declines. Calcium carbonate can be laid down in different ways and in

Calcifying organisms such as coralline algae play an important role in providing 3D habitats on the sea-bed

Figure 4 *Maerl – a loose accumulation of calcified red algae ('coralline' algae), which grow as small branched nodules on sandy sea beds. These calcareous accumulations enhance the three-dimensional structure of the sea-floor, providing a valuable habitat and nursey area for other organisms. (Field of view ~ 0.3 m across.)*

(Photo by courtesy of Peter Tinseley)

different chemical forms, so different calcifying species may have differing sensitivities to declining pH. A recent study of 18 different calcifying species found a range of responses to a reduction in pH under elevated CO_2 levels, including both increases and decreases in the rate of calcification. In the case of species that showed increased calcification under elevated CO_2 further studies are required to examine whether there are harmful trade-offs associated with increased calcification, such as a reduction in energy available for growth.

Indirect effects

Commercially important species that are not directly affected by ocean acidification may be indirectly affected if ecologically related species are affected; indirect effects may potentially cause the greatest impact on fisheries. The most obvious indirect effects are alteration in predator or prey abundance, although indirect effects could also occur if ocean acidification affected habitat-forming organisms such as cold-water corals and the red algae known as maerl (Figure 4). The complexity of ecological interactions means that indirect impacts of ocean acidification are hard to predict, although it may be possible to identify potentially sensitive species on the basis of the sensitivity of their prey, or essential habitats, to ocean acidification.

Many natural systems are highly flexible and whenever a resource becomes available consumers move in to make the most of it. Thus if one species is negatively affected by ocean acidification and its population declines, competitor species that share the same prey are likely to benefit. There is no *a priori* reason to believe that commercially important species are any more or less susceptible to ocean acidification than non-targeted species. Thus amongst commercially important species ocean acidification could variously lead to reductions and increases in population abundances. However predicting 'knock on' effects through a food web is difficult. Many marine organisms have broad and variable diets and are able to switch diet depending on prey availability. Predicting prey-switching behaviour is challenging, and yet essential for meaningful prediction of indirect food-web effects. This is illustrated by a comparison of fish diets on the Dogger Bank, in the North Sea, now and 100 years ago (Figure 5). This shows that several species have undergone significant changes in diet in response to the large changes in benthic community composition that have occurred, predominately as a results of trawling pressure, over the last 100 years. This comparison of diets is of particular interest in the context of ocean acidification, as it shows that some animals (e.g. plaice) can switch from a diet based predominantly on calcifying organisms to a diet of predominantly non-calcifying organisms, demonstrating the flexibility of marine food webs in the face of fundamental changes in community composition.

Whilst prey-switching can buffer organisms against changes in the relative availability of prey, it provides little assistance if the overall abundance of prey declines. As mentioned above, the cost of maintaining internal ionic balance against changes in seawater chemistry may reduce the efficiency of energy transfer up food webs. A reduction in transfer efficiency up a food web would progressively reduce production at higher levels of the food web. This could have significant implications for fisheries, so the extent to which ocean acidification will affect organisms' internal energy budgets should be a research priority.

The predominant source of energy fuelling marine food webs is photosynthesis by phytoplankton. Any alteration in the productivity of phytoplankton would be of note as it is likely to be followed by changes in productivity throughout the food web. Increased CO_2 can fertilise phytoplankton growth in the sea, but in many cases the main limit on phytoplankton growth is the availability of nutrients, rather than the availability of carbon. The overall effect of ocean acidification on phytoplankton production remains unclear. Ocean acidification may cause alterations in the timing of phytoplankton production and changes in the species composition of the phytoplankton community. Both effects could cause knock-on effects on food webs, but it is less clear whether ocean acidification will affect overall annual phytoplankton production.

Another form of indirect impact is an 'indirect management effect' that could come into play as fisheries managers have to increasingly consider multiple objectives for the marine environment. In the European context, the recently enacted *Marine Strategy Framework Directive* commits EU nations to achieving Good Environmental Status across European waters by 2020, and includes targets for biodiversity. Under the EU Integrated Maritime Policy all maritime sectors, including commercial fisheries, are expected to support achievement of 'Good Environmental Status'. Fisheries can have a negative impact on biodiversity, especially as they impact a range of species beyond those that are commercially targeted. If ocean acidification reduces the resilience of vulnerable species to the impacts of fishing, the extent of fishing may have to be reduced to achieve biodiversity objectives. However, within the *Marine Strategy Framework Directive* the target for the status of biodiversity has to be 'in line with prevailing physiographic, geographic and climatic conditions'; we can look forward to much contentious debate of the exact interpretation of this phrase over the years to come.

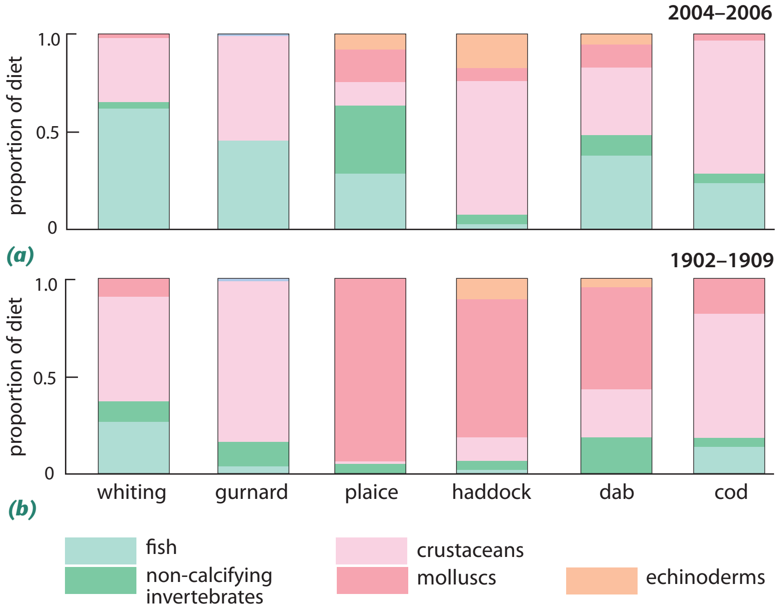


Figure 5 *The proportions of calcifying and non-calcifying organisms making up the diets of fish on the Dogger Bank in the North Sea, during the periods* ***(a)*** *2004–2006, and* ***(b)*** *1902–1909. The red/pink tones indicate calcifying species, blues/greens indicate non-calcifying species. Grouping the diets into broad categories hides additional variation between species within the categories. (The gurnard is the grey gurnard,* Eutrigula gurnardus.*)*

The contribution of calcifying organisms to fishes' diets can vary significantly over time

Population and fishery implications

The discussion so far has highlighted the fact that a given change in the physiological rate of an organism will not necessarily translate into a comparable impact at the population level. This point will be briefly illustrated and considered in terms of the possible impacts of ocean acidification on the reproduction and early development of fish.

Within fisheries assessment and modelling, reproduction is normally considered within stock–recruitment (*S–R*) relationships. This is the relationship between the reproductive potential of a population, typically expressed as a measure of spawning stock biomass (SSB), and the number of young individuals being 'recruited' to the population. General theory assumes that the maximum number of new 'recruits' that can enter a population each year is limited by the system's 'carrying capacity'. This is the maximum number of new recruits that the system can sustain. Recruitment is limited to this maximum level by competition for food or space. Beyond the carrying capacity of a system, another key aspect of an *S–R* relationship is the highest larval survival rate that can be achieved when population numbers are sufficiently low for there to be no competition between the young. Ocean acidification could act to affect the maximum survival rate if the development success of larvae is reduced. Alternatively, ocean acidification could affect the carrying capacity of the system by altering either the availability of planktonic food

Fishery yields and management reference points can show a non-linear relationship to physiological effects of acidification

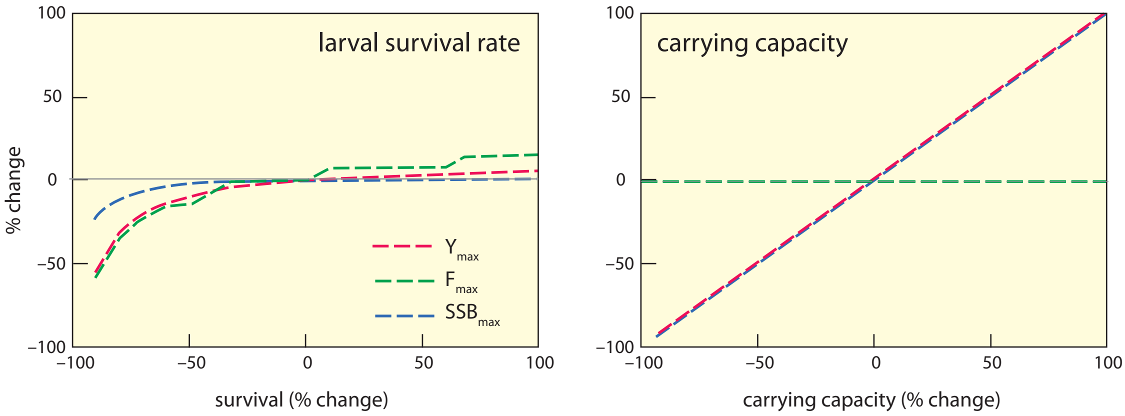


Figure 6 *The response of yield and management reference points to ocean-acidification-driven changes in **(a)** larval survival, and **(b)** larval carrying capacity. Dashed lines indicate the maximum yield (Y_{max}), fishing mortality rate (F_{max}) and spawning stock biomass (SSB_{max}) that lead to the Y_{max}. The horizontal grey line is a reference line for no change.*

for larvae, or the larvae's requirements for energy (food), so that limiting competition sets in at a different population level.

A simple population model, incorporating a Beverton–Holt stock–recruitment relationship*, was used to examine the impact of a change in maximum rate of larval survival, or of larval carrying capacity, for the maximum yield that can be taken from a hypothetical population (Figure 6(a) and (b), respectively). The model also addressed fishery management reference points: the fishing mortality rate and the spawning stock biomass at which maximum yield is achieved (F_{max} and SSB_{max}, respectively). As can be seen in Figure 6, the response of maximum yield and associated reference points varies depending on the nature of the acidification effect, and can show a highly non-linear relationship.

Examining the impacts on maximum yield effectively means considering how population dynamics and management goals are modified under optimum management conditions. In reality many populations are not subject to optimum management, so what are the potential implications of ocean acidification under sub-optimal management conditions? Here the situation is the reverse of that under optimum management. As larval survival declines the population becomes more vulnerable to population collapse and there is greater need to control fishing mortality, although the fishing mortality rate that would lead to population collapse is unaffected by a change in carrying capacity.

A full analysis of this case requires detailed scrutiny of the assumptions used and there are a number of important caveats associated with this form of analysis. However, the brief summary above serves to illustrate the complexity and challenge of following physiological effects through to population level effects. Two points in particular can be drawn out. First, the relationship between physiological rates and population rates varies depending on the mechanism by which ocean acidification affects the physiology of the fish in question. Secondly, the relationship between a given physiological effect and the dynamics of the population varies depending on the status of the population.

