National Science and Engineering Week Seminar on Thursday 20th March

BIODIVERSITY, DOING THE MATHS (WITH ALAN TURING)

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We live in the age of biodiversity, but are in danger of forgetting what it means. Church, State, we the people, and most certainly the media use the word so frequently it must be important. So what does it mean? How do you assess it, measure it, monitor it, protect it, and value it? Too many topics to address in one short article, so consider some of the numbers, the mathematics and the arithmetic of biodiversity.

BIOLOGICAL DIVERSITY

Biodiversity is a measure of variety in things biological. It refers to the variety of species present in a sample, or some given area. It can refer to any level of biological organisation – the genes within an individual, the biological community types present in a landscape, or the ecosystem types on a planet.

HIGHER, HIGHER, LOWER, LOWER

At its simplest, biodiversity could be a count of the number of different species in a collection. More species, higher diversity, fewer species, lower diversity. But life is never as simple as that. In most cases, the more specimens you examine the more species you will encounter – how do you compare diversity between samples of different sizes? And how do you deal with common species and rare species, do we count them as equals?

DOING THE MATHS (PART 1)

There are several ways of measuring diversity. The following is chosen for its common use and for its connection to Alan Turing, recently recognised for his exceptional contribution to many branches of computational science (including biology) [1]. The measure in question is the Shannon Index (H'), proposed by Claude Shannon in 1948 [2], pioneering the field of information theory. Like Turing, Shannon was a war time code breaker, the two meeting when Turing shared the Bletchley Park Cypher School's methods with the US Navy's cryptanalytic service. Shannon's formula is very simple, where S is the

$$H' = -\sum_{i=1}^{S} p_i \log_2 p_i$$

number of species and p_i is the proportion of individuals belonging to the i-th species, and has units of bits of information per individual. This formula is used in Information Theory (*war time code breaking, compressing the photo files on mobile phones*) and Thermodynamics (*building a better steam engine, understanding black holes*). It is perhaps easier to understand as probability – the bookmaker's odds on making a successful guess about future events (see Box 1).

Box 1

Sample	Blue odds	Blue %	Species no.	Shannon index
(a)	1:7	14.3	7	2.81
(b)	1:5	20.0	5	2.32
(c)	1:3	33.3	3	1.58
(d)	3:7	42.9	7	2.25
(e)	5:7	71.4	7	1.60

The diversity of coloured marbles. The samples are ordered by the chance of picking a blue marble at random. This is a measure of the dominance of blue (Blue %). The number of colours (species) present also influences diversity. The Shannon index attempts to combine the dominance and species richness aspects of biological diversity.

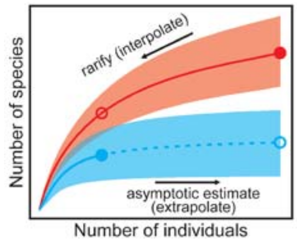
DOING THE MATHS (PART 2)

The Shannon Index, and many other diversity measures, deal with the question of counting both common and rare species. How do we compare diversity between samples of different sizes? A simple 'paper and pencil method' was developed by Howard Sanders in 1968[3]. Soon after a more formal method was published by Stuart Hurlbert [4], that examines the 'probability of interspecific encounters', the chances of two individuals of different species bumping in to each other, to predict the number of species expected to be present in a subsample of x individuals,

$$E(S_x) = \sum_{i}^{S} \left[1 - \frac{\binom{N-n_i}{x}}{\binom{N}{x}} \right]$$

where S is the number of species, N is the total number of individuals in a larger collection, and n_i is the number of individuals in the i-th species. This method is known as 'rarefaction', rarifying a larger sample to make it comparable with a smaller sample (see red sample in Fig 1).

Figure 1



Comparing species diversity (richness) between samples of different size, by interpolation and extrapolation. Solid symbols are field data, open symbols are calculated values, shaded areas represent statistical uncertainty.

Rarefaction is useful, but is costly in the sense that it discards much of the hard won field data by rarefying all larger samples down to the size of the smallest sample. The power to discriminate between real field differences may also be substantially reduced in the process. Fortunately Alan Turing comes to the rescue again through 'Good-Turing frequency estimation', as published by Irving Good [5,6], a statistical assistant to Turing at Bletchley Park. Following on from war time code breaking experience, the concept is that common words (or species) provide little information about words (species) not yet encountered, while the rarest words (species) provide the majority of information about these so far unseen words (species). Nicholas Gotelli and Anne Chao[7] review this approach in contemporary assessments of biodiversity, through the development of 'non-parametric asymptotic species richness estimators' such as the Chao1

$$\hat{S}_{Chao1} = S_{obs} + \frac{f_1^2}{(2f_2)}$$

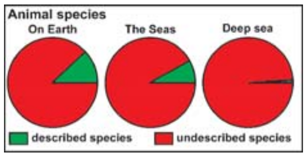
estimator, for f_2>0, where S_{obs} is the number of species observed in the sample, f_1 is the number of species represented by a single individual only (singletons), and f_2 is the number of species represented by two individuals only (doubletons). This approach allows the number of species observed in a sample to be extrapolated to the expected number of species observed in a larger sample (or perhaps an entire community) (see blue sample in Fig 1).

BIODIVERSITY, DOING THE ARITHMETIC

The first step in monitoring, protecting, and valuing biodiversity would seem to be understanding what it is, and how it can be appropriately measured (see above). There is, however, one step that must come before that – identifying the species in the first place. And here we encounter the *"taxonomic impediment"*[8] – a world-wide shortage of taxonomic knowledge, trained taxonomists and curators. Taxonomy is the science of recognising, describing, naming, classifying, and cataloguing life on Earth, taxonomists are those who carry out that work, and curators are those who obtain, maintain and sustain the specimens and data required by taxonomy.

The arithmetic of this problem is simple and staggering. In about 250 years of taxonomic endeavour, we have described about 1,000,000 animal species on Earth, about 12% of those that are currently thought to exist, or in other words some 7,000,000 animal species remain to be described[9]. The situation is a little worse in our seas where only 8% of the animal species thought to exist have been described, in remote sea areas (e.g. deep sea) that number will be appreciably lower, and for the smaller animals in remote seas that number will be approximately 0% (see Fig 2). Is there a vast army of taxonomists tackling this problem? The world total of professional taxonomists is numbered at a few thousand, who each describe a few new species each year – I leave you to do the final piece of arithmetic.

Figure 2



The taxonomic impediment – of some 8,000,000 animal species thought to exist on Earth, how many have we described in 250-years of science.

References

1 https://www.gov.uk/government/news/plans-for-world-class-research-centre-in-the-uk

2 Shannon CE (1948) A Mathematical Theory of Communication. *Bell System Technical Journal* **27**:379-423

3 Sanders HL (1968) Marine benthic diversity: a comparative study. *The American Naturalist* **102**:243-282

4 Hurlbert SH (1971) The nonconcept of species diversity: a critique and alternative parameters. *Ecology* **52**:577-586

5 Good IJ (1953) The population frequencies of species and the estimation of population parameters. *Biometrika* **40**:237–264.

