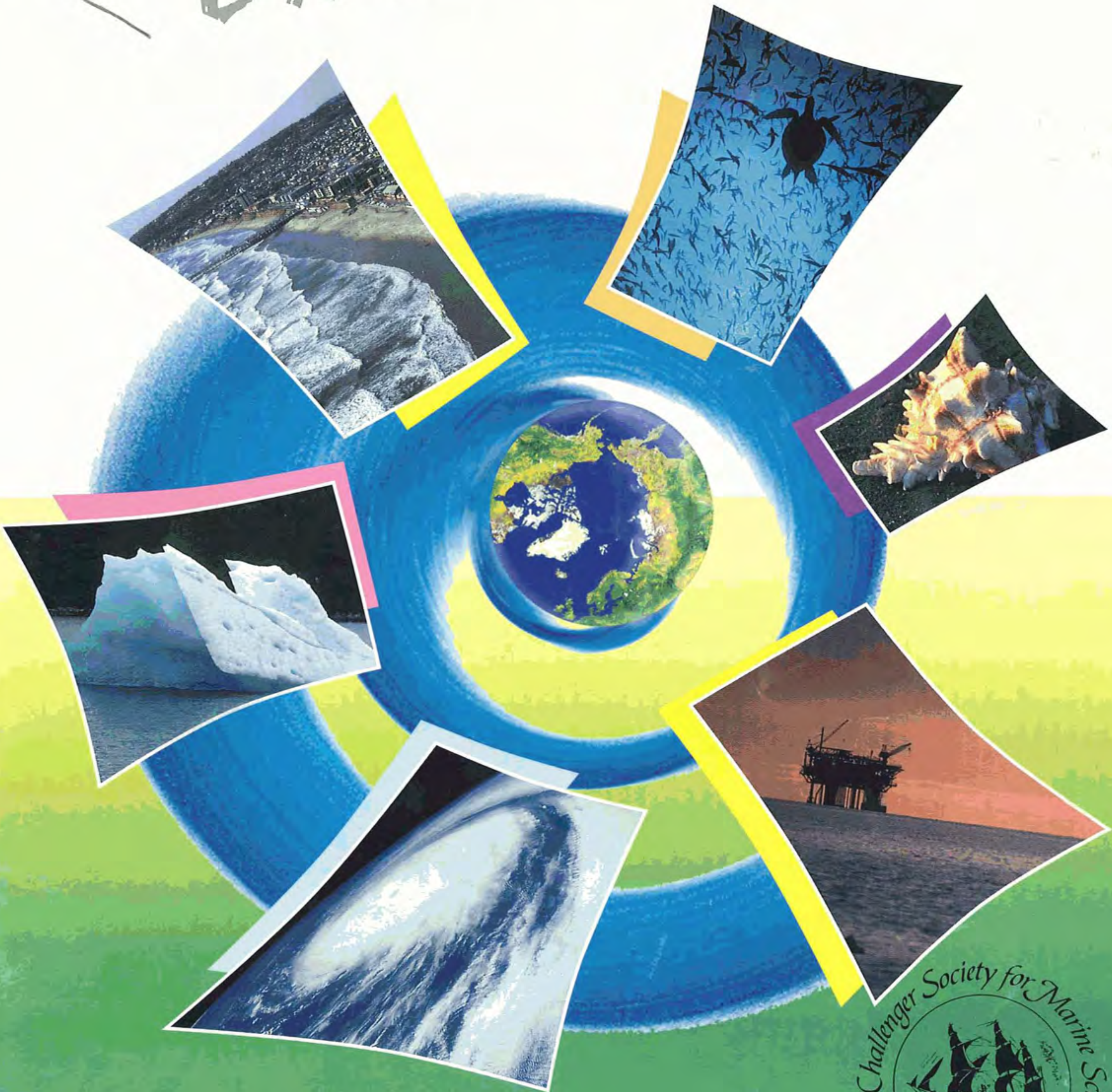
# OCEAN

# Challenge



The Challenger Society for Marine Science

Volume 11, No.1, 2001

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# OCEAN Challenge

The Magazine of the Challenger Society for Marine Science

## SCOPE AND AIMS

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

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# News & Views

## The Atmospheric Distillation Plant

An important corollary of convective atmospheric circulation transporting warmth and water vapour polewards is that evaporation exceeds precipitation ($E-P$ positive) at low to mid-latitudes, whereas precipitation exceeds evaporation ($E-P$ negative) at high latitudes. That relationship applies not just to water but to all volatile substances.

Our industrial society annually releases millions, if not billions, of tonnes of materials onto land and into sea and air. Some of these materials are the same as those liberated by natural (pre-human) biogeochemical cycles, such as metals, oil and gas, and organic wastes, but humans release them at rates much greater than those which characterize natural cycles – and they have been doing so for decades at least, probably for centuries. We have also generated innumerable cycles of our own, cycles of manufactured substances – fertilizers, pesticides, plastics, PCBs, dioxins, radionuclides, exhaust gases, to name but a tiny few – except that most of these 'cycles' aren't really cyclical at all, because the substances do not readily decompose and so are not re-integrated into natural systems.

Many of industry's by-products are volatile, and – like water – they rapidly evaporate at low latitudes, to be carried to higher latitudes by atmospheric convection cells. They may be washed out *en route*, but evaporation can still occur at mid-latitudes, and as some volatiles can stay in the atmosphere for years, the net movement is inexorably polewards. At high latitudes they will condense (like water) onto often snow-covered land and sea; and what falls on the land will be washed into the sea, especially during spring thaws. This process of fractional distillation of volatile substances has increased in scale (and variety of materials) throughout the twentieth century and has led to progressively greater concentratations of pollutants and toxins in polar regions, and the Arctic in particular, because most manufacturing industry is in the Northern Hemisphere. Further concentration occurs when the substances get into food chains. In the mid-1990s, for instance, fish in Spitsbergen's lakes contained six times more mercury than fish in the Scottish Highlands, 20 times more than fish in Spain. PCB levels were up to 90 p.p.m. in polar bears, more than in any other animal in the world. High concentrations of heavy metals (Pb, Zn, Ni, Cu, Hg), as well as of dioxins, PCBs, DDT and other pesticides, were recorded in seabirds, fish and mammals from many parts of the Arctic. The case of mercury is especially interesting, for it is the only metal that exists in the atmosphere predominantly in its gaseous state, as elemental Hg. Atmospheric mercury concentrations ($\sim 1\ \text{ng m}^{-3}$) are fairly constant during winter months, but begin to decrease soon after the Arctic sunrise, probably because mercury is converted to oxidized species which have very short residence times and are deposited, enabling the mercury to enter the biosphere 'at a time when the biota are preparing for peak summertime activity' (*Nature*, **394**, pp.331–32).

As we might expect, the fractional distillation of volatile compounds is altitude- as well as latitude-dependent. Great increases in concentrations of persistent organochlorine compounds have been recorded in the mountains of western Canada, for instance. Depending on the compound being analyzed, concentrations in snow at 3000 m altitude are 10 to 100 times greater than below 1000 m, as a consequence partly of washout, partly of condensation (*Nature*, **395**, pp.535–8).

So far as the marine environment is concerned, there must be some countervailing movement of these materials back towards the Equator, if only because – broadly speaking – that is the way convection drives circulation in the oceans. But the rate of movement of water masses is measured in centimetres per second, that of air masses in metres per second. The return flow cannot keep up with the poleward flow, so this fractional distillation of manufactured pollutants towards the North Pole will continue until we stop producing them.

### *The synergistic effects of global warming*

The adverse effects of higher average temperatures and thinning ice cover on Arctic ecosystems are becoming more widely recognized (e.g. *Ocean Challenge*, Vol.9, No.2, p.8), and reports last summer that open water had replaced pack ice at the North Pole, and that the North-West Passage was open (see opposite), are consistent with suggestions that global warming is more intense in the Arctic Ocean than elsewhere on Earth. This must be at partly because of the 'albedo effect' (open water absorbs more solar radiation than snow and ice) and because there is no circumpolar ocean, as in Antarctica, but it may also be because (despite mixing of air within the troposphere) concentrations of atmospheric $CO_2$ are measurably greater at high northern than at high southern latitudes, i.e. the enhanced greenhouse effect would be greater in the Arctic than the Antarctic. Admittedly there is much more seasonal variation of atmospheric $CO_2$ in the Northern Hemisphere because this is the 'land hemisphere' and supports most of the world's terrestrial vegetation cover. However, it also supports most of the world's $CO_2$-producing industries, emissions from which do not change significantly with the seasons.

If there really is greater northward than southward transport of anthropogenic atmospheric $CO_2$ and if this really does lead to stronger global warming at northern high latitudes, then the additional impact of northwards fractional distillation of volatile pollutants will not improve the survival chances of Arctic ecosystems. Rates of chemical reactions increase as temperature rises, and that presumably applies also to the effects of toxins on the metabolism of plants and animals. Faced with the 'double whammy' of increased pollution and accelerated warming, Arctic biodiversity may be in danger of declining fairly drastically in the coming decades.

## Global Warming Provides New Seaway

As Arctic ice continues to thin and northen winters continue to shorten in response to global warming, the North-West Passage has become navigable by ordinary ships during the summer months. A Holy Grail for maritime commercial interests since the 16th century, the North-West Passage would mean huge savings in time (and money) for ships plying between Europe and Asia (it links the Atlantic and Pacific Oceans between Baffin Bay and the Beaufort Sea, via the Canadian Archipelago). Several expeditions tried to find a way through, but it was always blocked by ice and could not be negotiated even in summer, until ice-breakers were developed.

Last summer, several press reports described large stretches of open water and very little ice along the route, and suggested that cargo vessels will soon be using it. First to exploit the passage will probably be oil tankers, foreshadowing considerable dangers for the fragile Arctic environment – especially as it is likely to encourage even more exploration for hydrocarbons in Arctic regions. It could also be an appealing proposition for cruise ships, which now travel to ever more exotic destinations – and the opportunity to see historical artefacts, camp sites and even the graves of doomed earlier explorers such as Franklin would provide extra attractions.

### *Meanwhile ...*

One of the presentations at Marine Science 2000 (by Martin Wadley and Grant Bigg) was about modelling the response of deep circulation in the North Atlantic to an 'open' Canadian Archipelago. Re-arrangement of the flow of Arctic surface waters would result in the Labrador Sea becoming cooler and fresher, while the Nordic (Greenland and Norwegian) seas would get warmer and more saline. The pattern of overturn in the North Atlantic would change, but not enough to stop the formation and southward export of deep water. However, deep-water formation could be slowed down or even shut off, if rates of Arctic melting were even higher, releasing still more fresh water into the North Atlantic. Europe's winters could then get a lot colder – a high price to pay for a more convenient shipping route; and how might such changes affect the state of the NAO?

## 'Get off the Global Warming Bandwagon'

This intriguing item was obtained from the BBC Worldwide website last November by a colleague who kindly passed it to the Editors.

It comes from William M. Gray of Colorado State University, who is a Professor of Atmospheric Science and an expert in tropical meteorology. The gist of his message is that changes in ocean currents may cause global warming.

Gray begins by asserting that no-one understood the large global warming that took place between 1900 and 1945, or knew if it would continue. Between the mid-1940s and the early 1970s, the warming was replaced by a small global cooling, which gave rise to speculations that a new 'ice age' might not be far off. In the 1980s it all changed back to the global warming bandwagon that US and European governments have been alarming us with ever since.

### *Not our fault*

The small global temperature fluctuations of the last century are 'likely natural changes that the globe has seen many times in the past'. Humans have little or nothing to do with them – we are not that influential. Furthermore (according to Gray) the recent warming trend probably results from 'natural alterations in global ocean currents which are driven by ocean salinity variations. Ocean circulation variations are as yet little understood'.

Gray claims that advocates of human-induced global warming assume that as anthropogenic greenhouse gases increase, water vapour and upper-level (cirrus) cloudiness will also rise and lead to accelerated warming – a positive feedback loop.

### *Negative feedback*

Gray also considers that the general circulation models which simulate significant amounts of human-induced warming are incorrectly structured to give this positive feedback loop – i.e. he believes that the assumptions upon which they are based are not realistic. On the contrary, as human-induced greenhouse gases rise, global-averaged upper-level atmospheric water vapour and thin cirrus should be expected to *decrease*, not increase. Water vapour and cirrus cloudiness should be thought of as a negative rather than as a positive feedback to increases in anthropogenic greenhouse gases. He states that there can be no significant human-induced greenhouse gas warming with a negative feedback loop of this kind.

### *Climate debate has a life of its own*

Average global temperatures have always fluctuated and will continue to do so, says Gray, irrespective of how much greenhouse gas we put into the atmosphere. He goes on: '... the initially honest scientific question of whether or not human-produced greenhouse gases might affect the climate has been grossly exaggerated and misused by those wishing to gain from exploiting peoples' ignorance of the subject. This includes the governments of developed countries, the media and scientists who are willing to bend their objectivity to obtain government grants for research ... I have closely followed the carbon dioxide warming arguments. From what I have learned of how the atmosphere ticks, over 40 years of study, I have been unable to convince myself that a doubling of human-induced greenhouse gases can lead to anything but quite small and insignificant amounts of global warming.'

So now you know.

## Climate Change in Europe and the US

It was probably deliberate rather than fortuitous that William Gray publicized his views during the Hague climate conference last November, which ended so inconclusively. His contention that global warming is a consequence of natural climatic fluctuations (i.e. not anthropogenic) may well have contributed to George W. Bush's repudiation of the 1997 Kyoto agreement to reduce greenhouse gas emissions; also for his determination to allow drilling for oil and gas in Alaska's Arctic wilderness.

### *People in glass houses ...*

Complaints by Britain (amongst others) about the President's environmental perfidy did not (of course) mention the £100 million subsidy awarded to the UK coal industry in April 2000, nor the UK Government's subsequent approval for a further half-dozen gas-fired power stations. Gas produces less $CO_2$ per joule than coal, so why subsidise the coal industry? OPEC has also raised oil production a couple of times during the last eighteen months, which slowed the increase in fuel price a little but didn't do much for $CO_2$ emissions.

**continued**

### Climate Change ... (cont.)

***Old King Coal as a source of gas***

Why build new gas stations when you can use the methane from abandoned coal mines? An enterprising new company called Alkane is collecting the methane that seeps out of the ground in Britain's coal fields and using it to generate electricity, which it sells to the grid. Since methane is a much stronger greenhouse gas than $CO_2$, it makes more sense to burn this 'coalfield legacy' than to pump a lot of new gas out of the ground and burn that instead. But industry is more about making money than making sense, so the new power stations will all be built anyway.

## Noah and the Black Sea Waterfall Revisited

New evidence of human settlements on the bed of the Black Sea, found by the indefatigable Bob Ballard and his underwater exploration team towards the end of last year, generated headline phrases like 'Home of Noah found ...' and '... Noah's ark flood victims'. However, the submerged buildings and artefacts are at a depth of only about 100 m, and the Black Sea is over 2000 m deep. Available evidence suggests that the settlements were overhelmed by flood waters about 7 000 years ago, but it remains an open question whether or not this was the legendary 'Noah's flood' – which was also recorded in the epic Gilgamesh saga.

The prehistoric Black Sea was probably a large freshwater lake, not a giant evaporation pan as previously suggested in these columns (*Ocean Challenge* Vol. 8, No. 3, p.9) – and subsequently disputed (*op. cit.* Vol. 9, No. 1, p.39). The lake was about half the size of the present-day Black Sea, and was transformed into the modern inland sea as global sea-level rose after the Last Glacial Maximum, and seawater flooded into the lake via the 'Bosphorus Waterfall' (cf. also *New Scientist*, 4 October 1997, pp.24–7). The Black Sea would have filled 'from the bottom up', as denser seawater plunged beneath the less dense freshwater, and this may have contributed to the anoxia that now characterizes Black Sea waters below about 200 m. During the intervening millenia, however, there must have been at least some mixing, to even out the salinity and develop the present-day salinity structure of the Black Sea: about 200 m of relatively fresh (salinity ~18) oxygenated water above some 2000 m of anoxic water with a fairly uniform salinity of 22.

The archaeological remains discovered by Ballard and his colleagues are at least consistent with the flood stories of legend. The question is, are they in the right place? According to Bible scholars, the cities that were submerged by 'Noah's flood' lay in Sumeria, near the head of the Persian Gulf, a good thousand kilometres from the Black Sea. This is also the flood plain of the Tigris and Euphrates, and the heavy rain and floods we ourselves experienced last autumn provide a reminder that '40 days and 40 nights' of rain could well have been enough to cause those major rivers to overflow their banks. Somewhat less plausibly, it has also been suggested that the cause of the flood was a tsunami generated by an earthquake in the Indian Ocean (*Terra Nova*, 2000, **1**, No. 4, pp.326–38) – or it might even have been a comet! (*Ocean Challenge* Vol. 9, No. 2, p.8). None of these stories does much to encourage those who seek the remains of Noah's ark in the mountains of eastern Turkey (*Ocean Challenge* Vol. 7, No. 3, p.18).

## Life's Tough

A viable spore of a halophilic bacterium, trapped in a fluid inclusion inside a 250 *million*-year-old halite crystal has been successfully cultured, i.e. 'brought back to life' (*Nature*, **407**, 844–5, 897–900). It makes earlier successes in reviving bacteria trapped in amber a mere 40 or 120 million years old look tame by comparison. It is also further evidence that unicellular life is extremely robust. Dormant spores could easily be transported about the galaxy by meteorites or comets or even as dust, and it's entirely possible that the earliest life-forms on Earth, found as fossils in the oldest rocks, didn't originate here at all, but came from outer space.

Incidentally, that salt crystal was from a mine nearly 400 metres down. How long would it have taken those salt deposits to become naturally exposed at the Earth's surface? Would the bacterial spores still have been viable then? Probably – after all, what's an extra hundred million years of sleep to an organism that doesn't dream?

## Another Coelacanth Find

Last November, divers from South Africa's Coelacanth Expedition 2000 found a juvenile and two adult coelacanth 100 metres down in Sodwana Bay, part of the St Lucia Marine Reserve, off the coast of KwaZulu-Natal. The fish are evidently quite common in the south-west Indian Ocean, for individuals or colonies have now been found off the Comoros Islands, Madagascar and Mozambique, as well as South Africa. Last year, a small colony was found on the other side of the Indian Ocean, off Indonesia (*Ocean Challenge*, Vol. 9, No. 1, p.4), though its affinities to the main centre(s) of population have not yet been established.

The KwaZulu Natal Parks Board runs a thriving conservation and fisheries protection programme, and has established several protected marine areas, including rocky shores, estuaries and coral reefs as well as parts of the adjacent open ocean, in the warm clear waters of the Agulhas Current. It is plainly a divers' paradise, which attracts many tourists – and conservation-minded coastal oceanographers would probably be particularly welcome visitors.

## A paradigm shift: An oceanic 'Lake Nyos Effect'?

Negative 'spikes' in the $\delta^{13}C$ record in marine sedimentary sequences are not uncommon. Well-documented examples occur at about 55 Ma (the Palaeocene–Eocene transition), at about 183 Ma (the early Jurassic), and at about 250 Ma (the Permo-Triassic transition). The carbon isotope 'spikes' are negative and signal that there was an abrupt addition of large amounts of 'light' carbon ($^{12}C$) to the atmosphere. 99% of carbon is the 'heavier' $^{13}C$ isotope, the lighter $^{12}C$ making up less than 1% (there are other carbon isotopes too, but they are even less abundant). The process of photosynthesis that fixes $CO_2$ into organic matter also fractionates the carbon isotopes, taking a significantly greater proportion of the lighter $^{12}C$ than of the heavier $^{13}C$ isotope. The $\delta^{13}C$ value, an index of the relative amounts of the two isotopes and hence of the extent of this fractionation, is typically of the order of –25 (per mil units) in organic matter, and normally ranges from zero to small positive values in carbonate sediments, formation of which does not fractionate carbon isotopes.

The favoured explanation for the negative $\delta^{13}C$ 'spikes' is catastrophic release of methane from gas hydrates in continental margin sediments, as a consequence either of slumping or of meteorite impact. But is it not equally plausible that a mid-ocean impact of a large meteorite could cause catastrophic turnover of a large chunk of ocean? That would bring deep water to the surface, releasing vast amounts of the $CO_2$ dissolved in it. The carbon dioxide dissolved in deep ocean water is the product of re-mineralization of organic matter, nearly all of which was originally fixed by photosynthesis in surface waters. So the $CO_2$ in the deep ocean must be enriched in $^{12}C$, and its release would liberate large quantities of 'light carbon' into the atmosphere. Since that carbon is already in the form of $CO_2$, it is immediately available for assimilation by carbonate-secreting organisms. 'Light carbon' from methane must first be oxidized to $CO_2$ before it can be used to form carbonates.