*The Beverton–Holt *S*–*R* relationship is regularly used in population models to predict the number of individuals in a new generation on the basis of the numbers of individuals in previous generations.

Socio-economic implications

Given the uncertainty and complexity in predicting ecological effects of ocean acidification, what can be said about the potential socio-economic impacts of ocean acidification on fisheries? Unsurprisingly, the link between ecology and socio-economics introduces further uncertainty and complexity to predictions as there is no direct link between resource productivity, yield and fishery revenues. The following overview will not cover this topic in any detail, but highlights some of the main areas for consideration.

Inevitably, any reduction in the productivity of commercially targeted species is likely to have a detrimental impact on fisheries. As noted earlier, whilst some commercial species may lose out as a result of ocean acidification, unless there is an overall reduction in system productivity other commercial species may benefit. In some cases, fleets may be able to redirect their attention to the 'benefiting' species, although there would be capital costs associated with transition (e.g. investment in different fishing gear).

In most markets, prices are related to supply and demand. As markets for fishery products have become more global this has led to a disconnect between 'local' supply and 'global' supply. In other words, where local supply has declined due to stock degradation there is rarely an increase in price as the decline in local supply has little bearing on global supply. If the impacts of ocean acidification occur globally and there is a synchronous reduction in global supply of fishery products such as shellfish, demand may drive prices up, offsetting losses in revenue due to reduced production.

Traditional analyses of fisheries economies examine the current economic condition of a fishery and examine how changes in, say, resource productivity would alter the current economic balance. Although such analyses are informative, their usefulness is limited when they are applied over periods from several decades to a century as the technological and socio-economic context within which a fishery operates can change markedly over this time-scale. This limitation can be illustrated by imagining that 100 years ago an economist was trying to predict the economic state of the North Sea cod fishery in 2010 on the basis of what he knew about the fishery in 1910. Realising that fuel represents a significant cost to the industry, our economist may well have begun by asking 'What will the price of coal be in 2010?' The analogy does not need to be taken any further to demonstrate the problems of long-range economic assessments. To supplement this form of traditional socio-economic analysis, assessments of 'adaptive capacity' can be conducted to examine which sectors of the fishery are most, or least, capable of adapting. Assessing adaptive capacity can highlight sectors of the fishery that are most likely to fail, or that will be in most need of assistance if they are to adapt to changing conditions. This form of assessment has yet to be applied in the case of ocean acidification.

Not all gloom and doom

In summary, the potential effects of ocean acidification on fisheries require further clarification. A number of plausible effects have been proposed, and hopefully research over the next three to five years will go a long way to answering many of the immediate questions. It seems likely that some commercially targeted species, especially shellfish, will suffer direct negative consequences of ocean acidification whilst other species will be unaffected. The critical question of whether ocean acidification will affect overall system productivity remains open.

Regardless of any detrimental effects of ocean acidification, it is not all doom and gloom which we can only watch from the sidelines. Markets for fishery products can be surprisingly flexible and consumer tastes can change. Given that the effects of ocean acidification are expected to set in over the course of decades, there may be ample opportunity for markets and tastes to adjust to variation in the supply of fishery products. Similarly resource managers do not need to sit idly by and observe changes as they occur – proactive steps can be taken to ensure that marine populations and ecosystems are managed to enhance their resilience to ecological change, and industry managed so as to support adaptation and restructuring to reflect changes in marine resource productivity.

Further Reading

Cooley, S.R. and S.C. Doney (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters,* **4**, 024007

Fabry, V.J., B.A. Seibel, R.A. Feely and J.C. Orr (2008) Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science,* **65**, 414–32.

Kaplan, I.C., P.S. Levin, M. Burden, and E.A. Fulton (2010) Fishing catch shares in the face of global change: a framework or integrating cumulative impacts and single species management. *Canadian Journal of Fisheries and Aquatic Science,* **67**,1968–82.

Melzner, F., M.A. Gutowska, M. Langenbuch, S. Dupont, M. Lucassen, M.C. Thorndyke, M. Bleich and H.O. Pörtner (2009) Physiological basis for high CO_2 tolerance in marine ectothermic animals: pre-adaptation through lifestyle and ontogeny? *Biogeosciences,* **6**, 2313–31.

Ries, J.B., A.L. Cohen, and D.C. McCorkle. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology,* **37**, 1131–4.

Walther, K., F.J. Sartoris, C. Bock, H.O. Portner (2009) Impact of anthropogenic ocean acidification on thermal tolerance of the spider crab *Hyas araneus*. *Biogeosciences* **6**, 2207–15.

Will Le Quesne is a senior marine ecologist at CEFAS, studying the potential impacts of ocean acidification on fisheries, with particular emphasis on exploring ways of emulating the potential effects of ocean acidification in existing ecological frameworks. Will oversaw the development of the experimental acidification facility in the CEFAS Weymouth Laboratory, which is currently being used to examine the impacts of acidification on scallops, a commercially valuable calcifying species.

Will.LeQuesne@cefas.co.uk

As the ocean acidifies, underwater sound travels further – are marine mammals at risk?

It has long been known that sound in the ocean is attenuated as a result of chemical changes, as well as by the viscosity of seawater. For low-frequency sound (100 Hz–10 kHz), at least one of these chemical reactions is affected by the pH of the water. As the sound (pressure) wave passes through, borate ions, $B(OH)_4^-$, lose an OH^- group and temporarily become boric acid, $B(OH)_3$, a more compact molecule, and this reaction takes energy from the sound wave. Under more acid conditions, there is less borate available, so less energy is lost from the sound wave, which can travel further. A study published in 2008 estimated that a decrease in pH of 0.3 (a possibility by 2050) would allow sound to travel 70% further, and a study published in 2010 suggested that by 2100 sound absorption in the frequency range affected could fall by 60% in high latitudes/areas of deep-water formation.

Decreased sound attenuation means that the oceans will become noisier, especially as underwater sounds generated by shipping, industrial and military activity generate low-frequency sound. There is concern that increased ocean noise will adversely affect marine mammals, because although they will be able to communicate over longer distances, a noisier ocean would make it more difficult for them to use sound to communicate, navigate and and hunt. However, a recent modelling study suggests that by 2100 the average increase in noisiness would be at most 2 dB, which is negligible compared with noise that results from natural events such as storms. The authors of this study point out that most sound waves hit the bottom and are absorbed by sediments, and that ocean topography/ geometry is therefore the main factor affecting how sound travels in the ocean.

For more information see: Hester *et al.* (2008) *Geophysical Research Letters*, **35**, No.31, 9601–605; Ilyina *et al.* (2010) *Nature Geoscience*, **3**, 18–22; Udovydchenkov, *et al.* (2010) *Journal of the Acoustical Society of America*, **128**, No.3, EL130–EL136.

OCEAN ACIDIFICATION AND PLANKTON

LITMUS-TESTING THE BASE OF THE MARINE FOOD CHAIN

Alex Poulton

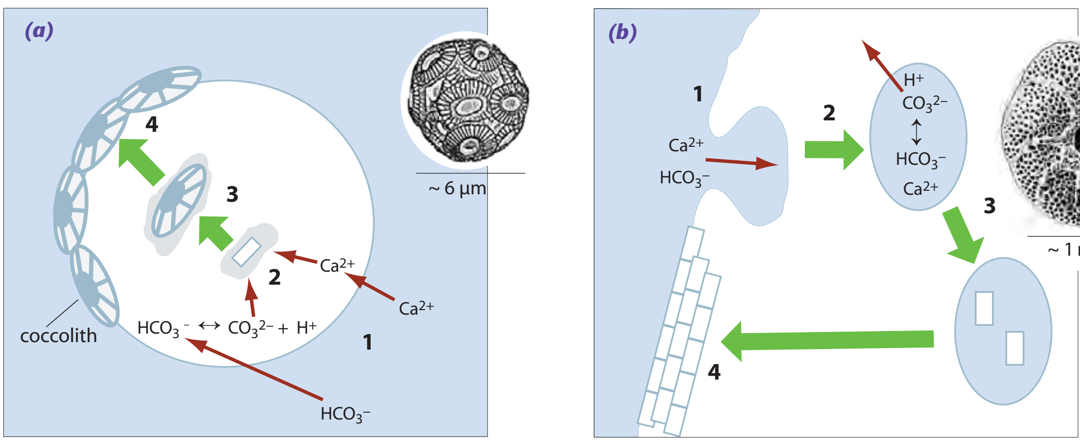
The last 50 years of oceanographic research have led to the basic paradigm: marine algae drive the ocean's biogeochemical cycles, putting carbon into the deep sea and fish onto the menu. Changes to the fundamental structure of marine ecosystems from the base up, as a result of ocean acidification, have the potential to cause a 'domino effect' of changes in unexpected directions. Ocean acidification represents a complex challenge for current and future generations of oceanographers – highlighting research areas about which we are still largely in the dark. It is a fast emerging 'hot topic' of research, with new studies being published daily, and yesterday's paradigms being rewritten today. Here is an overview of some of the current ideas about ocean acidifcation issues relevant to marine algae at the base of the marine food chain.

Pelagic calcification

With their mineral shells composed of calcite (coccolithophores, foraminiferans) or aragonite (pteropods), the marine calcifiers are the group expected to be hardest hit by ocean acidification. Research on the response of calcifiers to changes in carbonate chemistry has produced mixed results and highlighted differences between calcifying taxa: coccolithophores have reacted positively, producing more calcite, in almost as many studies as they have reacted negatively; foraminiferans generally calcify less; while pteropods (planktonic molluscs) dissolve. Such differing reactions may relate to fundamental differences in how these organisms calcify, as well as highlight the myriad of environmental and population interactions which determine the survival or success of an organism. Figure 1(a)

Figure 1 *Different calcifying organisms have different mechanisms for getting calcium and carbonate ions into the cell and providing an environment suitable for calcium carbonate formation. Current understanding of these complex processes is summarised in the cartoons below for **(a)** a coccolithophore, which is covered by calcite plates known as coccoliths, and **(b)** a foraminiferan. In each case, stages in the calcification process are labelled 1–4, explained below. Calcification can be represented by the chemical equation:* $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$.
(Details of model by courtesy of Debora Iglesias-Rodriguez)

Calcification mechanisms vary from organism to organism



1. Calcium and bicarbonate pumped into cell
2. Ions channelled through cytoplasm and into a specialised coccolith vesicle
3. Acidic polysaccharide(s) regulate formation and shape of calcite crystals to form a coccolith
4. Coccolith and polysaccharide coat extruded into the coccosphere outside the cytoplasm

1. A seawater inclusion is formed
2. Ions other than calcium and bicarbonate are pumped out
3. Removal of ions causes supersaturation of calcium and (bi-)carbonate ions, and calcium carbonate formation
4. Calcium carbonate laid down in outer shell

shows our current understanding of how coccolithophores (single-celled planktonic algae) produce the calcite plates or coccoliths that surround them, and Figure 1(b) shows the possible calcification stages for a foraminiferan – a planktonic protozoan that has a chambered calcite internal skeleton. (The model shown in Figure 1(b) summarises the current knowledge of calcification in benthic foraminiferans, and is thought to be applicable to planktonic ones as well.)

