OCEAN ACIDIFICATION

IN A CHANGING WORLD

Jason M. Hall-Spencer

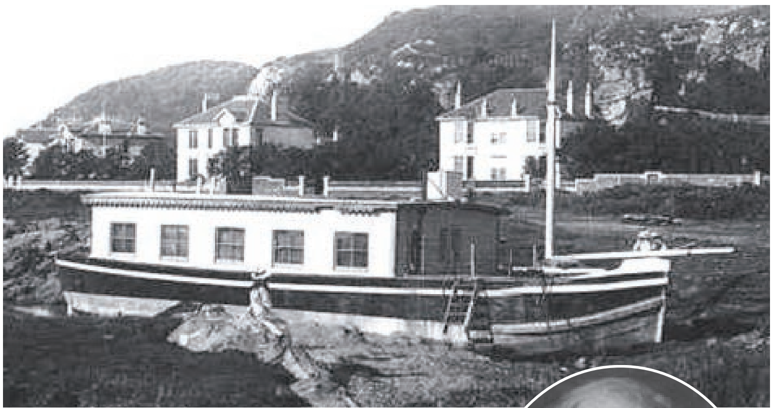
Victorian scientists of the HMS *Challenger* era would no doubt be shocked by the ways in which humanity, and our use of fossil fuels, is altering the physical, chemical and biological nature of the oceans. Since the 1950s, coastal ecosystems have been radically transformed by human activity – the world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

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

John Murray and the early marine biology stations

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

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



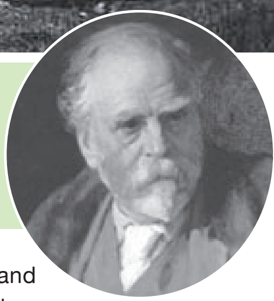


Figure 1 *The Ark floating marine station, which was wrecked by a storm in January 1900.*
Right *Its founder, John Murray.*
(Photo of the Ark by courtesy of North Ayrshire Council Heritage Service)

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

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

Overfishing and habitat destruction

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

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

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

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

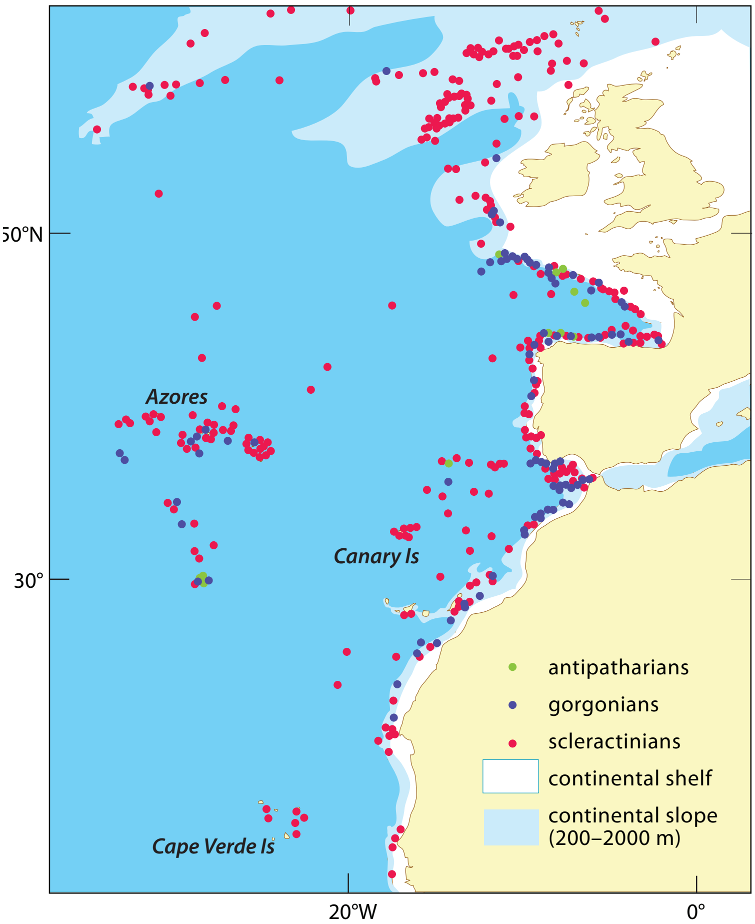
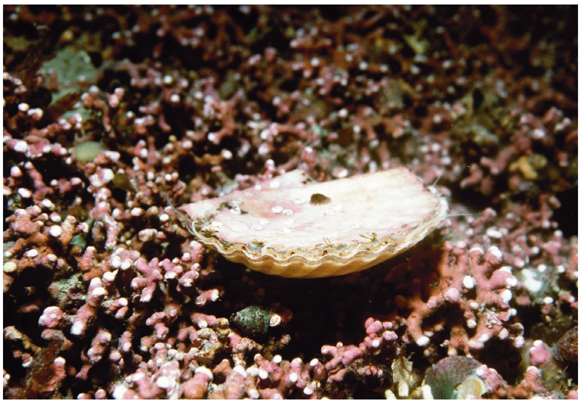


