House of Commons

Science and Technology Committee

Oral evidence: Ocean acidification, HC 860

Wednesday 1 March 2017

Ordered by the House of Commons to be published on 1 March 2017.

Watch the meeting

Members present: Stephen Metcalfe (Chair); Victoria Borwick; Chris Green; Dr Tania Mathias; Carol Monaghan; Graham Stringer.

Questions 1 - 92

Witnesses

I: Dr Carol Turley, Senior Scientist, Plymouth Marine Laboratory; Dr Ceri Lewis, Senior Lecturer in Marine Biology, University of Exeter; Dr Alex Poulton, Principal Researcher in Marine Ecology and Biogeochemistry, National Oceanography Centre; and Dr Ned Garnett, Associate Director Research, Natural Environment Research Council.

II: Professor Nicholas Bates, Director of Research, Bermuda Institute of Ocean Sciences; and Dr Melody Clark, Project Leader, British Antarctic Survey.

Written evidence from witnesses:

– Plymouth Marine Laboratory

– University of Exeter

– National Oceanography Centre

– Natural Environment Research Council

– University of Southampton

– British Antarctic Survey

Examination of witnesses

Witnesses: Dr Turley, Dr Lewis, Dr Poulton and Dr Garnett.

Q1 **Chair:** Good morning. Welcome. Thank you very much for joining us for the first session in our ocean acidification inquiry. For the record, could you say who you are and who you represent here today?

Dr Poulton: I am Alex Poulton, from the National Oceanography Centre in Southampton.

Dr Turley: I am Carol Turley, from Plymouth Marine Laboratory.

Dr Lewis: I am Ceri Lewis, representing Exeter University.

Dr Garnett: I am Ned Garnett, from the Natural Environment Research Council.

Q2 **Chair:** Thank you very much for joining us. The UK Ocean Acidification research programme was established back in 2010. In your view, what was its overriding focus? What was its purpose? Was it to explore the process of ocean acidification, its impact or the policy implications?

Dr Turley: Very simply, it was to improve understanding of ocean acidification and the processes involved, and to provide policy advice. It was devised by NERC, in collaboration with DEFRA and, to a lesser extent, DECC. There were three funding bodies involved. It was very much bottom up, but also top down, because we had policy makers involved with it. It was a great advantage to have that two-way exchange of knowledge at an early stage.

Within the programme, there were six consortia. One was observations of large-scale CO_2 exchange between the sea and the atmosphere. Another was ocean biogeochemistry on the ocean surface. Another was sea-floor benthic organisms. There was another consortium on commercially exploitable species and the socioeconomic aspects. Another looked at events in Earth's history—the palaeo studies of ocean acidification and warming events that have occurred previously. Then there was the regional and global scale modelling. The consortia were led by different individuals, but they contributed to the whole programme.

Q3 **Chair:** The six consortia were quite wide ranging. They must have generated quite a lot of expertise. Now that the programme has finished, has that expertise been lost?

Dr Garnett: It would be wrong to characterise the programme as the beginning and end of ocean acidification research at NERC. Much else has gone on. There has been a considerable gain in research capability as a result of it. A number of areas have followed on from it; for example, we have had a series of programmes collaborating with DEFRA—about £30 million-worth of programmes—in ocean science. Specifically, we are now funding grants to look at ocean acidification in the Arctic. One of the programme’s key findings was that you cannot look at ocean acidification in isolation; it needs to be looked at in relation to a range of stressors. In the case of the Arctic programme, we are putting £2 million into a programme that is looking at a range of stressors on Arctic ecosystems. There is work on ocean acidification going on. It would be wrong to say that that capability has been lost. It is carrying on and has developed from the findings of the programme.

Dr Lewis: One of the strengths of the UKOA programme was its support for early-career scientists. We developed some fantastically talented young scientists. They are the ones struggling to find their next position now that the project has finished. Personally, I have lost a couple of people from my lab. They have an amazing skillset, but there is no funding for them to carry on. The early-career researchers are the people we need to look after.

Q4 **Chair:** That suggests a slightly mixed picture as to whether we have lost some of that expertise. Dr Lewis is saying that we have, and Dr Garnett is saying that we are still doing something in the field.

Dr Garnett: We are still doing a lot of work. I certainly accept the issue of early-career researchers getting that step from a PhD to a postdoc, or from a postdoc to a permanent position. That is a problem throughout science in the UK.

Q5 **Chair:** I accept that early-career scientists are struggling to find similar positions. Are they doing something else involved in the marine sciences?

Dr Lewis: At the moment, some of them are ending up going into teaching.

Q6 **Chair:** That would be a disappointment.

Dr Lewis: Yes.

Q7 **Chair:** What was the outcome of the programme, as it stood between 2010 and 2015? What did it achieve? Did it have an impact on policy? Did it achieve everything that it set out to achieve?

Dr Garnett: I will say a bit about policy first. If we look at the policies in relation to mitigation of climate change, it had an influence in terms of the Paris agreement, to try to keep temperature rise down to 1.5º. Ocean acidification is mentioned specifically in the global goals for the ocean. That is another area where it has had an influence. Later we may talk a bit more about the G7 Science Ministers’ initiative. Healthy oceans are one of the priorities they set out at their meeting last year at Tsukuba. There are areas around policy. Carol has probably had more direct experience.

Dr Turley: UKOA funded a lot of international policy. In fact, they have kindly supported me to attend the UNFCCC COP since 2009. We brought ocean acidification to that; within a few years, we were bringing ocean warming and deoxygenation as a package. Some of the material I brought there, such as "Hot, Sour & Breathless—Ocean under stress," was produced to capture the delegates—the negotiators—attention and help them to realise the importance of the ocean to life on the planet. We started with basic messages about the ocean and then pulled in the ocean stressors. If you listen to the introductions to the Paris Agreement by Heads of State, you find that nearly all of them mentioned the ocean. About 20% of them mentioned ocean acidification. Going from zero to 2015, the oceans are up there[1].

The oceans are also part of the Sustainable Development Goals. Again, UKOA went there[2] and organised events and evidence. Bringing the evidence to the delegates really helped to write Sustainable Development Goal 14.3, which is on ocean acidification. The G7 is an important initiative as well. Because of the DEFRA and DECC funding, we were fortunate enough to go into DECC just before the climate change negotiations year on year to explain the ocean aspects to them; we were able to brief them on the ocean part of it. UKOA scientists also fed into the IPCC assessment reports, the Convention on Biological Diversity assessment report on ocean acidification and from OSPAR. Basically, there was a substantial impact at UN and intergovernmental level. The oceans are being noticed a little more.

Q8 **Chair:** Yes. It certainly raised awareness of the issue. Assuming that we fully accept that there is a problem, is reducing CO_2 emissions the only way of tackling it?

Dr Turley: For open oceans and much of the coastal environment, the answer is yes. However, there are other sources of ocean acidification in local environments—in coastal environments—due to land-ocean interactions. One of the great findings of UKOA was seeing that variability, which we had not realised was present in coastal waters until then. Discovering that variability gives us an option. If we reduce those local inputs of acidification, we can reduce the total effect and buy some more time for the Paris Agreement to kick in.

Q9 **Chair:** The interaction between sea and land is significant enough to make a difference, if you could do something about it.

Dr Turley: Yes, and ice — sea, land and ice.

Chair: I may come back to that, but I now pass over to Dr Tania Mathias.

Q10 **Dr Mathias:** My initial question is for Dr Poulton. We are told by DEFRA

---

[1] Note by witness: Comments should have been as follows: "If you listen to the introductions to the Paris Agreement by Heads of State, you find that around 20% of them mentioned ocean relate climate issues. Some of them mentioned ocean acidification. Going from zero understanding in 2009 to far greater understanding in 2015, the oceans are up there". The 20% figure is related to those leaders that made reference to ocean related issues (eg. ocean warming, acidification, coral bleaching, sea level rise and the plight of coastal and island nations).
[2] Note by witness: to the Rio+20 Earth Summit.

that there is one observatory monitoring the carbonate chemistry of UK seas. Is that sufficient for measurement purposes?

Dr Poulton: The L4 site in Plymouth certainly has the longest and most regular time series. There are other monitoring programmes that are more ad hoc. There is an open-ocean site that comes through the National Oceanography Centre, and there are a few others. More would be good, like everything else, but the focus has to be on getting high-quality international measurements that match—making sure that those are covered.

Q11 **Dr Mathias:** Have you any idea what an appropriate number would be, long term?

Dr Poulton: No.

Dr Lewis: I suggest that a real priority is to monitor sea-water chemistry around our aquaculture facilities. That is something that NOAA is doing very well in the States. It is noticing impacts of reduced carbonate chemistry on oyster beds—

Q12 **Dr Mathias:** Where are they doing that?

Dr Lewis: In America—on both the west and the east coast. NOAA has a fantastic programme for monitoring water input to their shellfish hatchery facilities. They have much bigger shellfish hatcheries than we have, but we have some pretty important shellfish aquaculture facilities around the UK. We have some evidence that the water chemistry there is already at a saturation state that might limit their production. I suggest that is a high-priority area, because of the high economic value associated with it.