As the design and focus of ocean acidification experiments develop over time, the consensus may well change again. Further complications arise as the experiments move to the open ocean, and the sage comment 'well maybe they didn't evolve *in vitro*' becomes difficult to ignore. At the heart of the uncertainty over the full effect of ocean acidification on calcifying organisms is the realisation that little is known about the purpose of cellular calcification, and only slightly more about what regulates it. The standard paradigm for coccolithophores is that nutrient-limitation increases rates of calcification, although it is questionable how well the ocean is represented by the 'boom and bust' of populations growing in laboratory conditions. Few studies have addressed ocean acidification in nutrient-limited or light-limited conditions, and of those that have, most show that coccolithophores react directly to the limitation rather than the chemical environment. We need to understand whether coccolithophore calcification is fundamentally more dependent on energetic or on chemical constraints. Given that calcification occurs inside the cell (Figure 1(a)) while coccoliths are excreted outside the cell within a polysaccharide coat, could coccolithophore calcification be shielded from the seawater environment? However, once the coccoliths become detached from the cell and bacteria break down the polysaccharide coat, the coccolith calcite is open to the environment and dissolution. Although marine calcification may well be the first or greatest victim of ocean acidification, in a perverse way, calcite production and dissolution may also provide long-term stability for the marine carbon cycle (for more on this topic, see p.35).

As well as changing calcification rates, ocean acidification may have indirect consequences on coccolithophores and associated climate processes. Coccolith calcite is a major cause of light-scattering in the ocean, and changing coccolith abundance may well have consequences for the underwater light field. As light is required for photosynthesis, changes in light availability could have implications for ocean productivity. Coccolithophores (along with several other types of marine algae) are also high producers of climatically-active trace gases (e.g. dimethyl sulphide (DMS), organohalogens) involved in atmospheric processes such as cloud formation and ozone degradation. Possible feedbacks between ocean acidification, the atmosphere and changes in the production of these biogases need to be investigated in the future – at the level of both individual cells and the entire ecosystem: both of these kinds of interaction are possible outcomes of ocean acidification.

Biochemical feedbacks

The story of ocean acidification does not begin and end with marine calcification. The potential for ocean acidification to directly or indirectly affect biogeochemical processes is becoming increasingly recognised by the scientific community. These effects do not act alone and there is significant interaction. The following sections summarise some of the possible feedbacks between ocean acidification and ocean biogeochemistry.

Ocean fertilisation

The effects of ocean acidification are not limited to calcite-producing organisms: for many marine algae, ocean acidification is a bonus – in fact, 'CO_2 fertilisation' may be a better term. CO_2 is the fuel of photosynthesis, although relative to the other gases making up the atmosphere, the solubility of CO_2 in seawater is quite low. Marine algae have developed various mechanisms to utilise dissolved CO_2 effectively, and many of these mechanisms are active and therefore energetically expensive – a situation not helped by the strangely inefficient catalyser RuBisCO* (which nature has refused to upgrade). Enriching the oceans with CO_2 is an algal dream – more fuel for less cost – and in fact many studies have shown positive effects of ocean acidification on algal photosynthesis and growth. For example, experiments with diatoms, a major group of marine algae which contribute ~50% to oceanic production, have shown increases in photosynthesis and growth, and shifts in the species composition of the community from small to large cells. However, more than CO_2 is needed to make a new cell, and simply revving the engine with more CO_2 may just deplete the other essentials faster. Bigger blooms (and bigger busts) may be another consequence of ocean fertilisation by CO_2.

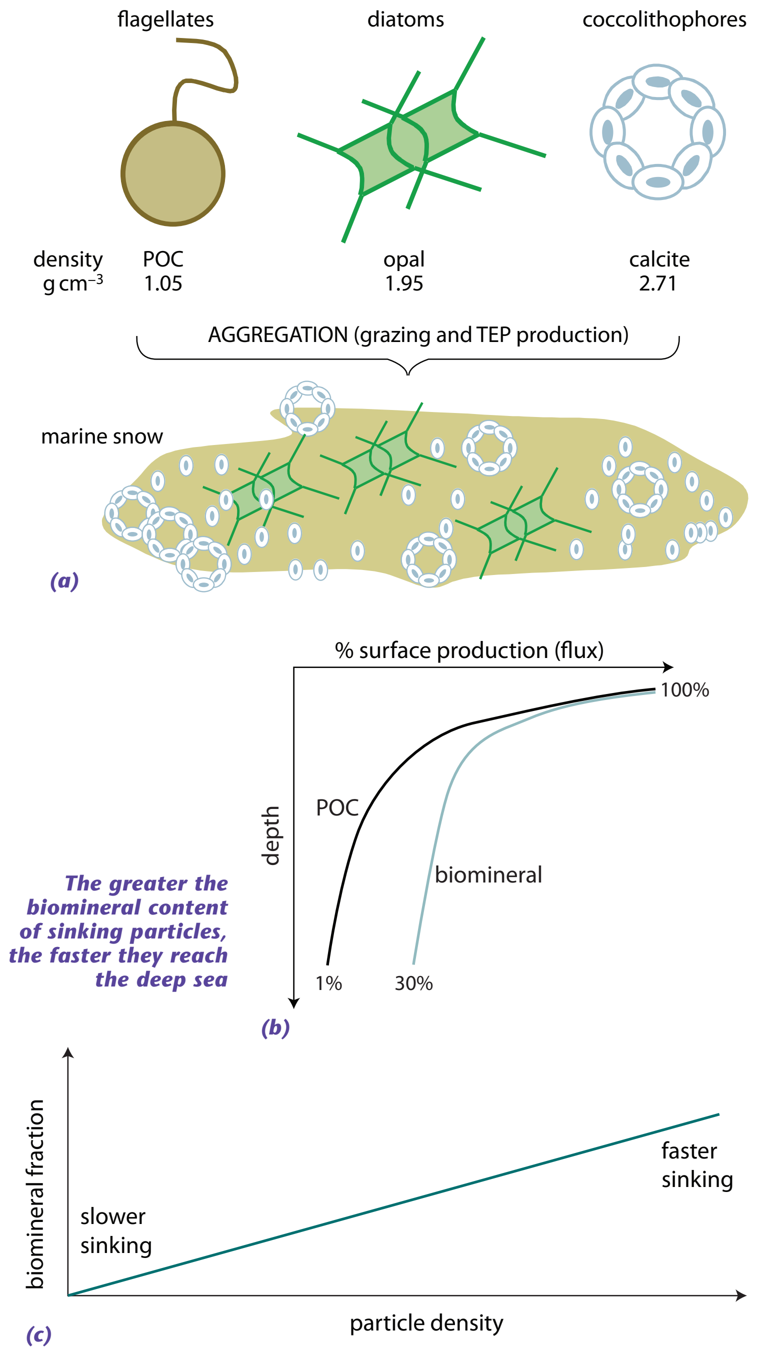
Elemental ratios

The ratio of carbon, nitrogen and phosphorus in algal cells represents the intersection of the marine cycles of these elements, and is key to our understanding of both algal ecology and marine biogeochemistry. Fertilisation of the ocean with CO_2 has the potential to shift elemental ratios, with 'carbon overconsumption' resulting in carbon enrichment of the various dissolved and particulate pools present in the ocean. Such

*RuBisCO stands for ribulose-1,5-bisphosphate carboxylase oxygenase, an enzyme involved in the reaction that catalyses the first major step of carbon-fixation, which makes atmospheric CO_2 available to organisms in the form of energy-rich molecules such as glucose.

changes in the basic biochemistry of marine algae could knock on to higher trophic levels by changing the quality of food, and how energy and material is transferred between trophic levels.

Despite a wealth of experimental evidence on the effects of CO_2 on algal physiology, we know little about how the fundamental cellular ratio of carbon : nitrogen : phosphorus will change. In laboratory conditions, the ratios in algal cells of carbon to nitrogen, and of nitrogen to phosphorus, either increase or show no change. However, in experiments with natural communities, there has been a greater variety in response – possibly linked to the different experimental methods used or the diverse communities involved (see Box opposite). Clearly, regional differences need to be addressed using identical or at least comparable methods, and a uniform global response is unlikely given the multitude of different species and ecosystems present in the ocean.



The Biological Carbon Pump

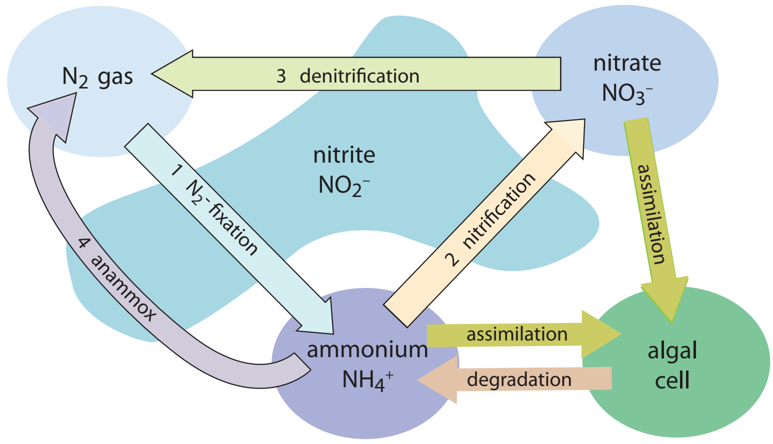
In terms of sequestering atmospheric CO_2 into the deep sea, moving organic carbon from the top of the ocean to the bottom via the Biological Carbon Pump (BCP) is a key process, and mechanisms by which this can be made faster or more efficient have now been linked to the biominerals produced by coccolithophores (calcite) and diatoms (opal) (see Figure 2).* Feedbacks that might reduce the efficiency of the BCP are thought to include decreased availability of calcite and opal through reduced production and elevated dissolution, increased attenuation of organic carbon, calcite and opal with depth due to slower sinking and more dissolution, and shallow (< 500 m) oxidation of organic matter which will decrease water-column oxygen concentrations. However, feedbacks may also exist that would increase BCP efficiency, including increased production of transparent exopolymer particles (TEP) – the glue that sticks particles together (Figure 2) – and increases in diatom production and algal cell size in a CO_2-enriched world. Although our understanding of the BCP and the factors which influence its efficiency are steadily developing, we need to understand fully how each individual factor is affected by ocean acidification in order to predict what will happen to the whole system.