Figure 2 *Collection sites of deep-water (>200 m) corals from the continental slope, seamounts >1000 m in height, and oceanic islands off Africa and Europe and in mid-ocean, compiled from late 19th century research reports. The corals are antipatharians (black corals), scleractinians (hard corals) and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

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

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

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



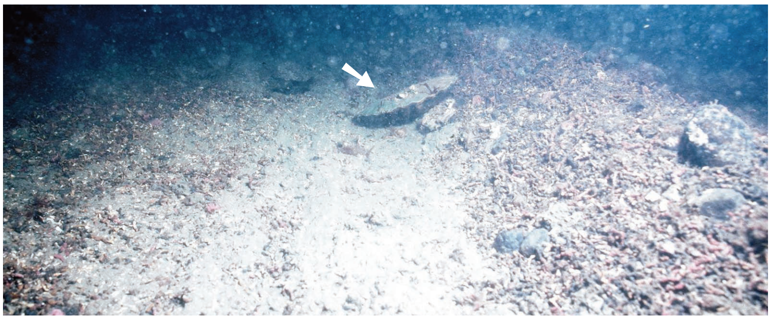


Figure 3 **Upper left** *A juvenile scallop (*Pecten maximus*, shell 1 cm across) living on a bed of pink twig-like maerl (*Lithothamnion corallioides*) at a protected site on St Mawes Bank in the Fal Estuary, England.* **Lower left** *A flame-shell (*Limaria hians*, shell 2.5 cm long) near Otter Spit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

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

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

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

Planetary change and ocean acidification

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

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

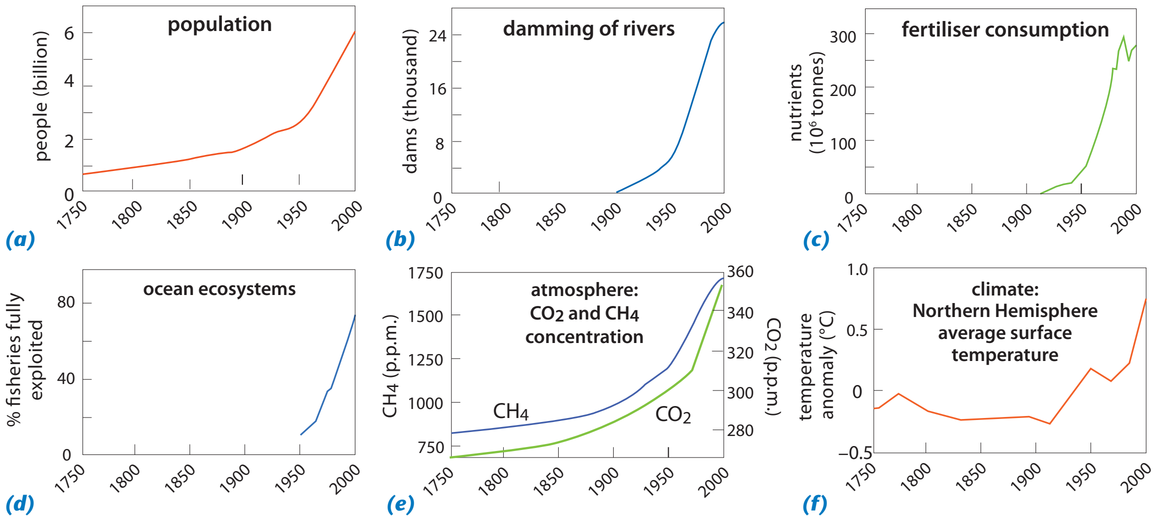


Figure 4 *The effects of the accelerating anthropogenic changes are now clearly discernible at the Earth system level. The increasing human population **(a)** is having global effects on coastal systems through the rising use of water **(b)** and fertilisers **(c)**, and through overexploitation of fisheries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