Some of the mass extinction events in the geological record are accompanied by negative carbon isotope signatures (e.g. *Ocean Challenge*, Vol.10, No.2, pp.2–3). However, these cannot be used to discriminate with confidence between the two most popular causes of such extinctions, *viz* flood basalt eruptions, versus meteorite impact, simply because $CO_2$ of volcanic origin is also enriched in the lighter carbon-12 isotope (e.g. *Nature*, **406**, pp.356–7). Nor is there any way of discriminating between release of gas hydrates (methane) and oceanic 'Lake Nyos events'* (carbon dioxide), since both $CH_4$ and $CO_2$ are greenhouse gases, and negative $\delta^{13}C$ 'spikes' in the sedimentary record are commonly accompanied by evidence of more or less contamporaneous global warming events.

Release of deep ocean $CO_2$ by meteorite impact was first mooted in these columns three years ago (*Ocean Challenge*, Vol. 7, No. 3, p. 6), and it is still a nice idea. Trouble is, 'Deep Impact' scenarios releasing greenhouse gases sounds too much like sci-fi to be taken up by serious scientists.

*Named after the catastrophic release of $CO_2$ (and many fatalities) that occurred in 1986 when a crater lake in Cameroon overturned following an Earth tremor.

# PRMES – A Grand Day Out

So what's this 'PRMES' thing about I hear you ask? Put simply, PRMES is a conference run for postgraduate students, *by* postgraduate students. This event has built up over the last nine years into a unique opportunity to meet with other postgrads from all over the UK and practise those vital presentation skills in a friendly atmosphere. It is also a good time to swap experiences of postgrad life. Hosted jointly by the Marine Studies Group of the Geological Society of London and the Challenger Society for Marine Science, the PRMES remit is to cover all aspects of geological and marine science – from ecology to sedimentology, physical oceanography to marine chemistry, geophysics to palaeoceanography. Every marine and Earth science postgrad in the UK could potentially make a presentation a at PRMES, and quite a lot regularly do.

I was one of 14 delegates from the Southampton Oceanography Centre who survived a mercifully uneventful minibus journey up to Durham for PRMES 2001. We made good time and arrived early on the eve of the conference. I think everyone would agree that our accommodation in Durham University halls was top class, nothing like anything we had experienced as undergraduates. Durham is a very pretty cathedral city, sitting high on the inside of a tight meander of the River Wear. Over the next two days we would have plenty of opportunities to explore Durham's historic city centre. Durham University were consummate hosts, laying on lunches each day, and a sumptuous cheese and wine reception at their newly built graduate centre. Despite the chilly March weather, the highlight of the trip was the BBQ and disco onboard a River Wear pleasure cruiser.

We heard 16 fantastic scientific talks, and the quality of poster presentation was very high indeed. It was really excellent to meet the various delegates from all over the UK, including some old friends from previous PRMES meetings. Encouragingly, everybody seemed to be very successful in their studies. When we returned to Southampton late on the Wednesday night, I had a bus full of tired but happy individuals, many of whom had given a talk for the first time, and all of whom had hopefully made some new friends.

I feel one must end a report such as this with a list of 'thank you's to everyone involved in making the Durham conference such a success – not least to Abi and Rich, my fellow convenors who put in most of the hard work organizing the event. Many thanks must go out to all the people who got involved: speakers, poster presenters, and delegates. Many thanks also to our sponsors for their financial support – the Geological Society, the Challenger Society, BP plc, Enterprise Oil plc, the Graduate Society of Durham University, and Southampton Oceanography Centre. A special thanks goes to all the Ph.D supervisors who encouraged their students to attend.

Finally congratulations to Sheila Stark, winner of the prestigious best talk award, and Mohammed Ali, winner of the best poster presentation award.

The PRMES conference has a moving home. Next year Cardiff will be hosting PRMES 2002. I look forward to seeing you all in Wales!

**Ian Burke**
*Southampton Oceanography Centre*

**A Date for Your Diary**

**UK Marine Science 2002**

will be held from 8 to 13 September
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# Estuaries and Coasts of NE Scotland

## Report of ECSA UK Local Meeting in Aberdeen

Estuaries form a boundary zone between the land and the oceans, where fresh water and salt water intermix. They are areas of global importance, maintaining high rates of primary productivity and supporting large food webs, as well as having a vital role in the protection of our coastlines. Scientists from disciplines encompassing biology, physics, geography and geology have long been curious about estuarine dynamics. Meetings of ECSA (the Estuarine and Coastal Sciences Association) aim to unite scientists from all these disciplines and provide a forum to review recent developments. The local meetings provide excellent opportunities to discuss findings and progress (both formally and informally) at a regional level. The meeting held on 29–31 March this year focussed on the estuaries of the north and east of Scotland, namely the Eden, Tay, Esk and Ythan estuaries, as well as areas of the Montrose basin.

The meeting was organized by Dr Martin Solan (Aberdeen University), Professor Dave Rafaelli (York University) and Professor David Paterson (St Andrews University). It was held in the Zoology Building at the University of Aberdeen, and delegates were accommodated in halls of residence within walking distance. A total of eighteen 30-minute talks were presented, as well as four posters. The meeting also incorporated the ECSA Annual General Meeting and a Council meeting.

The first session was opened by Scot Hagerthey (St Andrews University) who outlined how remote-sensing techniques can be used to examine estuaries at a broad scale, and discussed a project that does exactly that: the EU-funded BIOPTIS programme. Remote sensing was also considered by Graham Ferrier (University of Hull), who provided insights into some of the problems intrinsically associated with these methods. Judith Dobson (Scottish Environmental Protection Agency, SEPA) used a similarly broad appoach, providing an overview of the South Esk Estuary and examining its ecological status. Emma Defew (St Andrews University) also considered estuaries at the large scale and discussed the 'ground-truthing' component of the BIOPTIS campaign, with particular emphasis on predictions of sediment stability. These studies emphasized that estuaries are inherently areas of high variability in which simple relationships are almost impossible to discern.

The relevance of baseline monitoring was discussed by Gary White from the Aberdeen Harbour Project. Estuaries cannot be considered static, and this was highlighted by Jack Jarvis (St Andrews University), who provided a detailed dataset pertaining to channel movements and shoreline changes on the Eden. This talk highlighted the fact that what one sees and presents at such a meeting may not be the case one hundred years, ten years, or even one year later. This point is particularly relevant to scientists such as Claire Maynard (also from St Andrews University), who are looking at ways to accelerate saltmarsh accretion as a means to defend our coastlines.

Changes in estuarine environments and their fauna were considered by Andrew Hill (SEPA) who described the response of macrofauna to improvements in effluent discharge, as well as by Ian Patterson (Aberdeen University) who examined changes in bird populations on the Ythan. Reasons for such changes were picked up on by Udayangani Fernando (Aberdeen University) who discussed the effect of macro-algal mats on the distribution and feeding of shore birds. The resilient nature of macro-algal mats was examined by Rebecca Taylor (Dundee University). She discussed the survival of *Enteromorpha,* apparently against all the odds, in the inhospitable anoxic depths of sediments. Algal mats cannot be considered a permanent fixture and, in a switch from the macro to the micro, Dave Paterson (St Andrews University) discussed the transient nature of diatomaceous mats in estuarine sediments and whether or not algae got rhythm! Diatoms are unicellular algae which are often capable of movement, and Dave examined some of the factors that might control their temporal distribution over the low tide period; while Martin Wilkinson from Heriot-Watt University described the wider scale distribution and biodiversity of seaweeds around Orkney.

The term 'bio-engineering' has recently been introduced into the ecological literature, and Martin Solan and Richard Ford presented a joint talk examining this phenomenon in benthic estuarine systems. Bio-engineers were considered in more detail by Stefan Ragnarsson (Fisheries Institute of Reykjavik) and Catherine Biles (St Andrews University) who presented work on the influence of biodiversity on bio-engineering.

Undoubtedly it is important to bring together the work of scientists and legislators, and the meeting provided some insightful discussion. Peter Pollard (SEPA) introduced the Water Framework directive to a new audience. The importance of protection was further covered by Alison Matthieson (Scottish Natural Heritage) who discussed the challenging but enjoyable nature of work at the Forvie Nature Reserve.

All the delegates came to the ECSA meeting with their own theories about what an estuary is and why estuaries are important. The meeting highlighted the variability in scale at which estuaries are examined, and the necessity for all approaches. Perhaps one of the most curious statements made at the meeting was that, in fact, we are all wrong – estuaries are not estuaries, but bodies of 'transitional waters'!

The real lure of estuarine work was explained by Dave Rafaelli, who presented an informal slide show about his career on the Ythan, the host estuary of the meeting. Sadly, a field excursion to the Ythan was cancelled because of Foot and Mouth restrictions, but the estuary was nevertheless brought to life through the show. Dave's slides and enthusiasm encapsulated what it is that drives – and will continue to drive – mudlarkers the world over.

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# THEY DID THINGS *differently* THEN ...

## A tale of the unexpected

**Peter Foxton**

Not surprisingly, failed experiments are rarely reported. The incriminating evidence in notebooks and logbooks is usually consigned to dusty archives where it gets forgotten. As a distinguished scientist once remarked, the occasional failure is permitted, as long as your batting average remains high. The tale that follows concerns a field experiment that failed, and how in the end we gained a positive result in the most unlikely way.

In the 1950s, the biological programme of the National Institute of Oceanography, with its origins in the classic work of the *Discovery* Investigations in the Southern Ocean, started to focus on problems nearer to the UK, particularly in the North Atlantic. One of the new projects aimed to study the distribution and biology of the common oceanic squid as a contribution to a broad-based study of the growth, age and feeding of sperm whales, for which squid are a major food source. The experimental design was simplicity itself – hang baited hooks at intervals on a vertical wire, lower into the depths, leave for a time, haul in and remove catch. The clips, which allowed the hooks to be easily attached to, and removed from, the wire were based on the sea angler's paternoster, a simple wire frame to which the baited hook is attached.

A supply of fresh bait was obtained and off we sailed on RRS *Discovery II* to catch squid. The preferred time for fishing was between midnight and dawn, when the other scientific work of the ship had finished, and since only two persons were needed to operate the gear the project became popular with our colleagues, who were able to retire to their bunks leaving us to while away the night fishing. Although we were full of hope, our first attempts were a complete failure, with no evidence of the baits being taken. This was all the more perplexing because squid of up to 0.5 m length could be seen at the sea surface where they were attracted by the ship's lights. So we persevered, varying the time and duration of fishing, the spacing between baits on the line, the depth of the baits, and the type of bait. This last presented a problem because the available freezer space was jealously guarded by the Chief Steward, and our limited stock of fresh bait was soon used up. After that, the selection of baits tended to resemble the ship's menu of the previous day, with a virulent looking pink bologna sausage featuring prominently, along with canned pilchards and herrings. We even tried artificial baits. These included lures of various shapes, some luminous, a flashlight waterproofed with a condom, a bag of boiled hemp seed (to stupefy the squid), and a variety of ineffective mechanical devices (worthy of an article in themselves). Notwithstanding our commitment to long hours of fishing on cruise after cruise, we continued to amass negative results and failed to hook a single squid. The message was plain: our results were showing nothing about the distribution of squid, they were merely confirming the inadequacy of the method. Thus it was that eventually, and with great relief all round, we were allowed to terminate the project.

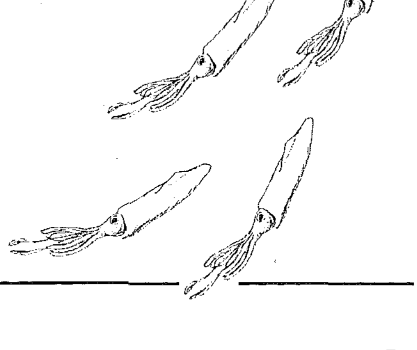
We were then asked to do something completely different, which had nothing to do with squid. At the time, John Swallow was breaking new ground, using his neutrally buoyant floats to study ocean currents and circulation. In contrast, down the corridor Dr J. (Jack) N.C. Carruthers, a senior scientist at the Institute, was convinced that there was a need for many Third World countries, with little or no tradition in marine science, to undertake local investigations and contribute to studies of global problems. Jack felt that there was a need for cheaper and simpler alternatives to the new electronic devices that were being developed. To this end, he was designing a range of current measuring instruments constructed from inexpensive everyday items that were readily available. With great ingenuity he utilized objects such as babies' feeding bottles, cycle inner tubes, gelatin, paraffin, and toy magnetic compasses, to make devices which, I have to say, under ideal conditions and with some dexterity on the part of the operator, could be used to measure current speed and direction.

At the time we were abandoning our fishing project, Jack was seeking a cheap form of positive buoyancy and viewed a well known brand of Irish Stout as a possibility. At that time, Guinness was sold in pint bottles made of thick brown glass and closed with a screw top fitted with a rubber seal. The question was, at what depth would a sealed empty bottle implode? Since a biological cruise was already planned, the failed fishing team were presented with a crate of a dozen pint bottles of Guinness and asked to undertake the definitive tests at sea. There was no shortage of volunteers to help with the convivial preliminary stage of the experiment, which required the bottles to be emptied. This achieved, the empty bottles were resealed, placed in a sack and then secured on a weighted plankton wire. The plan was to lower the bottles progressively (recovering them at intervals as a check), until we reached a depth at which they imploded.

As a night-time activity it had a lot to commend it and we set about emptying and lowering the bottles. My recollection becomes hazy, perhaps because of the soporific effects of Guinness. However, I do recall a feeling akin to horror on seeing the sack emerge from the sea with a large squid clinging firmly to it. Success at last – but what a comment on our previous miserable attempts!

I am ashamed to say that my immediate reaction was to throw the squid back before it was seen, but I was prevented by my more conscientious colleague, Arthur Baker, who recovered the specimen as testimony to our unique achievement. Sad to say, our success did not initiate more extensive comparative trials – although clearly there were great possibilities!

**Peter Foxton** joined the National Institute of Oceanography as a marine biologist in 1949, and later worked for the Marine Sciences Division of the Natural Environment Research Council.



# Dr Howard L. Sanders, Pioneer in deep-sea benthic studies

With the death of Howard Sanders, we have lost the founder of modern research into the fauna of the abyss. Saunders brought deep-sea benthic studies into the modern day, with exploration of transects across the major basins of the Atlantic, using novel sampling techniques designed to capture the minute animals that inhabit the deep-sea bed. He was responsible for transforming the science from what it had been during the first era of deep-sea research (which began with the *Challenger* Expedition of 1872 and culminated in the *Galathea* expedition of 1953), when major expeditions circumnavigated the world, sampling along the line of the ships' tracks.

Howard Lawrence Sanders was born in 1921 in Newark, New Jersey. From 1942 until 1945, during World War II, he served in the US Army Signal Corps and was involved in breaking German codes, intercepting a plan for a last effort to stage a strategic battle to surround the American Army within the Bastogne. For this he was awarded the Bronze Medal.

In his early childhood he had walked the beaches of New Jersey and had been fascinated by the marine environment. After the war, and following a brief enrolment at Rutgers University, he graduated in Zoology in 1949 from the University of British Columbia. During this time he spent his summers with the US Fish and Wildlife Service, first at Bristol Bay in Alaska, tagging fish, and then in Florida where he initiated a taxonomic survey of the fauna of Pensacola Bay. Thereafter he joined the first Oceanography Masters Class of the University of Rhode Island where he studied under Donald Zinn and then joined Evelyn Hutchinson's Department at Yale to study the benthic fauna of Long Island Sound and Buzzards Bay. With the inspiring guidance of Hutchinson he became immersed in the structure and interrelationships and diversity of animals living in soft sediments, completing his Ph.D in 1955.

***Howard Sanders, academician and leading marine ecologist, sampling for mystacocarids (tiny crustaceans) at Woods Hole in 1982.***

A momentous offshoot of his work on the fauna of Long Island Sound was the discovery of an unknown primitive crustacean of a new subclass of animals. Sanders named the animal *Hutchinsoniella* in honour of his Professor. This discovery completely changed the prevailing views of the evolution of the Crustacea. Furthermore, it ran counter to the opinion of the great Sidnie Manton of the British Museum, at that time the world expert on arthropod evolution. It was on a par with discovery of the coelacanth and led to great evolutionary debate, much of it tinged with acrimony. Sanders maintained his interest in primitive crustaceans, and over the years described a number of new families and species. This work came to the attention of Emperor Hirohito, himself a crustacean expert, who expressed a wish to meet with Sanders on the occasion of his state visit to the United States in 1975. Originally a week was to be set aside to visit Woods Hole, but this was reduced to four days and finally to six hours, which was sufficient time to see and receive specimens of the new species and to discuss their value to the evolution of the group.

After Yale, Howard Sanders joined the staff of the Woods Hole Oceanographic Institution (WHOI) and he stayed there throughout the remainder of his scientific career. Having decided to extend his work on diversity in soft sediments to those of the deep sea, he attracted a team of young scientists, most of whom were later to become eminent in their science. Together they devised new sampling techniques and set about a systematic exploration of the abyssal basins of the Atlantic, sampling along a series of traverses downslope and across the abyssal plain. They found that although relatively few in number, the animals of the abyss were among the most diverse in the sea. At WHOI the samples were sorted, each group being assigned to a specialist. Hundreds of new species have been described by Sanders and his co-workers. These discoveries led to great debates about the evolution of deep-sea fauna and how such wide diversity could occur in such monotonous expanses of soft sediments. This led Sanders to formulate his time/stability hypothesis. He argued that benign conditions over geological time-scales provide the conditions in which diversification can occur with minimum competition. This idea was to stimulate much argument, including a debate about the wisdom of disposing of wastes in deep waters, that continues to this day. The equipment used (particularly the epibenthic sled), and the systematic approach adopted, became standard practice for other nations to follow, including France and Great Britain.

Sanders attracted many international scientists. On one memorable occasion he invited an eminent Russian scientist to join him in the RV *Atlantis II* to sample the deep waters of the Gulf of Sirte in the Mediterranean, an area where it is doubtful whether a research vessel, particularly one from the USA, would now be allowed to operate. Regrettably, the scientist was refused permission but, unexpectedly, the ship was tracked closely by a Russian warship. For the whole of the cruise the follower stayed dangerously close and sounded on the same frequencies as the recording equipment attached to the sampling gear. With 5 000 metres of warp over the side sampling became something of a nightmare, particularly when the Russian ship decided to position itself a short distance ahead of the advancing tow.

Then, in 1969 the oil barge *Florida* ran aground in Buzzards Bay, spilling 700 000 litres of fuel oil. Sanders made what became a baseline quantitative study of the long-term effects of an oil spill on the shallow marine environment. This led him into direct confrontation with the oil companies over how serious the environmental impacts of oil spills could be. There was much criticism of 'grey research' carried out by the companies, which was accepted without review. Sanders said 'quick answers mean dirty answers'. His meticulous work on the oil spill now stands as an example of how the effects of such events should be investigated.

He was adjunct Professor at State University of New York at Stony Brook and an Associate in Invertebrate Zoology at Harvard. In 1986 he was elected to the American National Academy of Sciences. He always believed that scientists needed to make the results of their work known to policy makers and the public, and his election meant that he could increase his involvement in this field. In addition, he began to be involved in the complexities of funding of scientific research at government level.

Sadly he had little time to immerse himself in such national and international matters, for it soon became clear that he had succumbed to Alzheimer's disease. It was a great sadness to family, friends and colleagues to watch the slow decline of such a charming, gentle and loving family man, who had been a great debater and contributor to scientific discussion. He died in February, and is survived by his wife, Lillian, who had been his companion since his days at the University of British Columbia, and by their two sons and two grandchildren.

**John Allen**
*University Marine Biological Station, Millport*

# Prof. John M. Edmond FRS

It is with great sadness that we report the early death of John Edmond, one of the most brilliant marine geochemists of his – or of any – generation. Originally from the UK or, to be more specific, Scotland and Glasgow, John had worked in the USA since the mid-1960s and was a Professor in the Department of Earth Atmospheric and Planetary Sciences at MIT. John played a significant role in the Geochemical Ocean Sections expedition in the 1970s, and was involved in the first discovery of oceanic hydrothermal vent activity. He had a sustained interest in the chemistry of natural continental waters (pristine rivers, lakes and estuaries), and their relation to geology and the weathering environment, especially climatic conditions, and worked extensively on the water chemistry of rivers and lakes of East Africa, on the Amazon and Orinoco, and on the major rivers of the Russian Far East (Siberia).

John gained his BSc. from Glasgow in 1965 and his Ph.D in 1970 from Scripps Institution of Oceanography, University of California. He was awarded many honours: a Fellow of the Royal Society, and of the AGU, and a recipient of the AGU's Macelwane Medal. He served on the editorial boards for *Earth and Planetary Science Letters, Geochemical Journal* (Japan), and *Chemical Geology/Isotope Geochemistry*. He also served on the RIDGE Steering Committee and in the Geosciences and Astronomy division of the Royal Society.

He will be sadly missed by the many UK scientists who made the journey from British Universities to the E34 building off Kendal Square as NATO postdocs, research staff, and sabbatical or occasional visitors; also by those who encountered John's razor sharp intellect and critical perception at scientific meetings. He was a generous and truly inspirational scientist.

It is hoped that at some stage there will be an opportunity to honour John in a manner that he would have deemed suitable.