6 Good IJ (2000) Turing's anticipation of empirical Bayes in connection with the cryptanalysis of the naval Enigma. *Journal of Statistical Computation and Simulation* **66**:101-111

7 Gotelli NJ, Chao A (2013) Measuring and estimating species richness, species diversity, and biotic similarity from sampling data. In: Levin SA (ed) Encyclopedia of Biodiversity, 5:195-211. Waltham, MA: Academic Press

8 Convention on Biological Diversity, http://www.cbd.int/gti/problem.shtml

9 Mora C, Tittensor DP, Adl S, Simpson AGB, Worm B (2011) How many species are there on Earth and in the ocean? *PLoS Biol* **9**: e1001127

MARINE SCIENCE

THE ROLE OF THE OCEANS IN SECURING SUSTAINABLE FOOD FOR 9 BILLION PEOPLE

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Director of Science, Plymouth Marine Laboratory

Human societies face two challenges over the 21st century: anthropogenic climate change and population growth. The impacts of these will be significant, and the most urgent of these will be to produce enough food to feed 9 billion people while maintaining our natural ecosystems in a long-term sustainable state.

According to the FAO we will need 60% more food in 2050 compared to the present. Buried in this figure is that recent global economic development has increased demand for animal protein. We consume approximately 41kg of meat and 19kg of fish per person per year, 50% more than our consumption in the 1980s. This increase is even larger in the developing world for both sources of protein. If we expect these trends to continue, where will protein come from?

Marine ecosystems provide a significant proportion of the animal protein we consume. Capture fisheries and Aquaculture production yield approximately 170Mt of protein, roughly a third of the global protein production. Maintaining or even growing this will be essential in the future. Fisheries have two additional considerations that make them crucial to human societies. Over 500 million people depend directly or indirectly on fisheries, and a large proportion of these are in Asia. Fishing is a geographically-skewed activity in terms of volume, and thus in terms of livelihoods. 40% of all fish caught is internationally traded, bringing over 20 billion US$ to developing countries, a volume larger than their combined income from coffee, rubber, cocoa, bananas, meat, tea and sugar! Thus, fisheries sustainability has global trade implications, particularly for the developing world. Aquaculture, the fastest growing agricultural production industry, is responsible for a part of this trade, and is already exceeding global beef production in volume.

... 40% of all fish caught is internationally traded ...

THE OCEANS AND FOOD

The ocean is responsible for 50% of the primary production of the planet, and this fuels the food web that ultimately results in the 85Mt of fish (plus an additional 20Mt as estimated discards) that we catch annually. With so many examples of overfishing, can we count on capture fisheries to continue feeding our protein cravings? After decades of inefficient management there are indications that some of our fisheries have turned the sustainability tide. Recent work has shown that the majority of European stocks are now being fished sustainably, while at global level over 40% of assessed stocks are now on a sustainable trajectory. Assuming these trends continue and we develop sustainable practices, how much fish can the oceans produce? It has been estimated that this figure is between 100-200Mt, depending on the diversity of species caught, the upper figure achievable if we developed fisheries for species such as Antarctic krill and mesopelagic fish. But what are the expected impacts of climate change on these estimates?

... some of our fisheries have turned the sustainability tide ...

IMPACTS OF CLIMATE CHANGE ON FISHERIES PRODUCTION

As the IPCC reminds us, climate change is happening, and its impacts will become more apparent in coming decades. How will this affect the production of the oceans? A consortium of UK institutions led by the Plymouth Marine Laboratory investigated this from basic principles. Knowing that the majority of fish is caught along a very narrow margin around the continents (the Shelf Seas), which roughly coincide with the national Exclusive Economic Zones, we developed high resolution models capable of capturing the dynamics of tides, coastal upwelling, and other physical processes that determine production in these regions. We run these models for a present day scenario, and then for 2050, driven by the IPSL ocean-atmosphere climate change model, itself forced by the A1B IPCC greenhouse gas emissions scenario. A1B described a future of rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of more efficient technologies. As there is a degree of natural variability in the natural world, our model results were an average of 10 years of daily runs around the "present day" and the "2050" time slices.

We then used the output of these models to estimate fish production change, by country. The methods are explained in detail in Blanchard et al (2012).

The results indicated increased potential fish productivity at high latitudes and decreased productivity at low/mid latitudes, but with considerable regional variation. Overall, increases and decreases in fish production by 2050 are estimated to change by less than 10%, with a mean of +3.4% from present yields (Barange et al 2014).

Because we observed differences in production in different countries, we developed an index of fisheries dependency, based on the importance of fish and fisheries to national economies – in terms of trade and livelihoods – and to national food provision.

We then plotted individual nations on a 2D domain determined by the predicted changes in fish production by 2050, and their current sensitivity to fisheries (figure 1). Among the nations covered, those most nutritionally and economically dependent on fisheries are in West Africa (from Senegal to Nigeria), the Bay of Bengal (Bangladesh and Burma) and in SE Asia (Indonesia, Cambodia). Fisheries also played a significant role in the economies and food systems of Peru and Ecuador, Iceland, NW and SW Africa, India, Thailand, Vietnam and Japan. While other nations such as Norway, Chile and China have significant fisheries interests, they also have diverse economies to which fisheries contribute little overall. Combining dependency with projected impact of climate change on fish catches suggests that these impacts will be of greatest concern to South and South East Asia, South West Africa (from Nigeria south to Namibia), Peru, and some tropical small-island states.

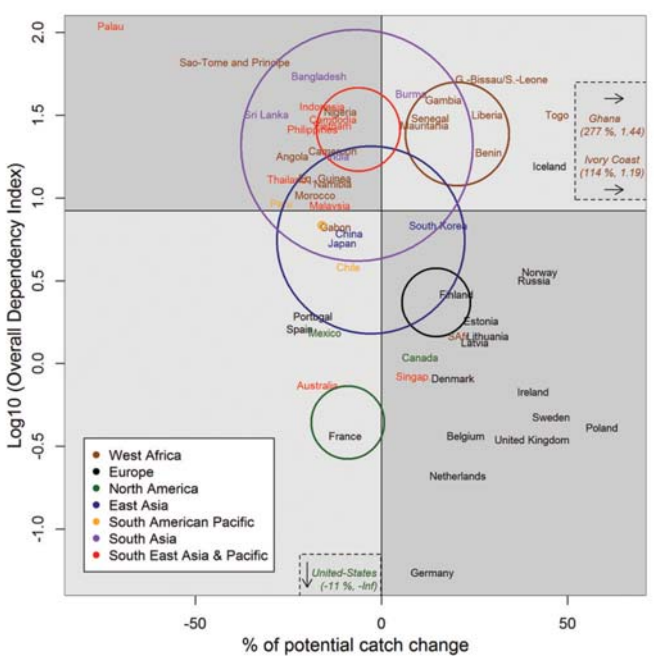

Figure 1. Potential catch change by 2050 and national dependency on fisheries. Circles correspond to the regional centroid, scaled by the expected population in the regions by 2050 (from Barange et al 2014).