Q13 **Dr Mathias:** Off the top of your head, geographically, where would it be? We've got Plymouth.

Dr Lewis: For example, there is an area in the Menai strait where 50% of our mussel aquaculture happens. It is worth £9 million a year. We are already seeing high PCO_2 levels and reduced aragonite saturation states. That is what affects shell growth in the area. That is just from really small measurements that we took on a few occasions, but I would say that it is a priority.

Dr Turley: If I were forced to give a number, I would say that around three long-term, high-quality chemical measurements—

Q14 **Dr Mathias:** Equivalent to what is already in Plymouth.

Dr Turley: Yes. I would very much like them to be built on to current observations that are going on, because then you get better value. I would also like to see them on ships—for example, when the DEFRA ships go out, as they did, funded by UKOA, to do the carbonate measurements.

Q15 **Dr Mathias:** Are the ships doing it ad hoc at the moment, rather than long term, or are they doing it long term?

Dr Turley: They are not doing it long term. I believe it has stopped now, because the funding from UKOA stopped.

Dr Poulton: It was continued within the Shelf Sea Biogeochemistry programme. A lot of the UK agencies that are in Scotland and AFBI in Ireland were also involved, but it ended with the funding.

Q16 **Dr Mathias:** Who is responsible for strategy and oversight of long-term ocean monitoring for us in the UK? Again, I will start with Dr Poulton, but I am interested in hearing all your views.

Dr Poulton: The science is quite interesting. From the policy side of things, I do not know that responsibility and oversight sits with us.

Q17 **Dr Mathias:** It does not exist.

Dr Garnett: There is a division in the drivers behind this. If the drivers are policy, it is DEFRA. I know you have a session with DEFRA in a few week's time.

Q18 **Dr Mathias:** But for the science.

Dr Garnett: For the science side, it is very much the science community. NERC has a clear leadership role with this. Through our centres, such as NOC and PML, we provide scientific leadership for the UK, in terms of the direction that the science takes.

Q19 **Dr Mathias:** Obviously, it is not clear for everybody in the field.

Dr Garnett: We do not have a "leader of ocean acidification," but a number of people, Carol included, are involved in co-ordinating the activity and dealing with policy makers and others, as knowledge exchange fellows. There is a lot of activity. I stress that there is more work being funded in this area. On the technical side, we are just about to fund things to put new sensors on to autonomous vehicles that can detect carbonate chemistry. Work is ongoing in that area.

Q20 **Dr Mathias:** From a science point of view, is there anybody co-ordinating with other countries?

Dr Turley: There is the Global Ocean Acidification Observing Network, which is a bottom-up (of scientists) network around the world that realised the importance of putting all the datasets together. That has been organised.

Q21 **Dr Mathias:** Who leads it?

Dr Turley: We could say NOAA, at the moment—the Americans—but UKOA put in quite a bit of funding and was one of the partners.

Q22 **Dr Mathias:** Do they meet regularly?

Dr Turley: They meet regularly. They have a portal. The idea is to upload the data, which are freely available to anyone. The data are quality assured. It is not really funded. It is all done piecemeal at the moment. It is an opportunity. There is a bit of money coming in from foundations. We try to raise money for it. If you could employ a couple of people internationally—somebody to do the synthesis of the data and to make the quality assurance—it would be a great thing to do. Of course, that is the hardest money to get.

Q23 **Dr Mathias:** Dr Lewis, I understand that research from your university has highlighted satellite remote sensing. Has DEFRA shown an interest in that?

Dr Lewis: I checked with the author of that work just before coming here. He said that he had had no direct conversations with DEFRA but that he knew that they were aware of the work. The work they have been doing is proof-of-concept work, to prove that the technique is viable for use. It is not being employed at the moment.

Dr Poulton: Part of that satellite work is part of the shelf sea biogeochemistry programme, which DEFRA co-funded with NERC. In the same way as the UK ocean acidification programme eventually spoke a lot to policy and things like that, when that programme comes to the point of fruition, there may be more communication with DEFRA.

Q24 **Dr Mathias:** That is optimistic. Is there scope to collect data, working with industry, which you mentioned, or things like military ships?

Dr Lewis: The aquaculture facilities would be very interested in collaborating to collect the information, but they could not do the full carbonate chemistry. They could collect water samples, pH measurements and all the other parameters that we need, but we would need some central place where they could send the water samples, and which would do the quality assurance and carbonate chemistry details for them. We have done some tiny projects with aquaculture facilities. They are very interested in doing it, because they can improve their output by having better water chemistry analysis.

Dr Poulton: Exeter, Plymouth and the National Oceanography Centre are also working with a lot of the ferry firms and some of the shipping firms—ship-of-opportunity work. We are working with Swire and Maersk in Southampton to put instruments on ships to monitor over large swathes of the ocean.

Q25 **Dr Mathias:** Does that go into the Royal Navy as well?

Dr Poulton: We have had discussions with them, but it has been quite difficult to get further, for various technical reasons.

Q26 **Dr Mathias:** Technical.

Dr Poulton: It is about trying to get the instruments on to the ship and insurance issues.

Q27 **Dr Mathias:** You can do it with a ferry company, but you cannot do it with the Royal Navy.

Dr Poulton: Yes.

Q28 **Victoria Borwick:** Because then the Navy would have to reveal where it was.

Dr Turley: We would need to know where the measurements had come from.

Q29 **Carol Monaghan:** Dr Lewis, there appears to be a lack of long-term data regarding the carbonate conditions in coastal waters, as opposed to the open oceans. Obviously, coastal waters around the UK are vital for the livelihood of fishing communities. Is there a reason why those data are missing?

Dr Lewis: Basically, it is highly variable in the coastal environments. You need long-term, regular measurements to make any sense of them. One or two measurements will not tell you what is really going on. We just do not have the kit to deploy. Long-term monitoring buoys out in the open ocean are incredibly expensive. We just do not have them to deploy in the coastal areas. There are a few projects working to develop that technology, but it is technology that we are missing, to get those measurements at an affordable price. They would need to be there all the time, logging all the ups and downs, to tell us anything useful.

Q30 **Carol Monaghan:** How much are we talking?

Dr Lewis: I will look to Alex for how much. It is thousands. Each site is different. In the coastal environments, every site will be different. You could not have one or two sites that would give you a nice picture of what a coastal environment is. The short-term monitoring we have done has shown that it is highly variable. Just around the corner of a bay, you get completely different measurements.

Dr Turley: Were you looking for cost?

Q31 **Carol Monaghan:** Yes. I wondered how much it would cost to have the instrumentation to do it.

Dr Turley: Off the west coast of the US, where they had a huge ocean acidification crisis for their oyster hatcheries and lost millions of pounds over four years, they worked with NOAA, which is just down the road, and found that it was due to an upwelling of high-CO_2, low-pH waters, which happens every now and again. If they can monitor it, they will be able to manage it. They put in a system that cost $500,000, and that has enabled them to spot it when it is coming up and heading towards them and to close, change or add chemicals to their system to control the pH.

That is pretty high tech, but there are lower-tech ones of $10,000 or so that are coming online and are being tested and the G7 initiative may help. The Wendy Schmidt XPRIZE funded low-tech pH meters, so that they can be applied in aquaculture, for example, where you need something easy, for the local people, that does not need very expert scientists to run it. You also need collaboration with the scientists to make sure that you are doing everything right.

Dr Lewis: That is not really developed enough yet to be deployable, is it?

Dr Turley: It is coming on. It needs testing, I think.

Dr Poulton: The autonomous technology is becoming cheaper in many ways, as it develops further. It is the same for the sensor technology.

Q32 **Carol Monaghan:** I imagine the idea is that the system would send data to a central collection hub.

Dr Lewis: That would be ideal.

Q33 **Carol Monaghan:** We know that biological and ecological conditions can also affect the carbonate conditions of water. Are we collecting enough biological data?

Dr Turley: You are quite right. The carbonate chemistry conditions change as the ocean's algae photosynthesise and take up CO_2. When they start to decompose or are eaten by animals like us and bacteria, CO_2 is given off. There is a seasonal cycle, which you can see in the long-term records, in the open ocean. Essentially, it is the ocean breathing in and out, through biology. In the coastal waters, there is an added interaction, with input from estuaries, nutrients and those sorts of things—even the benthic system itself. That is why you really need a long-term record of the chemistry linked to the biology, and the physics. The physics can play a huge role as well.

Q34 **Carol Monaghan:** We are not doing enough at the moment.

Dr Turley: We are doing it off Plymouth.

Dr Garnett: NERC has a programme running at the moment on marine ecosystems, concentrating on UK coastal waters. There is work ongoing, but I absolutely accept what you say about the amount of biology that has been done.

Q35 **Carol Monaghan:** My next question is probably directed to Dr Poulton. We have been told by DEFRA that water samples collected were analysed at your centre "until recently." Does that mean that samples currently being collected are not being analysed?