**Harry Elderfield**
*University of Cambridge*

***John Edmond: inspired researcher and inspirational colleague***

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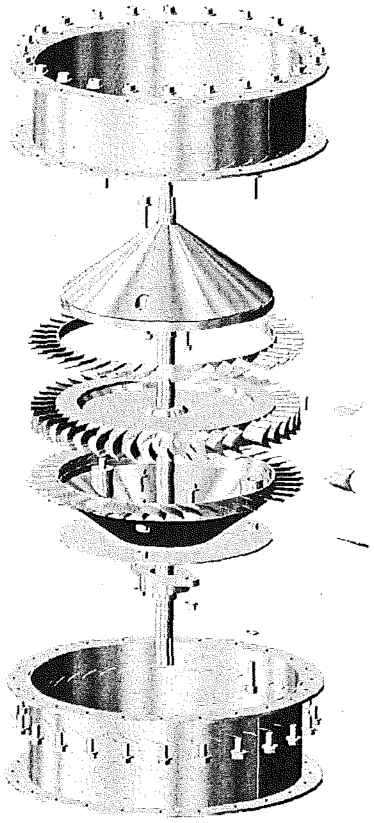
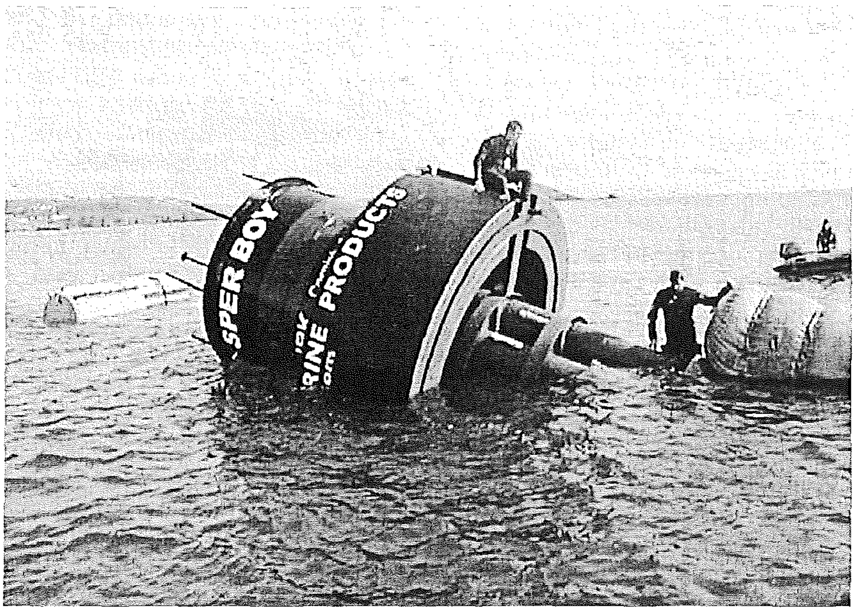
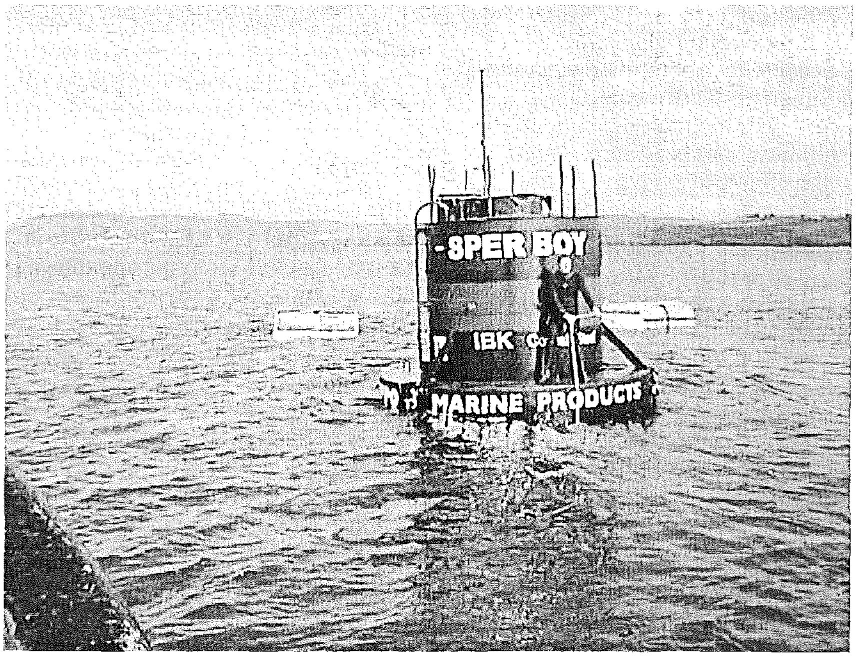
# Renewable Energy from the Sea

In early April we saw the official launch, in Plymouth, of *Sperboy*, a Wave Energy project developed by a consortium of five small companies and three universities from across Europe. The project is funded by the EC under the Joule-Thermie Non-Nuclear Energy Program, and the consortium includes PEP, which manages the commercial activities of the University of Plymouth. PEP hosted the event at the Royal Western Yacht Club, Queen Anne's Battery, where at least 50 invited guests were treated to drinks and a light lunch, prior to being introduced to the project by key members of the consortium, and then – highlight of the day – taken on a short boat trip to view the *Sperboy* device doing its stuff. What we saw was in fact a pilot unit that's been mooored in 20 metres of water a mile or so off the Plymouth breakwater since February, generating data to assess 'design feasibility and equipment performance under a range of sea conditions'.

***The Wells turbine rotates in the same direction, whether the air flow is up or down. The secret of the unidirectional flow lies in the curved teeth of the central 'gear-wheel'.***







***Above:* Sperboy at the test mooring site, outside the Plymouth breakwater.**

The underlying principle is simple: oscillations of the water surface, in response to passing waves, pump air up and down through a Wells turbine, which is a cunning device that continually rotates in the same direction even though the air flow through it reverses as each wave passes. *Sperboy* itself is a bit more complicated though. It is a 'multiple oscillating water column wave energy device, designed to capture energy across a broad waveband'. For a particular offshore location, the waveband over which *Sperboy* operates can be chosen to make the best use of the local wave climate.

Even the people who devised the thing aren't wholly convinced they understand exactly how it works, but they conveyed the basic idea. Columns of different lengths extend below the buoy, each tuned to 'resonate' at a particular wave frequency (period). Because of this 'resonance', the amplitude of oscillation of the water surface *inside* the column is actually greater than that of the water surface on the waves passing by outside the columns. The resonance thus allows more energy to be extracted from each wave.

The pilot plant we saw has four resonating columns of about 50 cm in diameter, their lengths 'tuned' to prevailing periods at the mooring site: 4 m for 4.5 s period waves, 5.5 m for 5.0 s, and 7 m for 5.7 s. A fourth column, 10 m long, extends below the wave base of most waves, and we were given to understand that its purpose is to provide extra 'drive' to the turbine, through vertical motions of the buoy itself as it oscillates up and down with the passage of the waves. On the day of our visit, waves were of the order of a metre in height.

The pilot plant is capable of producing some 200–300 kW of electricty, but it will be producing only data until April next year, because it is essential to test the design under storm conditions, especially in light of the sad demise of the *OSPREY* project off Scotland several years ago (*Ocean Challenge*, Vol. 7, No.1, p.7). The *Sperboy* monitoring programme is funded by the DTI, and next year the data will be analysed and the efficiency of the design evaluated.

### *Meanwhile, in Scotland ...*

A concrete ramp built into a small cove on the Inner Hebridean island of Islay absorbs most of the energy of breaking waves, but some of the water enters a column behind the ramp, forcing air up through it, and then down again as the waves recede. The Wells turbine inside the column is about the only feature that this installation shares with *Sperboy*. This plant (called *Limpet 500*) was commissioned in November last year and generates up to 0.5 MW, the same as will eventually be generated by *Sperboy*. The company running the project has secured a 15-year contract to supply electricity to the Scottish grid.

### *The energy's out there, can we tap it?*

A recent EU study estimated that Britain could generate all the electricity it needs if only 0.1% of the energy around its coasts could be collected. That estimate probably includes wind and tidal energy as well as energy from waves, and it could be exaggerated; but it gives an indication of the vast potential that's out there.

*Sperboy* and *Limpet 500* are relatively small examples of how that potential can be tapped, but wave power technology still lags far behind the development of offshore wind farms. The world's two largest wind turbines, off the Northumberland coast near Blyth (ironically once a thriving coal port) have been supplying 4 MW to the National Grid since the end of last year; and plans to increase the number are well advanced – even though the MoD wants to slow development of wind farms, because they might interfere with low-flying military aircraft. Surely that has to be nonsense? Wind farms are not unique to Britan; how do other countries cope? In Denmark for instance, 50 per cent of the country's electricity needs will be met by (mostly offshore) wind farms within the next couple of decades – migrating birds are likely to be more at risk from the turbines than military jets would be.

### *Thinking big about tidal energy*

Grandiose proposals for making use of tidal energy have featured in press reports over the last few months. One is the 'hollow island' scheme, to be sited in coastal waters off Rhyl in North Wales, where the tidal range approaches 10 m during spring tides. The company behind the scheme is an outfit called Tidal Electric, and their concept is an alternative version of the tidal barrage principle. They plan to build a wall in the sea to make a large (50 km$^2$) artificial lagoon. Sluices fitted with turbines will allow water to fill the lagoon and generate electricity on the flood tide. Closing the sluices while the tide falls outside enables a head of water to build up in the lagoon. Re-opening the sluices allows the water to flow out through the sluices and generate more electricity.

An ingenious refinement will be to have three separate compartments in the lagoon, so that electricity generation can be more nearly timed to coincide with periods of greatest demand – and off-peak tidal power could be 'banked' in the nearby Dinorwic pumped storage reservoir. This seems to be a more atractive proposition than damming estuaries, which can interfere with movements of fish and with exchanges of sediment and nutrients between estuarine and offshore waters and can adversely affect intertidal environments behind the barrage.

Moreover, at an estimated £500 million for an eventual generating capacity of 400 MW, the cost would seem to compare favourably with that for a large tidal barrage of conventional type and similar output. Vast quantities of rock would be needed, though: something like 300 million tonnes if not more (the amount depending on the configuration of the lagoon), which is a whole lot more than required to dam even a large estuary like the Severn. But the offshore lagoon concept has other advantages. There are plans to have a tram link to the lagoon, a cycleway round it, a fish farm inside it and a marina alongside, plus a wind farm on top, to boost generating capacity. The Welsh Assembly and environmental groups are reported to be backing this scheme, which would use tried and tested technology, albeit in a novel setting.

That is more than can be said for the 'marine turbine' scheme, another mega-project also proposed for North Wales. The idea is to place turbines in the sea off the north coast of Anglesey, to tap into the energy of the fast tidal currents (up to 2 m s$^{-1}$) there. This is not a new idea. Several years ago, a paper in *Underwater Technology* (Vol.19, No.4, pp.7–11) explored the possibility of putting 'tide mills' into channels between islands in Orkney and Shetland; and late last year a *Guardian* feature on renewable energy carried the throwaway phrase '... the world's first major marine turbine is about to be installed in the sea off Lynmouth, north Devon'. But the scheme proposed for Anglesey is on a truly enormous scale. The plan is eventually to have a 'tide farm' of a thousand 20-m diameter turbines on a 10 km$^2$ area of sea-bed, with a combined maximum generating capacity of 1000 MW. It sounds like a great idea, but the costs and logistics of installation and maintenance must surely be horrendous – and there's a lot of wave energy off North Wales too, perhaps it would be more sensible to moor some *Sperboy* units offshore.

**Eds**

If you would like to know more about *Sperboy*, contact Kate Bowling, Project Manager, PEP (Plymouth Enterprise Partnerships Ltd), Tel. +44-(0)1752-233700; Fax: +44-(0)1752-233711; Email: k.bowling@pep-research.co.uk

# NOW There's a FUNNY THING...

## *Exaggerating catastrophe*

When the Russian nuclear submarine *Kursk* sank in the Barents Sea last summer, there were fears of 'nuclear meltdown on the sea-bed', according to press and media reports. An uncontrolled chain reaction in the reactor could heat the fuel enough for it to melt its way through the reactor casing, releasing radioactive elements (uranium, plutonium, caesium) into the water column. The *Kursk* lies in relatively shallow (~ 100 m) waters that happen to be rich fishing grounds, where Norwegians catch a lot of cod, some of which they export to Britain,

Now, some six months later, the tragic end of the *Kursk* and her crew are no longer headline news, and no irradiated cod have been consumed. When another Soviet nuclear sub, *Komsomolets*, sank near Bear Island (in the Norwegian Sea) more than ten years ago, there were similar forebodings of nuclear catastrophe at sea. There has been some leakage but apparently not enough to contaminate fish or other marine organisms. Since the demise of the USSR, nuclear-powered submarines and other ships of the once mighty Soviet Navy have been moored in Murmansk and other Arctic ports, their reactors waiting to be decommissioned and made safe. From time to time through the 1990s, the press ran horror stories about 'Russia's nuclear time bomb', 'another Chernobyl', and about plans to dump the reactors at sea, with incalculable damage to the fragile Arctic environment. To date, however, the Arctic environment seems to be under threat more from global warming than from radiation sickness.

Do we underestimate Mother Nature's capacity for dilution, dispersal and bio-remediation? Even the Chernobyl accident, dire though it was, has left a relatively limited environmental legacy. And what about oil spills? What remains of the *Braer* and *Sea Empress* oil spills off Shetland and South Wales (respectively), a few years ago? Or the *Erika* accident off Brittany, only last year? When Saddam Hussein's people set the oil fields alight during the Gulf War in 1991, environmental scientists foretold that the contamination would persist for many decades. If they were right, why have there not been more accounts of decreasing biodiversity and declining quality of human life in Kuwait and adjacent states? In 1998 a vast area of wetlands in southern Spain, the Doñana National Park, was devastated by floods of acidic and metal-rich mine waters, a pollution event whose effects were predicted to last for 50 years. Yet by the beginning of this year, it was reported that reeds were growing in rivers, hardier plants were re-establishing themselves, birds were coming back, and some areas were looking green and lush again.

Further east, ecosystems of the Danube delta are beginning to regenerate, as the late Nicolae Ceaucescu's policies of reclamation and drainage for industrial development, agriculture and fish-farming are reversed. A biosphere reserve is being set up, with restoration of reed beds and swamps, and growing numbers of pelicans, cormorants and herons. The fish are still small, however, and their populations are not yet large enough to support the local fishermen, who have made no catches for many years. Nonetheless, the rate of recovery has been sufficient to encourage the development of eco-tourism and there is some optimism for the future.

Back in Britain, a premier eyesore on the north-east coast of England was removed when the colliery at Easington (County Durham) closed in the early 1990s. Since the 19th century, the coastline there had been the repository of coal waste that despoiled beaches for miles in each direction, and offshore waters were made permanently turbid by high concentrations of suspended sediment, deposition of which smothered the benthos over large areas. Yet once the colliery closed, it took only five years for wild flowers and grasses, butterflies, larks and seabirds to become re-established, and for coastal waters to become clear once more.

Mother Nature doesn't recover by herself, of course. Human intervention does much to ameliorate the effects of large pollution events, and is essential when it comes to persistent and chronic pollution. The chief reason that Britain's rivers are now cleaner than they have been since the Industrial Revolution, is because the industrial and domestic wastes that used to be poured into them year after year are going elsewhere. Natural processes have done the rest – they are very good at cleaning up the environment when we make it dirty.

## *Reefs for fish and surfers*

Marine conservationists in Cornwall are planning to buy an elderly frigate from the Navy for some £35 000 (a snip at the price), and sink it off Falmouth, making an artificial reef to improve the local diversity of fish and other organisms in coastal waters.

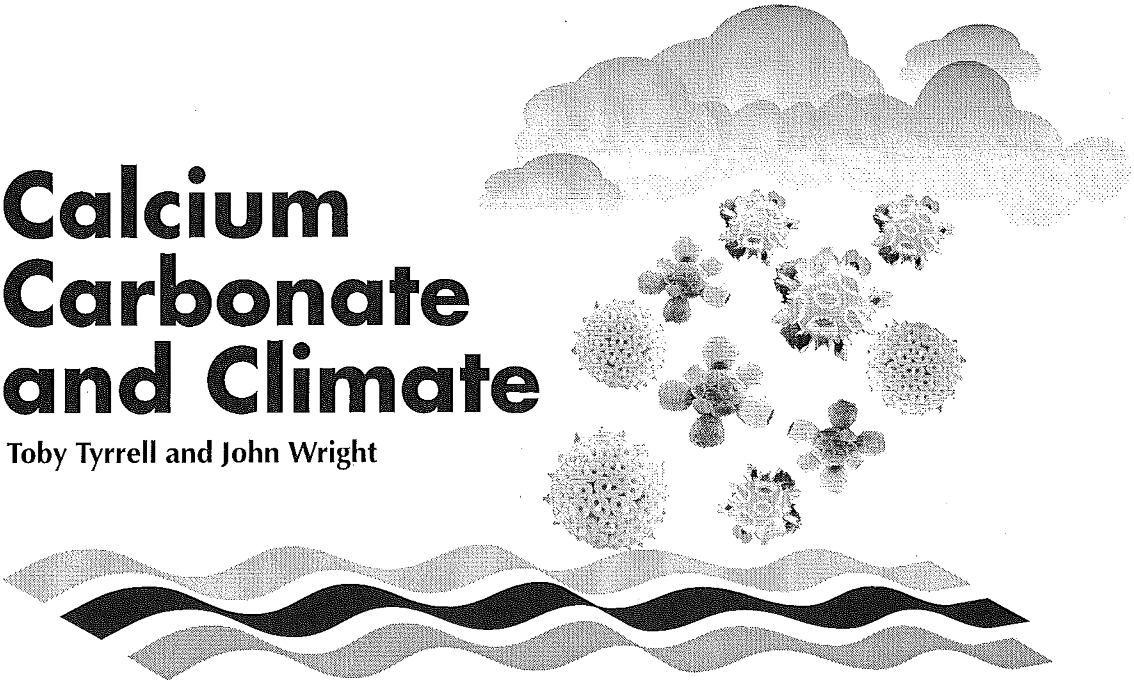
Further east, there are ambitious plans by Bournemouth Council to make a new surfers' beach by sinking thousands of 10-ton sandbags to form a 100-m long artificial offshore bar. The intention is to make Bournemouth the 'Bondi Beach of the South Coast'; Bournemouth is so much closer to London than the beaches of South-West England and South Wales. However, Newquay plans to enhance its existing surfing potential by building an offshire reef in exactly the same way. The tourist authorities there are keen to keep Newquay's reputation as the surf capital of Britain. The idea of 'surf-generating' reefs is not new. One was recently constructed near Los Angeles, and Australia already has two of them.

Surfing is traditionally associated with the 'sex 'n drugs' culture, but Christian Surfers UK (*sic*) hope to change all that, by evangelizing among the surfing fraternity to promote the spirtual dimension of the sport. In the heathen and blasphemous times in which we live, I doubt they'll have much success. In fact, they would be better employed proselytising in Australia rather than the UK. Apparently, certain Australian surfers routinely ridicule and abuse the lifeguards who try to warn them about dangerous waves and undertows. It is they who seem to be most in need of some Christian counsel.

**John Wright**

# Calcium Carbonate and Climate

Toby Tyrrell and John Wright



Many people are under the impression that precipitation of calcium carbonate to form limestone is a means of 'fixing' carbon dioxide, thereby reducing the atmospheric burden of this major greenhouse gas. It follows that the global decline of coral reef ecosystems that we read and hear about almost weekly must be a cause of great concern. Coral reefs are made of limestone, so surely their decline implies less 'fixing' of atmospheric $CO_2$? This perception of the role of calcium carbonate on present day climate is quite understandable – but is seriously flawed. Instead of helpfully absorbing $CO_2$, the growth of coral reefs causes its release! In this article we will show that precipitation of calcium carbonate in the modern ocean is actually *adding* $CO_2$ to the atmosphere. Nobody wants the next generation to preside over the world-wide disappearance of reefs and the extinction of corals, but the fact is that a reduction in the abundance of corals would actually help to counteract the fossil-fuel-induced warming – though probably not by a great deal.

However, that's only part of the story. The subject of calcium carbonate and climate has been aired more than once in *Ocean Challenge*, evidence in itself that the relationships are not simple. In this article we review how the formation of calcium carbonate (calcification) can affect climate in two opposite ways, depending on whether one takes the long-term or the short-term view; that is to say, whether one considers the effect of calcification in combination with other processes, or the effect of calcification alone. The first viewpoint is important for understanding the overall level of $CO_2$ in the atmosphere, and why Earth has a low atmospheric $CO_2$ content compared with other planets. The second viewpoint is important for understanding the present-day ocean response to climate change.

As most readers will be aware, calcium carbonate ($CaCO_3$) is a whitish or colourless mineral, of which typical examples are blackboard chalk and the chalk in the cliffs of Dover. Limestone rocks are also largely $CaCO_3$. Most $CaCO_3$ on Earth is of biological origin, the result of precipitation of $CaCO_3$ by organisms ranging from unicellular protists (notably coccolithophores and foraminiferans) to corals, coralline algae, molluscs and other shelly marine animals (Figure 1).