These rely relatively heavily on their fisheries sector in terms of wealth, food and employment creation, while climate change is projected to impact negatively their potential fish catches. Our results indicate greater instances of negative impacts in parts of the tropics, where countries have a greater economic and nutritional dependence on fish and fewer available resources to invest in climate adaptation.

FOOD FOR THOUGHT

Earlier in this article I made reference to the dramatic rise in aquaculture production, while the results so far only reflect trends in future capture fisheries. If human population growth continues as expected, and if fish production from the seas is expected to grow by only 3.4%, can we maintain current per capita fish consumption rates in the future? The answer can only be if aquaculture continues to grow. In a parallel study (Merino et al 2012) we used our fish production predictions, human population estimates from United Nations, fishmeal and oil price estimations (these commodities are used as feeds in aquaculture), and technological development projections in the aquaculture industry, to investigate the feasibility of sustaining current per capita fish consumption in 2050. The results were cautiously optimistic. We concluded that meeting current consumption rates is feasible, despite a growing population and the impacts of climate change on potential fisheries production, but only if the following conditions are met:

- Global fish resources need to be managed and used efficiently and sustainably,
- Aquaculture industry must reduce its reliance on wild fish for feed through significant technological development,
- The distribution of wild fish products from nations and regions with a surplus to those with a deficit needs to reflect food rather than trade needs.

... importance of fish and fisheries to national economies ...

Climate change will impact on marine ecosystems and their resources by changing their production patterns. Overall a small growth in fish production is achievable, consistent with recent projections from the World Bank. The impacts of the production changes will not be consistent across regions and countries: there will be winners and losers, with potential for conflict to arise. Our results challenge existing predictions of inevitable shortfalls in fish supply by the mid-21st century, contingent on successful implementation of strategies for sustainable harvesting, industrial development and trade efficiencies. Changes in management effectiveness and trade practices will remain the major influence on gains or losses in global fish production.

Barange, M., G. Merino, J.L. Blanchard, J. Scholtens, J. Harle, E.H. Allison, J.I. Allen, J. Holt, S. Jennings. 2014. Impacts of climate change on marine ecosystem production in fisheries-dependent societies. Nature Climate Change 4: 211-216.

Blanchard, J.L., S. Jennings, R. Holmes, J. Harle, G. Merino, J. I. Allen, J. Holt, N. K. Dulvy and M. Barange. 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Phil. Trans. R. Soc. B 367: 2979-2989.

Merino, G., M. Barange, J. Blanchard, J. Harle, R. Holmes, I. Allen, E.H. Allison, M.C. Badjeck, N.K. Dulvy, J. Holt, S. Jennings, C. Mullon, L.D. Rodwell. 2012. Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? Global Environmental Change, 22, 795-806.

MARINE SCIENCE

UNDERWATER MINERAL EXTRACTION – "What's Happening Already?"

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Lately, many projections have been made about the future of mining in the oceans and seas. The views expressed are wide-ranging, particularly from an environmental perspective. There is also significant debate on scientific and technical aspects, and on the best policy and regulation (both in territorial and international waters). This article gives a view of where the industry is now, the drivers behind it and the viability of the emerging industry, from both a commercial and environmental perspective. It also contemplates the future size of the industry.

WHAT'S HAPPENING NOW?

Recent seminars, summits and workshops refer to "deep-sea" mining. Oddly, there does not appear to be a consensus about "How deep is deep?" Therefore, let's take a look at what has been happening recently from the coast out to a depth of 6000m.

... "How deep is deep?" ...

Beaches have been mined for some time for minerals such as titanium. Mining is taking place in the surf- zone, using walking jack-up platforms and crawler-mounted suction equipment for diamonds and gold. Shallow deposits (such as tin and magnetite) are being mined off the coast of Malaysia and Indonesia. The Russians have mined polymetallic nodules in the Baltic Sea in the Bay of Finland using a standard suction

... much of this technology is already available ...

dredger. Diamond gravels have been mined for quite a while off the coast of Namibia at a depth of approximately 150m. Dredging is taking place at a variety of depths in softer materials for a variety of reasons (civil construction, flood alleviation, aggregate extraction etc). Extended dredging equipment is being lined up for the extraction of phosphates, off Namibia, Mexico and New Zealand, and of iron sands off the coast of the latter.

Some of these techniques may achieve extraction of softer material at depths of roughly 400m. With harder rocks and with increasing depths, it becomes more difficult (as it does with underground mining on land). At greater depths, different technology is required for cutting, sensing, positioning, navigation, ore-lifting and in

Figure 1: "Shallow" mining of softer sediments and gravels

some cases primary separation of the target minerals from the host rock or sediments. Fortunately, much of this technology is already available

... vast deposits of the Kalahari desert ...

from the oil & gas and subsea trenching industries.

At greater depths the focus is currently on polymetallic sulphides, rare-earth muds, ferro-manganese crusts (on sea-mounts) and polymetallic nodules (in abyssal plains). The equipment which has been designed for extraction of these materials ranges from high-power, heavy duty cutting equipment to lighter lower power collection devices. Examples include the Nautilus equipment (designed for harder materials at a depth of approximately 2000m) and a Korean prototype collector (designed for collection of nodules – potentially at depths of 6000m) - both shown in Figure 2. Similar advances have been made in Japan and India.

Figure 2: Nautilus' cutter and KIOST's collector

WHAT ARE THE DRIVERS?

In addition to an amount of entrepreneurial spirit, the drivers for these developments include:

- Decreasing average ore grades on land
- High grade quality of some of the ores offshore
- Absence of overburden or waste rock (stripping ratio advantage)
- Population Growth which is compounded by increased urbanisation and per capita metal requirements as economies develop
- Improved underwater technology
- Strategic reasons (in the case of rarer metals)

Some of these make offshore mining irresistible to so-called "Big territory/Small Island" states and present opportunities in a number of British Overseas Territories.

VIABILITY OF THE EMERGING INDUSTRY

Commercial viability

In the case of seafloor massive sulphide (SMS) deposits, such as those explored by Nautilus Minerals, JOGMEC and Neptune Minerals the commercial viability is based on reserve quality. The projected head-grade of copper is approximately 7 times that of the average inland copper mine. The "by-product" of gold is projected at a head-grade of approximately 5.5 times that of the average inland gold mine. The quality is so good that it can be sold and shipped from the site as a pre-concentrate. This is with a negligible stripping ratio and a mobile infrastructure that can sail off to the next deposit. Some of these deposits are in relatively calm sea areas. The commercial and technical barriers are comparatively small.

Crusts on seamounts and abyssal nodules have similar metal concentrations. In terms of the manganese grade of these deposits, this is below that found inland in the vast deposits of the Kalahari desert and in Ghana. However, some contain attractive percentages of cobalt, nickel and titanium and they also contain rare earth elements (REE's). It must be stressed however that the total metal content in these precipitations is not necessarily 100% recoverable. "Nodules are not nuggets" and with some processing methods increasing the recovery rates of one mineral can reduce the potential recovery of the next. Advances in targeted industrial and organic solvents are however occurring with a number of recent patents.