Dr Poulton: The national carbonate chemistry facility was funded under the UKOA programme, so it was funded to the University of Southampton side of the building. When UKOA ended its funding, the facility effectively lost its funding. There is still the equipment and the desire. We are still analysing samples on an ad hoc basis; it is just that the underpinning funding is not there. Within talks on the future of science and rebidding for our national capability activities, we are thinking about how we can do that in the future, but at the moment it is quite difficult.

Q36 **Carol Monaghan:** Was there a reason why the funding stopped? Was it simply the end—

Dr Poulton: It was just within the timeframe of the UKOA programme.

Q37 **Carol Monaghan:** It seems strange that at the moment when we see something like ocean acidification causing more damage we stop the programme.

Dr Garnett: As I said before, it is important not to characterise stopping the programme as stopping the research, in terms of what is going on. We fund research by a number of different routes. We fund it through what we call discovery science, which is judged just on scientific excellence. We fund strategic research in programmes such as the UKOA and the shelf sea biogeochemistry programme, which we have heard about, where you have a specific focus where you want to bring the science together.

The other area we fund is what we call national capability. That is a significant proportion of NERC's funding. It goes principally through our centres, to manage the infrastructure, the data and the equipment and to try to maintain well-found labs. At the moment, we are reviewing that. We are going through a commissioning process with all our centres around national capability. Yes, there are hard choices to be made about where the funding goes—which type of equipment and which type of science. I think that I am right in saying that there are places where you can do carbonate chemistry. It is just that at the moment the facility we had is not being particularly used, from what Alex says. I am not involved in that.

Dr Poulton: NERC runs several facilities with high-end equipment to do various types of mass spectrometry molecular work. This was not funded or set up in quite the same way. It was funded within the UKOA to recognise the huge expansion in the number of samples and measurements that were wanted within that framework. Certainly, we are still running samples. It was partly continued through the shelf sea biogeochemistry programme, which came afterwards and finished recently. That has been the more pressing cut-off.

Q38 **Carol Monaghan:** Dr Lewis, you look like you have some concerns.

Dr Lewis: No. It was to do with the comment that we can still measure carbonate chemistry. You need a person sitting by the machines to run them. That is the problem. We do not have a funded person doing it as a facility now. If anyone not in a university who had the kit generated samples, they could not just send them to any of us, because we do not have the person who sits there and runs it. The samples that are being analysed are being analysed off the back of projects. Only those specific samples get analysed. It would be fantastic to have a facility with someone who was paid to run those machines, and then everyone else could use it. There has been an awful lot of research going on where they cannot analyse their own samples.

Q39 **Carol Monaghan:** Finally, if we continue to see an increase in CO_2 emissions, is there a point at which the ocean will stop buffering? Is there a tipping point? How close are we to reaching it?

Dr Poulton: I guess there has to be.

Dr Turley: My understanding is that the ocean will keep taking up CO_2. It will take hundreds of years, but it will reach a level where there is equilibrium. It will probably take up 90% or thereabouts of the CO_2 emissions.

Q40 **Carol Monaghan:** Is there a point at which, by absorbing that CO_2, irreparable damage will be caused to the ecosystem of the ocean?

Dr Turley: The ocean is absorbing over 90% of the heat from global warming. It is losing oxygen because it is warming, sea levels are rising, and you have ocean acidification. If we keep doing what we are doing—business as usual—in terms of CO_2 emissions, in my opinion, by the end of this century a combination of those stresses will mean that ecosystems as we know them will change. The goods and services we depend on will ultimately change as well. It will affect food security and livelihoods.

It is not something that will be all over by the end of this century. If we keep on with business as usual, it will take tens of thousands of years for the ocean eventually to buffer it all out. It will not happen just for a few centuries. It will be a very long period before the ocean eventually buffers out all that CO_2. It is a biggie. The rate of change is 10 times faster now than during the last event, which was 56 million years ago and resulted in the mass extinction of many benthic species, and the Great Dying 300 million years ago[3], when over 90% of the ocean species on planet Earth became extinct. Basically, evolution kicks in at each of the events and marine organisms re-evolve. Life on the planet will go on. Whether we are part of it or not is another matter.

Dr Garnett: Am I right in saying that it took 10,000 years for systems to recover from the acidification during the event 56 million years ago?

Dr Poulton: I think it was 100,000.

Dr Turley: It occurred over several thousand years, but took 100,000 years to recover from.

Dr Garnett: I do not know what you call irreparable, but 100,000 years seems quite a long time.

Q41 **Carol Monaghan:** It will not be repaired in our lifetime, that's for sure.

Dr Turley: It scares me. That said, if the Paris Agreement is successful and we achieve a rise of under 2ºC, things will still change, but it will not be as terrible. We will probably still lose a lot of the coral reefs around the world, perhaps not all. It all depends on their ability to transfer

[3] Note by witness: Great Dying was 252 million years ago and not 300 million years ago.

energy, which depends on the ecosystem in which they live and the food they are getting. You will hear more about that, hopefully, in the next session.

Carol Monaghan: On that frightening note, thank you very much.

Q42 **Chair:** It is quite a bleak outlook. When you were answering my questions earlier, you talked about the interaction between sea, land and ice, and the part that that plays. While we are waiting for the rest of the planet, potentially, to come up with a way of reducing the man-made CO_2 that is contributing to ocean acidification, there is more that we can do around our coastlines. What precisely could we be doing, quickly, that would make a difference?

Dr Turley: We can reduce nitrogen, nutrient, input—pollutants. This is particularly important for other countries such as China, where they are finding that the huge input of nutrients is causing hypoxia—low-oxygen waters. They are low in oxygen and high in CO_2, so you have ocean acidification and oxygen loss at the same time. We really need to clean up our coastal waters and reduce the amount of metals too. Ceri may want to say something about metal toxicity.

Dr Lewis: We have been talking a lot about direct effects of ocean acidification, but there are also indirect effects. Unfortunately, our coastal sediments have lots of historic pollutants still buried away in them. There is now some quite compelling evidence that the change in ocean chemistry will alter the fluxes of those historic contaminants and make some of them—not all of them—more bio-available. Anything to reduce pollutant input will also knock down the effects of increased toxicity from the stuff that is already present in our sediments, which will start to leach back out into the water with the change of pH. Most contaminants are pH sensitive. A lot of them are pH sensitive within the range of ocean acidification. Some of them will become less toxic, but quite a lot of them will become more toxic and start to leach back into the water.

Dr Turley: The other thing we can do is look after the ecosystems that we have, such as seagrass beds. They are carbon stores, but also carbon extraction mechanisms. They can buffer acidification locally, as can kelp beds—large seaweeds. They can draw down CO_2 and even bury it in the sediment. It is about looking after our marine carbon stores and the things that remove CO_2 from the seawater, and even replanting them. In aquaculture, we could look for species that may be less vulnerable to ocean acidification and look at breeding species to help aquaculture.

Q43 **Dr Mathias:** With the blue belt around our British overseas territories and the farmers who would be affected, is there a role for citizen scientists, especially with your autonomous measurements?

Dr Garnett: The autonomous measurements are quite high tech, in terms of how they operate.

Q44 **Dr Mathias:** For the simpler measurements.

Dr Garnett: Citizen science has been really significant for measuring biodiversity on land. I am not sure about the extent to which it occurs in the marine—

Q45 **Dr Mathias:** I have it in my constituency on the rivers. That works very well.

Dr Garnett: Yes.

Dr Poulton: There is notification of harmful algal blooms via citizen science. I think a phone app was developed by an EU programme to assess ocean colour.

Dr Lewis: The problem is that measuring pH accurately is very difficult. Even a simple pH probe has to be really well calibrated to give you the sensitivity that is relevant for ocean acidification levels. I have seen a few projects proposed for citizen science measurements of carbonate chemistry, but none of them has been successful, to my knowledge, because of the intricacies of measuring with the sensitivity we need. We need the carbonate chemistry to back it up; pH on its own does not tell you very much unless you have the carbonate chemistry, and that requires sensitive kit to measure.

Q46 **Graham Stringer:** Obviously, this is extremely complicated science. What are the pros and cons of doing the experiments under laboratory conditions, where you can hold variables and look at the interaction of just a couple of them, compared with doing similar experiments, to try to find out the same things in situ—in the field?

Dr Lewis: We have learned an awful lot about how to do these experiments through the UKOA programme. We have really changed the way we do the experiments now. We started by doing time-machine experiments—just transporting organisms into future conditions, to see how they responded. Now we are doing much more long-term exposures and changing the pH more gradually, so that they are not shock experiments. We are now using the information that we have about where the organisms come from as our starting point, rather than using open-ocean values. We have changed the way we do the experiments.