Calcification occurs when calcium carbonate is precipitated in surface waters according to the reaction:

$$Ca^{2+}(aq) + 2HCO_3^-(aq) \underset{\text{dissolution}}{\overset{\text{precipitation (calcification)}}{\rightleftarrows}} CaCO_3(s) + CO_2(aq) + H_2O\,(l) \qquad \text{Eqn (1)}$$

where (aq) indicates 'in solution' (i.e. $CO_2(aq)$ is $CO_2$ gas in solution); (l) indicates liquid; and (s) indicates a solid. The central double arrow indicates a reversible reaction, and the reverse reaction here is dissolution of $CaCO_3$ (water and $CO_2$ gas in solution (i.e. $CO_2(aq)$)

*(a)*

*(b)*

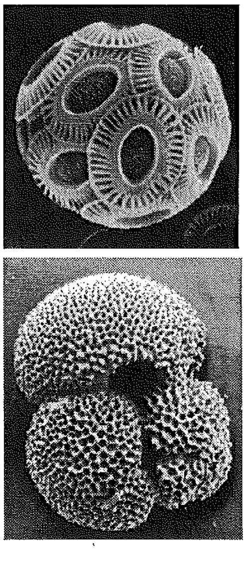


***Figure 1*** *Some forms of biogenic calcium carbonate found in the oceans:* ***(a)*** *a coral reef;* ***(b)*** *(Upper) a scanning electron micrograph (SEM) of the coccolithophore* Emiliania huxleyi, *showing the intricate cell-covering of calcium carbonate 'shields' or coccoliths; (Lower) SEM of a foraminiferan test.*

*(b)(Upper) Courtesy of Jeremy Young;*
*(b)(Lower) Courtesy of John Murray.*

***If the present-day cycle of calcium carbonate burial and weathering were in balance, with burial fluxes matching weathering fluxes, there should be no change in atmospheric $CO_2$ concentration***

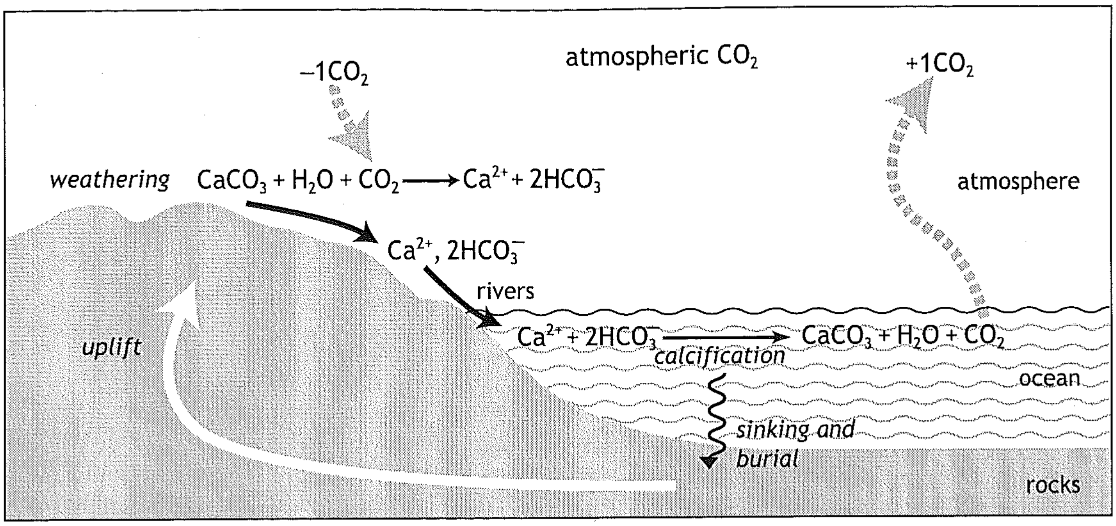


***Figure 2*** *The cycle of calcium carbonate weathering and burial. Weathering of one molecule of calcium carbonate removes one molecule of $CO_2$ from the atmosphere, but on precipitation of $CaCO_3$, one molecule of $CO_2$ is again released to the atmosphere.*

react with the solid calcium carbonate and dissolve it, releasing calcium and bicarbonate ions into solution). The most familiar process involving dissolution of calcium carbonate is weathering of chalk and limestone rocks on land. Dissolution also occurs when calcium carbonate remains sink into the deep ocean, where the water is under-saturated with respect to $CaCO_3$. As a result of this undersaturation, deep ocean sediments contain little or no $CaCO_3$; calcium carbonate remains are mostly preserved in relatively shallow water marine sediments.

Figure 2 shows a simplified representation of the calcium carbonate cycle, in which only calcification and dissolution by weathering are included. Were dissolution and calcification to proceed at equal rates, they would cancel out and there would be no net effect on atmospheric $CO_2$.

## Where did the early atmosphere go to?

It is likely that soon after the Earth was first formed, it had a very dense atmosphere, approximately 55 times denser than now, made up almost entirely of $CO_2$. This very treacly atmosphere, dominated by $CO_2$ and with no oxygen, would have been impossible for us to live in. The high pressure (i.e. ~ 55 bar) would have resisted movement, and the density of the air would have been about 7% that of surface water (i.e. about 70 kg $m^{-3}$), compared to just over 0.1% (1.225 kg $m^{-3}$) now.

The composition of the initial atmosphere can be estimated by comparing the Earth's atmosphere with that of its nearest planetary neighbours (Table 1). There are several major differences between the planets, one of which is the very small amount of $CO_2$ in the Earth's present-day atmosphere (the total amount of $CO_2$ in Mars' atmosphere is in fact not particularly high either, but that is because Mars is so cold that a lot of its $CO_2$ now exists in solid form, in $CO_2$ ice-caps).

If there was so much $CO_2$ in the Earth's early atmosphere, what happened to it all? Where did it all go to? The answer is to be found in the results of audits that geologists have carried out on the rocks of the Earth's crust (Table 2). The carbon in Earth's early $CO_2$-stuffed atmosphere

***Table 1*** *Comparison of planetary atmospheres and surface conditions*

| Gas | Venus | Mars | Earth (no Life) | Earth (Life) |
|---|---|---|---|---|
| $CO_2$ (%) | 96.5 | 95 | 98 | 0.03 |
| $O_2$ (%) | 0.0 | 0.13 | 0 | 21 |
| $N_2$ (%) | 3.5 | 2.7 | 2 | 79 |
| Atm pressure | 90 bar | 0.006 4 bar | 55 bar | 1 bar |
| Surface temp. | 460 °C | –53 °C | warm/hot (>50 °C) | 13 °C |

*Notes:* The third column is a speculative reconstruction of the possible composition of the early Earth's atmosphere, prior to the evolution of any Life, and prior to the condensation of the ocean. It is based partly on comparison of the Earth with its nearest neighbours. The atmospheric pressure and % $CO_2$ were calculated by assuming that all the carbon currently in crustal calcium carbonates and kerogens (organic matter in rocks) was initially in the atmosphere as $CO_2$. Very little geological evidence survives to prove or disprove such speculative reconstructions of the earliest Earth.

***Table 2*** *Carbon budget for the present-day Earth*

| Reservoir | Mass of carbon ($10^{18}$ g) |
|---|---|
| Atmosphere | 0.7 |
| Ocean | 37 |
| Biota (land + ocean) | 0.6 |
| Soils | 1.5 |
| Fossil fuels | 5 |
| C in rocks as $CaCO_3$ | 60 000 |
| C in rocks as $CH_2O$ | 14 000 |

*Notes*: 1.0 bar $CO_2$ would correspond to $1400 \times 10^{18}$ g of carbon in the atmosphere;
1 $km^3$ of $CaCO_3$ contains ~ $0.0004 \times 10^{18}$ g of carbon.

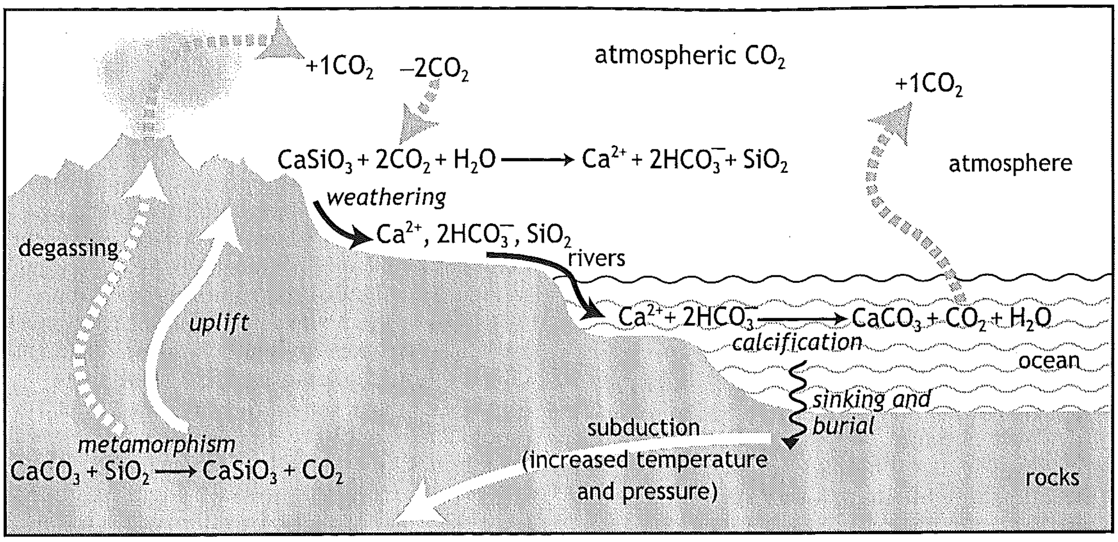


***Figure 3*** *The calcium carbonate–silicate cycle.*

***Unlike weathering of calcium carbonate, silicate weathering reults in a drawdown of $CO_2$ from the atmosphere***

now resides mostly in the massive calcium carbonate vaults of the Earth's crustal rocks. The rest is in organic matter remains (abbreviated to $CH_2O$ in Table 2) which are disseminated throughout the sedimentary rocks of the crust, and which include our fossil fuels (although these constitute only a tiny proportion of the total). The detailed picture is complicated, not least because there is not yet a definite consensus on just when photosynthesizing organisms first appeared. Be that as it may, the oldest sedimentary rocks include limestones and contain traces of primitive life-forms. So we know that very early in the Earth's history, limestones were being formed by simple unicellular organisms that have a strong resemblance to those building the layered stromatolites found in shallow sheltered bays and inlets at low latitudes today. Limestones were probably formed by *in*organic processes too (see below), and there is good evidence that organic matter ($CH_2O$) was also being sequestered into sediments, a point we return to later.

The fact that the oldest rocks (3.8 billion years old) include sediments deposited under water is strong evidence that there were oceans on the early Earth, and hence that precipitation of limestone could take place. The initial 55 bar $CO_2$ atmosphere must have resulted in the diffusion of large amounts of $CO_2$ across the sea-surface, into solution in the ocean. Although we cannot be sure of the acidity of the early ocean, it must surely have had high concentrations of carbon dioxide, and it is possible that it could in fact have been an alkaline (high pH) 'soup', rather like the 'soda lakes' in the Rift Valley of present-day East Africa (Lake Magadi in southern Kenya, Lake Natron in northern Tanzania). Like them, it would have been well supplied with cations (sodium, calcium etc.) leached by weathering from lavas erupted by the volcanoes which were surely widespread on the early Earth. Under alkaline conditions such as these, calcium carbonate precipitates spontaneously from solution – to the extent that in the East African soda lakes, no calcium remains in solution.

The nearest modern marine analogues of this ancient 'alkaline soup' scenario are on the Bahama Banks and in the Persian Gulf. In these places the seawater is warm and quite a bit more alkaline than normal (pH can be as high as 10), and inorganically precipitated calcium carbonate commonly forms suspensions of minute crystals ('whitings') that accumulate as carbonate muds. Also formed in such environments, especially where current action is strong, are sub-mm-sized spherical grains produced by inorganic precipitation of successive microlayers of calcium carbonate, accreting around tiny sand or shell particles as they are rolled to and fro on the sea-bed. These spherical grains are called ooliths, because aggregates of them resemble fish roe, and oolitic limestones, as well as inorganically precipitated carbonate mudrocks, are common in the geological record.

Inorganic precipitation of calcium carbonate in the modern ocean is a localized and seasonal phenomenon, but in the early ocean large amounts of calcium carbonate could have been precipitated in this way, as well as by organisms. Irrespective of the precise mechanism(s) of calcium carbonate precipitation, however, there must have been a limit to the rate of deposition of limestone in the early ocean. That is because something like $50 \times 10^{20}$ moles of calcium are required to form all of the limestone presently in the Earth's crust – and the present-day ocean contains only about $0.135 \times 10^{20}$ moles of calcium. So a continuing supply of calcium was needed, and that can only have come from weathering of the Earth's continental crustal rocks (Figure 3).

The importance of the silicate weathering reaction in Figure 3 is that *there is net removal of $CO_2$ from the atmosphere.* For every atom of calcium released into solution, two molecules of atmospheric $CO_2$ are used up, but only one is released back into the atmosphere when calcium carbonate is precipitated. In contrast, weathering of limestone followed by re-precipitation of calcium carbonate does not result in net removal of atmospheric $CO_2$ – see Figure 2.

Figure 3 shows another crucially important geological component of this cycle: metamorphism of limestone rocks (their modification at high temperatures and pressures deep within the Earth's crust) results in slow release of $CO_2$ back into the atmosphere, mainly via volcanoes. Were all the reactions in Figure 3 to be in balance, there would be no change in atmospheric $CO_2$, because for every two molecules of this gas removed from the atmosphere by weathering, two would be returned to it, first by formation of limestone and then via its metamorphism. But the very fact that Table 2 shows an enormous crustal store of limestone rocks is evidence that the rate of return of $CO_2$ from the Earth's interior back to the atmosphere must be very slow, because it hasn't kept pace with weathering and limestone formation. In other words, although the weathering and precipitation reactions shown in Figure 3 have created our low-$CO_2$ atmosphere over geological time, they are *not* important over the 'climate change' time-scale that is of direct concern to humanity.

Something near to 0.2 GtC, the equivalent of only 0.1 p.p.m. (or 0.03%) of atmospheric $CO_2$, annually sinks to the sea-floor in the form of $CaCO_3$ particles and becomes permanently buried there. At present-day rates, over a 100-year period, only $0.1 \times 100 = 10$ p.p.m. of atmospheric $CO_2$ is buried as calcium carbonate. This is a small amount in comparison to the 100–300 p.p.m. of extra $CO_2$ that industrial emissions are likely to add to the atmosphere between now and the year 2100 – and even if the carbonate burial rate were to double (which is most unlikely), the effect on atmospheric $CO_2$ would still be small – especially as most of the carbon buried as extra $CaCO_3$ would come out of the ocean rather than the atmosphere. So in fact even less than 10 p.p.m. of atmospheric $CO_2$ would be removed.

## Calcification, ocean alkalinity and atmospheric $CO_2$

Calcium carbonate formation has another effect, which has nothing to do with changing the total ocean-plus-atmosphere inventory of carbon atoms (which is what the conversion of silicate rocks to carbonate rocks does). This effect works by forcing a redistribution of those carbon atoms among the different reservoirs in that inventory.

After a $CO_2$ molecule crosses the sea-surface from the atmosphere into the ocean, it does not necessarily remain as a dissolved $CO_2$ molecule. Instead the following reactions rapidly take place:

$$\begin{array}{r} H_2O + CO_2(aq) \rightleftarrows H_2CO_3(aq) \rightleftarrows H^+(aq) + HCO_3^-(aq) \\ \uparrow\downarrow \\ H^+(aq) + CO_3^{2-}(aq) \end{array}$$

Eqn (2)

where:

$CO_2(aq)$ is carbon dioxide in solution;

$H_2CO_3(aq)$ is carbonic acid, the concentration of which, regardless of pH, is always very low compared with that of $CO_2(aq)$ (it is therefore ignored in the remainder of this article);

$HCO_3^-(aq)$ is bicarbonate ion;

$CO_3^{2-}(aq)$ is carbonate ion.

The relative proportions of these different forms of dissolved inorganic carbon are determined to some extent by temperature, salinity and pressure, but the most important factor is how acid the water is, as measured by its pH (see Figure 4, opposite). Normal seawater is slightly alkaline, and its pH is close to 8. So according to Figure 4, of the ~2000 µmol kg$^{-1}$ of carbon dissolved in the oceans, most (about 1800 µmol kg$^{-1}$) is in the form of bicarbonate ions ($HCO_3^-$), a little (about 200 µmol kg$^{-1}$) is as carbonate ions ($CO_3^{2-}$), and only a tiny amount (about 10 µmol kg$^{-1}$) is as dissolved $CO_2$ molecules ($CO_2(aq)$). Only the carbon atoms in the dissolved $CO_2$ molecules interact directly with the $CO_2$ in the atmosphere, by diffusive exchange across the sea-surface.

An acid ocean (lower pH) pushes more of its C into $CO_2$, less into $CO_3^{2-}$ and $HCO_3^-$ (Figure 4), i.e. the reactions in Equation (2) move to the left, and the ratio of $[CO_2(aq)] : [\Sigma CO_2]$ increases with acidity. The square brackets denote molar concentration and $[\Sigma CO_2]$ represents the total molar conentration of all inorganic carbon species dissolved in seawater. It is synonymous with [DIC], the total concentration of dissolved inorganic carbon. In short:

$$[\Sigma CO_2] = [DIC] = [HCO_3^-] + [CO_3^{2-}] + [CO_2(aq)].$$

If the present-day ocean's pH were somehow instantaneously to drop by one whole unit (pH to change from 8.2 to 7.2) then, without any addition or removal of C atoms to/from the ocean, this would bring about something like a 10-fold increase in the number of $CO_2$ molecules in each litre of *surface* seawater (Figure 4). The greater numbers of $CO_2$ molecules would increase the partial pressure of $CO_2$ in the surface ocean (the pressure exerted on the atmosphere just by the $CO_2$ component of the seawater mixture, written as $pCO_2(aq)$), which in turn would cause diffusion of huge amounts of $CO_2$ into the atmosphere until the two partial pressures once more balanced.

Conversely, if oceanic pH were to change in the opposite direction, from, say, 8.2 to 9.2, then the concentrations of $HCO_3^-$ and $CO_3^{2-}$ ions would become roughly equal (Figure 4); i.e. the reactions in Equation (2) would move to the right. The proportion of $CO_2(aq)$ in the surface seawater would be zero, with the result that $CO_2$ would diffuse into the ocean from the atmosphere.

This easy interchange between the different carbon forms means that phytoplankton, most of which can only directly assimilate $CO_2$ from solution, have indirect access to the whole store of dissolved carbon. When the growth of a phytoplankton bloom consumes $CO_2$ and causes $[CO_2(aq)]$ (the concentration of $CO_2$ molecules in solution) to fall, $[HCO_3^-]$ and $[CO_3^{2-}]$ decrease as they convert to $[CO_2(aq)]$, tending to restore the $[CO_2(aq)] : [HCO_3^-] : [CO_3^{2-}]$ ratio. $[CO_2(aq)]$ therefore rises again to

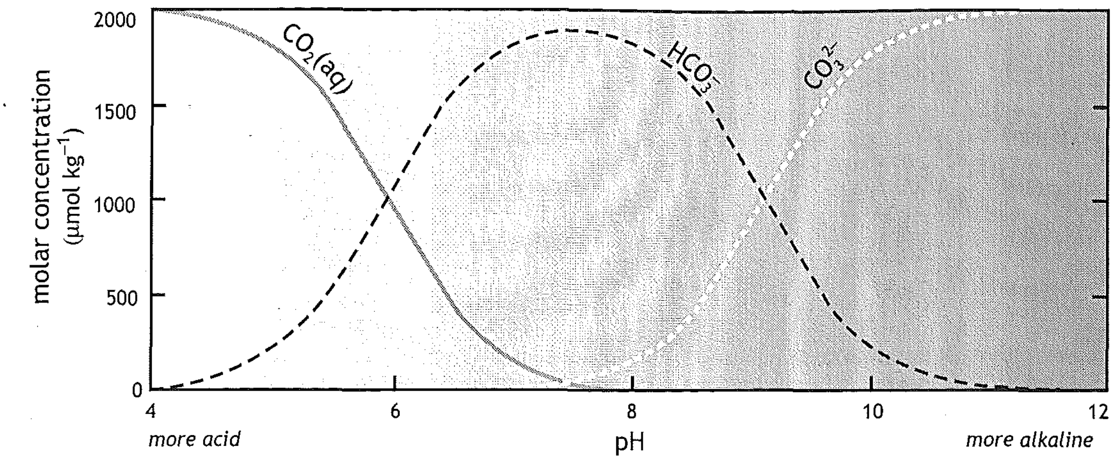


***Figure 4*** *Changes in concentration of the three dissolved carbon species with changing pH. These values have been calculated for a water temperature of 15 °C and a salinity of 35 (p.s.u.), and for* $[\Sigma CO_2]$ *= 2000 μmol kg*$^{-1}$ *for all pH values. This type of diagram is called a Bjerrum plot.*

***'Bjerrum plot' showing the variations in concentrations of the three inorganic species of carbon in response to changing pH***

almost its original value. This important relationship is illustrated by data obtained during cruises (1981–1991) in the north-east Atlantic, during the spring phytoplankton blooms there. Concentrations of dissolved carbon and nutrients are high during the winter, when low light and deep mixing prevent phytoplankton growth, but then plummet during the spring bloom and remain low throughout the summer as phytoplankton use up all available nutrients. Figure 5(a) shows that at latitude 49° N, between julian days 100 and 135 (~10 April–15 May), the total concentration of all inorganic carbon species in solution decreased by about 60 μmol kg$^{-1}$, whereas Figure 5(b) shows that the concentration of dissolved $CO_2$ gas ($[CO_2(aq)]$) fell by only about 4 μmol kg$^{-1}$, from 14.5 to 10.5 μmol kg$^{-1}$, over the same period. Both figures also show that the region of rapid uptake of carbon by the phytoplankton spring bloom migrates north with the spring bloom as the season advances.