... because plumes are effectively "gold-dust"...

Smart investors will want to look at relative risks and opportunities across the whole value chain from exploration to market as well as the social, strategic and environmental implications.

Many relatively low-volume-requirement and rare minerals are also present in the gangue material of inland mines in small quantities. They currently pass through processing plants into tailings. With improving technology and a growing market there is scope to syphon off some of these.

COMPARATIVE ENVIRONMENTAL IMPACT

Some view this emerging industry as part of a wider human plague which is hazardous to the planet. I think of it as evolution and make a number of comparative observations:

• Mining and dredging is already occurring at sea and has been for a long time – particularly in shallow areas of territorial waters.

• Industrial effluents and waste materials are pumped directly into the sea in many parts of the world already.

• We "mine" approximately 1,400Mt of crude oil per annum offshore already. What are the comparative risks for solid minerals?

• We "mine" approximately 150Mt of seafood and slaughter over 2000 whales (that we know of) per annum already.

• Flat-topped seamounts exist which are the size of Kent. Some of them have been scoured by bottom trawling. A bottom-trawling fishing unit can scour 10km^2 of seamount per day. With a typical crust thickness, this equates to an area allowing approximately 2 years of mining. So there is perhaps some room for **vertical integration of all activities in the water column.**

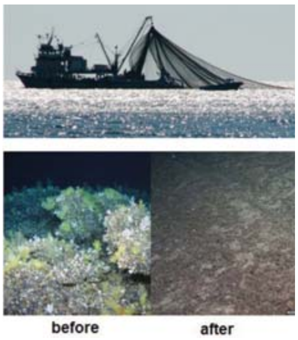


Figure 3: Effects of bottom-trawling

• Recycling efforts are improving (such as street sweeping to collect REE's from clean fuel exhaust technology).

• Some of the metals targeted by subsea mining are used in "green" technology – indeed they are critical to it (electric car batteries, clean fuel technology and high power magnets in wind turbines for example).

• In shallow, low turbidity environments, plume generation can be a problem due to the importance of light in shaping the ecosystems found there. But many SMS deposits are too deep to be penetrated by light and are characterised by "black smokers". The creation of a mining plume in this situation would have a negligible impact. Design of the collection apparatus of subsea equipment for this sort of deposit aims to minimise the generation of plumes – because plumes are effectively "gold-dust" and because low turbidity enhances pilot visibility.


Figure 4: Black smokers, fresh volcanic deposits and rainforest clearance

• The environmental risks in metalliferous mining are usually higher in the processing arena than in the mining activity itself.

• Is volcanic activity in the oceans a renewable source of minerals and how much is created naturally per annum already? Should we harvest this rather than strip further tracts of tropical rainforest to get the minerals we require?

• The International Seabed Authority (ISA) has adopted robust precautionary principles and set aside conservation and monitoring areas. There is perhaps some room for further **horizontal integration of policies, practices and regulation across territorial boundaries.**

FUTURE VOLUMES

The EU relies on the rest of the world for 80% of its consumption of strategic minerals (100% in some). As reserves and grades are depleted on land and demand grows it is inevitable that offshore mineral extraction rates will increase. There will be acceleration if strategic reasons emerge – as they did previously in the oil & gas industry, where approximately one third of the volumes are "mined" offshore and where there is an increasing trend towards deeper deposits already – (Figure 5).

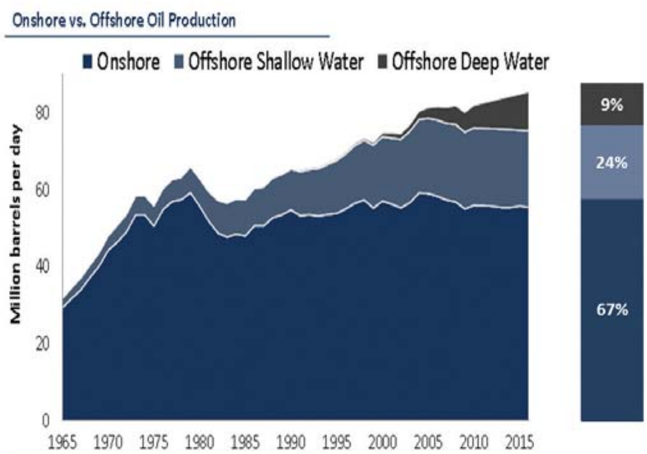


Figure 5: Offshore growth

MARINE RENEWABLE ENERGY

Dr Paul S Bell
National Oceanography Centre

Paul Bell has worked at the National Oceanography Centre in Liverpool since 1992, and leads the NERC/DEFRA funded FLOWBEC project investigating the interactions of marine renewable energy devices with the environment, and also leads NERC's Marine Renewable Energy Knowledge Exchange Programme.

During 2014-2015, installation of the first arrays of small numbers of tidal stream turbines are expected to begin in UK waters, with plans for the first commercial arrays of wave energy devices also in the advanced stages of development.

The UK is home to plentiful tidal energy resources, as well as large areas of ocean exposed to the full force of Atlantic waves. This wealth of natural resources has stimulated the development of dozens of designs for marine energy harvesting devices[1], many originating with UK universities and SMEs. Some of the leading developers have now tested several generations of devices at sites such as the European Marine Energy Centre[2] in Orkney. Many other test sites and facilities such as the National Renewable Energy Centre (Narec)[3], Strangford Lough, and Wave Hub[4], are able to offer a range of different marine conditions or test facilities.

During the last 2-3 years as more prototypes have been successfully tested in the ocean, many of the device developers have received major investments from or been acquired by large multinational companies[5]. This shows the sector is entering a new phase as prototypes give way to the first commercial installations of multiple devices, backed by established industry and energy companies.

The large areas, extreme conditions and relative inaccessibility of many of the potential sites, particularly for wave energy may lead to some novel approaches in how energy is actually used, as electricity cables to shore may not always be practical or affordable. Alternatives to cabling include usage of the energy at the point of generation to manufacture high energy-cost products, fuels or even fresh water through desalination of seawater.

... tested several generations of devices ...

THE CHALLENGES

Developing an understanding of the type of high energy marine environments suitable for energy harvesting is a challenging task for scientists and engineers. Key questions are:

- Where are the greatest concentrations of energy and how much is harvestable?
- What forces should the devices be designed to survive?
- What effects will energy-harvesting devices have on the environment both individually and cumulatively?
- How can the costs and risks of operating in such extreme environments be minimised?

These issues are the focus of significant research in the academic sector, funded in part by UK Research Councils and partly by industry. The Engineering and Physical Sciences Research Council (EPSRC) has focused largely on the resource and engineering challenges through the SuperGen programme[6], and the Natural Environment Research Council (NERC) together with the Department for Environment, Food and Rural Affairs (DEFRA) funded a number of research projects which are currently under way investigating the environmental costs and benefits of marine energy[7].