The key problem is adaptation, because we are trying to look at future problems. That is where in situ experiments come in, such as those on the CO_2 vents in Italy, where there are communities that have been exposed to high CO_2 levels for decades—centuries, maybe. We are seeing diversity changes in those ecosystems, where adaptation should have happened if it was going to happen. There are proxies you can use to get away from the difficulties with laboratory experiments. Those have been used very well recently. The key issue is variability. In coastal systems, which is where our economically important species are, we have that variability. Only now are we starting to understand how it plays out. You can do that in the lab, but people are only just starting to do it, because it is slightly harder to control.

Q47 **Graham Stringer:** Two questions follow from that, one of which you have partially answered. First, does that make invalid or less useful the experiments that have been done?

Dr Lewis: No. We would never have got to where we are now without that knowledge. We have learned a lot from that process. We have learned which physiological mechanisms will be impacted. With our much more sophisticated experimental techniques, we can now home in on the degree of the impacts, but we would not have got to that point without the early experiments. It is a learning curve. That is how science works. You start off probing something and find out that there is a better way of doing it. It is a continuous learning curve. We would never have got to the understanding and knowledge we have now without the early experiments, but the way in which we do the experiments has now changed.

Q48 **Graham Stringer:** It has changed the balance from the laboratory to in situ.

Dr Lewis: And better-designed laboratory experiments that last longer.

Dr Poulton: The laboratory experiments allow you to control a single organism and its environment and to look at its entire physiological space—how it reacts to different things at extremes. When you want to put that into the ecological system, where it is interacting with other organisms, you can only do it in the field. In many ways, it is very difficult to control all the variables in the field, because of the weather, the currents and everything else. That is why the two of them go nicely together. You must have that basic understanding to start with.

Dr Lewis: The additional problem with field experiments is that, unfortunately, there is no such thing as a pristine marine environment any more. There are chemicals everywhere—plastics, PCBs and phthalates. It is a very big jump to be able to pin something down as an ocean acidification effect in a field experiment without the laboratory experiments, using lovely clean artificial seawater, to back that up. You need both.

Q49 **Graham Stringer:** That is clear and interesting. DEFRA has told us that the responses of shellfish species to acidification studies have been inconsistent. Do you know why there are inconsistencies, or is that still work to be done?

Dr Lewis: There is probably a lot underpinning those different responses. It will be to do with the way in which the experiment is done, and the habitats from which the organisms were collected prior to the experiment. We are now just starting to get the coastal measurements that tell us that. Mussels in one habitat could be used to nice, stable conditions, whereas literally just around the corner, in another bay, they were previously exposed to variable conditions. Their previous exposure, before you take them into the lab, will affect their responses. That is something we were not aware of until recently, so that is likely to be involved. Food, nutrients and things like that in experiments will also affect the outcomes, and they probably were not consistent across different studies.

Dr Turley: One of the things that UKOA really showed was that, if you give your experiments sufficient food, they may be able to adapt, because they have the energy resources coming in to fuel their physiological processes and keep everything going. In the natural environment, they go through periods when they have food and no food. That was a major finding. It has enabled a huge conceptual model to be developed about energy flux and trade-offs in marine organisms in response to ocean stressors. That is a major step forward.

Very recently—just this year—there was a fantastic publication about the periwinkle that you find on the rocks on the beach. It looked at the thermal range of those, from Spain right up to Norway, took samples and found out their vulnerability to ocean acidification. The ones at the two extremes are far more vulnerable than the ones sitting happily in the middle. You therefore have the organism's in-built adaptability and reaction to the multiple stressors to take account of as well.

An experiment was carried out a year ago on the Great Barrier Reef. What they wanted to find out, which we really do not know, was whether there are impacts from ocean acidification already. We assume that there are none, but we do not know, because we have not been measuring the biology and the chemistry for long enough. They took a whole coral reef ecosystem, changed the chemistry back to that of pre-industrial times and then looked at the rates of reef growth—calcification. They found an 8% increase in calcification[4]. Basically, that was done on an open reef.

Dr Lewis: Similar experiments have been done in the oyster hatcheries in the States. They are worried about the upwelling vent on the Pacific coast, but they have also just had a look on the east coast, because they are now very concerned. They did the same thing and manipulated the water chemistry back to pre-industrial levels. They got dramatic increases in their oyster production and hatchery success rates, which have huge economic value involved. That was surprising to them, because they thought it was a west coast problem, not an east coast problem. It turns out that we are already at a reduced saturation state that would limit shellfish production. You need huge datasets to see those patterns. When it adds up across a whole industry, the economic value is in the millions. We have not done that in the UK, so we do not know. Certainly, the data from the States are very compelling. The saturation levels at which you start to see impacts are the saturation levels that we are already measuring here in the UK.

Q50 **Graham Stringer:** There are huge quantities of money going into looking at global warming, climate change and the impacts of CO_2 in the

[4] Note by witness: Indicating that change is already happening.

atmosphere. It strikes me that not much of that money is going into studying ocean acidification. I know that is a bit of an open-goal question to people from your background, but do you think it is a fair assessment? Do you think the balance should be changed?

Dr Lewis: Yes.

Q51 **Graham Stringer:** I know it is an open-goal question. Could you justify that more than my basic feeling about it?

Dr Turley: I could justify funding on the impacts of multiple stresses—the combined impact of ocean acidification, warming and deoxygenation. That is what is happening out there. They are happening at the same time, often in the same place. We need to know those interactions and their multiple effects in our coastal waters, the overseas territories and the Arctic.

I will give you an example. Last month I was in Japan, where they are two years into their first five-year funding tranche for ocean acidification. Japan is long and thin, so it runs from the sub-Arctic down to the near tropical. It is an island nation. They have coral reefs, so they have looked at the sensitivity of coral reefs to warming. They realise that the warming is going to push them northwards, if they can travel—if they can migrate fast enough—but then they have acidification coming down from the cold polar waters. Within just decades, there will be no habitable space for coral reefs, and therefore no sushi. A lot of fisherman are subsistence fishermen, so it will affect jobs. That is just one nation that has woken up to it. China is another nation that is waking up to it. Although Europe was very fast off the ground on ocean acidification research, other countries are now realising that it is a major issue.

Dr Garnett: Can I come back on the question about balance, in terms of spending? Maybe I would say this, but I think we have the balance about right when I look at the programmes we have funded recently. We have had a major £15 million programme on the changing Arctic Ocean, which is looking at exactly those issues of biogeochemistry. We have had another major programme looking at the Southern Ocean. That has a biogeochemical element, but it also includes work looking at carbon fluxes, which has more of a climate angle. We are doing a broad range in different areas. I do not feel that climate science is overfunded, which was slightly the premise of your question.

Q52 **Graham Stringer:** I was not saying that climate science was overfunded. I was saying that, within the quantum of money going into looking at the different impacts of CO_2, whether on atmospheric temperature or on other things, the balance was possibly wrong.

Dr Turley: Scientists can apply to the normal NERC funding schemes.

Dr Garnett: The way we come up with programmes now, effectively, is that the academic community and stakeholders such as DEFRA have the opportunity to pitch ideas, which are then reviewed. Both the Arctic programme and the Southern Ocean programme came out of that. The opportunity is certainly there. If there are particular areas that the ocean acidification community wants to take forward, I encourage them to propose a programme, which we can then pursue.

Q53 **Graham Stringer:** Can I ask a couple of very specific questions? Dr Lewis, you said that there is "currently no support for the monitoring of ocean acidification at UK shellfish aquaculture sites." Who do you think should provide that funding?

Dr Lewis: It is a very good question. I do not know whether you could convince the Shellfish Association to support it. I think they would be interested in it, but if it is monitoring for fisheries and food security, it needs to be someone like DEFRA.

Q54 **Graham Stringer:** Why has it proved so difficult, given the increasing amount of information that there is to date, to assess the impacts of ocean acidification?

Dr Lewis: On shellfish in particular.

Graham Stringer: Yes.

Dr Lewis: I guess we just haven't got to that knowledge step until now. As I said, it has been a learning process, just to learn how to ask the questions sensibly. We have got to that point now, and we need the next tranche of funding to take the next step forward.

Q55 **Graham Stringer:** My next question is similar. Socioeconomic impacts appear to be limited around the UK at present. When do you think we can expect to see those impacts become significant?

Dr Turley: The uncertainty increases as one moves from chemistry right up to the socioeconomic impacts. By 2050, we may see changes in fisheries and shellfisheries, perhaps even earlier for shellfisheries.

Dr Lewis: There might be an impact now and we just have not been aware of it—shifting baseline syndrome. If we were to manipulate water chemistry in aquaculture facilities, we might see an increase in production. That is what we are starting to suspect from the information coming out of the States. A sustainable aquaculturist still has mussels growing, so he does not think that there is a problem yet, but he could be seeing reduced growth rates and just not be aware of it. Shifting baseline is a big part of why we might not realise that there is an impact already.

Q56 **Chris Green:** Dr Garnett, funding for the ocean acidification research programme ended in 2015. Were efforts made to extend the length of the programme?