The sinking of dead spring phytoplankton, along with consumption by zooplankton and production of faeces, exported ~ 60 mmol kg$^{-1}$ of carbon from the surface layer, as shown by the fall in $[\Sigma CO_2]$, but the fall in $[CO_2(aq)]$ was much less than this. The small amount of $CO_2$ the phytoplankton can 'see' at any one time is therefore a window to the much larger stock of total dissolved carbon. Recent research has shown that while the great majority of phytoplankton use $CO_2$ in solution, some can also use $HCO_3^-$ ions. But this does not invalidate the general principle – these phytoplankton also have access to the total stock of dissolved inorganic carbon.

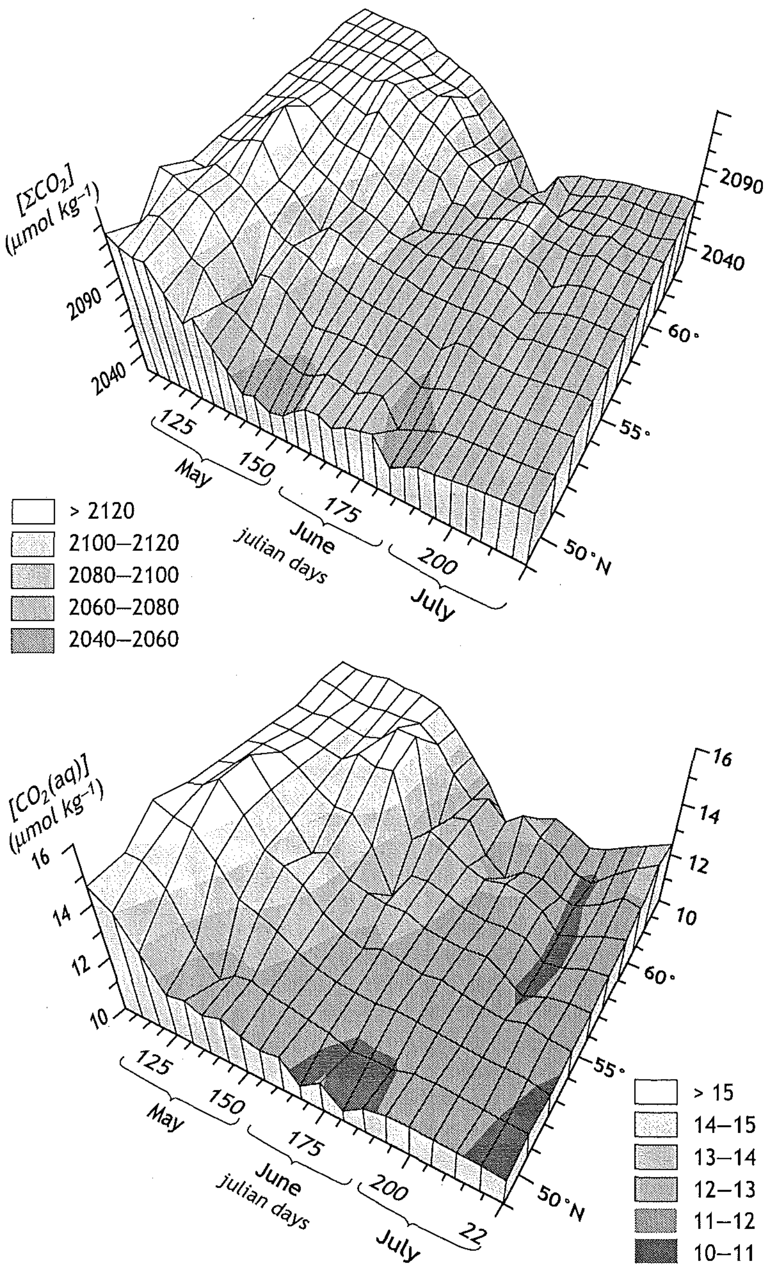


***Figure 5*** *Changes in* ***(a)*** $[\Sigma CO_2] = [HCO_3^-] + [CO_3^{2-}] + [CO_2(aq)]$*, and* ***(b)*** $[CO_2(aq)]$*, during the spring bloom in the north-east Atlantic.* $[\Sigma CO_2]$ *was measured directly;* $[CO_2(aq)]$ *was calculated from measurements of surface water p*$CO_2$ *(the partial pressure of* $CO_2$*) and the solubility. The 3D surfaces were derived by interpolating data collected during different years and at at different latitudes, but all at a similar longitude, near to 20°W.*

***Phytoplankton blooms can cause a large decrease in the*** $[\Sigma CO_2]$ ***of surface waters, but the change in*** $[CO_2(aq)]$ ***is much smaller***

# Box: Acids, Bases, pH and Alkalinity

The whole topic of acids and bases (alkalis) is concerned with the availability of $H^+$ ions (protons). Acid solutions have high free proton concentrations because they contain compounds which readily dissociate to release positively charged protons ($H^+$ ions), and negatively charged *anions*, e.g.:

$HCl \rightleftarrows H^+(aq) + Cl^-(aq)$ and $H_2SO_4 \rightleftarrows 2H^+(aq) + SO_4^{2-}(aq)$

Alkaline solutions contain compounds called bases, which also dissociate, to release positively charged cations and negatively charged (base) anions that readily accept protons, e.g.: $NaOH \rightleftarrows Na^+(aq) + OH^-(aq)$
*and* $Na_2CO_3 \rightleftarrows 2Na^+(aq) + CO_3^-(aq)$

When acids and bases are put together, they neutralise one another, as the protons combine with the base anions and the cations combine with the acid anions, e.g.:

$HCl(aq) + NaOH(aq) \longrightarrow NaCl\ (aq) + HOH(aq)$ (i.e. $H_2O$).

## What is pH?

pH is a measure of how acid or alkaline a solution is. It is calculated as: $pH = \log_{10}(1/[H^+]) = -\log_{10}[H^+]$ Eqn I
where $[H^+]$ is the concentration of free protons in units of moles $litre^{-1}$.

## What is Alkalinity?

Alkalinity is formally defined as the amount of hydrogen ions ($H^+$) needed to convert all the weak acid anions back to their un-ionized acids. Another definition is: the equivalent sum of all the bases that can accept a proton to the carbonic acid endpoint (this will have more meaning later on).

For practical purposes, however, the alkalinity of seawater (indeed, of most natural waters) is the combined negative charge due to bicarbonate ($HCO_3^-$) and carbonate ($CO_3^{2-}$) ions in solution: $A = [HCO_3^-] + 2[CO_3^{2-}]$ Eqn II

Alkalinity can be expressed in molar concentration units, but it is more convenient to use 'charge-equivalent' units, i.e. equiv. $kg^{-1}$ (or for seawater, $\mu$equiv. $kg^{-1}$). That is because the doubly charged carbonate ion carries a double weighting, such that its contribution to alkalinity is twice its molar concentration. For example, if the molar value of $[CO_3^{2-}]$ is 0.2 $\mu$mol $kg^{-1}$, then its contribution to alkalinity will be 0.4 $\mu$equiv. $kg^{-1}$.

As shown in Equation (2) of the main article, bicarbonate and carbonate ions are the dissociation products of carbonic acid ($H_2CO_3$), which is classed as a weak acid. In contrast, HCl and $H_2SO_4$ are classed as strong acids, and their anions in seawater ($Cl^-$ and $SO_4^{2-}$) are neutralized/balanced by base cations, mainly $Na^+$, $Ca^{2+}$, $K^+$ and $Mg^{2+}$. These other ions can be ignored in considerations of alkalinity, because their proton-releasing or proton-accepting capacity does not change over the pH range of 3 to 10 that is required to measure the alkalinity of normal seawater.

Seawater is a complex solution, however, and it contains ions of other weak acids, the most abundant of which is borate, $B(OH)_4^-$. The full expression for alkalinity includes these *minor ions*, as well as taking into account the concentrations of both $H^+$ and $OH^-$ ions:

$$A = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] + [B(OH)_4^-] + [SA] \quad \text{Eqn III}$$

where *SA* stands for Surplus Alkalinity, which includes minor terms that, along with $[H^+]$ and $(OH^-]$, can be ignored when dealing with normal seawater (although they may become important in anoxic conditions). The borate contribution to alkalinity is typically less than 5% of the total in normal seawater, i.e. bicarbonate and carbonate are by far the dominant ions,. So the alkalinity of seawater is in effect its *carbonate alkalinity.*

Equation (1) of the main article shows that each unit of calcification removes 2 units of $HCO_3^-$ and therefore decreases alkalinity by two units. However, $[\Sigma CO_2]$ is decreased by only one unit, because the calcification leaves behind a unit of $CO_2(aq)$ which does not feature in the expression for alkalinity (Equation II, above).

Alkalinity is a property that is used for practical reasons, because it can be easily and directly measured, whereas many other useful properties of the ocean cannot. It is frequently used by oceanographers in preference to pH because, like $\Sigma CO_2$, it does not vary with temperature, pressure or salinity. The alkalinity of a given parcel of surface seawater will not vary with the day–night cycle or with weather changes. Alkalinity is not affected by photosynthesis or respiration, since these processes change only $\Sigma CO_2$. The most significant causes of variation in alkalinity are formation and dissolution of $CaCO_3$.

The equations of the dissolved carbon system in seawater are such that knowledge of any two out of $[\Sigma CO_2]$, *A*, pH, $[HCO_3^-]$, $[CO_3^{2-}]$, $[CO_2(aq)]$ and $pCO_2$ is sufficient to allow us to calculate all of the others, provided that temperature, salinity and pressure are all known. One is not enough. $[\Sigma CO_2]$ and $[A]$ are the ones most frequently measured.

## How is Alkalinity measured?

Alkalinity is measured by successively adding more and more acid to a seawater sample and observing how the pH changes as a result. The concentation of free protons (i.e. $[H^+]$) at a typical seawater pH of 8.2 is $6.3 \times 10^{-9}$ mol $l^{-1}$ and at pH of 3.0 it is $1.0 \times 10^{-3}$ *mol* $l^{-1}$ *(Equation I above). In theory,* therefore, $0.9999937 \times 10^{-3}$ mol $l^{-1}$ of protons would need to be added to a sample of pure water with initial pH of $8.2^{\dagger}$ to shift it to pH 3.0.

However, much more acid has to be added to *seawater* to shift it from pH 8.2 to pH 3.0, because of the presence of proton acceptors (>90% of which are carbonate and bicarbonate ions), and the extra amount required for a given sample is the alkalinity (see Figure A below). Hence the alternative definition of alkalinity, that it is the equivalent sum of all the bases that can accept a proton to the carbonic acid endpoint.

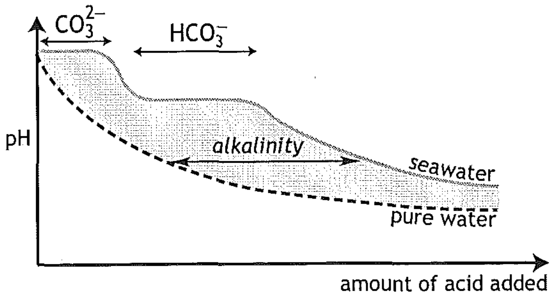


***Figure A*** The principle behind measuring alkalinity by adding acid while monitoring pH.

Given its name, one might expect alkalinity always to increase as pH increases, and decrease as pH decreases. However, this is not always the case, especially in the deep oceans. Deep ocean waters are more acid than surface waters, because of the remineralization of carbon in organic matter, while at the same time they have higher alkalinity, due to dissolution of calcium carbonate.

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† Pure water has pH = 7. To raise its pH to 8.2, a strong base (e.g. NaOH) would have to be added – and the water would no longer be pure!

The easy interchange between the different forms of carbon also affects the ocean's ability to absorb $CO_2$ from the atmosphere, as the amount there increases because of modern industrial emissions. It follows from the foregoing that the oceans act as a huge buffer: when a lot of $CO_2$ is pushed into the ocean from the atmosphere, most of it disappears into $HCO_3^-$ and $CO_3^{2-}$ so $[CO_2(aq)]$ does not actually rise that much.

But we should get back to the short-term effects of calcification on climate. Each time calcification occurs in the ocean, two units of $HCO_3^-$ (bicarbonate) are used up for each unit of solid $CaCO_3$ formed, according to Equation (1) on p.13 (see also Figures 2 and 3). There is a net reduction in $[\Sigma CO_2]$ of one unit, lost in the C of solid $CaCO_3$. But there is also a second and *more critical* effect of the $HCO_3^-$ removal, namely its effect on pH. In brief, removal of two units of $HCO_3^-$ from the seawater solution (one to form a unit of $CaCO_3$, the other to form a unit of $CO_2(aq)$, Equation (1)), releases hydrogen ions ($H^+$) into the solution. These 'extra' hydrogen ions make the seawater more acid (pH decreases), and therefore drive the reactions in Equation (2) to the left, with the result that the proportion of the total stock of carbon held as $CO_2(aq)$ increases. This can also be seen in Figure 4: the lower the pH, the greater the concentration of $CO_2(aq)$ relative to the other forms of dissolved carbon.

Thus, although calcification reduces the total stock of dissolved carbon, it actually leads to an *increase* in $[CO_2(aq)]$, the concentration of $CO_2$ molecules in solution. This somewhat counter-intuitive effect has been experimentally verified in mesocosm* bags in Norwegian fjords, in which rapid growth of coccolithophores took place (see Further Reading). Paradoxically therefore, it turns out that any extra removal of carbon atoms into coccoliths, coral reefs, and foraminiferans leads to elevated atmospheric $CO_2$. As surface seawater becomes more acid, $[CO_2(aq)]$ rises, and some of the extra $CO_2$ can diffuse out into the atmosphere and raise the concentration there.

## What price coral reefs?

The corals and the associated shellfish (such as bivalves and gastropods) that form reef assemblages in shallow water, all occur in equatorial and tropical latitudes, where the average $pCO_2$ in seawater exceeds the $pCO_2$ in the atmosphere, resulting at the present day in a net sea-to-air flux of $CO_2$. Precipitation of additional calcium carbonate in these regions could enhance this effect and thus exacerbate global warming.

As we noted in our opening paragraph, it seems that not many people are aware of this paradox. If it were more widely recognized, the often vigorously expressed concerns about the decline and destruction of coral reef ecosystems might perhaps become more muted.

## So what of the future?

The changes summarized above can be more formally expressed in terms of alkalinity (see the Box), and this approach helps us to arrive at some predictive conclusions. We have seen that removing two units of $HCO_3^-$ to form a unit of $CaCO_3$ and a unit of $CO_2(aq)$ results in a net decrease of only one unit of $\Sigma CO_2$. However, according to the definition of alkalinity (see Box), this same reaction reduces alkalinity by *two* units.

A back-of-envelope calculation can give us an estimate of how important the $CaCO_3$–alkalinity effect could be over the next 100 years. The amount of $CaCO_3$ produced in surface waters by foraminiferans, coccolithophores and shallow-water coral-reef assemblages, as well as by whitings, is of the order of $80 \times 10^{12}$ moles $CaCO_3$ $year^{-1}$. Since each unit of calcification reduces alkalinity by 2 units, this means an annual alkalinity reduction of $160 \times 10^{12}$ equiv. (see Box for definition of 'equiv.').

These reductions in $[\Sigma CO_2]$ (as the carbon removed in $CaCO_3$) and in alkalinity are more or less permanent. That's partly because corals and the remains of other shallow-water calcifiers such as bivalves and gastropods (cockles, mussels, whelks etc.) remain *in situ* and are preserved indefinitely. It's also partly because many of the planktonic coccolithophores and foraminiferans that sink to the deep ocean floor accumulate there as calcareous oozes; and together, these remains make up the annual 0.2 Gt of carbon buried as calcium carbonate that we mentioned earlier. Of course, as most people who've heard about the carbonate compensation depth (CCD) are aware, a large proportion of planktonic remains are in fact redissolved in the deep ocean, since below about 4 km depth seawater becomes sufficiently acid (lower pH) to be corrosive to $CaCO_3$. However, most of the carbon released by such dissolution will not return to the surface ocean for centuries, because the average turnover time of the oceans is measured in hundreds of years; which is very long on the human time-scale.

But the oceans are more or less at steady state, so removal of these constituents must be balanced by equivalent fluxes of dissolved carbon and of alkalinity to the surface ocean, in order to maintain the present levels of ~2000 $\mu mol\ kg^{-1}$ of $\Sigma CO_2$ and ~2300 $\mu equiv.\ kg^{-1}$ of alkalinity. The equalizing fluxes are of course supplied by rivers transporting the products of continental crustal weathering to the oceans (Figure 3), and partly by the return of deeper water to the surface.

Because of climate change, the calcification fluxes could increase in the future, if (for example) warmer waters favour growth of $CaCO_3$-secreting organisms. Or they could decrease, if (for example) lower pH inhibits calcification or promotes surface dissolution – the surface waters of the world are already more acid than they used to be, because of anthropogenic emissions increasing $CO_2$ in the atmosphere and hence – by diffusion – forcing

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* A 'mesocosm' is a large floating enclosure containing a volume of sea plus its ecosystem.

more $\mathrm{CO}_2$ into solution in the surface ocean. Evidence from the coral reef in 'Biosphere II' indicates that calcification rates decrease at high $p\mathrm{CO}_2$; while evidence from laboratory experiments suggests that calcification in coccolithophores likewise decreases when whey grow under conditions of high $\mathrm{CO}_2$.

How large an effect could changes in calcifications rates have on atmospheric $p\mathrm{CO}_2$ via changes in surface alkalinity? Box models which include particle fluxes, vertical mixing and other processes predict that if calcification fluxes were to double (to $160 \times 10^{12}$ moles $\mathrm{CaCO_3\,yr^{-1}}$) then, if everything else stayed constant, after 100 years surface alkalinity would have decreased by about $33\,\mu$equiv. kg$^{-1}$ and surface [$\Sigma\mathrm{CO}_2$] by about $20\,\mu$equiv. kg$^{-1}$. On the other hand, if the calcification fluxes were to halve (to $40 \times 10^{12}$ moles $\mathrm{CaCO_3\,yr^{-1}}$), then after 100 years surface alkalinity would be about $17\,\mu$equiv. kg$^{-1}$ higher and surface [$\Sigma\mathrm{CO}_2$] would be about $10\,\mu$equiv. kg$^{-1}$ higher.

If we plug these changes in alkalinity and [$\Sigma\mathrm{CO}_2$] into a carbon chemistry model (Figure 6), we can get an idea of how the $p\mathrm{CO}_2$(aq) of surface seawater might change. $p\mathrm{CO}_2$(aq) is the partial pressure of $\mathrm{CO}_2$ gas in solution in the surface ocean, and it is not very different from the partial pressure (i.e. the relative proportion) of $\mathrm{CO}_2$ gas in the atmosphere. The present-day atmosphere contains about 370 parts per million (p.p.m.) of $\mathrm{CO}_2$ by volume, which 'translates' to a partial pressure ($p\mathrm{CO}_2$) of $370 \times 10^{-6}$ atmosphere (370 µatm). The present-day average value of $p$CO2(aq) in the surface ocean is also close to 370 µatm. The result of the calcification changes discussed above would be *either* an increase in $p\mathrm{CO}_2$(aq) of some 8 µatm, with calcification rates doubled; *or* a decrease in $p\mathrm{CO}_2$(aq) of some 4 µatm, with calcification rates halved. Once equilibration between $p\mathrm{CO}_2$(aq) and atmospheric $p\mathrm{CO}_2$ was reached following these changes, then the concentration of $\mathrm{CO}_2$ in the atmosphere would increase or decrease by similar amounts.

Percipient readers will have noticed that with continued addition of anthropogenic $\mathrm{CO}_2$ to the atmosphere, the oceans will become more acid and calcification rates are likely to decrease – aided by the continued death and destruction of coral reef communities. The tiny changes implied in Figure 6, however, suggest that any change in calcification rates will have only the most trivial effect on $p\mathrm{CO}_2$.