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

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

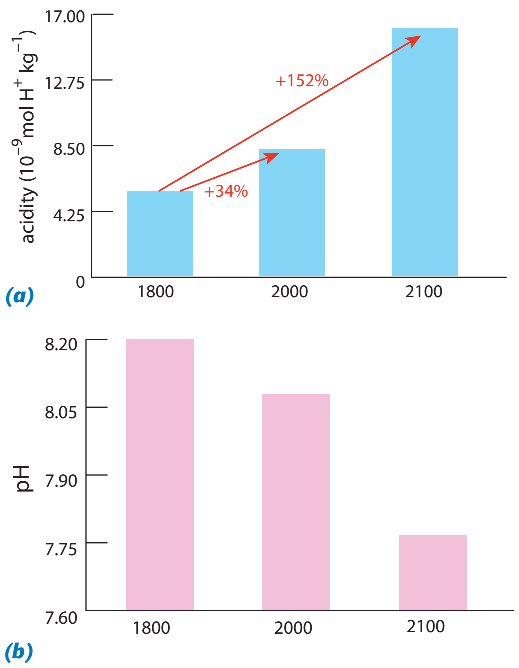


Figure 5 ***(a)** Average surface ocean acidity and **(b)** pH, in 1800 and 2000, and projected for 2100.*

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

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

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

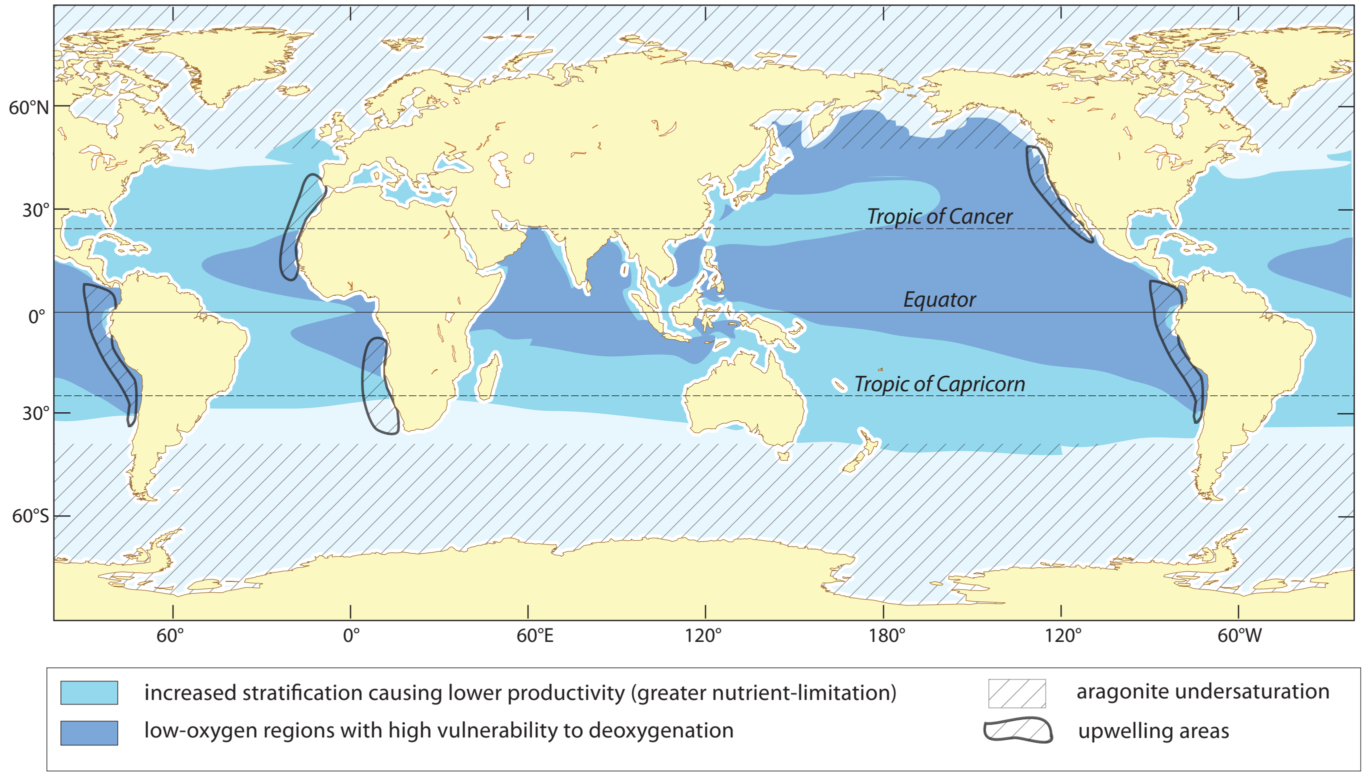
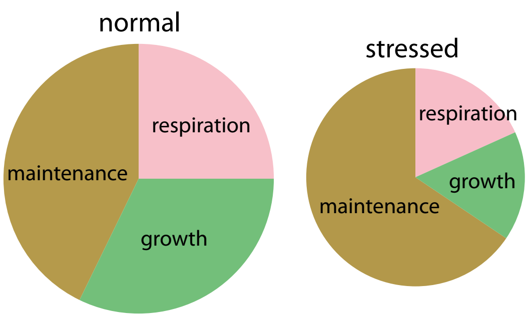