Dr Garnett: We very rarely have a second phase for a programme. The one where we have had two phases is the RAPID programme, which is monitoring the overturning circulation. That was effectively a new programme that was pitched in competition with everything else. The difficulty with extending programmes is that it leaves us no flexibility to do different things in the future. If we look at research we are doing around flooding, air pollution and other areas, there is a huge number of different environmental issues across NERC's portfolio that we want to do. The programme was not extended, but ocean acidification research was continued, and is continuing. There is the work that has been done in the Shelf Sea Biogeochemistry programme and the Arctic programme. As detailed in our submission, the topic area of ocean acidification had 22 grants funded by NERC, with a value of £9 million, over that period.

Q57 **Chris Green:** Fourteen of those had ended by 2016.

Dr Garnett: Yes. I am just trying to characterise the fact that not all the ocean acidification research takes place within the programme. What it provides is a co-ordinated opportunity. The idea of a programme is that the whole is greater than the sum of the parts. The fact that there were a number of elements working together has yielded real benefits.

Q58 **Chris Green:** Would it be fair to say that there was not an attempt to keep the funding going, because there were other projects ongoing?

Dr Garnett: Yes. That is accurate.

Q59 **Chris Green:** The marine sciences are particularly dependent on large-scale, capital-intensive facilities. Is adequate resource funding available to keep those facilities running, or is there a risk that they will fall into disrepair when programmes like ocean acidification research end? I am thinking particularly about funding for individuals doing particular work.

Dr Garnett: I do not think you would find any Research Council that said that sufficient funds had been given to the infrastructure. I certainly say that in relation to the Research Councils. As I described earlier, we divide our funding between strategic research and discovery science, which is about £110 million a year, and our national capability, which is about £130 million a year. We have that, but it is still stretched thinly. Our ability to do monitoring or carbonate chemistry or to maintain the data that come out of those programmes, so that they are available for everybody to use, is stretched. We are going through a process of prioritising our national capability, as we call it, to do that. Is there sufficient? No, there is not.

Q60 **Chris Green:** I got the impression that developments in the science and our understanding in the UK of ocean acidification have reached a certain level, where we understand the questions to ask and we understand far more about the subject. It sounds as though we need to take the next step and invest in that research. Given that finances are restricted, can we divert money from other programmes to do with ocean research, or as Graham Stringer suggested, does climate change investment take so much money that there needs to be a diversion from there?

Dr Garnett: I would challenge the suggestion that it takes so much. If we look at NERC's budget over the last five years and for the next five years, we find that the budget NERC has control of has been flat. In fact, it has gone down slightly. The additional funding, which is very welcome, that has come into science through the Global Challenges Research Fund and, now, the industrial strategy is being managed centrally. That is not currently—as it is—available for our national capability and our infrastructure, but there is a big opportunity.

As you may know, Jo Johnson has been promoting the oceans as an area of great interest. Earlier, we mentioned the G7 Science Ministers at Tsukuba coming out with a declaration looking at five areas of focus, of which the future of the seas and oceans is one. Part of that—obviously, it involves all the G7 countries—is to have enhanced global sustained sea and ocean observing systems. If we are talking about infrastructure, there is a real opportunity. There is also a good tie-in with the industrial strategy. One of David Willetts' eight great technologies was autonomous vehicles and robotics. Nobody does autonomous vehicles better than the marine environmental science community in the UK, in terms of their range, their depth and what they are able to do. There is a real opportunity here. Clearly, the oceans are an international issue. The G7 provides the ability to co-ordinate that internationally and, hopefully, get more funding for the area.

Q61 **Chris Green:** I realise that we are pressed for time and that funding was covered previously, but do you have any other comments about funding?

Dr Poulton: Although the NERC budget has been flat over time, costs have increased—for example, fuel costs for the ships and things like that. It puts on additional internal pressure, as salaries go up, to try to get PhD students through to postdocs and career science.

Q62 **Chris Green:** Inflation is one thing, but your costs are a bit higher than inflation.

Dr Garnett: And our budget is going down slightly in actual cash terms—not even in cash-adjusted terms.

Dr Turley: You should not think that the UKOA scientists have been sitting on their hands. They have been writing and submitting proposals.

Dr Garnett: We have been funding some of them.

Dr Turley: Yes, some, but an awful lot do not get funded. The success rate was about 10% a year ago. It is very tough.

Dr Garnett: Success rates for our standard grant—discovery science—were getting down to 10%, which was unsustainable on all fronts. We have introduced a demand management-type quota process, so it has got up to about 20%. When we grade our science, grade 8 is high priority for funding. In the last grant round, we had 67 graded 8 and above. We could fund only 44 of those. We had 23 high priority for funding grants that we could not fund. We had lots that were also fundable at the next grade down. There is a lot of capacity that is not being exploited.

Dr Turley: We have also taken advantage of European funding until now. We were part of at least two or three EU Framework 7-funded programmes. That really enabled extra funding to come in to UKOA scientists.

Q63 **Chris Green:** That message about funding our collaboration with European partners needs to go through to DExEU, to ensure that there is continuity.

Dr Lewis: Absolutely.

Dr Poulton: EU money and many of the programmes that NERC has been able to support have allowed that internationalisation to happen—apart from the network. It is quite important to have that global scope.

Dr Turley: Look at the authors of the papers from UKOA. They are not only from throughout the UK, showing national collaboration; there is also huge international collaboration. It is very impressive—from South America, North America, China, Japan and Europe. It is massive.

Chair: Thank you very much for your contributions this morning, which have been very helpful and have set the scene for our investigation.

Examination of witnesses

Witnesses: Professor Bates and Dr Clark.

Q64 **Chair:** Welcome. Thank you very much for joining us this morning. For the record, could you state who you are and in what capacity you are here this morning?

Professor Bates: I am Professor Nick Bates. I am here on behalf of the University of Southampton, and I am also director of research at the Bermuda Institute of Ocean Sciences, which is a US organisation based in Bermuda.

Dr Clark: I am Dr Melody Clark. I am a project leader, and I am here on behalf of the British Antarctic Survey.

Q65 **Chair:** Thank you very much for joining us. Building on the contributions from the previous panel, which I think you heard, do we currently have a good understanding of the risks of ocean acidification to UK overseas territories' waters? How does that vary in different parts of the world?

Professor Bates: I can speak to Bermuda's importance for the UK overseas territories, and perhaps a little bit for other territories—Anguilla, Cayman and so on. The marine resources of the UK overseas territories are about eight times the territorial waters of the UK. They cover a wide diversity of ocean systems, from subpolar and polar to tropics and tropical marine environments. There are different environments and ecologies, from tropical coral reefs to polar communities in the open ocean and in the benthic shallows and shelves that the UK overseas territories encompass. In augmenting what we understand about the science of ocean acidification in the territorial waters of the UK, the overseas territories add significant complexity and diversity to our understanding of how the oceans function, and how they function in relation to environmental issues such as ocean acidification, global warming, changes in stratification, ocean deoxygenation and other pollutants and impacts.

If you would like, I can talk about Bermuda as an overseas territory. Bermuda has a landmass of 55 sq km. It has an economic exclusion zone of about 450,000 sq km, so it contributes to the 6.8 million sq km of the overseas territories and UK territorial waters economic exclusion zone area. It is a significant portion of the UK overseas territories economic exclusion zone.

Bermuda has a series of tropical and subtropical reef systems in the surface ocean, to a depth of about 30 metres. It is of the order of 100 sq km. Deeper, there are mesophotic reefs, which are typically in lower-light conditions from about 30 metres to 100 metres. Then there is an area of patch reefs and seagrasses. It is an area the size of the Isle of Man and the Isle of Wight combined. Those coral reefs are in a healthy state at the present time, and they contribute to the total economic value of

Bermuda. On Bermuda's economy, its GDP is about 6.8—let me think—$1.3 billion. Some economic assessments of the marine value to the economy are about 12% of GDP. The marine resources, the coral reefs, are very important to the total economic value of Bermuda, at 12%. In the UK, all marine activities are about 6% to 7% of GDP. For Bermuda, with data going back to the late 2000s, it is about 12%. With the America's Cup coming to Bermuda, the economic value of the oceans and the economic health of the oceans are obviously of importance to Bermuda as an overseas territory.

Dr Clark: The Antarctic—the Southern ocean—is slightly different—

Chair: Very different.

Dr Clark: It is very different, it has to be said. In terms of ocean acidification, it is one of the regions that is predicted to become undersaturated first. The current predictions are that we will see seasonal undersaturation by 2030. That will spread rapidly, so 30% of the Southern ocean will be covered by seasonal undersaturation by 2060, and that will go to 70% by 2100.