Because there is about 50 times more carbon in the ocean as a whole than the atmosphere, the ocean $p\mathrm{CO}_2$ normally forces the atmospheric $p\mathrm{CO}_2$ rather than the other way round. In fact, however, anthropogenic $\mathrm{CO}_2$ emissions *do* affect $p\mathrm{CO}_2$ in the surface ocean. That is because emission rates are high relative to oceanic overturning times, and because of the enormous amounts of carbon emitted (~5 Gtonnes yr$^{-1}$).

## The carbonate pump and the biological pump

Over the course of geological time, calcification in the oceans has been a vital factor in removing carbon dioxide from the Earth's original high-$\mathrm{CO}_2$ atmosphere. The presence of an early ocean on Earth, plus the tendency for $\mathrm{CaCO}_3$ to precipitate if large amounts of carbon dioxide dissolve in it (particularly under alkaline conditions) has been largely responsible for the low-$\mathrm{CO}_2$ atmosphere we enjoy ... so far.

We have concentrated on calcification in this article, to show that coral reefs, coccolithophores, foraminiferans and the like do nothing to sequester the vast amounts of excess $\mathrm{CO}_2$ we pump daily into the atmosphere –

***Even large changes in amounts of calcium carbonate precipitated by corals etc. would not greatly affect the alkalinity and concentration of total dissolved carbon in ocean water; and the effect on atmospheric $\mathrm{CO}_2$ concentrations would be small***

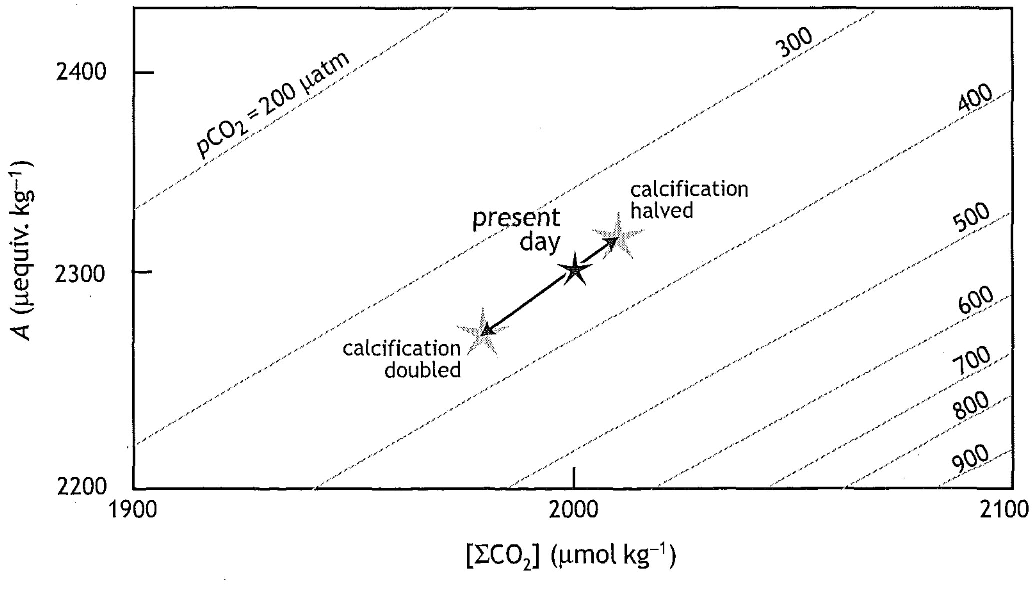

***Figure 6*** *Diagram to show how* $p\mathrm{CO}_2$*(aq) (contours, in µatm) in the surface ocean, varies as a function of the concentration of* $\Sigma\mathrm{CO}_2$ *and alkalinity (calculated fora temperature of 15 °C, and a salinity of 35 (p.s.u.)). It can be used as a rough 'ready-reckoner' of the climate impacts of different* $\Sigma\mathrm{CO}_2$ *and alkalinity scenarios. The* $p\mathrm{CO}_2$*(aq) gives a good indication of the atmospheric* $p\mathrm{CO}_2$ *after ocean–atmosphere equilibration, when allowance is made for anthropogenic emissions. The two arrows show the effects of calcification being doubled and calcification being halved, over 100 years.*

rather the reverse, in fact. Selectively poisoning calcifying organisms across vast reaches of ocean could slightly offset the accumulation of $CO_2$ in the atmosphere. But such a drastic step would surely be most unwise, even if we knew how to do it, which – thankfully – we don't.

Stimulating the formation of organic matter in the surface ocean and encouraging its removal to the deep sea remains a more plausible means of helping the ocean to take up greater quantities of atmospheric $CO_2$. That is why there has been so much interest in 'fertilizing the oceans', especially with iron, to encourage the growth of phytoplankton. Then, so the reasoning goes, either more phytoplankton are consumed by more zooplankton, whose populations rise in response to increased food supplies and which export the extra carbon to the deep sea in corpses and faeces; or more phytoplankton sink and take down carbon with them; or both. But it's not enough to stimulate more phytoplankton, they must also be of the right type. Stimulating more coccolithophores would not help!

## Aknowledgements

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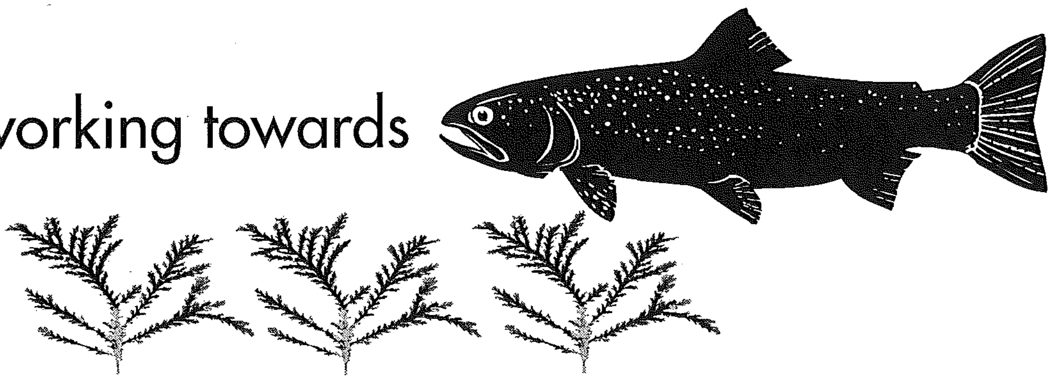


# working towards Environmentally Friendly Marine Farming

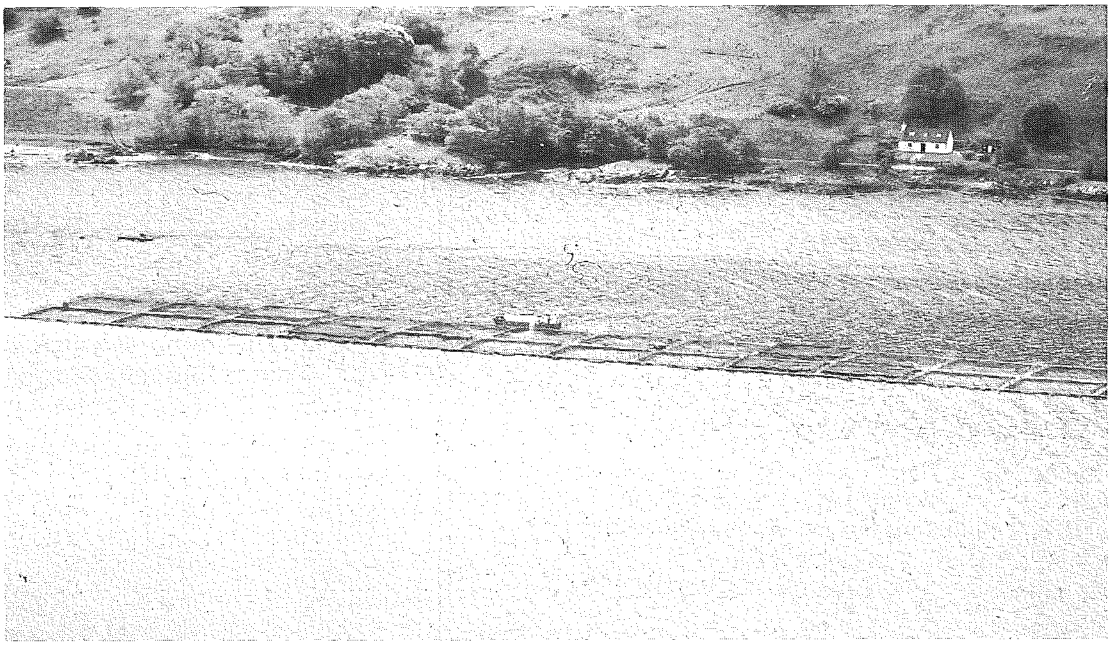
**Michael D. Krom, Amir Neori, Jaap van Rijn, Simon W. Poulton and Ian M. Davies**

It is well known that marine fisheries are in trouble, mainly because of our increased efficiency in finding and catching fish. The total catch of almost all commercial species has levelled out at around 85–95 Mtonnes per year, with a gradual shift from large and valuable carnivorous species to smaller, less valuable species. Many of the traditional great fishing grounds are seriously depleted and new fishing grounds are heading the same way. The shoals of herring that used to support a major industry on the east coast of the UK are no more. Even the Grand Banks of Newfoundland have had to be closed to allow the population of cod and other fish to recover. We are also becoming seriously concerned about the 'collateral damage' that we are doing to the marine ecosystem by modern industrial fishing methods, and about the distortion of the natural food web caused by removal of many of the top predators. Research is being carried out to determine the effect of repeated trawling on the benthic ecosystem.

In 2002, the European Common Fisheries Policy is to be renegotiated. A lively debate has already begun about what changes are needed, and there is vigorous discussion between those trying to maximize fish catches and those who wish to protect the marine ecosystem and environment.

But is this whole approach wrong? We get almost all the food we need from an integrated and sophisticated system of farming. We long ago accepted that this type of farming would destroy much of the terrestrial ecosystem, and have done little to try to protect it (except in a very few locations such as the Scottish Highlands where agriculture is marginal, and where we allow hunting to take place). The destruction of the marine ecosystem is not yet inevitable, so should not our aim therefore be to promote a system of marine farming that is environmentally friendly? And if so, how can the oceanographic community promote this aim?

***Figure 1** Salmon cage culture in Loch Duich, Scotland*



***Salmon farming is now the third largest industry in the Highlands of Scotland***

## Development of aquaculture

Freshwater aquaculture in China began more than 3000 years ago. More recently, many of the European medieval monasteries had carp ponds, enabling the monks to eat fresh fish on Fridays and during Lent. Today, farmed freshwater fish represent more than 80% of the total world production of finfish aquaculture (i.e. aquaculture excluding shellfish), with the largest proportion being carp, farmed predominantly in China and the Far East. But there is not much scope for further expansion of freshwater aquaculture, partly because the market for freshwater fish is limited, particularly in the industrialised nations. Another more fundamental factor restricting freshwater aquaculture is that in many parts of the world freshwater is itself a very valuable and diminishing resource and is needed more urgently for other human activities.

By contrast, mariculture is in an early stage, and current developments mirror those which occurred long ago in conventional farming, except that they are being carried out using modern scientific technology and skills. These include selective breeding and other methods to produce animals and plants more suitable for farming than the natural wild stock, modification of the breeding cycle, and development of suitable animal foods for various stages in the life cycle. In this article we will concentrate on the development of environmentally friendly grow-out systems, that take fish from juvenile to adult.

## Sea-cage culture

By far the most widespread type of system for growing marine fish is cages, suspended in the sea from floating rafts (Figure 1). There has been extensive development of this type of mariculture, involving a wide variety of fish, in the Far East including Japan, Hong Kong, Indonesia and the Philippines. In western Europe and North America, salmon are cultivated in this manner. Over the past 15 years, the annual production of salmon in sea-cages has increased from 10 000 tonnes to over 130 000 tonnes (in 2000). Salmon-growing is now the third largest industry in the Highlands of Scotland, after tourism and whisky.

It is expected that the sea-cage fish-farming industry will continue to expand over the coming years in terms of both total tonnage and the number of different species being cultivated. At present, this is by far the most common type of mariculture system in Europe and North America. However there are a number of factors limiting the expansion of sea-cage mariculture. The number of locations suitable for fish cages is relatively small. The site needs to be protected from the worst of the weather. It needs to be accessible to the fish farmer, who needs to feed and carry out maintenance of the nets and infrastructure on a regular basis. Sea-cage culture can also conflict with other activities in the coastal environment.

There are also undesirable environmental consequences of sea-cage culture which need to be addressed. Since the fish are being grown at high density, they can be susceptible to diseases and parasites. This requires treatment with antibiotics and other chemicals, which are by definition toxic to some marine organisms or microorganisms.

Typically only 30% or less of the food supplied to a marine fish farm is retained as fish growth. The remainder is excreted either as dissolved nutrients (~50%) or as particulate matter (~20%). At present, this waste is simply discharged into the environment, with particulate matter tending to accumulate in a pile underneath the cages, particularly at low-energy sites.

This waste material is high in labile organic matter. The organic-rich sediment rapidly decomposes, resulting in the reduction of the concentration of dissolved oxygen in the overlying water and the accumulation of free hydrogen sulphide in the pore waters. As well as increasing the oxygen demand of the sediment, this added organic matter can change the ecosystem in the vicinity of the cage. Generally, there is a dramatic increase in the density of other marine organisms in the area. They like a free lunch too!

Some initial attempts have been made to remove the excess nutrients discharged from such systems. In Chile, salmon have been farmed along with a red alga (*Gracilaria chilensis*) that removes large amounts of dissolved nitrogen and phosphate from the salmon cages. The added revenue from this second crop, which is a source of agar, more than pays for the extra infrastructure needed. However, the potential of this technology to remove the dissolved nutrients produced in the sea-cages is limited by various physical and chemical factors to less than 10% of total nutrient input. Another suggestion for reducing the environmental impact of the cages is to grow mullet or other scavenger fish underneath the fish cages as a secondary crop. After all, the waste material from the fish farm is not toxic waste but actually very good fish food. Although these measures are technically feasible at present, fish farmers are reluctant to implement them because they complicate the operation of the culture systems.

## Mariculture in ponds

Ponds potentially offer the opportunity to solve many of the environmental problems of sea-cage culture. In such systems, it is possible to remove the waste nutrients either by growing one or more additional crop(s) or by treatment. Simple earthen marine ponds are used on a wide scale for shrimp farming in China, Indonesia, Ecuador, India, the Philippines, Taiwan, Thailand and Japan. Unfortunately, excavation of the ponds is often associated with destruction of natural habitats, including mangroves. Furthermore, in many of the ponds built in mangrove areas the culture of aquatic organisms has ceased

*Table 1* *Areas of expertise required to understand the reasons for mass mortalities in semi-intensive earthen ponds*

| |
|---|
| Phytoplankton ecology |
| Chemical oceanography |
| Groundwater hydrology |
| Air–water exchange processes |
| Sedimentary microbiology |
| Sedimentary geochemistry |
| Benthic biology |

because of environmental problems. Mangrove sediments contain naturally high levels of iron sulphide in the subsurface layers. When the ponds are excavated, these layers are exposed to the atmosphere or to oxygenated water, and the iron sulphide is oxidized to form large quantities of sulphuric acid, as often occurs in abandoned mines.

In desert and other regions where there are warm/hot conditions and almost unbroken sunlight, marine algae have been used both to clean the water of ammonia and other undesirable nutrients and to form the basis of other commercial crops. Initial work on such environmentally friendly systems was carried out in a semi-intensive earthen pond using a fish–plankton–oyster system. The system was never commercial because the fish were subject to occasional mass mortalities. In order to understand the reasons for these deaths, a large range of expertise was required (Table 1). Eventually it was shown that the ponds operated like a 'dirty' chemostat. The swings in water column chemistry resulted from bloom and crash conditions resulting from classic predator/prey cycles. The accumulation of labile particulate organic matter resulted in extraordinarily high levels of microbial respiration and, in particular, sulphate reduction in the sediment. This resulted in the production of high levels of toxic hydrogen sulphide in the sediment. As a result of these water quality problems, this design of semi-intensive earthen ponds was abandoned in favour of an intensive concrete pond system.

## Mariculture systems based on marine algae

Two systems of this type have been developed at the National Centre for Mariculture in Eilat, near the Gulf of Eilat (Aqaba) in southern Israel; see Figure 2, below.

### *Fish–phytoplankton–bivalves*

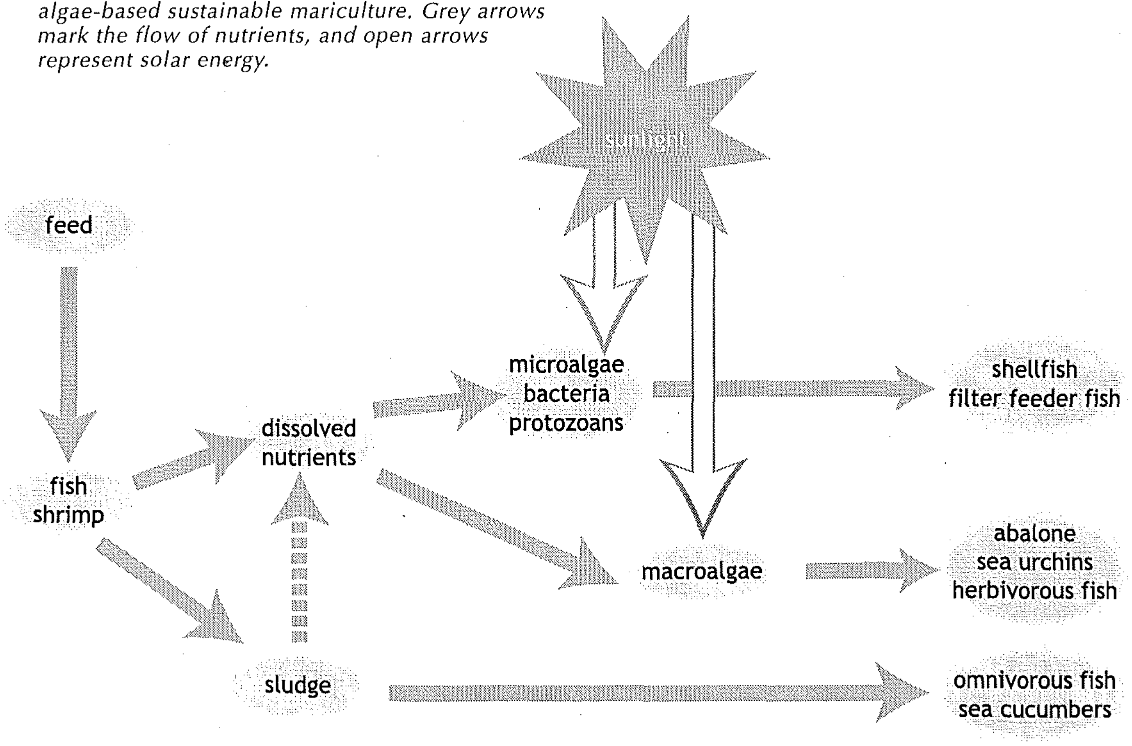
In the first system, the waste nutrients from the fish are removed by phytoplankton, which develop both in the fish ponds and in the sedimentation ponds that collect the effluents. The waste nutrients support dense populations of microalgae which are then fed to oysters and clams (*Crassostrea gigas* and *Tapes semidecussatus*) that grow on the bottom of the sedimentation ponds or in rearing tanks. Brine shrimp (*Artemia* sp.) can also be produced at high rates on these phytoplankton. The bivalve species reach commercial size in 18 months, and a commercial facility using this design has recently begun to operate in Eilat.

### *Fish–seaweed–abalone*

An alternative system uses seaweed to clean the fish pond effluent of waste nutrients. This has the fundamental advantage that seaweed populations do not bloom and crash, and can be harvested simply by means of a plastic screen. The system consists of a concrete fish pond containing fish at a density of up to 200–300 tonnes ha$^{-1}$. The water in the fish pond is circulated by mechanical paddle wheels, which also keeps the dissolved oxygen at acceptable levels. Small volumes of liquid oxygen can be added to prevent low oxygen levels.