Nutrient cycles

As well as carbon, nitrogen and phosphorus, other essentials for building new algal cells include silica and iron. The full effects of ocean acidification on nutrient cycles are just being recognised and there is substantial research still to be done. One crucial realisation is that ocean acidification may act on different steps within a nutrient cycle in different ways, so that the net effect is differ-

Figure 2 *How the efficiency of the Bological Carbon Pump (BCP) is affected by the biomineral content of algae contributing to marine snow.*
(a) *Aggregation of planktonic algal remains, plus other organic debris, forms marine snow; the flagellate represents algae with no hard parts, the diatom represents algae with high silica content, and the coccolithophore represents algae with hard parts of calcium carbonate; TEP stands for 'transparent exopolymer particles' (see text).*
(b) *As marine snow sinks, bacteria remineralise particulate organic carbon (POC) faster than the biominerals calcite and opal dissolve, so that more biomineral than POC survives to reach the deep sea.*
(c) *Biomineral density is higher than POC density (see (a)), so increasing the fraction of biominerals in sinking aggregates increases their density and sinking speed. This 'ballast effect' is seen in the strong correlation of POC and biomineral fluxes in both the deep sea (>2 km) and upper ocean (<1 km).*

Editor's note *For certain organisms, the biomineral is celestite (strontium sulphate), which is denser than both calcite and silica: see the article on p.27.*



(a)

(b)

Process	Agent	Response to lower pH	Result
1. nitrogen-fixation	blue–green algae	increase	increase in NH_4^+
2. nitrification	bacteria	decrease	increase in NH_4^+
3. denitrification	bacteria	increase	decrease in NO_3^-
4. anammox	anammox bacteria	unknown	unknown
OVERALL			increase in NH_4^+

Figure 3 *The marine nitrogen cycle and ocean acidification.* ***(a)*** *The main pools and processes of the marine nitrogen cycle. Nitrogen-fixation is the biological transformation of atmospheric N_2 to a form of dissolved nitrogen that can be used by bacteria and phytoplankton. Nitrification is the biological oxidation of ammonium to nitrite followed by the oxidation of the nitrite to nitrate. Denitrification is the reduction of nitrate to form N_2 gas. Anammox is an abbreviation for ANaerobic AMMonium OXidation.* (All the transformations in the nitrogen cycle involve nitrite as an intermediate step.)*
(b) *Current thinking about how each step of the marine nitrogen cycle responds to ocean acidification. Crucially, reduced nitrification and increased denitrification will combine to decrease nitrate availability, causing a decline in primary productivity. Increased nitrogen-fixation and reduced nitrification will also act to increase the amount of ammonium present.*

Figure compiled from article by Hutchins et al. *(see Further Reading).*

Increased ocean acidity could result in a reduction in the availability of NO_3^- and a decline in primary productivity

ent from what might be predicted from just one step in the cycle. For example, within the marine nitrogen cycle (see Figure 3) inputs and outputs of nitrogen into the fixed nitrogen inventories may balance, but due to a bottleneck effect associated with one of the main processes involved, the net effect may be enrichment of the surface ocean with ammonium and dissolved organic nitrogen compounds, and a decline in nitrate. As nitrate-based primary production is the main driver of the Biological Carbon Pump, reductions in nitrate availability may also equate to a decrease in the export of material to the deep sea. As diatoms are the main 'new producers'† in the ocean, their production may also decrease (despite the positive effects from other ocean acidification-related processes such as increased silicic acid availability via increased dissolution of silica remains, or CO_2-fertilisation), which will have direct consequences for marine fisheries. The effect of ocean acidification on other macronutrient cycles (e.g. phosphorus and silica) is not fully clear at present. Currently, phosphorus and silica cycles seem less likely to be affected directly through the impact of changes in pH on algal physiology, but are more likely to be affected by increased demand as the compositions of algal communities change, as well as through the close link between marine nutrient cycles.

*Anaerobic ammonium oxidation is undertaken by certain bacteria discovered relatively recently; these convert ammonium (and nitrite) directly to N_2 gas, and may be responsible for up to 50% of the N_2 produced in the oceans.

†To grow, diatoms use inorganic nitrogen (nitrate) newly supplied from depth, rather than organic nitrogen-containing compounds (e.g. NH_4^+) regenerated from organic matter in the upper ocean.

Box 1 Moving towards a consensus?

The lack of a current consensus on algal responses to ocean acidification may be partly explained by the diversity of techniques and methodology used to investigate them. For example, there are currently several ways to control the carbonate system in an experimental set-up – each has its pros and cons – and each also alters the carbonate system slightly differently. Discussion continues, and – in the best traditions of science, is likely to continue – over which methods and/or techniques should be adopted for future experiments. There have been attempts to consolidate current methodologies and a suggestion for ocean acidification researchers to adopt 'Best Practices' (see http://www.epoca-project.eu/index.php/Home/Guide-to-OA-Research/).

For culture studies, further complications centre around choosing which strain of organism to experiment with – for example, differences in the response of coccolithophores to ocean acidification may relate to the hundreds of strains of *Emiliania huxleyi* currently growing in laboratories around the world – many have adapted to living in culture conditions and potentially lost the physiological traits that would have characterised them in their natural environment. Such diversity in laboratory populations of organisms will be minor when compared to the diversity seen in natural populations.

Field studies have the additional difficulty of proving a response to ocean acidification – in the multivariate natural environment all factors need to be accounted for before we can properly assess the relative influences of ocean acidification versus variability in other growth-limiting factors. Simple linear correlations are inadequate, and are likely to lead to more confusion and less consensus.

Effects on trace metal chemistry

Iron is among a number of trace metals whose availability may be negatively affected by decreasing ocean pH. Iron is present in seawater in several pH-sensitive forms, so that decreasing pH changes the solubility and form of iron available for algal growth. In culture studies, decreases in pH have been accompanied by a decreased iron uptake related more to changes in iron chemistry than to changes in cellular physiology. Decreased iron availability may also interact with CO_2 fertilisation – carbon over-consumption may increase iron requirements. In combination with a decrease in iron availability due to chemical reactions, cellular CO_2-enrichment may lead to increased iron stress in areas of the ocean that are already iron-limited (e.g. the Southern Ocean). Possible feedbacks to increased iron demand may come in the form of changes in atmospheric dust supply, although the direction of change is unclear.

Clearly, as with the other biogeochemical cycles, an understanding of both cellular and biogeochemical processes under elevated CO_2 is required to fully understand the impact of ocean acidification. As ocean pH changes, changes in the concentration of various ions (e.g. OH^- and CO_3^{2-}) may also affect the solubility, absorption, toxicity, and rates of oxidation and reduction of trace metals other than iron (e.g. cobalt, manganese). Clearly, understanding how such changes in trace metal chemistry and availability may affect marine algae is another important aspect of ocean acidification research.

A global 'geochemical experiment'

Ocean acidification represents a multifaceted problem for marine algae – a real life hydra of issues and consequences which we are only just beginning to fully appreciate. However, ocean acidification is just one part of the 'global geochemical experiment' – other mechanisms of climate change will also directly and indirectly impact marine ecosystems: for example, increased sea-surface temperatures, changes to water-column mixing regimes, and changes in seasonal ice-cover.

Changes in the marine environment may well modify species biogeography, with species and ecosystems responding to expansion or contraction of their favoured biomes. Such large-scale regime shifts, where whole ecosystems change in their basic composition from the top to the bottom, may come with coupled changes in biogeochemical cycles as key species are lost or are replaced with less efficient analogues. Obviously there will be winners and losers as a result of ocean acidification and climate change, with ecosystems and marine organisms adapting (possibly evolving) and ultimately surviving.
On the global scale, we urgently need to understand what the full consequences of ocean acidification will be for marine biogeochemical cycles.

Further Reading

Boyd, P.W. and T.W. Trull (2007) Understanding the export of biogenic particles in oceanic waters: Is there consensus? *Progress in Oceanography,* **72**, 276–312. (A review of the Biological Carbon Pump.)

Hofmann, M. and H.J. Schellnhuber (2009) Oceanic Acidification affects marine carbon pump and triggers extended marine oxygen holes. *Proceedings of the National Academy of Sciences,* **106**, 3017–22. (Consequences of ocean acidification for the Biological Carbon Pump.)

Hutchins, D.A., M.R. Mulholland and F.X. Fu (2009) Nutrient cycles and marine microbes in a CO_2-enriched ocean. *Oceanography,* **22**, 128–45.

The special issue on ocean acidification in *The Oceanography Magazine* is highly recommended, and was used heavily in this article. It can be found at http://www.tos.org/oceanography/issues/issue_archive/22 4.html.

Alex Poulton is a NERC postdoctoral fellow based at the National Oceanography Centre, Southampton, researching the factors that control coccolithophore calcification and growth rates. His interests also include links between plankton community structure, oceanic productivity and the efficiency of the Biological Carbon Pump.
alex.poulton@noc.soton.ac.uk

Other sources of information about the effects of ocean acidification

A special report into ocean acidification and avenues for future research can be found in the 2005 Royal Society report: http://royalsociety.org/Ocean-acidification-due-to-increasing-atmospheric-carbon-dioxide/.

For research news, see the European Project on OCean Acidification (EPOCA) website: http://www.epoca-project.eu/, and the UK ocean acidification programme: http://www.nerc.ac.uk/research/programmes/oceanacidification/ or the US equivalent http://www.pmel.noaa.gov/co2/OA/. (See also the article about EPOCA on pp.12–13 of the most recent issue of *Ocean Challenge*.) For up-to-the-minute news on research, check out the ocean acidification blog at http://ocean-acidification.wordpress.com/

The Woods Hole online publication, *Oceanus*, has produced some useful articles on the topic, e.g. 'Ocean acidification: a risky shell game' (posted 4 December 2009) and 'The socioeconomic costs of ocean acidification' (posted 8 January 2010).

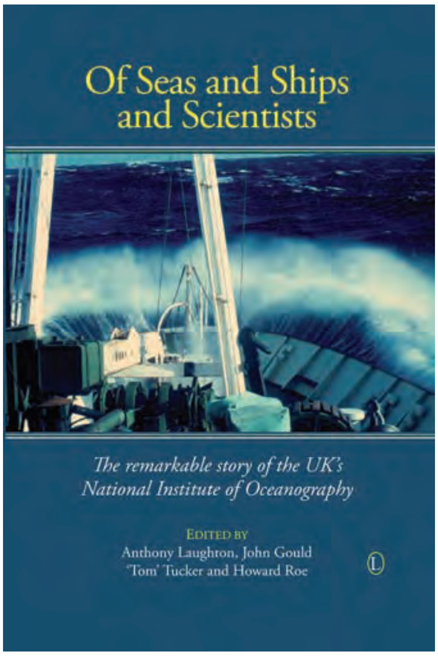
Book Reviews

The pioneers of Wormley

Of seas and ships and scientists: the remarkable story of the UK's National Institute of Oceanography 1949–1973 edited by A.S. Laughton, W.J. Gould, M.J. Tucker and H.S.J. Roe (2010) The Lutterworth Press, 350pp. £25 (flexicover, ISBN: 978-0-7188-9230-2).

When I first studied oceanography in the 1960s the terms 'NIO' and 'Wormley' seemed synonymous, so it may still be useful to distinguish between the Wormley site, which hosted oceanographic research for more than forty years (1953–95), and the Institute (1949–73) that occupied the site for the first twenty of those years and is the subject of this book.