The extent of the seasonal undersaturation will increase from one month to six months. Of the regions of the globe that will be affected first, you would expect to see it in the Southern ocean. We also have, in many ways, added complications in that carbonate is more difficult to extract from cold water, so there is a latitudinal gradient in skeleton size—skeletons of animals with carbonate. Skeletons are smaller in the Antarctic and the polar regions, unless there is an ecological reason why. Clams, for example, thicken their shells in response to iceberg damage, but even in those cases, the amount of skeleton per unit tissue is lower than in temperate and tropical regions. Also, the animals live a long time. They have very long generation times. Those animals have relatively poor capacities for adaptation to change; they will not have many generations in which to adapt to change. We have the added factor of seasonal sea ice, which doubles the size of the continent around the coastal regions. We need to increase our confidence in modelling the sea ocean atmosphere fluxing for seasonal sea ice. We do not have a very good handle on that at the moment.

Q66 **Chair:** As you rightly pointed out, you come from two very different parts of the world, but to what extent did the UK ocean acidification research programme provide you with funding to investigate your own individual waters and look at the impact that ocean acidification was having?

Professor Bates: Essentially, no resources from the UK support Bermuda offshore or coral reef research. The work that is done off Bermuda is supported by the National Science Foundation, so it is US funding; it is the US taxpayer who supports research activities off Bermuda. It is the longest time series we have on the planet. The first measurements were in 1954. We have seen warming of nearly a degree, we have seen ocean deoxygenation, and we have the longest record of ocean acidification, going back to the 1970s, nearly 40 years, and continuously for about 34 years. We get no resources from the UK.

Dr Clark: For the Southern ocean, we had a group involved in the sea surface consortium, and the evidence for that was presented by Professor Toby Tyrrell. In addition, we had a PhD student, who conducted long-term experiments on brachiopods and calcification. We had a NERC algorithm studentship, but there was relatively little that we could actually bid for in terms of the Antarctic.

We started monitoring carbonate chemistry at Rothera in late 2010. The manpower for that is largely funded by national capability, so the marine team take samples. The actual carbonate chemistry and the analyses were paid initially—for a couple of years—by the University of East Anglia. Then we had a Dutch project that was linked to long-term monitoring, which lasted for about four years, and they paid for the carbonate chemistry measurements. Now it has gone back to the University of East Anglia. We can take the samples, but—

Q67 **Chair:** Do you think the programme should have done more to fund research in overseas territories?

Dr Clark: We would probably say yes.

Professor Bates: In my personal opinion, yes, absolutely.

Dr Clark: My personal opinion is yes, but there is a limited pot of funds. It is better to do some things really well rather than scattering everything too widely.

Q68 **Chair:** But were there missed opportunities by not funding that? Of course you can say, yes, you should have had some funding, but do you think that the funding, or some of the funding, would have been better spent where you were rather than where it was, and why?

Dr Clark: That is rather difficult. My personal opinion is that some absolutely excellent work was carried out under the UKOA programme, and it has contributed to our knowledge incredibly. It has also helped to inform what sort of studies we should be doing in the Antarctic. I personally would have liked to see more money put into polar research, particularly in the biological area, which I am more interested in, but, as I said, there is a limited pot of money. We would not be where we are today with our knowledge without the UK programme.

Professor Bates: In an ideal world, yes, it would be wonderful to have representative sampling and experimental strategies cross-bridging across ocean systems, from polar to tropics. In an ideal situation, you would be able to fund OA work and associated work in the Indian ocean overseas territories, perhaps associated with the MPAS in the Caribbean. There are lots of opportunities and, at present, there is a lack of understanding of what is going on in many of those regions. We are lucky that we know what is going on in Bermuda and the Antarctic, but what is our scientific evidence for change in other regions of the overseas territories?

Q69 **Graham Stringer:** You heard the previous evidence session, where it was explained to the Committee that most of the baseline studies do not go back very far. You are ahead of the curve, Professor Bates. Why did you take the decision so early? What were the factors that led to your deciding to study ocean temperature and acidification so long ago?

Professor Bates: There is a long anecdotal history, but it was originally set up by the Woods Hole Oceanographic Institution. There was a scientist called Hank Stommel, who was a very well-known oceanographer. He is no longer with us, but he had the foresight to think that Bermuda, because of the close access to the deep ocean, would be a very good place to start measuring the ocean regularly.

Post second world war was an era of scientific endeavour and expedition, and Stommel set up the time series off Bermuda in 1954-55. Since then, additional work has been done on the biology and chemistry, and more about the physics and understanding seasonality. Some of the very early paradigms of how we understand the oceans, how they work, how they are productive, how they change seasonally and our concepts of how nutrients are used in the oceans, come from those early studies in the early 1960s off Bermuda.

Ocean acidification—pH—monitoring came later, and was of very high quality. Making time series and sustained observations that are of sufficient quality to tell you something about how the ocean atmosphere system is changing needs effort, skillsets and expertise. We were very lucky in the early 1980s to have the help of Dave Keeling, the scientist who really started the atmospheric CO_2 measurements in Hawaii. Dave Keeling was instrumental in saying, yes, you should be making measurements of carbon dioxide. We did those, and I took over in about 1989-90.

We are very fortunate geographically. We have a ship, and we have the opportunity to go out to sea regularly each month. That is very important. If you go to a place in the ocean and you measure the chemistry and the biology only once a year or, say, every few years, it takes many decades to establish the timescale of emergence of a trend. If you go out and measure four or six times a year, understanding the seasonality allows you to assess the amount of variance in the data because of the seasonality, and it allows you to establish trends in CO_2 or nitrogen changes, oxygen changes or water or temperature changes over a much shorter timescale. For example, off Bermuda, the timescale of emergence of trends is of the order of 10 to 15 years. We have a time series of 30 years. We know very robustly the changes in the chemical and biological environment of the oceans we study, because we are able to go out and measure frequently. We do so seasonally, every month. That gives us a much better handle on establishing trends. That will feed into policy instruments and into the IPCC and the WMO. It allows you to assess the state of the ocean and its change in a shorter timescale.

Q70 **Graham Stringer:** We heard from the previous panel that some studies are complicated by pollution coming off the land in one form or another. You have the benefit, in Bermuda, of not having any industrial pollution to mention. What have you been able to observe, having been able to separate ocean acidification from pollution? What impacts have you observed to date?

Professor Bates: We have the longest time series anywhere on a coral reef. It is 20 years. That does not seem very long, but it is the longest sustained observation on the planet. It is a mixed message. The corals are calcifying. Today, they are creating the framework structures that we all know charismatically as coral reefs at a rate 30% higher than they did 20 years ago. They are doing that because they are feeding more, they are getting more energy and they are able to compensate for the effects of ocean acidification. The pH changes are almost three times as fast; the decrease in pH is three times as much as in the surrounding open ocean. At the moment, there is a real mixed response. The corals are calcifying and the reef is healthy. Perhaps Bermuda's reef will act as refugia.

My fear is that, as soon as the ocean becomes less productive, the energy required for corals to create their calcium carbonate framework will diminish, so OA, ocean deoxygenation, stratification and warming will have a very detrimental impact on the coral reefs going forward. At the moment, however, we are very fortunate. That is very different from many other reef systems.

Q71 **Graham Stringer:** You said, Professor Bates, that coral reefs in Bermuda appear to be an important global refuge for coral species. Can you expand on that?

Professor Bates: If you look at other coral reef systems—the Florida systems and the Caribbean—there are a multitude of stresses and impacts: coral disease, bleaching, ocean acidification, overfishing, cyanide use and turbidity. Those impacts all contribute to the deterioration of the health of coral reefs globally. Unlike many other reef systems, Bermuda still has substantial amounts of corals that calcify. In Florida, much of the hard coral is now replaced by algae. We have a traditional view of a coral reef, when we scuba dive and swim there; we can go to the Great Barrier Reef, and see that kind of archetypical view of the reef system. It is harder to see in Florida. There is now evidence in Florida that the reef system is undergoing dissolution, so they are not creating calcium carbonate in a net sense; they are beginning to dissolve.

There is a complexity of different responses in reef systems geographically. Overall, the pressures on coral reefs globally are for a reduction in the area of coral reefs and their overall health and viability. In Bermuda they are refugia; the mesophotic reefs, those deeper reefs, are acclimatised to slightly lower light levels, and are in a reasonably healthy state. We have invasive species such as lionfish, like many of the Caribbean reef systems, but there is a potential refuge for coral species in the future, for broadcast spawners and so on basically to resettle juvenile corals. I must give you the caveat that, when we look at juvenile corals, there is impact on young corals as they settle. Essentially, they have to settle on a hard substrate and lay a plate. We can already see the impacts even in Bermuda; they do not have a strong basis from which to create a colony. That lays the coral colony open to vulnerability from other stresses: disease, leaching, pollution and so on.

Chair: Before we continue, Victoria wants some clarification on language.

Q72 **Victoria Borwick:** Could you clarify the complexity of the language? I appreciate that our physics experts and others may have understood all of that, but, in simplistic terms, did you just say that in Bermuda you are still making coral, while in Florida they are not?

Professor Bates: Yes.

Victoria Borwick: I just wanted to be absolutely sure.

Professor Bates: In simple terms, yes.

Victoria Borwick: Thank you.