Figure 6 *Surface water regions of particular vulnerability to ocean warming, acidification and de-oxygenation. Aragonite is the form of calcium carbonate used by hard corals and many other organisms to build their skeletons; waters in high latitudes and upwelling regions are corrosive to aragonite (see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

Surface waters across the globe are subject to three main stressors

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

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

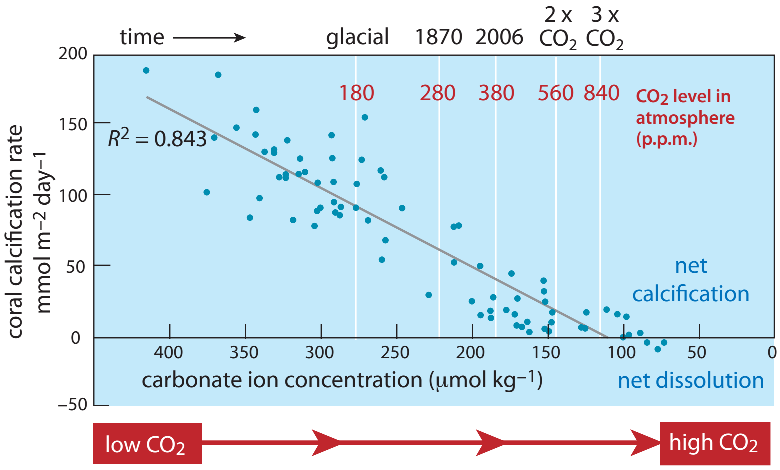


Ways of studying ocean acidification

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

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

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



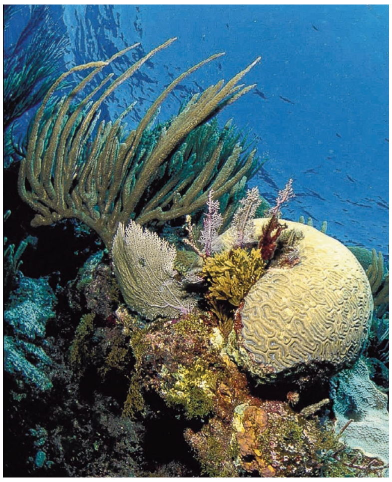


Figure 8 Upper *Work in aquaria has shown that as CO_2 levels in the atmosphere rise, carbonate ion concentrations in seawater fall, which slows down tropical coral calcification rates until eventually the reef begins to dissolve (see Langdon and Atkinson, 2005).*

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

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

As CO_2 levels rise, coral reefs begin to dissolve

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

CO_2 seeps

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

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

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

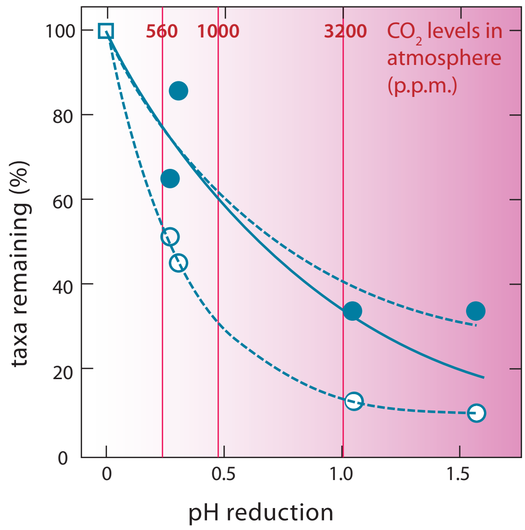


Figure 9 *The diversity of calcified (open circles) and non-calcified (filled circles) taxa falls as rising CO_2 levels cause pH to fall at volcanic vents off Ischia (Italy). Red vertical lines show atmospheric CO_2 levels required to cause the seawater pH changes observed and the solid blue curve shows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