The National Institute of Oceanography was formed by bringing together scientific staff from three existing organisations: the Discovery Investigations, which began in 1923 with the primary objective of conducting research to support the whaling industry in the Antarctic, based at the British Museum (Natural History); Group W (for Waves) of the Admiralty Research Laboratory at Teddington, set up in June 1944 to develop methods for predicting the waves encountered by amphibious landings on hostile shores, and the Oceanographic Branch of the Hydrographic Office at Cricklewood. The new body was placed under the leadership of George Deacon, previously head of Group W. The political and adminstrative background to its formation, and the history of Britain's relative neglect of oceanography during the preceding half-century, are well described in Chapter 2 by Deacon's daughter, Margaret, using largely unpublished sources. (Chapter 1 summarises the development of marine science in Europe and North America since the mid-17th century.) Deacon had left the Discovery Investigations on secondment to the Admiralty in 1939 and joined the Royal Naval Scientific Service in 1946. His oceanographic experience already went back to 1928–29, when he sailed as chemist on the *William Scoresby* in the waters around South Georgia. Chapter 3, by Margaret Deacon and Sir Anthony Laughton, is devoted to his career.



The Institute remained an 'invisible college' until its scattered personnel were brought together by the move to Wormley in 1953, making fresh synergies possible. The spacious building acquired for NIO was well suited to its new purpose, although its location in Surrey, about 40 km from the sea, was something of a compromise, proximity to London being a major consideration. Thus UK oceanographers had, for the first time, a worthy focus with a name to match. This happy congruence lasted for twenty years until the reorganisation of 1973, when incorporation of the Institute of Coastal Oceanography and Tides at Bidston near Liverpool and the Unit of Coastal Sedimentation at Taunton brought about a change of name to the Institute of Oceanographic Sciences (IOS). There were further changes in 1987, when the Bidston laboratory was separated to become the Proudman Oceanographic Laboratory (POL) and IOS was renamed the Institute of Oceanographic Sciences Deacon Laboratory. (The Taunton laboratory had been closed two years earlier.) Soon afterwards, planning started for a radically different approach to oceanographic education and research in conjunction with the University of Southampton. This eventually led to creation of the Southampton Oceanography Centre (SOC) and closure of the Deacon Laboratory. The move to Southampton took place in 1995 and the buildings vacated at Wormley were subsequently demolished to make way for luxury flats. Sir Anthony Laughton and Howard Roe describe this series of changes in the final chapter – Chapter 20.

Between these 'bookends' lies the heart of the book: sixteen chapters written by a total of fifteen NIO veterans, recounting life and work in Britain's oceanographic community during its formative period and consolidation. They cover the Institute's research activities in all departments of marine science. To mention a few examples: pioneering studies of vertical structure in pelagic ecosystems; invention of the neutrally buoyant (Swallow) float to track deep water movements; precise measurement of relationships between the fundamental properties of seawater, on which the International Oceanographic Tables were based; combined theoretical and observational investigations of wind waves, which had important applications in the offshore oil industry; and the development of a powerful side-scan sonar mounted in a towed body (GLORIA) for surveys of the ocean floor.

All these achievements were underpinned by close liaison with the Institute's support services, in particular the Engineering and Applied Physics Groups who designed and built the necessary instrumentation and underwater gear – from the once familiar yellow polypropylene water bottles to the six-tonne bulk of GLORIA – and the officers and crew of the research vessels from which the equipment was deployed (RRS *Discovery II* until 1962 and the new RRS *Discovery* thereafter). Their essential contributions, together with those of the Library and Information Service, the Secretary and his administrative staff, are all recorded here.

The level of treatment ranges from the mildly personal to the seriously technical, depending as it must on the style of the individual author. For similar reasons the same episode is sometimes described more than once, although from different viewpoints. Despite these changes of focus several themes emerge. One of these is the leadership given by the Institute's founding director, George Deacon, knighted on his retirement in 1971, and by his worthy successor, Henry Charnock, who had worked at NIO for most of its existence prior to 1966. It seems clear that Deacon's informal approach to recruitment and his encouragement of staff to pursue promising ideas of their own were reflected in the respect they had for him. Charnock took a similar view about the priority of research and saw NIO through the difficult years of transition to IOS and beyond.

The value of cooperation is another recurrent feature, whether it was within NIO or between the Institute and outside organisations. The teamwork necessary for successful research at sea consolidated working relationships between all concerned. Productive relations were maintained, often through personal contacts, with the Admiralty, with other government laboratories, the universities (Cambridge in particular), and with industry. On the international scale there was participation in major programmes of research, including the International Geophysical Year (1957/8), the International Indian Ocean Expedition (in 1963–64) and the Deep Sea Drilling Project (from 1969), as well as frequent collaboration with scientists from laboratories overseas, especially the Institute's neighbour across the pond, Woods Hole. During its residence at Wormley, NIO expanded roughly threefold in both staff numbers and (real-terms) expenditure. It seems to have been an unusually happy ship.

Some of these advantages diminished when the Institute was absorbed into NERC in 1965; as bureaucratic control spread, the element of autonomy was lost. After 1972, balanced long-term funding became problematic, following introduction of the policy of commissioned research based on the Rothschild report. A justified air of nostalgia for the earlier years is present in several chapters.

Looking back half a century from these days of bigger science and tighter budgets, it's obvious that much has changed, although some original features remain: the joys and terrors of working at sea, to name but a few. Only one sea-going woman appears in these pages, a small figure in the group photo on p.275 taken aboard RRS *Discovery* in 1963 (Betty Kirtley, where are you now?) – some things have changed for the better. And what of the future? Inevitably uncertain, but if recent history is any guide the Bidston laboratory can expect to regain its independence around 2025, thereby completing its second cycle of administrative accountability. There's nothing as recurrent as change!

When I heard about this book I feared it might be a dull institutional chronicle, a tale of committees, budgets and memoranda; it is not. The editorial team has assembled these first-hand accounts of oceanographic research and set them within a broader context in order to tell the illustrious story of NIO. The result is a book that is both accessible and historically valuable. Finally, I must mention that it has clear illustrations throughout, a comprehensive index and several useful annexes, including detailed cruise lists for both 'Discoveries'.

John Phillips
MIlton Keynes

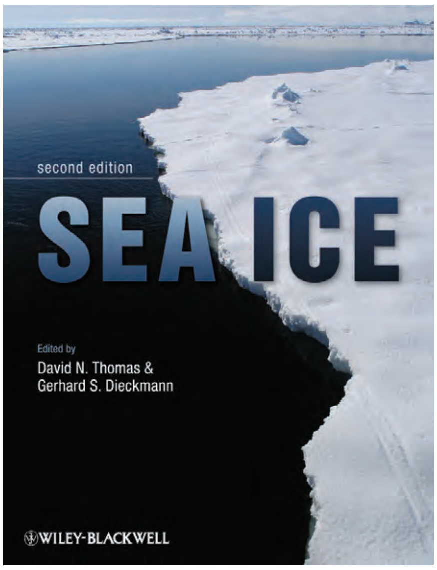
The multidisciplinary science of sea-ice

Sea Ice edited by David N. Thomas and Gerhard S. Dieckmann, 2nd edition (2010) Wiley-Blackwell, 640pp. £88.99, hard cover (ISBN: 978-1-4051-8580-6).

I recently had the good fortune to join an international team of sea-ice scientists on a research cruise to the Weddell and Bellingshausen seas, during which we investigated the structure and properties of sea ice shortly after the onset of the spring melt. I brought along a copy of *Sea Ice*, thinking this would provide a good foundation to brush up on some of the aspects of sea-ice research techniques, theory, and paradigms with which I was not familiar and that I expected to crop up during the cruise. I was not disappointed (with either the cruise or the book).

Thrashing through sea ice with an icebreaker is an inherently messy and fascinating process which, by breaking up the ice and turning it onto its sides, often reveals layers of algae below and even within the sea ice, and thus dramatically shows how intimately connected physical and biological processes are within that sea ice. This book starts from the premise that the study of sea ice should therefore be interdisciplinary. It presents a variety of topics dealing with sea ice and related processes, which are variable over a wide range of spatial and temporal scales, as well as the various components of ecosystems that have adapted to life under these conditions. The chapter topics range from the details of sea-ice formation at the smallest scales to multidecadal and Arctic basin-scale changes in sea-ice concentration, and from bacteria to megafauna with a focus on the unique aspects of sea ice as an environmental medium.

This book, now in a second, expanded edition, is nicely edited in the sense that the various chapters, authored by an impressive array of leading researchers, have been well coordinated and cross-referenced. It contains a useful glossary and index, though at times I felt that these could be more comprehensive and reflect greater detail. This is a well illustrated volume, with numerous high quality colour plates, including photographs that illustrate characteristic features of ice formation and deformation, detailed colour maps of sea-ice concentrations in both polar regions (but be prepared to get out your magnifying glass), as well as micrographs of sea-ice biota, illustrating taxonomic differences and relationships between organisms and the ice structure.



The book contains a minimum of mathematics and should thus be accessible to upper level undergraduate science students of all stripes, but will also be a valuable source of contemporary references for practising researchers and lecturers. Although marine science is by nature interdisciplinary, most of us are still more firmly grounded in one of the fundamental sciences, and thus the more discipline-specific aspects of some of the material may require a bit of a stretch for some readers. In my case, although my palms don't quite go sweaty at the mention of genome sequencing, the figures illustrating phylogenetic trees were a bit outside of my physical oceanographic comfort zone.

Following an introductory chapter on the climatic importance and societal relevance of sea ice, the first half of the book addresses its physical aspects. The second half largely addresses biogeochemical and ecosystem aspects of life in and around sea ice. Many of the chapters are excellent and enjoyable reading, providing background information on general principles and practical techniques, as well as outlining current and future research issues and prognoses within the context of the current rapid and pronounced expression of climate change in the polar regions. For example, an aspect that I had not previously considered is that one of the most profound and immediate changes associated with snow on sea ice is related to the likely disappearance of multiyear ice in the Arctic Ocean, without which early winter snow will fall on open water and contribute fresh water directly to the surface of the ocean.

This book's greatest value for me, however, lies in the difference in approach between it and the other polar oceanography and sea-ice books with which I am familiar. This difference is summarised in the introductory statement to the chapter on heterotrophic protists (i.e. microbial consumers), by David Caron and Rebecca Gast. 'Sea ice makes up a physically complex, geographically extensive but often seasonally ephemeral biome … despite the extremely harsh environmental conditions under which it forms and exists for much of the year, sea ice can serve as a suitable, even favourable, habitat for dense assemblages of [micro]organisms.' The entire book can be thought of as fleshing out that statement: an exploration of the small scale details and the trends in spatial and temporal variability in the habitat, as well as an exploration of the unique aspects of adaptation to life within, and in close proximity to, sea ice. In this sense then, the real heart of the book consists of the chapters on 'Sea Ice Bacteria and Viruses', 'Primary Producers', 'Heterotrophic Protists', 'Sea Ice Meio- and Macrofauna' (such as copedpods, euphausids, and amphipods), 'Polar Marine Mammals and Birds' and 'Biogeochemistry of Sea Ice'.