Q73 **Graham Stringer:** In the hierarchy of threats to the Arctic and Antarctic, where does ocean acidification come? Are there different threats in the Arctic and the Antarctic?

Dr Clark: No, I think the threats are the same. Ocean acidification comes pretty high up. As you realise, it is a very complex issue. The animals in Antarctica and in the high Arctic are very temperature sensitive. My opinion and that of the people I talk to is that temperature is potentially the major effect, but we know that ocean acidification acts with it to exacerbate that. For example, we know that the Antarctic sea urchin takes six months to acclimate to plus 2°—it takes six months to get used to a 2° rise in temperature. If you add ocean acidification on top of that, it takes an extra two months for that animal to acclimate. It is not a simple question of which is the most important. In every case, you are talking about multiple stresses, as I think you have heard before, and we need to understand how they interact with each other. There may be one main stress, but the other stresses have an impact, and they reduce the tipping point of populations and ecosystems. I do not think it is a simple answer. In other regions of the globe there is pollution, hypoxia, freshwater run-off and so on. It is complicated.

Professor Bates: In the Arctic, particularly the western Arctic where most of the sea ice loss has occurred in the summertime, the rates of ocean acidification are double what we typically see in the open ocean in the north Atlantic. There is a compounding of impact in the Arctic of OA with warming and loss of sea ice. There are studies; US colleagues look at benthic communities. For example, the Bering sea is 50% of the US fisheries, so it is very important economically. The Bering sea feeds into the Chukchi sea in the Arctic. In benthic communities there, the evidence is that the shelly fauna—the clams and molluscs—are already impacted. They are less robust; the calcium carbonate of those clams and molluscs is less robust. They are more flexible and more susceptible to breakage. That is something we have been seeing over the last 20 or 25 years. There are records to show that OA is already having an impact in the western Arctic.

Q74 **Graham Stringer:** Dr Clark, you said that Antarctic animals can thrive over quite a variation of pH. Does that mean that Antarctic animals will be more resilient to ocean acidification?

Dr Clark: No, not necessarily. There are very few studies looking at variation in pH, and there are certainly no real long-term studies, but coastal animals appear to be able to survive in fluctuations of temperature. I emphasise that we do not have much data. If you look at the studies for animals that you can see—those I work on—there are about 20,000 species in the Southern ocean, and the studies have covered only 14 of those. Most are single-species studies, and about 40% of the studies are all on the Antarctic sea urchin, because it is a very tractable model species. When you look at adult and larvae studies as to which life stage is more sensitive, it is about 50-50 in the studies. Most of the larvae studies, again, are on the Antarctic sea urchin.

The sea urchin seems pretty resilient, but most of the studies are short term. We have only two real long-term studies: one is the study by Cross, who kept Antarctic brachiopods in altered pH for seven months. Those animals are 95% calcium carbonate, and they seemed fine. We kept the sea urchin in altered conditions for more than two years, largely because the animal takes two years for its gametogenic cycle—it takes two years to make its eggs and sperm. To ensure that those had all matured in altered conditions we had to do a two-year study. When you spawn the animals at six months and 17 months, the larvae do much better at 17 months. But that is only two studies.

I am a molecular biologist. Just because an animal looks fine, that does not mean to say that it is fine. If you have altered conditions, you have to compensate for that somewhere. As we have heard, if there is enough food, animals can cope much better than if food is limited, which is more typical of the natural environment. I do not think we have a really good handle of what the trade-offs are. If something looks fine, it could be. Usually with animals, if there are restrictions on their energy budget, they start to have a reduced immune system, or reproduction is impacted, which affects the future generation.

There was one study in the States, a really nice one, led by the Palumbi Lab, where they took the purple sea urchin, put it into altered conditions and then spawned the larvae. Under a range of conditions everything looked fine, but when they looked at the gene expression level and the cellular level, there were differences between the different conditions—

something like 40 functional groups—and biomineralisation was affected. There were subtle changes. That is the real message of the ocean acidification programme. There are some very subtle changes going on, and we are only just starting to get a handle on the subtlety of those changes. Another example is from the Munday group, which saw that the ability of reef fish to sense predators is compromised by OA, but again the animals look fine. It is complicated.

Q75 **Graham Stringer:** Does all that mean that we do not know whether the Antarctic ecosystems have already been adversely affected?

Dr Clark: Correct, yes. We simply do not have the long-term data.

Q76 **Dr Mathias:** To pick up your last point about genetic changes, do you think that is adaptation or mutation?

Dr Clark: Mutation rates are much slower than adaptation in intergenerational change. The study at the Palumbi Lab showed that there was selection for certain genotypes under the different conditions. They saw that as evidence of rapid genetic change, which could decrease diversity in future. As we have seen from the periwinkle study, there is genetic diversity between populations, which predicates their response to ocean acidification. In terms of adaptation, we are talking about genetic adaptation through generations, and that really depends on the generation time of the animals involved.

Q77 **Dr Mathias:** We know that Bermuda has long-term monitoring. Are we too reliant on ad hoc monitoring elsewhere, Professor Bates?

Professor Bates: Ideally, it would be helpful if we had more sustained observations and time series across the globe, in the open ocean and in the coastal environment.

Q78 **Dr Mathias:** Do you think the barriers for us in other territories are just funding?

Professor Bates: Access, expertise, local logistics—there are many complexities in that. If you have an ad hoc way of sampling, you might potentially fall into the issue of continuity. Ocean acidification is complex and requires a lot of expertise and capacity building in our young scientists' career paths, and among technicians and engineers. Consistency in the way we strategically approach capacity building that can bridge across funding gaps, and that allows continuity of sampling and gets away from an ad hoc sampling regime, is helpful. There is always value to sometimes being able to sample an event.

Dr Mathias: But in the context of your long-term monitoring.

Professor Bates: Yes. Having that flexibility is always really helpful. Having a strategy where you have continuity and a robust framework to support sustained observations and experimental design, data collection and process understanding of how the ocean works in relation to OA and other multiple stresses is really important.

Q79 **Dr Mathias:** Following the conclusion of the UKOA—the ocean acidification research—do you think, Dr Clark, that anyone is providing long-term strategic leadership?

Dr Clark: Particularly in the overseas territories.

Dr Mathias: In the UK and in the UK overseas territories.

Dr Clark: I am not sure I can really answer that. As a scientist, it is not immediately obvious to me, but I am not very involved in strategic research.

Dr Mathias: Okay, that's fine.

Dr Clark: I don't know if Nick has a view.

Professor Bates: I would reinforce that.

Q80 **Dr Mathias:** Having noted what you say about the expertise required, is there a role for other groups—industries or military vessels—to be involved with data collection at all?

Professor Bates: Absolutely. There are uses of ferries and of people's personal yachts.

Dr Mathias: Brilliant.

Professor Bates: There are the SeaKeepers—

Dr Mathias: I am getting a strong image of Bermuda.

Professor Bates: High-wealth individuals go to nice places in the tropics and subtropics, but they cross the oceans, and there are programmes to instrument some of those yachts. Using those opportunities is really helpful. If you could use submarines and military vessels to collect data, it would be incredibly helpful. The US used to collect a lot of data from submarines in the Arctic, but, although you can access the data, you do not know where it is from, obviously.

Dr Mathias: I see—yes.

Professor Bates: There are limitations to some of those data. There are commercial vessels and merchant ships crossing the oceans, as well as ferries; having those partnerships and having ways to foster them, and getting commercial entities interested as stakeholders in the science that one does is really important.

Dr Clark: I agree entirely. There are cruise ships that go round the Antarctic, and military vessels. If we could put remote sensors on those, it would be absolutely fantastic.

Dr Mathias: I can imagine that. My constituency has a river, and everybody involved near or in the river is passionate about it, so I can imagine—just—what it is like in the ocean world in Bermuda.

Q81 **Carol Monaghan:** Can I ask about the specific experiments that have been carried out, both in Bermuda and in the Antarctic? Are they specifically looking at the pH levels of the water? Are they also looking at temperature and salinity and things like that?

Professor Bates: For Bermuda, there is a framework of observations that we make. We look at temperature and salinity. We look at oxygen and nutrients. We look at the biological community, which could be marine plants or from animals to fish larvae. It is a comprehensive strategy of ocean observation. It is not just pH. Looking at OA has to be in context with what the biology is telling you about how the ocean is working as well.

Dr Clark: I agree with that. At Rothera, the carbonate chemistry is based on the Rothera time series, which was started in 1997. The aim was to measure temperature, salinity and nutrients twice a week in the summer, and when they can in the winter. Linked to that, people are looking at long-term reproduction of benthic animals—sea urchins, terrebellid worms, and sea stars—and are also looking at iceberg scour. Those observations have been going on since 1997, so it is a comprehensive biological survey. Since 2011, they have been able to carry out carbonate chemistry on top of that. As Nick says, it has to be holistic; you have to look at more than just the carbonate chemistry.

Q82 **Carol Monaghan:** If you are looking at the pH levels and the temperature, are you superimposing those sets of data and trying to discover whether the two are linked? Is temperature causing effects? Is pH causing effects?