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

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

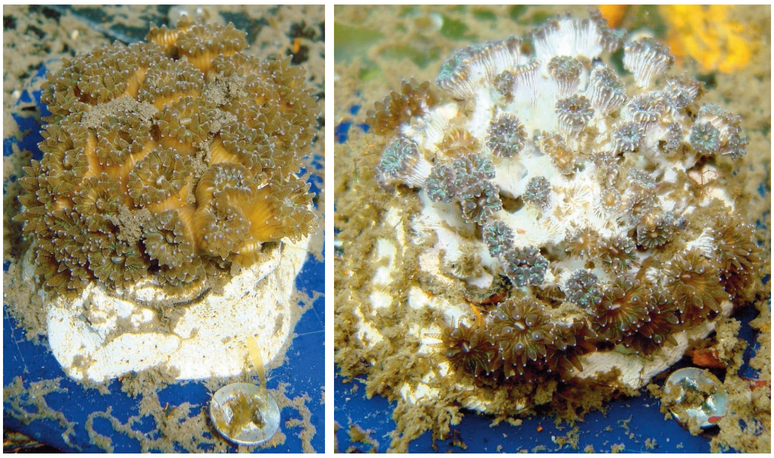


Figure 11 Left *The scleractinian coral* Cladocora caespitosa *grows well at high CO_2 levels.*
Right *When ocean acidification combines with unusually high summer temperatures these corals are killed (see* Rodolfo-Metalpa *et al. 2011).*

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

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

Further Reading

Global change

Gruber, N. (2011) Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Phil. Trans. R. Soc.* A **369**. doi: 10.1098/rsta.2011.0003.

Steffen, W and 11 others (2004) *Global Change and the Earth System: A Planet Under Pressure*. Springer-Verlag.

IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2014) Field, C.B.and 15 others (eds) Cambridge University Press, 1132pp. https://ipcc-wg2.gov/AR5/report/full-report/

Overfishing and habitat degradation

Hall-Spencer, J.M. and P.G. Moore (2000) Scallop dredging has profound long-term impacts on maerl habitats. *ICES Journal of Marine Science,* **57**, 1407–15.

Hall-Spencer J, V. Allain and J.H. Fossa (2002) Trawling damage to Northeast Atlantic ancient coral reefs. *Proceedings of the Royal Society,* **269**, 507–11.

Molfese, C., D. Beare and J.M. Hall-Spencer (2014) Overfishing and the replacement of demersal finfish by shellfish: an example from the English Channel. *PLoS ONE,* **9** (7), e101506.

Effects of rising CO_2; ocean acidification

Brodie, J. and 26 others (2014) The future of the NE Atlantic benthic flora in a high CO_2 world. *Ecology and Evolution*, **4**, 2787–9. onlinelibrary.wiley.com/doi/10.1002/ece3.1105/full

Garilli, V. and 9 others (2015) Physiological advantages of dwarfing in surviving extinctions in high CO_2 oceans. *Nature Climate Change.* doi:10.1038/nclimate2616

Hall-Spencer J.M., R. Rodolfo-Metalpa, S. Martin S, E. Ransome, M. Fine, S.M. Turner, S.J. Rowley, D. Tedesco, M.-C. Buia (2008) Volcanic carbon dioxide vents reveal ecosystem effects of ocean acidification. *Nature,* **454**, 96–9. doi: 10.1038/nature07051

Langdon, C. and M.J. Atkinson (2005) Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *J. Geophys. Res*. **110**, C09S07 doi:10.1029/2005JC003086

Manzello, D.P., I. C Enochs, A. Bruckner, P.G. Renaud, G. Kolodziej, D.A. Budd, R. Carlton and P.W. Glynn (2014) Galápagos coral reef persistence after ENSO warming across an acidification gradient. *Geophysical Research Letters,* **41**, 9001–08.

Rodolfo-Metalpa, R. and 10 others (2011) Coral and mollusc resistance to ocean acidification adversely affected by warming. *Nature Climate Change,* **1**, 308–12. doi:10.1038/nclimate1200

Jason Hall-Spencer pioneered the use of natural analogues to study the effects of rising CO_2 levels on marine ecosystems. He is Professor of Marine Biology at Plymouth University, Editor-in-Chief of Regional Studies in Marine Science, a UK Government Scientific Advisor on Marine Conservation Zones and serves on the Ocean Acidification International Reference User Group.
jason.hall-spencer@plymouth.ac.uk