Could this volume be more comprehensive? Sure. With respect to physics, for example, it could cover air–ice and ice–ocean interactions in greater detail, but to do so would be to stray into territory already well covered by the classics of sea-ice physics (*Sea Ice Geophysics*, N. Untersteiner (ed.) 1986; *Polar Oceanography, Part A, Physical Science*, W.A. Smith, 1990, and *Physics of Ice-Covered Seas*, M. Leppäranta, 2001) or more recent, specialist works (*Ice in the Ocean*, P. Wadhams, 2000, and *Air–Ice–Ocean Interactions*, M. McPhee, 2008), and it would become more mathematically oriented and less accessible to some of the intended audience.

While the book is not completely comprehensive, it will serve as a valuable introductory text for upper division undergraduate courses in polar marine science, as well as more specific graduate courses in polar oceanography, and will be a valuable reference for researchers just entering, or seeking to gain a broader understanding of, this rapidly evolving and exciting field. It carries a fairly steep price tag, which might deter the casual reader, but it is not outside the expected price range for a text and reference book of this quality.

Tim Boyd
Scottish Association
for Marine Science

A tale of heroism, tragedy and horror

Franklin: tragic hero of polar exploration by Andrew Lambert (2009) London: Faber & Faber, 448pp. £20 (hard cover, ISBN: 978-0-571-23160-7) and £9.99 (paperback, ISBN: 978-0-571-23161-4).

Amongst the various unsolved mysteries of the Arctic the fate of Sir John Franklin's 1845 expedition, involving 129 men aboard two ships, has a perennial fascination. This work provides a summary of the present state of knowledge in which the author does not hesitate to assert, and vindicate, his interpretation of some of the aspects that have caused much controversy, both ancient and modern. Many writers have published a variety of books on the Franklin expedition and its aftermath but the author of this text has the uncommon distinction of having visited many relevant parts of the Canadian Arctic while involved in making a film of the fateful expedition. His formal qualifications, Professor of Naval History at King's College, London, unite theory and practice.

The account appears as four books in the one volume which include revealing material about contemporary circumstances. The first sentence of the prologue gets straight to the major controversial point; cannibalism. The entire page emphasises the dire circumstances expedition members found themselves in, and leaves no doubt about the author's certitude of these events: 'The Arctic expedition of Sir John Franklin ended up in large-scale cannibalism.'

After the prologue. Book One describes the 'pursuit of science' during the mid-19th century, emphasising the role of Sir John Barrow. The author indicates some of the conflicting ambitions and machinations of the period, one of great change in naval careers with the alluring proposition of the Northwest Passage. The account continues with a concise description of development of the career of Franklin, noting that, although he 'has had many biographers, he remains an elusive subject'. His naval career began in 1800, aged only 14 – and his rise in rank was spasmodic, affected by changing circumstances much of which involved experience in survey and navigation. Franklin's polar experience began with a land expedition in 1819 which, although it made major discoveries of the Arctic coasts of continental North America, suffered severe hardship. He returned an 'Arctic Hero'. In 1826 he was dispatched on a second Arctic land expedition which also experienced increasing adversity. The author notes 'He abandoned his dream in order to save his men, and never regretted the choice'. Surveys were improved, links made, and even more of the continental coast revealed. Practical experience of land travel in the Arctic improved; though the missing links of the Northwest Passage, through the complex insular regions, remained. On his return, John Franklin, by then a widower, was knighted; he remarried, taking Jane Griffin as wife. The indefatigable Lady Jane came to have a significant role in the Franklin story. There was, however, an interim period in the Mediterranean and Tasmania, during which Arctic exploration was continued by others. These are the themes of Book 2: Public Visions.

The last chapter of Book Two, 'Magnetic Empires', describes the circumstances of what has been called a 'magnetic mission', which necessarily had Arctic and Antarctic ramifications. Indeed, it was major stimulus for polar exploration involving a degree of personal and national rivalries. The ships HMS *Erebus* and HMS *Terror*, while engaged in Antarctic exploration, had visited Hobart during Franklin's term as Governor, and their ice-worthiness was dem-

Sledges passing extraordinary masses of ice pressed against the north shore of Bathurst Land during one of the expeditions in search of Sir John Franklin, by Commander Walter W. May (taken from the cover of the paperback edition).

onstrated. Just over a year after his return Franklin was commander of these vessels bound to discover the last links of the Northwest Passage. In 'Magnetic Empires' the author observes 'The origins of Franklin's final expedition were more complex than existing accounts assume ...'.

The third book is titled The Politics of Tragedy. The last report of Franklin's expedition was from whalers in Melville Bay at the end of July 1845. Time passed and no further news was received, anxiety slowly increased. The many persons involved, their continued machinations and committees, and the increasing involvement of Jane are reported in detail, providing a revealing account of the activities in London relating to the beginnings of Franklin searches. The book has comparatively little to say of what happened in the Arctic for the valid reason that so few details are known. The earlier work by Richard Cyriax (1939) and charts annotated by Rupert Gould (Admiralty, 1927 and 1956) summarise much of what had been found, although more relics from the expedition continue to be discovered, and many are rediscovered.

The situation in London, with speculations, publicity, rewards, several wild schemes involving psychics and scoundrels, and destruction of records, is reported in detail. Sir Edward Belcher's searches, during which HMSs *Assistance*, *Bredalbane*, *Intrepid*, *Investigator, Pioneer,* and *Resolute* were lost (although the last was fortuitously recovered), combined with new wars, reduced the naval contributions to the search. Jane, however, persisted, and eventually her efforts secured results. Although many remains were found, cannibalism was not mentioned in the 1859 published report (McClintock). John Rae, an experienced Hudson Bay Company factor and explorer, brought news about the southernmost remnants of the expedition in 1854 and with it what the author refers to as 'Mutilated Corpses'. Thus the account of cannibalism began and with it the controversy which is recounted in detail, with observations on the Victorian sensibilities involved. The section concludes with details about Jane and the unveiling of Sir John's statue in Waterloo Place, after the only two, terse, documents from the expedition had been retrieved. There is speculation about the loss of the other writings of the expedition. Ironically at least four of the routes through the Northwest Passage were charted from discoveries made during the many searches.

Book Four, The Cost of the Past, pursues the prevailing themes of heroism and sacrifice until the time when the First World War caused profound changes. Its last chapter, 'What Really Happened', is the author's summary and interpretation of the disaster. Penetration of the central parts of the Arctic archipelago by old ice forced down McClintock Channel is now well known to be a major obstacle to navigation of the Northwest Passage. This is what occurred in 1846–47 and persisted during some exceptionally cold years. A note on the much-derided 'curtain rods', actually non-magnetic survey rods, refers to interpretations of loss of reality proposed by authors who have failed to understand their significance (Berton, 1988). Speculations on the thoughts of the surviving officers, combined with personal experience of the barren frigid shores of King William Island, allow the author to hypothesise about actions of the commanders ordering a trek to the south with very small chances of success. Their condition progressively deteriorated, starvation became acute, command and discipline were lost and basic survival instincts came to prevail.

The fate of the expedition has been attributed to many factors including: tuberculosis with other diseases, scurvy and other vitamin deficiencies, ptomaine and lead poisoning, botulism, hypothermia, and starvation. The combination of those, with the state of morale after a third Arctic winter (during two of which they had made virtually no progress), may have been more powerful than the sum of adversity. Lambert's comment that 'Historians should check that their evidence would stand up in a court of law' refers to some earlier hypotheses. The trek southward, by 105 survivors including only six officers, towards the Back River and a difficult, but known route, with an increasing discrepancy between the proportion of officers and other ranks, is where the author postulates that it 'ended up in large-scale cannibalism'. The term 'death march' is applied, which is supported by skeletal evidence (Keenleyside *et al*., 1997), but other authors have different interpretations. Coleman (2007), for instance, is recently published and strongly asserts a contrary opinion with more Eskimo involvement.

The book is very well referenced; it includes comprehensive notes, and is provided with a detailed index. The digitisation of the 'Arctic Blue Books', by the University of Manitoba has been a vast asset to the research. A dozen colour illustrations and two small maps indicate specific features. Readers accustomed to historical writings will note Eskimo are referred to by the neologism Inuit (and the pleonasm 'Inuit people'). There are occasional misconceptions: the assertion that cold degrades ascorbic acid is made several times although it is heat, not cold, that can do this. What is now known as Ross Island was a 'farthest south' for the expedition in 1841, not Franklin Island. Bellot died on sea-ice, not in a crevasse.

The title 'Franklin: tragic hero of polar navigation' is both terse and apt for this well written contribution to Arctic history. Current interest in the Northwest Passage demonstrates the subject has continued to be topical. Analyses of the fate of Franklin's expedition are well established aspects of polar literature, although I wonder how many will agree with the author's broad statement 'There is no mystery about the fate of the Franklin expedition'. One may be certain that more discussion, and perhaps discoveries, will follow.

Further Information

Admiralty (Hydrographic Office) (1927) *King William Island.* London: Chart 1501.

Admiralty (Hydrographic Office) (1956) *Discoveries in the Arctic Sea 1616–1927.* London: Chart 1500.

Berton, P. (1988) *The Arctic Grail.* Toronto: McClelland & Stewart.

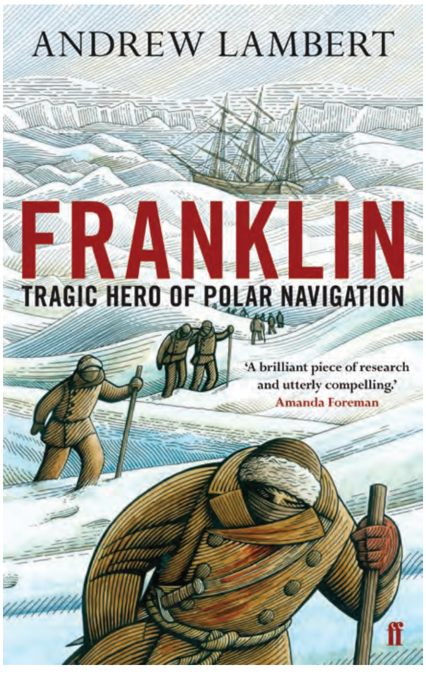
Coleman, E.C. (2007) *The Royal Navy and Polar Exploration, Volume 2: from Franklin to Scott.* Stroud: Tempus

Cyriax, R.J. (1939) *Sir John Franklin's Last Arctic Expedition.* London: Methuen (reprinted 1997, Plaistow: The Arctic Press.)

Keenleyside, A., M. Bertulli and H.C. Fricke (1997) *The Final Days of the Franklin Expedition: New Skeletal Evidence.* Calgary: *Arctic.* **50** (1), 36–46

McClintock, F.L. (1859) *The voyage of the* Fox *in the Arctic Seas: A Narrative of the Discovery of the Fate of Sir John Franklin ···.* London: John Murray.

Robert Headland
Scott Polar Research Institute
Cambridge



Life and death of an ocean

Vanished Ocean: How Tethys reshaped the world by Dorrik Stow (2010) Oxford University Press, 320pp. £16.99 (hard cover, ISBN: 978-0-19-921428-0).