Professor Bates: If we look at the open ocean, there are about seven long-term time series that extend beyond 20 years. There is one off Bermuda, one off Hawaii, one off New Zealand, two off Iceland, one off Venezuela and one off the Canary Islands. They are all connected because, in a sense, they are close to an island. They are geographically fortunate, and you can get out to the deep ocean and sample.

When you look at pH changes, you look at all the other factors such as the temperature and which environment it is located in. We are talking about tropical to subpolar environments, so the impact of things like temperature on pH will be different in a polar ocean compared with a tropical ocean. The biology will be different in a subpolar region. The ocean's biology tends to generate a lot more activity and a lot more growth. We look at all those other factors when comparing systems. What is remarkable from what we know about the global ocean is that the rates of change of pH and other ocean acidification indicators are fairly similar.

There are differences. The Arctic is changing at a faster rate than most other parts of the world's oceans. The Cariaco basin off Venezuela is doing the same. The Irminger Sea is also changing at a faster rate than other parts of the world's oceans. That relates to things such as how the ocean is circulating—how deep water is formed and how Arctic sea-ice melts change or impact those regions. There is complexity, but the time series we have show concerted changes in pH across the globe. We have to analyse that in the context of the physics, the chemistry and the biology. What are the other factors at play—the multiple stresses that impact on pH?

Q83 **Carol Monaghan:** We have heard concerns that experiments conducted previously exposed plants and animals to rapidly changing pH, and therefore produced a shock reaction. How valid is that as a scientific method? Should we really be conducting those experiments, or should we be looking at the experimental design to consider things over a much longer period?

Dr Clark: Definitely. The field has matured, and we are now moving to much longer-term experiments. Some of the initial very short-term experiments are very good for understanding what the different resiliences and potential sensitivities are between different animals. Sometimes you can only do those rapid experiments if you are on a cruise, for example—you are taking out deep-water animals and you only have two weeks. We do not know the long-term husbandry of a lot of animals. They can be useful for that, but the field is maturing and I think you will find that most of the experiments are now very much more long term.

Professor Bates: I totally agree. I would just add that it is sometimes difficult to understand and evaluate the indirect impacts. If, for example, we are looking at pteropods, which are sea butterflies, a Pacific species, they are directly impacted by OA and pH levels, but they have an indirect impact on the salmon fisheries in the Pacific north-west of the US, Canada and Alaska. Evaluating experimentally from a pteropod to a salmon and fisheries impact, whether you do that in the field, in a mesocosm or a laboratory, cross-bridging and interpolating between those different experimental strategies, we have ways to go.

Q84 **Carol Monaghan:** You are saying that what we should be looking at is the entire ecosystem, rather than an organism in isolation.

Professor Bates: It depends on your questions. There is value in looking at an individual species and its response to, perhaps, temperature change or pH change, and there is obviously value in looking at the whole ecosystem. Sometimes it is logistically much easier to look at a single species and its response with the resources you have. There are trade-offs. There are trade-offs in trying to get the best understanding of how the oceans function.

Dr Clark: Allied to that, in medical research, a lot has been made of model organisms such as Drosophila and C. elegans, which have really impacted on our understanding of medicine. It is fair to say that we do not have such model species in environmental research, and we do not have the facilities or the resources for them. Looking at single species in great detail can tell you an awful lot about what the other potential responses are.

Q85 **Carol Monaghan:** Dr Clark, if you were asked to make a modification to the experimental work you are doing, and let's imagine that money was not an issue, how would you change things?

Dr Clark: I would do multiple species, and very long-term experiments, with a minimum of two years, possibly four years. I would try to cultivate larvae for much longer. We only manage to keep them going for about 17 days, whereas most Antarctic species need about 100 or 150 days. If money was no object, I would have a bigger facility, with multiple species in the same tank so that we could see what the interactions were, and perhaps try to cultivate larvae over a much longer term. We could also try to develop some in situ experiments, although it is difficult to do that.

Professor Bates: I would agree. If you are looking at coral species, all the experimental data are on relatively few species and taxa. I would reinforce that; expansion to multiple species and of length of experimental design would be very helpful.

Q86 **Victoria Borwick:** Some of my questions have slightly been touched on, so perhaps we could have some quick answers—I am conscious of the time. Funding and the short-term nature of research council funding was touched on in the earlier session. It obviously presents a barrier to long-term monitoring. You have just touched on funding again, in the sense that Carol said, "Open your Pandora's box." What type of funding and what system of funding could support longer-term ocean observations?

Dr Clark: That is a difficult one. You really need Ned to answer that.

Victoria Borwick: Okay. I am sure that they can put that in writing. He will have heard the question, and I am sure he can send that in to us afterwards.

Dr Clark: That is politically quite difficult for a scientist to answer, so I had better refer it to Ned.

Victoria Borwick: No problem at all.

Professor Bates: We have our personal opinions.

Q87 **Victoria Borwick:** Going back to the Antarctic survey, the Government announced a £100 million upgrade of the British Antarctic survey's polar infrastructure including, as you touched on earlier, the Rothera research station. Will any of that help with your longer-term ambitions?

Dr Clark: We are obviously very grateful for the funding, and it provides a fantastic scientific platform for the research, but it really depends on what research is funded for the larger infrastructure and for the ship. That will be the shorter-term funding, presumably. That is all I can say. It depends what science you fund with it. They are fantastic science platforms.

Q88 **Victoria Borwick:** Do you not get to choose?

Dr Clark: No.

Victoria Borwick: Ah. Who chooses?

Dr Clark: What do you mean? Who chooses what?

Q89 **Victoria Borwick:** The implication was that, by upgrading the ship, more research could presumably take place, but who makes the decision as to what it is?

Dr Clark: We still have to bid for research funds to do the research on the ship.

Victoria Borwick: Understood. Although you have the infrastructure, you do not necessarily have the actual research projects funded.

Dr Clark: No. The scientists had input in the design of the ship, but, ultimately, the funding for the science on those ships is additional.

Victoria Borwick: It is good to clarify that in open session. We would have presumed that one meant the other.

Dr Clark: No.

Q90 **Victoria Borwick:** That is good for us. You have to understand that we do not come from such a scientific background, although some members of the Committee do. One of the things the Committee has been talking about is making science more accessible to people, making it more interesting and getting more people involved and therefore passionate as to why it is important. The Committee considered NERC's polar research ships, in particular Boaty McBoatface, which gripped the nation for a short while, as part of its inquiry into science communication and the role that we can all play in demystifying it. Will the Sir David Attenborough, which I believe is now the correct name, have any role in monitoring ocean acidification?

Dr Clark: I am not an oceanographer, so I really cannot answer that. I do not know if there will be—

Victoria Borwick: Fortunately, one of the audience in the gallery is indicating—

Dr Poulton: Yes. A system that can go on ferries to monitor pH will be on the Attenborough.

Victoria Borwick: Thank you. Does anybody else want to write in about that? Is that acceptable, Chair?

Chair: It is on the record now.

Q91 **Victoria Borwick:** What scope is there for international collaboration and co-ordination? You touched on some of those, with the work that is going on in Bermuda, and you were talking about private yachts as well as commercial vehicles. What sort of potential is there for international collaboration and co-ordination of ocean acidification research? How could it be fostered to get more interest?

Professor Bates: Again, this is a personal opinion. International collaboration is really important, fostered through as many avenues as possible, whether it is commercial partners or NGOs; for example, there is the UK Overseas Territories Conservation Forum, the FCO, the IPCC, the WMO and the UN. I have contributed, as many of my colleagues have, to all those bodies. Fostering international collaboration is really important. You build on the strengths of individuals. The group experience is much greater, and you get more understanding from a group if there is international collaboration, fostering outreach and educational understanding, training primary school kids to enjoy science, seeing "Planet Earth II" and getting really excited about the Earth system. All of those things really help.

Dr Clark: I agree entirely. We collaborate wherever we can internationally. The Antarctic community is very international. Wherever we can, we collaborate. It largely depends on national funding from each country, but we share our data, our data are publicly available and we try to improve international collaborations as much as we can and foster them.

Victoria Borwick: Thank you.

Q92 **Chair:** Before I draw the session to a close, may I clarify a point with you, Professor Bates? It appears that the majority of funding for research around Bermuda is paid for by the US. Is that historically because of the large naval base that was there, and is the funding likely to evaporate now that the base is closed?

Professor Bates: The US naval base closed quite a long time ago. BIOS is a US institution, so it is just like Woods Hole or the Scripps Institution of Oceanography. It is eligible for all the federal agency types of funding—NASA, NOAA, NSF, EPA and DARPA, which is the defence agency in the US. We do not know the future. Obviously there are some uncertainties about future funding—continuing resolution for the budget in the US—and how that impacts on the National Science Foundation. Those are uncertainties we cannot answer. We will see.

Chair: Thank you. I won't push you further on that. Thank you both very much for joining us this morning and for your contribution.