Once a day, 0.5% of the water is drained out through a hole in the centre of the pond. This removes the accumulated particulate organic matter, which collects in a sedimentation basin. The water from the fish pond is circulated from the fish tank through a series of parallel tanks containing seaweed, at a rate of ~10% of the total system volume per hour. The water, with ammonia and phosphate removed by the seaweed, is then recycled back into the fish tank. Although maximum rates of nutrient removal occur during daylight hours, sufficient

***Figure 2*** *A conceptual diagram of integrated algae-based sustainable mariculture. Grey arrows mark the flow of nutrients, and open arrows represent solar energy.*



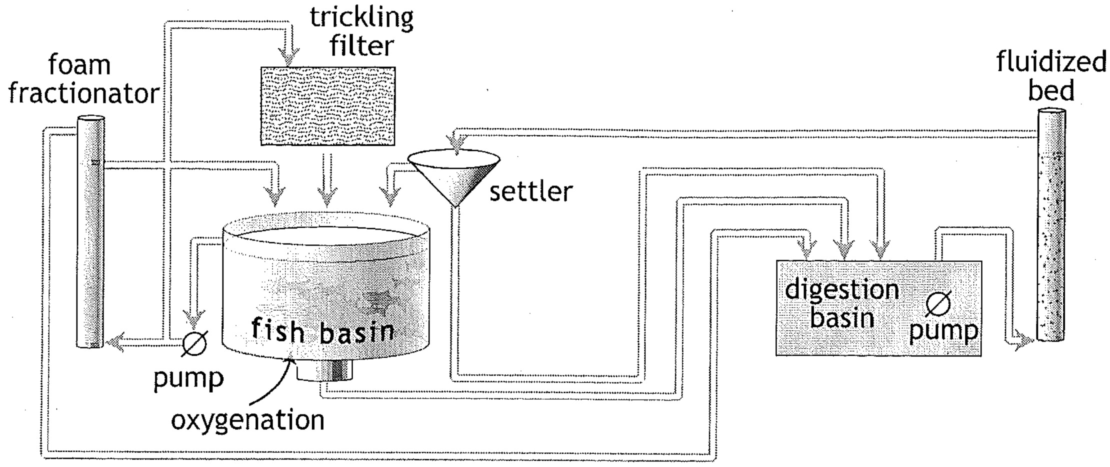


***Figure 3*** *Schematic diagram of the recycling biofilter system (see also Figure 4).*

nutrient removal continues during the night to keep the water quality levels in the fish tank within acceptable levels. The seaweed yield can subsequently be fed to macro-algivores such as abalone, consumed by people, or used in the chemical industry.

### Intensive recirculation systems using bacterial biofilters

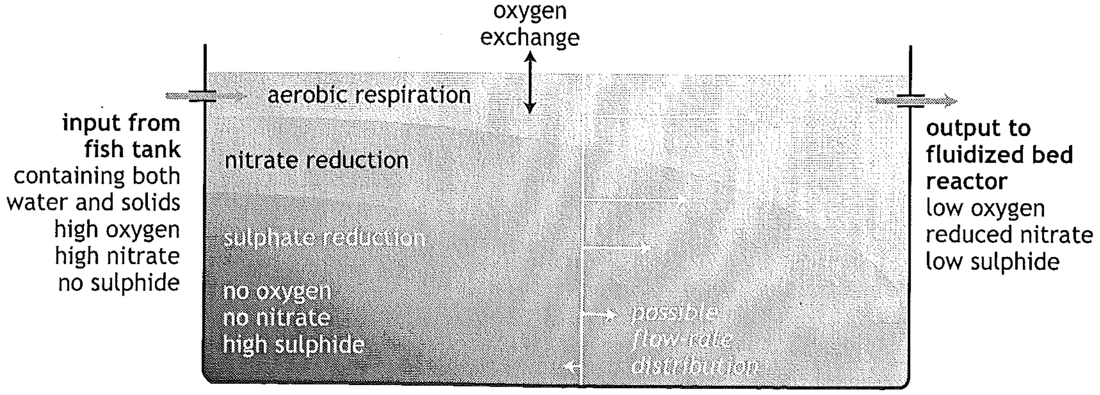
An alternative method of intensive pond mariculture makes use of bacterial biofilters. This type of recirculating system does not depend on sunlight and can grow fish anywhere, including places that are typically cold and cloudy, like northern Europe. Because the system can be placed entirely indoors, it is possible to modify the temperature so that it is optimal for fish growth. Previously, this was impossible to do economically because in flow-through systems with a large proportion of the water discharged as waste, the cost of heating tanks of water (or of cooling them, in the case of cold-water fish grown during the summer months) was simply too great. The system can be operated far from the sea because the only seawater it uses is that required for the initial set up. Freshwater is added to make up for evaporative losses. This method allows fish to be grown or stored close to the market, thus providing a fresher product.

In this system (Figure 3), fish are grown intensively in concrete or plastic-lined tanks. The water quality is maintained by a combination of aerobic and anaerobic processes. Bacteria convert the (toxic) ammonia excreted by the fish into relatively harmless nitrate in an aerobic (nitrifying) loop. Nitrate is then converted to nitrogen gas by denitrification in an anaerobic loop.

This biofilter system presently operates as pilot plants in Rehovot and Eilat, in Israel. Gilthead seabream (*Sparus aurata*) are grown at a density of 30 $\mathrm{kg\,m^{-3}}$ in 5–10 $\mathrm{m^3}$ tanks which are aerated with either air or oxygen. This not only replaces the deficit caused by respiration of the high density of fish, but also provides the dissolved oxygen required for the next stage, involving aerobic microbial processes. Water from the fish tank is pumped through the bacterial nitrification stage (trickling filter) at a rate of one tank volume every 60 minutes. This trickling filter system converts all of the ammonia produced into nitrate.

The waste sludge (faeces, waste food etc.) is continuously drained from the fish tank into a sedimentation tank (or 'digestion basin'). The water that flows into this tank has high levels of dissolved oxygen and nitrate (cf. Figure 4). The high concentration of labile organic matter in the tank consumes most of the dissolved oxygen in the uppermost layer. Beneath this layer there is a region where nitrate-reduction dominates. In the lowest layers of the sedimentation tank, sulphate reduction occurs and high concentrations of $H_2S$ are found. The rate of bacterial

***Figure 4*** *Schematic diagram of microbial processes in the sedimentation tank or 'digestion basin' (cf. Figure 3).*



activity in the sedimentation tank, and hence of the reactions which occur, is controlled by the rate of production of small labile organic molecules, such as volatile fatty acids, by *in situ* fermentation reactions.

The water which flows out of the sedimentation tank has low levels of dissolved oxygen (1–2 p.p.m.), moderate nitrate and small amounts of dissolved sulphide (~10 μM). In the fluidized bed reactor, oxidation of sulphide occurs, but whether this is by reaction with dissolved oxygen or nitrate has yet to be established. The water is then recycled back to the fish tank. During routine operation of this system, no hydrogen sulphide reaches the fish tank. However, there is a significant reservoir of highly toxic hydrogen sulphide in the lower layers of the sedimentation tank. If this were accidentally to be released into the flowing water and reach the fish tank, it would cause instant mass mortality. In order to prevent this, a novel safety device has been developed (Figure 5). This consists of a cartridge of beads coated with ferrihydrite, a red labile iron oxyhydroxide. As long as the system does not contain any significant sulphide, the beads will remain red. If sulphide begins to flow through the system, the beads will turn black. A photodiode registers this change and shuts off the circulation between the anaerobic loop and the fish tank. The device will also scavenge out enough of the sulphide to prevent it killing the fish in the short period before the pump is shut down. The fish farmer will then have time to solve the initial problem by, for example, cleaning the sedimentation tank, before returning the system to normal operation.

***This novel safety cartridge provides a warning of the presence of hydrogen sulphide, and will scavenge out enough sulphide to prevent it killing the fish before the pump is shut down***

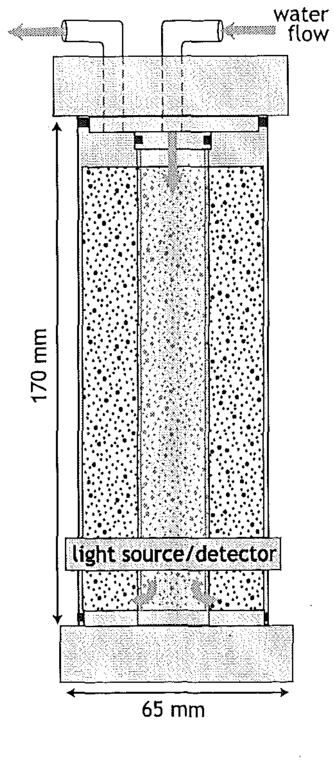


***Figure 5*** *The iron cartridge for detecting and removing hydrogen sulphide from the fish-culturing system*

## Mariculture as significant exploitation of the marine environment

The following question was raised at the Challenger Marine Sciences 2000 Meeting at UEA:

*'How can we sell what we are doing as marine scientists to the general public and their political masters?'*

We contend that a significant future use of the seas will be mariculture. Mariculture is already an important use of the marine environment. In 1998, the total aquaculture production (including plants) was 39.4 million metric tonnes (m.m.t.), with a value of US$52.5 billion. In comparison, the landed value for capture fishery production in 1997 was about US$83 billion. Furthermore, an increasing proportion of this capture fishery is used for the production of fish food for aquaculture. Aquaculture is the fastest growing food sector, and has been increasing at a compound rate of 11% per year since 1984, when production stood at 10.1 m.m.t. This growth rate compares with 3.5% per annum for terrestrial livestock meat and 1.85% for capture fisheries.

The days of hunting for fish in the seas are surely limited. We should retain the health of the marine ecosystem for its primary function as far as we are concerned, namely as the life-support system of the planet. To the extent that we harvest the seas, it should be for new biochemicals that can be used for medicine and other sciences, and for new organisms that may form the basis of new strains of marine organisms that can be cultured.

Mariculture represents a use of seawater that is clean and unpolluted. It provides, therefore, a real and obvious incentive not to discharge our wastes into the sea, either directly or via rivers and estuaries. The long-term aim of this industry should be to grow marine organisms in an integrated manner, where the waste material from the primary cultured organism is treated before discharge.

As described above, systems are being developed to do this in regions with abundant sunlight, using marine algae to remove the toxic and polluting by-products (ammonia, dissolved organic nitrate and phosphate). The algae can then be sold directly or fed to algivores which represent an additional commercial crop. Alternatively, bacterial biofilters can be used to treat the effluent, and this allow systems to be developed where the water in entirely recycled. Such systems represent a significant and desirable development for this new marine farming. However, they are in their infancy and require expertise and scientific skills from a very wide spectrum of the marine science community. The more knowledgeable and sophisticated the scientific input to these problems, the faster and better the solutions will be to the many remaining problems.

*About the authors ....*

## Further Reading

Naylor, R.L., *Goldburg, R.J., Primavera, J.H. and others* (2000) Effect of aquaculture on world fish supplies. *Nature,* **405**, 1017–24.

Neori, A. and M. Shpigel (1999). Using algae to treat effluents and feed invertebrates in sustainable integrated mariculture. *World Aquaculture Magazine,* **30** (2) (June), 46–51.

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**Michael Krom** is Professor of Marine and Environmental Geochemistry at the School of Earth Sciences, Leeds University. He is currently coordinator of the BIOFILTER EU project to develop a recycling mariculture system.

**Amir Neori** is an Associate Scientist at the National Centre for Mariculture, Eilat, Israel. He has pioneered the use of algae in cleaning the effluent from marine fishponds and has developed this to a commercial system.

**Jaap van Rijn** is senior lecturer at the Faculty of Agriculture, the Hebrew University of Jerusalem, Israel. He has a keen interest in water quality processes in fish culture systems; currently he is Co-Editor-in-Chief of *Aquacultural Engineering.*

**Simon Poulton** is a postdoctoral fellow at The School of Earth Sciences, Leeds University. He developed the iron oxide device for detecting hydrogen sulphide mentioned in the article.

**Ian M. Davies** is leader of the Environmental Impacts Group at Fisheries Research Services Marine Laboratory, Aberdeen. His interests include the fate and effects of marine contaminants, and he is a recent Chairman of the ICES Working Group on Environmental Interactions of Mariculture.

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# Book Reviews

## *A Journey through Ideas in Natural Science*

**Tides: A Scientific History** by David E. Cartwright (1998), Cambridge University Press, 304pp, £45 ($74.95) (hard cover, ISBN 0-521-62145-3).

Ocean tides must have been a matter of curiosity and concern to sea-shore dwellers since earliest times. The question of what causes them certainly ranks amongst the oldest problems in natural science, pondered by philosophers and scientists. Dr Cartwright in his *Tides* traces the evolution of the subject from early times to the present: from the early ideas of Indian, Arabic and Greek scholars, through the Middle Ages to the time of Newton, and on to the space age. Raised by the Moon (and to a lesser degree by the Sun), the tides impinge on a number of scientific disciplines as well as being of practical significance. Foremost is the effect of tides on ocean levels and circulation, particularly in shallow coastal waters. But the periodic lunar and solar rhythms also occur in the atmosphere and in the solid Earth itself. The tides modify the Earth's rotation, perturb the motion of Earth-orbiting satellites, and feed back into the motion of the Moon itself. An understanding of the tides requires knowledge of not only the dynamics of the oceans but also the motions of the Sun and Moon and of the physical properties of solid Earth and atmosphere. Each of these areas have their own independent histories but the tides provide a common thread. Thus in traversing the history of the subject it quickly becomes apparent to the reader that it is a journey of the evolution of scientific ideas in natural science as much as of the seemingly esoteric subject of tides – a journey in which one meets many of the giants in natural science and mathematics.

The early chapters (1–4) of the book lead from the era of megaliths, through the Middle Ages, and on to the seventeenth century. They cover briefly some of the thinking and speculation on tides, of attempts to measure and predict them. The quantitative understanding of tides starts with the development of classical mechanics and the work of Newton, and the book also begins to take on substance at this point, with discussion and description of Newton's contributions to the subject, followed by those of Euler and others. Cartwright strikes a good balance here, providing enough information to be able to identify key aspects of the theory without getting lost in detail. Cartwright notes that an important element in tidal research has been the parallel development of theory and measurement: increasingly accurate theories demand measurements capable of testing the ideas, while improved data provide the impetus for renewed theoretical effort. Thus matters of measurement and theory are interwoven in a well balanced way throughout the book, illustrating in the process the futility of attempting to distinguish between pure and applied research.

Modern tidal theory rests very much on the work by Laplace, with the formulation of his tidal equations. This work of the late 18th century is discussed in enough detail by Cartwright to be able, again, to follow the essential arguments. This is followed by discussions of subsequent contributions to the theory by Kelvin, Lamb, Hough and others, adding layers of increasing complexity in the search for solvable formulations. But 'usefulness' was not overlooked, as Cartwright makes clear in several chapters, and it is interesting to reflect, once again, on how early scientific advances were driven by well-posed practical needs. The ever-increasing numbers of tide observations led to advances in predictive techniques, including the important application of harmonic analysis to the problem by Kelvin and G.H. Darwin. Instrumental developments are also described, including the mechanical harmonic tide predictors.

By the 19th century, the observational information had grown to the point where thought could be given to constructing tidal models beyond local regions, and the first attempts at describing empirically the global behaviour of the tides began to appear, culminating in the world map

## Further Reading

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By the 19th century, the observational information had grown to the point where thought could be given to constructing tidal models beyond local regions, and the first attempts at describing empirically the global behaviour of the tides began to appear, culminating in the world map by R.A. Harris. It is interesting to read how Harris' monumental work was received by the theoreticians of the day, a debate that finds echoes in the tidal work of the latter half of the twentieth century.

The journey to this point – to the early 20th century – occupies the first half of the book, and the second half covers subsequent developments: the continual refinement of tidal theory, including improvements in the treatment of tidal velocities and dissipation of tidal energy; improvements in instrumentation, analysis and prediction of tides; and the ability to observe the tidal phenomenon from space. Perhaps the major impact came from the advent of computers, not only because they facilitated analysis of tidal records but also because they permitted, for the first time, realistic global models to be developed for the tides under different assumptions about the treatment of dissipation. Some of these models are discussed but little is learnt about the validity of the assumptions inherent in them.

Tidal work during the 20th century is also characterized by the broadening of the subject to include atmospheric and solid Earth tides, because of improved measurements of these phenomena. The book touches on these matters and gives a brief commentary on their interactions with the ocean tides. Another aspect of tidal developments was the re-emergence of an old problem, that of the acceleration of the Earth and Moon under the influence of the gravitational torque exerted by the Moon on the Earth's tides. The magnitude of this acceleration is a function of the dissipation of tidal energy in the ocean–Earth system and, if present rates are representative of the past, this leads to the untenable conclusion that the Moon was very close to the Earth relatively late in the planet's history. But the assumption of constant dissipation is not valid for ocean configurations that change with the drift of continents, nor for oceans whose extent of shallow seas has fluctuated with the waxing and waning of ice sheets. Hence the importance of understanding the nature of the dissipation mechanisms, so that past tides can be adequately predicted in the absence of observational constraints. This may be a forlorn hope and Cartwright's book, while briefly raising some of these issues, does not point to future directions.

A final chapter for tides in the 20th century has been the contribution from the space programme. Like the Moon, the motions of satellites are perturbed by the Earth's tides; mainly by the solid tide but also by the ocean tide. By the 1970s, orbital theory and tracking capabilities had reached the stage where it was possible to measure these tidal perturbations in the orbits of some satellites and it became possible to measure the bulk elasticity of the planet as well as the rates of dissipation of tidal energy. The other contribution from space research has been the direct measurement of the shape of the ocean surface with satellite-borne altimeters, and this has led to the most complete descriptions of the ebb and flux of the oceans. Cartwright's discussion of these matters, albeit again rather brief, forms a fitting end to a journey of over two millenia of thought on tides and related matters. As noted before, the journey extended beyond the narrow bounds of the phenomenon and the book's readership should likewise extend beyond the strict practitioners of the subject.

**Kurt Lambeck**
*Australian National University, Canberra*

## *Luigi Fernando Marsigli: scientific 'virtuoso' and investigator extraordinaire*

*Facsimile edition of* **Histoire Physique de la mer** by Luigi Fernando Marsigli (1725), with English translation, and introduction and notes by Anita McConnell (1999). 582pp. Also contains 52 plates, fold-out maps and tables. Published by the University of Bologna. For details of purchase, see the end of the review.

Since a recognized science of oceanography came into existence, in the years before and after 1900, and those involved began to construct a narrative of its past, Luigi Ferdinando Marsigli's *Histoire Physique de la Mer*, published in 1725, has been accorded unique status as the first book to concentrate exclusively on the science of the sea. But as Anita McConnell points out in the introduction to this new edition of the *Histoire*, which includes both a facsimile of the original and her English translation and notes, 'few persons ... have read this book perceptively'. A combination of factors have meant that only the truly determined will already have done so: the rarity of the volume and its use of theoretical concepts and techniques long since abandoned, especially in the chemical analyses, have rendered much of its content impenetrable and disappointing to modern readers who expected something rather different from the title.

Yet in fact the *Histoire* is a masterwork, if a flawed one, which has not been given its considered due – principally because of lack of understanding of what Marsigli was trying to achieve. The appearance of this superb volume means that it is now possible to study the text in detail, and in the light of the information provided about Marsigli's own aims and expectations for the project, to understand more fully just what a remarkable achievement it was, even though he was unable to fulfil all the objectives he had set himself.

Marsigli was born in Bologna in 1658, into a noble family. He was delicate and educated at home, but later studied under leading Italian academics of the day, having early demonstrated enthusiam for both natural and physical science. He followed the family tradition of diplomatic service and, aged 21, was attached to an embassy to Turkey. He used the opportunity to make copious scientific observations on different topics, the best-known being his study and explanation of the countercurrent in the Bosporus.

In 1682 Marsigli entered the service of the Hapsburg emperor, at a time when the Austrian and Turkish empires were fighting for possession of the Balkans and central Europe. For almost 20 years Marsigli was engaged in this combat – an account of his fortunes and misfortunes forms the major part of a detailed and readable book on his career by John Stoye (1994). He specialized in military engineering and surveying; when the war was concluded at the Treaty of Carlowitz in 1699, it was Marsigli who surveyed the line of demarcation on behalf of the Austrian emperor. Throughout this time he had been collecting a mass of information on geography, science, natural history and antiquities, which he later published in his massive six-volume work *Danubius* – his revision of the cartography of central Europe was the first to show the river's true course.

Marsigli's scientific training and instincts were those of the late 17th century. He was a contemporary of

Boyle, Hooke, Newton and Halley, but up to this point was perhaps more a virtuoso – as Stoye calls him (as indeed were many of the enthusiasts who made up the rank and file of the Royal Society in Britain) than a true philosopher. Throughout his long life Marsigli continued this energetic and diverse pursuit of information and curiosities. However, an unexpected and unwelcome turn of fortune now provided him with the opportunity to focus on a particular theme.

Like others at the time who were engaged in trying to unravel the history of the Earth, Marsigli had convinced himself by his study of the land that a full understanding of its geography and structure would only be possible through knowledge of the sea; but there had hitherto been little opportunity for him to explore this aspect of Earth science. Following the eastern peace, he had been transferred to another war zone in the west, but suddenly found himself in disgrace and unemployed, after a town he was helping to defend capitulated to the enemy (on this occasion, the French forces of Louis XIV). Marsigli went to Paris, where he was welcomed by the Académie Royale des Sciences, but decided to settle in the south of France, at Montpellier, which was in the process of establishing its own Royal Society (see Further Reading). In the summer of 1706, he examined the Languedoc coast, continuing eastwards to Provence, where he was able to go to sea with the coral fishermen. The possibilities opened up by this experience were a revelation, and Marsigli established himself at Cassis, where he could go out regularly with the fishing boats to examine their catches and make observations of his own. He was particularly fascinated by the coral and other items brought up by the dredges, but also undertook surveys of the sea-bed, and studied the seawater, its temperature, and water movements – observations that form the opening sections of the *Histoire Physique*.