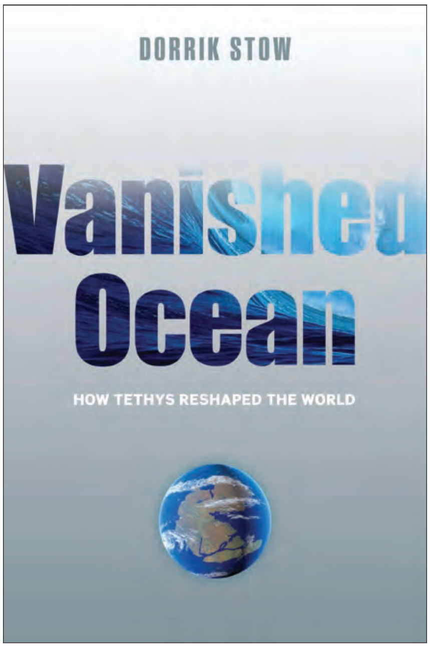
I am sure I read a very brief review, perhaps in *Geoscientist*, of *Vanished Ocean*, in which the reviewer said that the book couldn't make up its mind whether it was a textbook or a popular science book. Well I must disagree with this entirely – the book clearly is a popular science book, and a good one at that. Whilst Stow is a durable academic (although I see he worked in the oil industry earlier in his career), and therefore there could be concerns that this might resemble a dry textbook, he has written a book much in the style of Richard Fortey (in my view perhaps the greatest communicator of the popular geosciences that we have).

I picked up the book and – as most people do – read the back cover. Like the trailer for a big disaster movie, that text hooked me. *Vanished Ocean* contains all of the things that I look for in popular science books. A palpable sense of the author's passion for his subject, a bit of history including some of the key players, a human narrative relating to the author's research wanderings. For an academic he has quite an ability to set the scene – read the first paragraph on page 243. After that, though, he dives right into his subject matter without lingering a moment more. More than anything, Stow has achieved a good balance which makes for easy reading. Some popular science books (with all due respect), such as Benton's book on the Permian extinction, are pretty hardcore for the layperson (even for the graduate geologist!) and require a certain tenacity to reach the end (which in Benton's case is some 500 pages later). You can waltz through *Vanished Ocean* at ease, and get explanations of myriad geological phenomena at a level of detail suited for the lay-person. You are reminded that a good 'hard rocker' is as much a biologist as a geologist. Stow also gives both a sense of the global scale of Tethys as he travels to many different counties in support of his evidence, and a sense of the power of geology to reconstruct these past times.

I learned about stuff and places that I had never heard of before. The Valley of Whales, 250 km south-west of Cairo, where entire whale skeletons lie exposed on the ground, sounds like a truly astonishing place. I love his use of snippets of poetry at the outset of each chapter:

compressed life
beyond our knowing
curled in a coma of stone

is, quite simply, enchanting. And some of



it is his own poetry. I also quite like his boldness is advancing his reasons for the K/T mass extinction (when the dinosaurs, amongst others, were wiped out), which seem to differ from those of many of his professional colleagues. Few would attempt to say as much in a popular science book without the weight of scientific research in close support. However, it serves (importantly I feel) to highlight to the reader – and this is repeated numerous times in the book – that many geological topics and issues are a 'work in progress' – much is yet to be learned, and scientists frequently do not agree.

There are a few minor niggles. Some of the illustrations are occasionally a few pages or more from the text describing them, and I think perhaps the use of some SEM (scanning electron microscope) images of micro-organisms, which are simply very impressive, or even more impressive photographs of deep-sea vents and their communities, could have been included to the benefit of the book. And the subtitle 'How Tethys re-shaped the world' seems a little odd to me. I waited for ages to see 'how' (which I took to mean how Tethys had contributed to what we have today), and then came across Chapter 5 (on the formation of oil deposits). That was about it. It seems to me that the world's tectonic machinations created and then destroyed Tethys; life's canvas evolved there as well as elsewhere. Clearly, what we have today – other than oil – is the geological and biological evidence for this magnificent ocean, and a man who has devoted a substantial portion of his life sifting through this evidence to tell us this remarkable story. We are lucky, I think, that he has taken the time to write it all down for us.

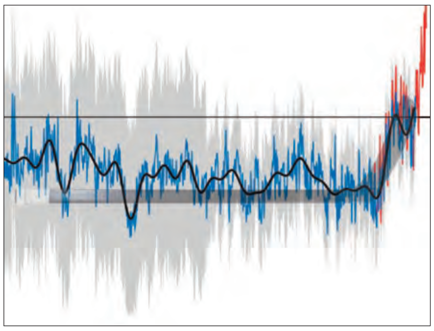
One final remark, on page 60 it says that 95% of all life has never been fossilised. How do they know that?

Kevin Black
Marine consultant

Not so Jolly hockey sticks

The Hockey Stick Illusion – climategate and the corruption of science by Andrew W. Montford (2010) Stacey International, 482pp. £10.99 (paperback, ISBN: 978-1-906768-35-5).

In 1998 a graph which was to become famous as the 'Hockey Stick' made its debut on the pages of the prestigious journal *Nature*. The graph, constructed by climate scientist Michael Mann and his colleagues, purported to show that late-20th temperatures were unprecedented in at least 1000 years. For many, this was the smoking gun of Anthropogenic Global Warming (AGW). Before long, the Hockey Stick became the icon of the International Panel on Climate Change (IPCC) and took (unacknowledged) centre-stage in Al Gore's film, *An Inconvenient Truth*. The scientific community immediately, and virtually unanimously, accepted the Hockey Stick at face-value, even though it eliminated such familiar episodes of climate history as the Mediaeval Warm Period and the Little Ice Age; these were explained away as regional or diachronous phenomena (occurring in various places at different times).



Northern Hemisphere temperature trends for the last thousand years produce a shape resembling a hockey stick – or do they?

Not everybody, though, was prepared to take this new climate history on trust. Foremost among these sceptics was a Canadian mining engineer, Steve McIntyre. Over several years, in the teeth of resistance from the palaeoclimatological community, he laboriously collected the raw data (mainly tree-ring measurements) from which the Hockey Stick was derived. MacIntyre identified numerous shortcomings with the reconstruction. The charges included cherry-picking of data, use of unvalid proxies and poor statistical techniques, which together produced a picture of exceptional 20th century warming that was not supported by the underlying data.

The response of the 'Hockey Team' (as Mann and colleagues came to be known) was to circle the wagons. McIntyre was dismissed as a crank or a flunky of the oil companies. Attempts were made to prevent publication of his analyses in the scientific press. When these tactics failed to silence him, the Hockey Team claimed that many independent studies confirmed their results. McIntyre, though, was able to show that these 'independent' studies used the same flawed datasets and techniques as the Hockey Team, and inevitably reached the same erroneous conclusions. The debate eventually reached Washington where two congressional committees concluded that Mann's statistics could not support the conclusions he drew from them. Nonetheless, the Hockey Team, with the support of the IPCC, pressed ahead with their depiction of the Hockey Stick as 'settled science'.

Andrew Montford tells this detective story in exhilarating style. He has assembled a persuasive case that the consensus view on recent climate history started as poor science and was corrupted when climate scientists became embroiled in IPCC politics. His assessment of the palaeoclimatology community is devastating: they are portrayed as amateurish, secretive, evasive and belligerent. But the most serious charge is that they have simply failed to demonstrate any scientific integrity in confronting McIntyre. The University of East Anglia emails, which appeared just as he was completing his book, suggest that the Hockey Team were more interested in knobbling McIntye than in addressing his arguments.

The wider scientific community does not escape criticism. No serious effort was made to subject the Hockey Stick to independent scrutiny, despite its profound implications for the future of the planet and its inhabitants. In response to external challenge the scientific establishment's reflex action was to side with the palaeoclimatologists without reviewing the evidence. This approach, typical of any vested interest group, should dismay everyone of genuine scientific spirit.

Monford's book ends on a somewhat anticlimactic note, because the Hockey Team has refused to admit defeat. However, if *The Hockey Stick Illusion* provokes a truly independent review of the evidence it will have served its purpose.

Joe Brannan
Geologist working in the petroleum industry

This review of The Hockey Stick Illusion *was first published in* Geoscientist *August 2010.*

For a different take on the interplay of politics and science, see *Merchants of Doubt: how a handful of scientists obscured the truth on Issues from tobacco smoke to global warming* by Naomi Oreskes and Erik M. Conway (2010), Bloomsbury Press, £25 (ISBN-13: 978-1596916-104; ISBN-10: 1596916-109).

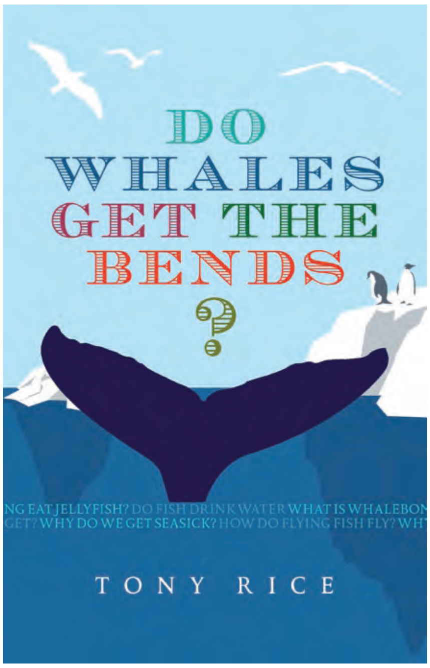
A marine Q&I

Do Whales Get The Bends? by Tony Rice (2010) Adlard Coles Nautical, 176pp. £9.99 (paperback, ISBN: 978-1-40811326-4)

This book is based upon the author's years of experience as a cruise ship lecturer. After traversing the oceans, from Greenland to the Antarctic Peninsula, he decided it was time to bring together his years of sea-faring knowledge in one book bursting with quirky questions and informative answers.

Do Whales Get The Bends? begins by laying out all its questions in a contents, under headings grouping them into topics. This is where we begin to see just how much depth of knowledge Tony Rice has extracted from his years upon the waves. His introduction on the following pages is also a nice touch as it gives us a little background about our author, allowing us to understand more about his passion for the ocean.

The saying 'You should never judge a book by its cover' is very appropriate here



Great for diving in and out of ....

as although the brightly coloured cover illustration suggests that this book has been created for children wanting to learn more about the fascinating world around them, it turns into much more from the very first page. The author's conversational style draws you in, and he neatly packs in a vast amount of in-depth scientific information.

Although the design and choice of title seem more geared towards the younger generation, once you open up, it is apparent that anyone wishing to read this book will need to have at least some understanding of certain scientific principles: states of matter and movement of particles, the visible spectrum and the Earth's structure, to name just a few.