... may lead to some novel approaches ...

WHERE IS THE ENERGY?

In 2007 the UK Department for Business, Enterprise and Regulatory Reform (BERR) commissioned the production of the Atlas of UK Marine Renewable Energy Resources[8], which used computer simulations (models) of the tides and waves to produce maps of the available energy, validated against a variety of measurements such as the tide gauge measurements from the National Tidal and Sea Level Facility[9] (NTSLF) and a range of wave buoy records. This was later refined to provide more detail. The Crown Estate[10] has leased a number of the most promising sites to developers for both testing purposes and commercial energy extraction, with some of those now having received consent and additional funding[11] to install the first arrays of devices.

Site developers usually commission more detailed studies using computer models based around highly detailed seabed surveys together with measurements of the waves and currents at their sites. The computer models used fall into two broad types:

- 2D Models – Assume simplified vertical differences in flow from surface to sea bed, but can often run on a desktop PC as a result and hence popular with industry users.
- 3D Models – Allow different water layers to behave more realistically, but the increased level of complexity necessitates the use of high-performance computing facilities usually only available in academia and large research organisations.

All models depend on the quality of input data – with availability and cost of high-quality seabed maps being a critical issue. Models also need to be checked (validated) and in some cases calibrated against measurements.

MEASURING CURRENTS AND WAVES

The industry-standard approach to wave and current measurement is to deploy wave buoys and acoustic (sonar) current meters at specific places of interest. Unfortunately, the inherently high energy of these sites leads to a significant risk of equipment loss or damage. Additional costs of recovering lost equipment can more than double the original planned cost of the measurements, a particularly difficult issue when resources are limited.

The type of sites with strong tidal currents can also be very spatially variable, with headlands, tidal channels and shoals all causing variations in currents and wave patterns. As a result, the usual approach of taking measurements at a small number of points may not provide an adequate representation of conditions across such complex sites.

Not surprisingly, there has been significant interest in the use of remote sensing techniques based on a variety of radar, camera and satellite methods to map various aspects of the ocean from shore based vantage points, from the air or from space. The NERC/DEFRA funded FLOWBEC[12] project for example includes the use of two different types of radar for mapping tidal currents and waves at different study sites.

The drawback of remote sensing methods is that they are an indirect measurement of the ocean and the quality of the results is often dependent on local conditions at the time. Despite this, there are significant advantages to being able to locate the equipment out of the water in terms of ease of operation and maintenance, and it can allow near immediate access to the resulting data rather than having to wait for an instrument to be recovered from the sea bed. The ability to map ocean conditions across a site can provide a valuable spatial context to the point measurements and help plan the best places to put future in-water measurements.

DEVICE – ENVIRONMENT INTERACTIONS

In order to understand the interactions between devices and the flow and wildlife at a site, it is necessary first to have an understanding of the undisturbed environment and how the various types of wildlife are using these areas. Then one can begin to investigate whether the wildlife are likely to be in the same place at the same time as operating devices, what physical effect they might have and whether this might be an issue.

The methods of assessing what forms of wildlife are present at a site and how that wildlife may be using that site include:

- Visual observations by expert human observers on shore or on a vessel
- Video/camera surveys, eg from aeroplanes or from boats with underwater cameras
- Passive underwater recordings of marine mammal sounds
- Active sonar tracking of marine wildlife underwater such as seals, diving birds, fish etc

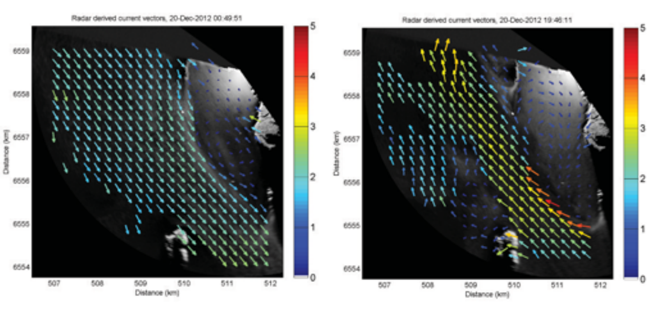
A radio tagged harbour seal (Phoca vitulina) with GPS/GSM transmitter glued to its fur. Photo courtesy of the Sea Mammal Research Unit.

- Radar tracking of birds in flight, and possibly larger marine species when on the water surface, such as whales
- Satellite images of large marine mammals
- Tagging and tracking of individual animals

Concurrent observations of wildlife above the surface (radar, visual) and below the surface (sonar) made during the FLOWBEC project show the advantages of this approach when combined with environmental information (eg from radar).

A reward poster for the return of electronic fish tags – image courtesy of Dr Stephen Cotterell, The Marine Biological Association of the UK

Tagging of specific individuals to observe longer term behaviour is becoming more common and tags suitable for attachment to birds, seals and fish are now available. The larger tags may transmit their information back to the researchers via satellite, radio or phone networks, but the smaller ones on birds and fish usually rely on being returned on a voluntary basis by those that find them once they are separated from their host or following capture of the animals involved. Two of the NERC/DEFRA funded projects, RESPONSE and QBEX[13], are employing such methods to track seals and fish respectively. What is becoming apparent is that individual animals of the same species tagged at the same location may behave in



Examples of marine radar remotely sensed tidal currents (left: flood tide and right: ebb tide) overlaid on marine radar images at the European Marine Energy Centre tidal test site. The radar is operated by the National Oceanography Centre as part of the FLOWBEC project. The arrow colours indicate current speed in metres per second.

The FLOWBEC sonar frame being prepared for lowering to the sea bed for a 2-week period monitoring marine wildlife at the European Marine Energy Centre tidal test site in 2012. The OpenHydro tide turbine test platform can be seen in the top right of the image. Photo by Dr Beth Scott, University of Aberdeen.

very different ways, demonstrating the need for information on sufficient numbers of individuals to capture these natural variations in behaviour.

Embarking on studies such as this highlights how much we still have to learn about marine wildlife, as there is often relatively little information available about presence and behaviour of marine animals individually and collectively at particular sites.

AND FINALLY

What is undeniable is that there is energy available, and in quantities significant enough to be harvested, provided costs and environmental effects can be minimised.

The ongoing work investigating the interactions of marine renewable energy devices with the environment is driving innovation across all environmental technologies to develop novel tools and methods to support both industry and regulators. Ultimately this will begin to allow society to move towards low-carbon electricity [14] with a clarity of understanding regarding the trade-offs between methods to support both industry and regulators.