Marsigli intended his work to be an introduction to the science of the sea. As he made plain in a summary (1711), it was planned in five sections, one on the sea-bed, the second on seawater, the third on water movements, the fourth on marine plants and the fifth on fishes and other marine animals. Trying to make sense of currents in the sea, he had already come to the conclusion that the subject was too complex for one person, and that the simultaneous observations that were needed would only happen if the resources of the state were brought to bear on the problem. Likewise he found the profusion of marine life too great to cope with, so the last section was omitted from the version sent to the Paris Academy for publication.

During the second decade of the 18th century Marsigli was again in military service in Italy, on behalf of the Pope. He was also busy in Bologna where he was establishing an institute, having made a bequest of his scientific and artistic collections to the university. He also continued his study of the sea, returning to Cassis when time and opportunity permitted. His book, however, had still not appeared when in 1721 he set out on a sea journey that would take him to London, and eventually to Holland. This was almost certainly the first time he had been on the open ocean – and was indeed one of the reasons why he chose that route – he was busy observing during the voyage. After a brief stay in London (where he was admitted as an Honorary Fellow of the Royal Society), Marsigli crossed to the Netherlands, still busily observing. Here he was able to arrange for the publication of several books, including the huge Danube treatise (1726) and his essay on the natural history of the sea (1725). Both were intended to be in Latin, which up to that time had been the international language of science. However, times were changing and Marsigli was persuaded to allow his work on the sea to be translated into French. When the printed text arrived in Bologna he was dismayed to see that not only were there a large number of typographical errors but that, worse still, the title itself had been changed. The *Histoire Physique de la Mer* gives an emphasis to the volume that Marsigli had never claimed for it; he was well aware that he had only made a start in unravelling the secrets of the sea – just enough to get an inkling of the size of the task involved. Notwithstanding this, the volume became enormously influential in the 18th century. It was frequently quoted – not always correctly. Any library of any importance surviving from that time has a copy, and the present edition contains an essay by Jacqueline Carpine-Lancre on the book and its diffusion.

In one important respect Marsigli's enthusiasm let him down. When he began studying coral he, like most others at that time, thought it was a mineral. However when a piece was put into a jar of water he saw what he took to be flowers appear, and decided that after all it must be a plant. Apparently, he disregarded the suggestions of a young associate who thought that the so-called 'flowers' were showing animal or insect-like properties. Thus corals, along with sponges and lithophytes, are to be found in Section 4 of the *Histoire Physique*, in the marine plants section. Notwithstanding its flaws and incompleteness, the book was the first work to attempt a comprehensive picture of the sea and to lay down broad lines for future study. It is full of interest, such as for example the profiles of the sea-bed, and Anita McConnell and the University of Bologna are to be congratulated for reproducing the work so faithfully that the plates, fold-out charts, diagrams and tables are reproduced on the same scale as in the original. Now we have not only the book itself but also the scholarly basis for understanding the circumstances that led to its writing and the ideas that shaped it, linked to the story of its publishing history which meant that it appeared not quite as originally intended. Whatever the imperfections of the original, the present publishers have handsomely redressed the balance, enabling the scale of Marsigli's achievement to be fully appreciated at last.

**Margaret Deacon**
*University of Southampton*

## Further Reading

Carpine-Lancre, J. and McConnell, A. (1985) Le Comte L.F. Marsigli et la Société Royale des Sciences de Montpellier, *Actes du 110e Congrès national des Sociétés savantes, Montpellier, 1985. Histoire des Sciences et des Techniques,* **1**, 33–44.

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Stoye, J. (1994) *Marsigli's Europe, 1680–1730. The life and times of Luigi Ferdinando Marsigli, soldier and virtuoso* (Yale University Press: London and New Haven).

This book may be obtained, price 124 Euro or 240 000 Italian Lira, C/C Postale n. 25024407, from: FARAP Editrice di F. Forni, via Fulton 17, I-40017 San Giovanni in Persiceto, BO, Italy. http://wwwintermed.it/farap/nagozio.ht

## *A Captivating Gem*

**Deep Ocean** by Tony Rice (2000) 96pp. Natural History Museum. £9.95 (flexicover, ISBN 0-565-09150-6).

This is a really wonderful little book. It brilliantly conveys the excitement and mystery of the deep ocean and its often weird inhabitants, and there are also sections on the surface and mid-water layers that successfully place the depths in context. The range and quality of the colour pictures are as appealing as the text is accessible and authoritative. There is a good glossary and index, and the 'Further information' section includes major websites from which many other links can be made.

The whole book, part of the Natural History Museum's 'Life Series', is clearly well planned; indeed it is hard to see how the end result could have been improved. The richly illustrated text is essentially linear, but with a sprinkling of apt, well-placed boxes.

Who will fail to be captivated by, for example, the luminescent blue-spotted squid *Watasenia scintillans*, the grotesquely ugly rat-trap fish, or the simply bizarre tripod fish? Even the sea-cucumbers enthrall. Buy this book; you won't be disappointed.

**Peter Sheldon**
*Department of Earth Sciences*
*The Open University*

## *El Niño as never seen before ...*

**Currents of Change: Impacts of El Niño and La Niña on Climate and Society** 2nd edition, by Michael H. Glantz (2001) Cambridge University Press, 252pp. £17.95 (flexicover, ISBN 0-521-78672).

The first edition of *Currents of Change: El Niño's Impact on Climate and Society* was published in 1996, and was a moderate-length book (194pp.) that was designed to be easy to read for a non-scientist, and to cover as many of the diverse aspects of ENSO as possible in a readily accessible way. Accordingly, it featured sections not only on the physical mechanisms involved, but also historical aspects, personal anecdotes, socio-economic implications, and various other bits and pieces thrown in as appropriate. It was certainly a rather quirky publication – eminently readable on the whole, but let down somewhat by some hugely cumbersome figure captions (which extended for several pages), and some slightly odd choices of emphasis. It was also notable for having an El Niño crossword, something I can honestly say I haven't seen elsewhere.

With all this in mind, I read the recently published second edition with interest. I was keen to see whether the author had managed to tighten up the loose bits of the first edition without losing any of its character. Well, it seems that he did – the second edition is a definite improvement on the first, but if anything is even quirkier. The most immediate change is the title – gone is *El Niño's Impact ...*, to be replaced by *Impacts of El Niño and La Niña ....* This can only help increase awareness that what we call El Niño is simply one extreme of an irregular cycle. The crossword has gone (except now the acknowledgements are presented in the form of a cross-word solution), but has been replaced by an ENSO colour-by-numbers. I kid you not. I haven't finished mine yet – I'm still trying to find an orange crayon (the recommended colour for the 10-cm contours). And, in a world obsessed with DVD and computer animation, it was certainly refreshing to see the equatorial Pacific brought to life by flicking rapidly through pages 123–203 whilst staring at the bottom right of the page. Walking stickmen will be eating their hearts out everywhere!

Leaving aside these (and other) entertaining diversions, the most impressive thing about this second edition is that it has kept everything that was good about the first (in particular the multi-aspect approach and accessibility), improved them further, and then added some really nice touches. The figures (and especially the captions) are generally better, the rather dull section on 'personal experiences of El Niño researchers' has wisely been dropped, and the new sections brought in are of a high standard. The one concerning El Niño in the media is well worth a read – I was amazed to see how unscrupulous businesses in America try to play on people's paranoia about El Niño to sell them storm windows and snowthrowers. The descriptions of the physical processes remain relatively comprehensive, without getting too technical – this should help keep the book appealing to non-specialists. Similarly, the other aspects of ENSO covered are still presented in a readily accessible way; Glantz seems to realize that virtually nobody reading it will have expertise in every topic he deals with.

So, overall, a definite improvement. Don't expect to find yourself consulting it while writing your next journal paper about ENSO – it just isn't that type of book. It is, however, an excellent introduction to the subject for a non-scientist, or an interesting bit of entertainment for the enthusiastic scientist who just can't leave the subject alone.

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*British Antarctic Survey*

## *Chemistry in the Sea*

**Chemical Sensors in Oceanography** edited by Mark S. Varney (2001) Gordon & Breach Science Publishers, 333pp. £65 (hard cover, ISBN 90-5699-225-4).

Any review of this book, which is essentially a collection of papers, may be considered somewhat artificial, because the reviewer reads it from cover to cover. The real value of the book is as a reference work, offering detailed accounts of various methodologies and instrumentation for chemical measurement in the marine environment. In all, there are thirteen chapters from researchers around the world who are united in their need to acquire high-quality chemical data from *in situ* or near-*in situ* measurement in order to improve understanding of marine processes and systems. As much of the work presents details of development of instrumentation, it was inevitable that some of it would already be out of date by the time the book was published. However, I do feel that the book offers a good overview of sensor-development, with enough detail to satisfy some specialists in their respective disciplines. I have a few niggles about the layout and presentation (which are covered later), but overall the content is good and well presented.

The book opens with an introductory chapter by the editor, Mark Varney. He explains the need for chemical sensors, and outlines the criteria he used to select sensors for inclusion in the book (e.g. acoustic, magnetic and pressure sensors are classed as physical sensors and so are not included). Details are given of the various sensor types and their application. There is discussion of the demands of the marine environment (which is subject to high pressure, biofouling, corrosion etc.), and of the value of *in situ* measurement. These aspects are also included in several of the later chapters, which means that there is some degree of repetition for the cover-to-cover reader. Table 1.2 shows typical requirements (range, accuracy, resolution) for several common seawater sensors and would be extremely useful for instrument developers. Mark has succeeded in bringing together all the major aspects of the book in this detailed introduction, at the expense, I suspect, of presenting less of his own work with thick-film sensors.

The next nine chapters can be broadly grouped into spectroscopic (Chapters 2–5), optical (Chapters 6–8) and electrochemical (Chapters 9–12), with the final Chapter 13 (Tokar *et al.*) providing an overview of chemical sensor technology. Some authors have dealt with the development and operation of *in situ* instrumentation for the measurement of dissolved nutrients or trace metals, by miniaturized wet chemistry systems (Blain *et al.*, Hydes *et al.*, Worsfold *et al.*) or direct-reading instruments (Clayson). Others have dealt with the use of microoptodes for oxygen, pH, $CO_2$, temperature and radiance (Holst *et al.*), fibre optics for $CO_2$ (Degrandpre *et al.*) and laser fibre optics for dissolved organic matter (Chen). The use of electrodes for chemical 'odours' (Moore *et al.*), trace metals (Achterberg *et al.*) and oxygen (Reimers *et al.*) is also covered. Whilst some of the chapters are concerned with direct *in situ* measurement, other methods described are predominantly shipboard operations with potential for *in situ* operation (Achterberg *et al.;* Chen).

The micro-electromechanical systems (MEMS) described by Tokar *et al.*, and the optical micro-sensors described by Holst *et al.* and by Chen, have their origins in non-marine applications, but offer exciting possibilities for development. The use of diffusive gradients in thin film (DGT), described by Davison *et al.*, is a relatively new technique for the *in situ* separation of chemicals for subsequent analysis, which offers opportunities for the measurement of a range of metals, and possibly phosphate as well.

All of the authors point out the difficulties associated with measurement in the sea, but I particularly liked the detail provided by Reimers *et al.*, in their review of benthic *in situ* sensors, of interferences caused by sediment disturbance and by compression of the diffusion boundary layer by electrodes. I also liked the technique of Moore *et al.*, who placed their micro-sensors for organics on different parts of a lobster and demonstrated the effect of morphological features on the boundary layer.

The production of the book leaves a little to be desired. Colour plates are presented in one section only, and all other graphics and pictures are in black and white within the text. Some of the figures (e.g. Figures 11.16 and 11.17 in Reimers *et al.*) really needed to be in colour for proper interpretation, whereas one or two of the instrument pictures would have been perfectly adequate in black and white. Some of the typesetting is inaccurate, with the symbol for nickel presented as 'NI' in the titles for Chapter 10, and two chapters showing authors apparently with with no place of work (although these details are provided in the list of contributors at the beginning of the book).

Overall, though, *Chemical Sensors in Oceanography* represents a good reference for anyone involved in the measurement of chemical components of seawater and sediments. The analysis of a range of trace metals, nutrients, and organic and inorganic compounds, is often covered by more than one technique. Some of the chapters will appeal to the student requiring an overview of various sensors, whereas the more detailed descriptions of systems will be of use to researchers active in marine chemistry. This book will also be useful to electronics and mechanical engineers involved in sensor development. Although the technology continues to evolve, the authors have given a good explanation of their work and provide a comprehensive bibliography for further study.

**Paul Ridout**
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**The Carbon Cycle** (2000) edited by T. M. L. Wigley and D.S. Schimel (2000) Cambridge University Press, 292pp. £40 (hard cover, ISBN 0-521 58337-3).

This book is a fascinating and informative time-capsule providing a clear and succinct statement of the state of the carbon cycle and global warming debate in the early 1990s. Although the book was published in 2000, it is based upon the deliberations of a 1993 workshop of the Global Change Institute (GCI) of the Office for Interdisciplinary Earth Studies (OIES) at the University Corporation for Atmospheric Research (UCAR). The document was updated in 1996 by the incorporation of relevant excerpts from the 1994 and 1995 IPCC (Intergovernmental Panel on Climate Change) Reports. A number of authors took the opportunity to update their bibliographies at that time, and the presence of several '1996 (in press)' citations attests to their hope that publication would follow soon thereafter. Although the discussions at the GCI were important in formulating the IPCC Reports, the value of reproducing them for a 21st century readership is limited, especially when a new series of IPCC Reports has just been released.

As the editors themselves admit (p.4) 'the science, however, continues to advance at a rapid rate and across a broad front'. A lot has happened over the intervening eight years, so that this collection of tightly written and carefully crafted essays cannot be considered to represent the state-of-the-art. For example, one of the key new insights emerging from the GCI was the potential impact of feedbacks on climate stability. This topic has been the focus of much recent research, and areas of science addressed only peripherally at the 1993 GCI have now moved centre stage. Marine scientists will note, for example, that there is little mention of iron fertilization or of the debates concerning the potential for the abrupt switching off of North Atlantic Deep Water formation in a warming world. Nor is there any mention of the role of dimethyl sulphide in cloud formation over the oceans. Paleoceanographers will regret that the evidence for rapid changes in climate and ocean circulation at the end of the last glaciation could not be considered. Many similar examples could be quoted. The economists and social scientists will also regret that the implications of the 1997 Kyoto agreement and its subsequent rejection by the USA could not be addressed. Such gaps are an inevitable consequence of the extended period from completion to publication.

However, as a retired senior citizen I know that many good things can be found in apparently out-dated packages. It is important, therefore, to consider the volume in the light of the original intentions of its editors and authors, and to assess its current relevance to marine scientists. The book is intended to address three key issues: (1) The missing carbon sink (how big is it, how can it be explained, how important is it?); (2) past $CO_2$ variations (what is the past record, how can it be explained, and how important is it in estimating future changes?); (3) modelling strategies (what tools are available, what are their respective merits and weaknesses, and how are they best employed to predict future changes?).

The first theme, the missing carbon sink, is dealt with in nine chapters. Only one chapter deals primarily with marine processes (air–sea exchange of $CO_2$). This chapter is of only limited contemporary interest since the JGOFS programme has greatly expanded the global dataset of oceanic $CO_2$ partial pressures, and there have been very significant advances in relating exchange velocities to wind speed and sea state. A further two chapters, considering constraints on the atmospheric carbon budget and the interpretation of atmospheric oxygen measurements, have substantial sections on marine systems. All the chapters are succinct and well written. They are intended to be accessible to those who are not expert in the particular areas of science addressed. Paradoxically, therefore, it is the chapters on terrestrial systems that are likely to prove most enlightening to marine scientists – providing them with a more rounded view of the global carbon cycle.

Past $CO_2$ variations are dealt with in a scant two chapters, only one of which addresses marine systems. This is focussed on shallow water calcium carbonate deposition and therefore does not address *inter alia* the many issues related to rapid changes in climate and ocean circulation.

The third theme, modelling strategies, is addressed in eight chapters, three of which are wholly marine in their perspective. Again the quality of the chapters is high and the authors have provided clear and accessible accounts of the strengths and weaknesses of the different modelling approaches. I found this section to have aged the most gracefully, since the foundations for the modelling strategies have changed less rapidly than the raw computing power needed to implement them.

Overall this is definitely a book for the institutional libraries where its 1996 dateline will not raise any eyebrows. If it is purchased by your local library then you should take the time to browse through it and benefit from this well edited and carefully written set of essays by a galaxy of carbon cycle experts.

**Mike Whitfield**
*Visiting Professor in Marine Science,*
*University of Plymouth*

# Forthcoming Events

## Events in 2001

**2001: An Ocean Odyssey** (Joint Assemblies of IAPSO and IABO). (21–28 October, Sheraton Hotel, Mar del Plata, Argentina. *Contact* 2001 Secretariat, Instituto Argentino de Oceanografia; Fax: 54-291-486-1527; Email: iado@criba.edu.ar

**The OI Pacific Rim** event scheduled for December in Singapore has been ***postponed***. The organizers, Spearhead, feel that the number of companies planning to exhibit was not enough to attract a sufficient attendance and so would not justify exhibitors/speakers the investment in time and expense.

***Note:*** *Details of forthcoming meetings can also be found in the monthly Challenger Society newsletter,* ***The Challenger Wave.*** *If you would like to advertise your meeting there, please send details to John Allen at the Southampton Oceanography Centre, Email: John.T.Allen@soc.soton*

## Events in 2002

**Phytoplankton Productivity: An appreciation of Fifty Years of the Study of Oceans and Lakes** 18–22 March, University of Wales, Bangor. Conference website: http://www.plankton.productivity.org Details of accommodation can be obtained from the conference office: Tel. +44-(0)1248-382561.

**Benthic Dynamics: *In situ* surveillance of the sediment–water interface** 25–29 March, University of Aberdeen. *Contact* Martin Solan, Ocean Laboratory and Centre for Ecology, University of Aberdeen, Newburgh, Scotland, AB41 0AA; Tel./Fax: +44-(0)1358-789631/789214; Email: m.solan@abdn.ac.uk Website: http://www.abdn.ac.uk/ecosystem/conference/

**Bioluminescence and Chemiluminescence** (12th International Symposium), 5–9 April, Robinson College, University of Cambridge. See the conference website: http://www.lumiweb.com

**Tracer Methods in Geophysical Fluids Dynamics** (34th International Liège Colloqium on Ocean Dynamics), 6–10 May, University of Liège. Conference website: http://modb.oce.ulg.ac.be/Colloquium

**Acoustics in Fisheries and Aquatic Systems** (ICES Symposium) 10–14 June, Montpellier, France.

**UK Marine Science 2002** 8–13 September, University of Plymouth.

**Low-lying Coastal Areas, Hydrology and Integrated Coastal Zone Management** 9–12 September, Bremerhaven, Germany, Bundesantalt für Gewässerkunde. *Contact* IHP/OHP Secretariat, Postfacfah 200253, 56002, Koblenz; http://www.bafg.de/Fax: 0261-1306-5422: Email: atrigel@bafg.de stage. Marine scientists will note, for example, that there is little mention of iron fertilization or of the debates concerning the potential for the abrupt switching off of North Atlantic Deep Water formation in a warming world. Nor is there any mention of the role of dimethyl sulphide in cloud formation over the oceans. Paleoceanographers will regret that the evidence for rapid changes in climate and ocean circulation at the end of the last glaciation could not be considered. Many similar examples could be quoted. The economists and social scientists will also regret that the implications of the 1997 Kyoto agreement and its subsequent rejection by the USA could not be addressed. Such gaps are an inevitable consequence of the extended period from completion to publication.

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# OCEAN Challenge

## The Magazine of the Challenger Society for Marine Science

### SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

***The Society's objectives are:***

To advance the study of Marine Science through research and education.

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

To contribute to public debate on the development of Marine Science.

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

Holding regular scientific meetings covering all aspects of Marine Science.

Supporting specialist groups to provide a forum for discussion.

Publication of a range of documents dealing with aspects of Marine Science and the programme of meetings of the Society.

***Membership provides the following benefits:***

An opportunity to attend, at reduced rates, the biennial five-day UK Marine Science Conference and a range of other scientific meetings supported by the Society.

A monthly newsletter (*The Challenger Wave*) which carries topical marine science news, and information about jobs, conferences, meetings, courses and seminars.

**The Challenger Society Website is**
**www.challenger-society.org.uk**

### MEMBERSHIP SUBSCRIPTIONS

The subscription for 2001 costs £40 (£20.00 for students in the UK only). If you would like to join the Society or obtain further information, contact the Executive Secretary, Challenger Society for Marine Science, Room 251/20, Southampton Oceanography Centre, Waterfront Campus, Empress Dock, Southampton SO14 3ZH, UK; Fax: 023-80-596149; Email: jennifer.jones@soc.soton.ac.uk

### COUNCIL FOR THE CHALLENGER SOCIETY

### ADVICE TO AUTHORS

Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. If at all possible, they should be well illustrated (please supply clear artwork roughs or good-contrast black and white glossy prints). Copy may be sent electronically.

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