The small-scale format of the book means that it can be carried on any journey, whether you are making a short train journey, or your very own voyage across the ocean like Tony Rice. The ease of access this book provides to information that would not necessarily be at your finger tips otherwise, makes it unique. Although many of us have 24/7 access to a computer, how many websites would give us these answers in ways we would actually understand, or would make them interesting? Having tried it myself, I can tell you not very many. This then leads onto the question of value for money – is it worth paying the price of this book for what you will get out of it? Well, Tony Rice presents us with the answer to 118 questions revolving around the sea, which if you were to research yourself, would take up a great deal of your time. Having investigated myself, if you are wanting to purchase a quality book about our oceans, you are most likely going to have to part with around ten pounds, and even then the book may be specialising in a particular area of the marine environment. With *Do Whales Get The Bends?* you are given a broad range of topics which allows you to delve in and out as you please, and the structure gives you the flexibility to explore further your new-found interests. In fact, this book can be considered your own personal tour guide for the oceans.

I see this book as appealing to older adolescents and upwards, as they are more likely to be armed with sufficient basic knowledge to fully appreciate the answers given. If the book were to include a little more colour inside, then I think its prospective audience could be broadened again, as although the cover draws you in, the excessive amount of small type and lack of colour may push people back out again. Anyone already seriously interested in the ocean would be able to look past this as they would primarily be interested in the facts, but if this is not your subject or interest area to begin with, it could be daunting to dive straight into a book packed with black font and no space to breathe in a picture or splash of colour. To a non-scientific person, a book with a vibrant, eye-catching cover like this could swiftly become a disappointment before any of it is even read. However, I recommend that you delve into it regardless as it will not disappoint you in the long run.

So all we need to answer now is: Do whales get the bends? You'll just have to read the book to find out!

Sarah Gray
Felpham Community School
(Year 11)

Much more than mousers

Ships' Cats in War and Peace by Val Lewis (2010) published jointly by Nauticalia Ltd and G2Entertainment Ltd, 216pp. £12.99 (flexicover, ISBN: 978-1-90780328-4).

This is most definitely a book for people who like cats, but it also conveys how seamen and boys tried to deal with the emotional hardship of long months at sea, away from home and loved ones. Onboard sailing ships, warships and ships on scientific expeditions, cats have provided a focus for affection and comfort for the homesick.

Altogether there are 197 stories, varying in length from a paragraph to 16 pages. Almost every story has an illustration – perhaps a sketch made at the time, or a photograph. Two photos show cats asleep in miniature hammocks made for them by the crew – this seems to have been a common practice, and indicates the important role that cats had onboard ship as pet, rat-catcher and mascot.

The book begins with a chapter on the 'evolution of ships' cats'. Here we learn that the tradition of having a cat onboard began when traders visiting Egyptian ports noticed the efficiency with which the local cats (domesticated African wildcats) guarded grain stores against rats and mice. The traders acquired cats to protect their own ships' stores from rodents, and as the trading vessels travelled from port to port, the cats would jump ship, and breed with local cats. Thus domesticated cats arrived in Greece in 500 BC and in China around 200 BC.

Simon, the cat shown on the book's cover, was a fearless hunter. He was 'promoted' to Able Seaman by the crew of HMS *Amethyst* in appreciation of his killing an enormous rat, that – along with its followers – was depleting dangerously low food stores. It was 1949, and the *Amethyst* was sailing up the Yangstze to relieve the *Consort* which was guarding the British embassy at Nanking. Despite there being a truce between Nationalist and Communist Chinese, the *Amethyst* was fired on by a Communist battery, with the result that a number of the crew were injured or killed. Simon (himself injured) became famous for comforting the wounded men and boys, and when the story of the 'Yangtze incident' was made public, he became famous and received fan mail from all over the world.

Apart from the cats, perhaps the most intriguing character of the book is the appropriately named Count Felix von Luckner, a German buccaneer who during the First World War captured and sank 16 Allied ships. Despite his nickname – the 'Sea Devil' – von Luckner claimed never to have taken a man's life, nor that of a cat. Before sinking any ship he first transferred all the crew and the cats to his own vessel, the *Seeadler* (the *Sea Eagle*). Each ship he sank would have at least one cat on board, and at one point the *Seeadler* was carrying 400 prisoners and 140 cats.

Simon, hero of the 'Yangtze Incident'. Simon was awarded the Dickin Medal for bravery and was promoted to Able Seaman for killing 'Mao Tse-tung', an enormous rat.

Other celebrated seamen that the book enables us to see another side to include the explorer Matthew Flinders, who adored his cat Trim. By contrast, Shackleton, so admired by most of his men, seems to have been less caring when it came to the *Endurance*'s cat (Mr Chippy) and indeed the huskies, which were neglected.

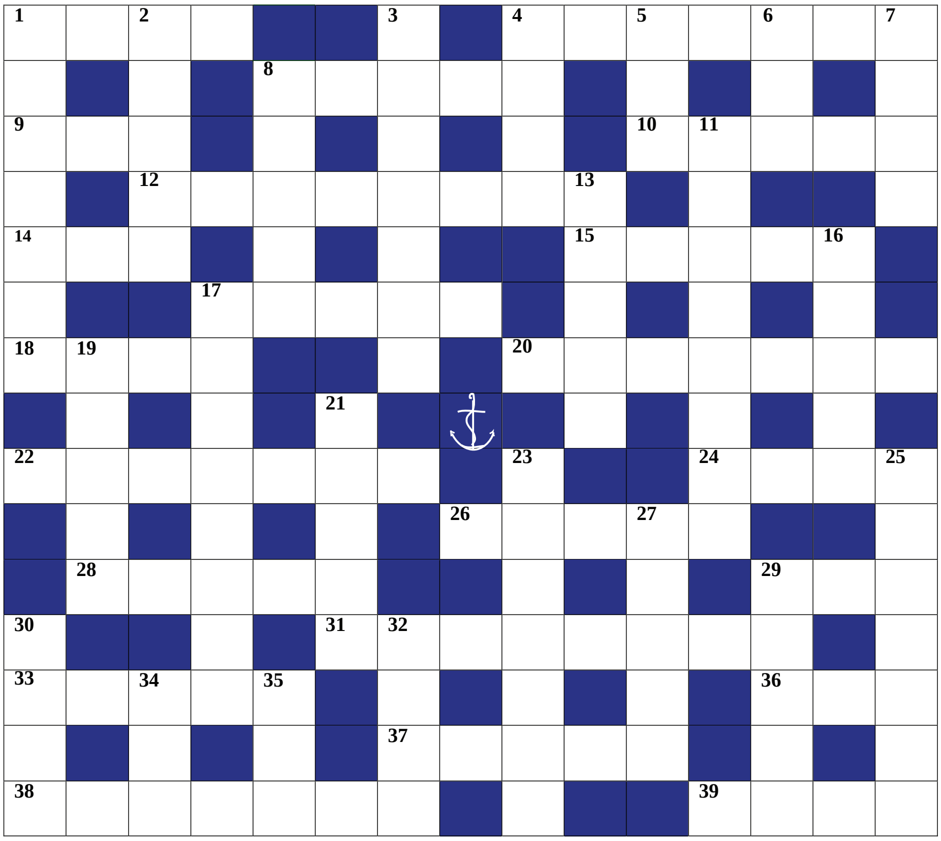
The story of Mr Chippy comes in what was for me the most interesting part of the book: 'Cats that braved the frozen wastes', where we learn something of the lives of cats and men in polar waters, aboard vessels including *the Terror*, the *Discovery* and the *Terra Nova*. The first cat to spend a whole winter in Antarctic waters is thought to have been Nansen of the sailing ship *Belgica*. The *Belgica* expedition, which set out from Antwerp in 1897, was the first Antarctic expedition of a purely scientific nature. Nansen was brought onboard as a kitten by the Norwegian cabin boy, who had named him after his hero. Nansen seems to have been content, particularly enjoying eating the flying fish that flew over the rails at night, but with the endless dark of the Antarctic winter, he went into a decline and died. The ship's doctor wrote: 'A day or two ago his life departed, we presume for a more congenial region. We are glad his torture has ended, but we miss Nansen very much. He has been the attribute to our good fortune to the present, the only speck of sentimental life within reach. We have showered upon him our affections ... In future we shall be without a mascot and what will be our fate.'

There are some negative aspects to the book. Some may find the semi-jocular language rather irritating, and there are a number of typos and formatting problems. A few of the longer stories are rather rambling and would benefit from editing, should the book go into another edition. Furthermore, the design and typography do not help convey the structure of the book which is rather confusing. I was mystified by the relationship between the section headings and the chapters, and the Contents list does not help much. However, this is not too much of a problem, as *Ships' cats in war and peace* is a book to dip into from time to time, and – who knows? – even if you are not a 'cat person', you may find yourself feeling more warmly towards cats as a result.

Angela Colling
Ocean Challenge Editor
and unashamed admirer of cats

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; a good many relate to stories that have appeared in *Ocean Challenge*. The first correct solution to be received by the Editor (address on inside back cover) will earn the sender a £40 book voucher.



ACROSS

1, and 7 & 8 Down. Now known as the Antarctic Circumpolar Current (4, 4, 5)

4. Famous for his floats (7)

8. In electronic equipment, the semiconductor — has replaced the type involving a vacuum tube (5)

9. European research centre, named after the proposer of continental drift (3)

10. You would stand here to watch the wake (5)

12. Samuel — greatly improved safety on ships (8)

14. Prefix that replaced HBMS (3)

15, and 27 Down. Also known as being caused by poor choice of sampling rate (5, 5)

17. Third word of the famous first line of a poem about youthful heroism during the Battle of the Nile. (5)

18. There were 144 miles of this on HMS *Challenger* (4)

20. High tides are higher at solar and lunar — (7)

22. The complete personnel on a ship (7)

24. Soulful member of the Aleutian islands (4)

26. Some seals are this, but not those mentioned in 4 Down (5)

28. On a long research cruise, this may result if the 22 Across isn't good!

29. Tool used to stitch sails (3)

31. Kind of giant tortoise, found on an atoll in the Seychelles (8)

33. Hold still (me hearties)! (5)

36. — Khordadbeh was a 9th century Persian geographer, with knowledge of monsoon winds over the Indian Ocean (3)

37. To do this you use a wheel or tiller (5)

38. Lobster sailed in by seal scientists (7)

39. ¿Mexican wave (4)

DOWN

1 and 2. Since the 1960s, their role has been increasingly taken by satellites, aircraft and buoys (7, 5)

3. Underlying cause of the Hawaiian islands (3, 4)

4. Hooded and monk are kinds of — (4)

5. The Australian version of the Roy. Soc. (3)

6. — waves are associated with topography (3)

7 and 8. See 1 Across.

11. Caribbean island named by Christopher Columbus (8)

13. Brine — are found in the Gulf of Mexico and the Mediterranean (5)

16. These whales are champion divers (5)

17. New wave-power devices resemble sea- —— (8)

19. That great sea-side smell is not ——, but DMS!

21. Perhaps surprisingly, a research project on the south coast of Portugal (5)

23. Marine mammal threatened by Gulf of Mexico oil blow-out (7)

25. Genus of gastropod mollusc (or a mythical huntress) (7)

27. See 15 Across.

29. Charged, positively! (5)

30. Important area for migratory birds, produced by a passing boat (4)

32. Surname of recent Challenger Society President (4)

34. Appendage of starfish (sometimes up to 50 of them) (3)

35. Term once commonly used for a seaman (3)