Further Information:

1. http://www.aquaret.com/ An e-learning site with illustrations of the main types of marine energy harvesting devices.
2. http://www.emec.org.uk/ The European Marine Energy Centre website
3. http://www.narec.co.uk/ The National Renewable Energy Centre website
4. http://www.wavehub.co.uk/ The Wave Hub website
5. http://www.renewableuk.com/en/publications/reports.cfm/wave-and-tidal-energy-in-the-uk-2013 Wave and Tidal Energy in the UK, Conquering Challenges, Generating Growth, Report by RenewableUK, February 2013
6. http://www.supergen-marine.org.uk/ Supergen Marine website
7. http://www.nerc.ac.uk/research/funded/programmes/mre/NERC & DEFRA Marine Renewable Energy Programme
8. http://www.renewables-atlas.info/ Atlas of UK Marine Renewable Energy Resources website
9. http://www.ntslf.org/ National Tidal and Sea Level Facility website
10. http://www.thecrownestate.co.uk/energy-infrastructure/wave-and-tidal/ Crown Estate Wave and Tidal Energy web pages
11. https://www.gov.uk/government/news/20-million-boost-for-uk-marine-power Marine Energy Array Demonstrator funding announcement
12. http://noc.ac.uk/project/flowbec FLOWBEC project webpage
13. http://www.mba.ac.uk/simslab/QBEX QBEX project webpage
14. http://www.lowcarboninnovation.co.uk/working_together/strategic_framework/overview/ Coordinating Low Carbon Technology Innovation Support, The LCICG's Strategic Framework

MARINE SCIENCE

OCEAN ACIDIFICATION: THE SILENT STORM

Dr Carol Turley OBE
Plymouth Marine Laboratory

It will last for 10,000's of years, cover three quarters of Earth's surface and impact us all. We cannot hear or see or feel it but its effects are already being felt, from oysters and the multimillion dollar aquaculture business on the west coast of North America, to the sea butterfly, a key link in the ocean food web in polar and sub-polar waters.

This silent storm is called ocean acidification but despite our normal senses being unable to detect it scientists and their sensors can measure it accurately at long term stations in the ocean. These sensors show a year on year change in the chemistry of the ocean (Figure 1) and these changes are affecting the organisms, including humans, that live in and depend on the ocean for their food and livelihood. The cause is global – carbon dioxide (CO_2) produced from our fossil fuel combustion, emitted to the atmosphere. Half of emitted CO_2 remains in atmosphere (causing climate change) and the remainder is absorbed nearly equally by ocean and land. The ocean absorbs 24 million tons of CO_2 every day. The average person is responsible for 4kg of the CO_2 that is absorbed by the ocean each day.

These observations have been conducted over decades by hundreds of researchers (Figure 1). CO_2 when combined with water forms an acid (carbonic acid). By definition, an acid produces hydrogen ions when added to water. When CO_2 enters the surface of the ocean it rapidly causes a series of chemical reactions, which increase the acidity of the surface seawater. Acidity may be thought of as simply the hydrogen ion concentration (H+) in a liquid, and pH is the logarithmic scale on which this is measured. Acidity increases as the pH decreases. The pH of the open-ocean surface layer is unlikely to ever become acidic (ie drop below pH 7.0), because seawater is buffered by dissolved salts. The term "acidification" refers to a pH shift towards the acidic end of the pH scale, similar to the way we describe an increase in temperature from 2°C to 4°C it's still cold, but we say it's "warming." Ocean acidification is changing seawater carbonate chemistry –

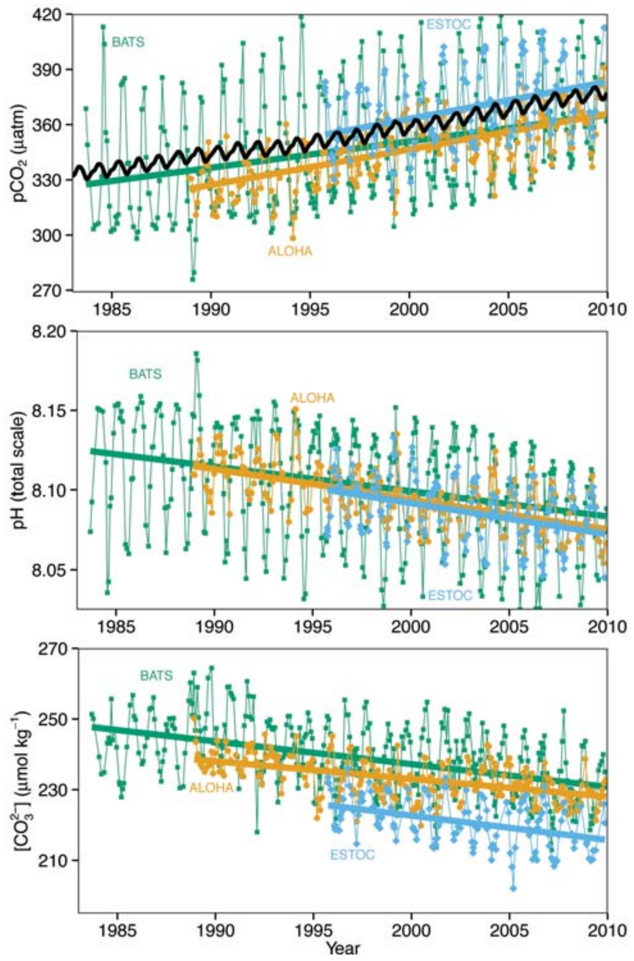


Figure 1: Long-term trends of surface seawater pCO_2 (top), pH (middle), and carbonate ion (bottom) concentration at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including: a) Bermuda Atlantic Time-series Study (BATS, 31°40' N, 64°10' W; green) and Hydrostation S (32°10', 64°30' W) from 1983 to present, b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term oligotrophic Habitat Assessment; 22°45' N, 158°00' W; orange) from 1988 to present and c) European Station for Time series in the Ocean (ESTOC, 29°10' N, 15°30' W; blue) from 1994 to present. Atmospheric pCO_2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel (IPCC AR5 WG1 Report, Chapter 3, 2013).

concentrations of dissolved CO_2, hydrogen ions, and bicarbonate ions are increasing, and the concentration of carbonate ions is decreasing.

The ocean has already removed about 25% of anthropogenic CO_2 over the last 250 years. This can be considered beneficial, since it has slowed the accumulation of CO_2 in the atmosphere and the rate of global warming; without this ocean sink, atmospheric CO_2 levels would already be greater than 450 parts per million. However, the continuation of such a fundamental and rapid change to ocean chemistry is bad news for life in the sea. The current rate of acidification is more than 10 times faster than at any time during the last 56 million years. If we keep emitting CO_2 at the same rate (Business as Usual) ocean acidity is projected to increase to more than double by 2100.

Changes in pH and carbonate chemistry force marine organisms to spend more energy regulating chemistry in their cells. For some organisms, this may leave less energy for other biological processes like growing, reproducing or responding to other stresses. It will not only cause problems for many organisms with calcium carbonate skeletons or shells (such as oysters, mussels, corals and some planktonic species) but could also affect the physiology, metabolism and behaviour of many other organisms, ecosystems and processes, with potentially serious implications for society. The biological impacts of ocean acidification will vary, because different groups of marine organisms have a wide range of sensitivities to changing seawater chemistry (Figure 2). Impacts from ocean acidification at any life stage can reduce the ability of a population to grow or to recover from losses due to disturbance or stress, even though juvenile forms tend to be most vulnerable to acidification (eg Pacific oyster larvae).

Corals and shell builders are expected to decline, seagrasses may increase, some fish become disoriented and there may be changes in how prey and predators interact. Some species will not be directly affected but if their prey or predator, or their habitat or ecosystem changes then they could be indirectly impacted.

Natural laboratories occur where CO_2 bubbles rise through the seafloor acidifying the surrounding water close to the vents (Figure 3). This creates a gradient of pH. As you move away from the vents pH increases and gives us a glimpse into what a high CO_2 ocean may look like. Numerous studies show that the closer to the vents (and the higher the CO_2 and lower the pH) there is less biodiversity, fewer calcifiers, more fragile, dissolving shells, more invasive species, more seagrasses and degraded corals. These observations support the

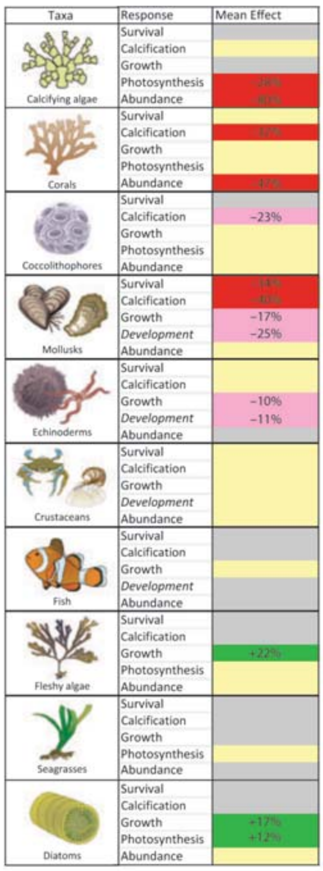
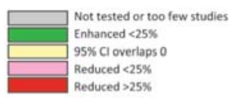


Figure 2. Results of a metanalysis of all the experiments and observations show that some species are more susceptible than others. Kroeker et al. (*2013, Glob. Change Biol.*)



conclusions of controlled experiments in the laboratory that marine ecosystems and the organisms within them will change.

Predicting what marine ecosystems will look like in a future high CO_2 world is difficult but as fish is a primary source of animal protein for 1 billion people, mostly in developing countries there must be a risk to food security and livelihoods. There may be a decline in wild fish catches due to decreases in their prey, weakened foodwebs and deteriorating ecosystems like coral reefs. Shellfish aquaculture may experience increasing difficulty as already seen on the Pacific coast of North America. Coral reefs seem particularly vulnerable. They provide home for millions of species, storm protection for coastlines, houses and

Figure 3. CO_2 bubbles rise from seafloor at Ischia, Bay of Naples, a natural lab to study acidification.
Photo credit: Jason Hall-Spencer, University of Plymouth.

infrastructure, income from tourism and a biodiversity legacy.

In addition, ocean acidification can also make species more susceptible to the impacts of warming waters, which have decreased oxygen levels, further stressing marine organisms. Acting together, these three major stressors (warming, acidification and deoxygenation) could more rapidly threaten biodiversity, biogeochemical cycles, ecosystems and the goods and services the ocean provides to society, thereby increasing the risk to human food security and industries that depend on productive marine ecosystems.

The Working Group II contribution to the IPCC Fifth Assessment Report (Climate Change 2014: impacts, adaptation and vulnerability) concluded in its Summary for Policy Makers (http://www.ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf) that:

"For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (medium to high confidence). Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (high confidence) and fishes (low confidence), with potentially detrimental consequences for fisheries and livelihoods. Ocean acidification acts together with other global changes (eg, warming, decreasing oxygen levels) and with local changes (eg, pollution, eutrophication) (high confidence). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems."

The world is already committed to some acidification (Figure 4) and we are now detecting impacts from it. We need to consider adaptation

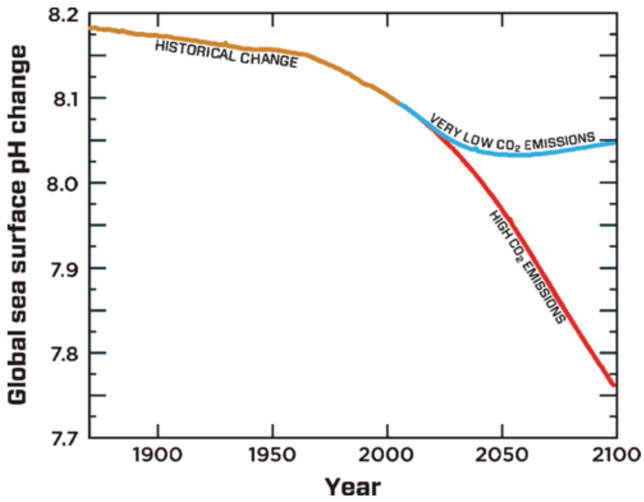


Figure 4. Modelled global sea-surface pH from 1870 to 2100. The blue line reflects estimated pH change resulting from very low CO_2 emissions to the atmosphere (IPCC Representative Concentration Pathway, RCP* 2.6). The red line reflects pH from high CO_2 emissions (the current emissions trajectory, RCP* 8.5).
Credit: Adapted from in IGBP, IOC, SCOR (2013). Ocean Acidification Summary for Policymakers – Third Symposium on the Ocean in a High-CO_2 World. International Geosphere-Biosphere Programme, Stockholm, Sweden, adapted from Bopp et al., 2013.

strategies, as well as the all-important mitigation strategies, to prevent further acidification. If we keep emitting CO_2 at the same rate (Figure 4: High CO_2 emissions) then ocean ecosystems and the goods and services that they provide humankind will change rapidly from both warming and acidification. However, if we reduce CO_2 emissions to the atmosphere we will keep global temperature between 0.9° - 2.3°C and reduce risks from ocean acidification too (Figure 4: very low CO_2 emissions).

A partnership of research programmes and institutions has been bringing the science of ocean acidification to the delegates at the UNFCCC climate negotiation meetings since 2009 and at the UN Conference on Sustainable Development, Rio+20. The partners include Plymouth Marine Laboratory, UK Ocean Acidification Research Programme, European Programme on Ocean Acidification (EU), Mediterranean Sea Acidification in a Changing Climate Programme (EU), Biological Impacts of Ocean Acidification Programme (Germany), SCRIPPS Institution of Oceanography (US), OCEANA and the Ocean Acidification International Coordination Centre (IAEA, Monaco). Working together we have shared the cost, the effort and our findings and synthesised them in different media for policy- and decision-makers. To help increase awareness of the key issues impacting on the ocean in a high CO_2 world, the partnership has produced an Ocean Stress Guide (www.oceanunderstress.com). It is imperative that international decision-makers, in particular, understand the enormous role the ocean plays in sustaining life on Earth and the consequences of high CO_2 emissions for the ocean and society. The publication has already received support from a number of significant bodies including the World Bank, European Union and UN bodies.

Short guides to ocean acidification:

Hot, Sour and Breathless: ocean under stress – a short guide for policy makers: www.oceanunderstress.com

Ocean Acidification Summary for Policymakers from the Third Symposium on the Ocean in a High-CO2 World: http://www.igbp.net/news/news/news/oceanacidificationsummaryforpolicymakersreleased.5.30566fc6142425d6c911265.html

Short films on ocean acidification:

A powerful 12 minute film on Ocean acidification: Connecting science, industry, policy and public: https://www.youtube.com/watch?v=_BPS8ctVW2s

A 5 minute film on ocean acidification "The Other CO2 Problem" produced by the World Bank as part of its first Massive Open Online Course on climate change "Turn Down the Heat: Why a 4°C Warmer World Must be Avoided" http://www.youtube.com/watch?v=Dr4jhgxDQSI&list=PLk8mh9aWmPaRzVoQTI-mjuBHOJ0x4y113&index=5

And for the younger readers try this amazing award winning 7 min animation by school children aged 11-15 yrs from Ridgeway School, Plymouth: https://www.youtube.com/watch?v=F5w_FgpZkVY. They researched it, wrote and acted the script, produced the characters and animated them and even wrote and produced the music. The children have a clear message to policy makers and it is now in six other languages.

Useful web sites:

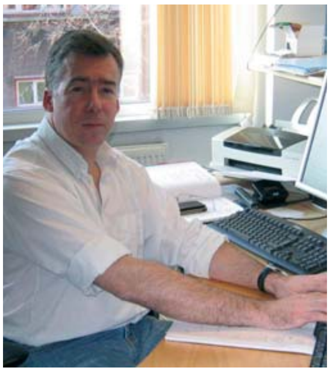
The UK Ocean Acidification Research Programme (UKOA): http://www.oceanacidification.org.uk/

The Ocean Acidification International Coordination Centre (OA-ICC): http://www.iaea.org/ocean-acidification/page.php?page=2181

The Intergovernmental Panel on Climate Change (IPCC): http://www.ipcc.ch/index.htm

MARINE SCIENCE

NATURAL HAZARDS AND SEA LEVEL RISE

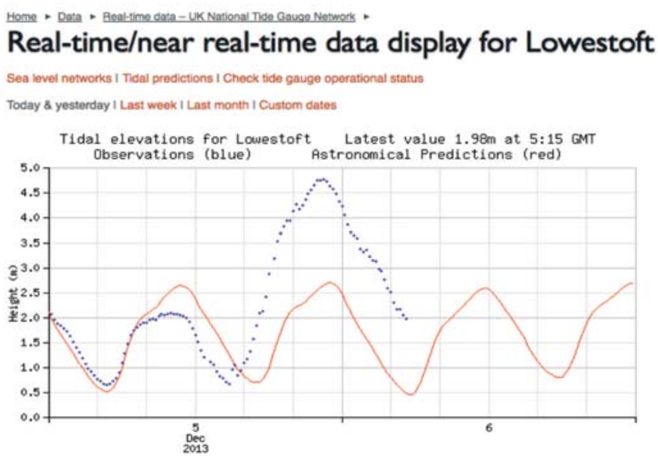


Professor Kevin Horsburgh
Head of Marine Physics and Ocean Climate
Chair of the IOC/WMO JCOMM Expert Team on Waves and Coastal Hazards
National Oceanography Centre

The storms that battered the UK during December 2013 and January 2014 marked some of the most severe weather in recent years. During 5th and 6th December, sea levels in parts of the North Sea were the highest since the 1953 floods and the Thames Barrier and Dutch flood barriers were closed for several tides. The largest storm surges struck the north east coast of England from Tyneside to Norfolk. Some flooding occurred (with 400 homes flooded near Hull and about 10000 homes being evacuated in East Anglia).

A storm surge is a large scale increase in sea level due to a storm. They can last from hours to days and can elevate sea level over an area of hundreds of square kilometres. Low atmospheric pressure allows sea level to rise and gale force winds, combined with the Earth's rotation, force water towards the coastline. Storm surges are caused by our European weather systems (extra-tropical cyclones) and also tropical cyclones (hurricanes). They affect low lying coastlines around the globe and are responsible for significant damage and loss of life. In 1970 a devastating storm surge resulted in approximately a quarter of a million deaths in Bangladesh. In the USA, Hurricane Katrina and Superstorm Sandy are recent reminders of this global hazard. Storm surges can raise sea levels by up to 8m in tropical areas and by over 3m in the North Sea.

Coastal flooding around the UK is a threat to life as well as to economic and environmental assets. The worst natural disaster in modern times was the North Sea storm surge of

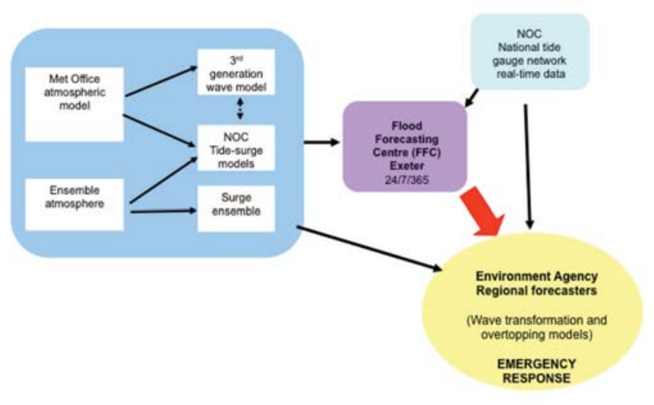


The storm surge at Lowestoft tide gauge on 5 December 2013. The storm surge is the difference between the observed sea level and the predicted tide – in this case 2m

31 January –1 February 1953. Flood defences were breached by huge waves, and coastal towns in Lincolnshire, Norfolk, Suffolk, Essex and Kent were inundated as seawater flooded the streets. In the Netherlands, 1800 lives were lost, whilst in England and Scotland 326 people were killed and over 600 square kms of land were flooded[1]. The estimated cost of the floods then was £40-£50 million which would be around £1 billion in current prices. Today, £150 billion of assets and 4 million people are at risk from coastal flooding in the UK[2].

The fact that the damage was so limited during the December 2013 storm, compared to the tragedy of 1953, is thanks to significant government investment in coastal defences, flood forecasting and sea level monitoring. The modern coastal flood warning network is called UK Coastal Monitoring and Forecasting (UKCMF)[3]; it is a partnership between the Environment Agency, the Met Office and the National Oceanography Centre. Numerical weather models feed into computer models of storm surges and waves. The model forecasts are combined with real-time monitoring of coastal sea levels, and are interpreted by a team of forecasters working around the clock at the Flood Forecasting Centre to provide regional forecasts. The numerical models of both atmosphere and ocean are subject to continuous improvement as more powerful computers and new scientific insight becomes available. The system also makes use of a technique called *ensemble forecasting* to quantify the inherent uncertainty in short-term weather prediction. Multiple model runs are made, adjusting model boundary conditions and parameters, to provide a range of outcomes that can then be used to judge the reliability of the forecast and provide a probabilistic approach to flood warning.

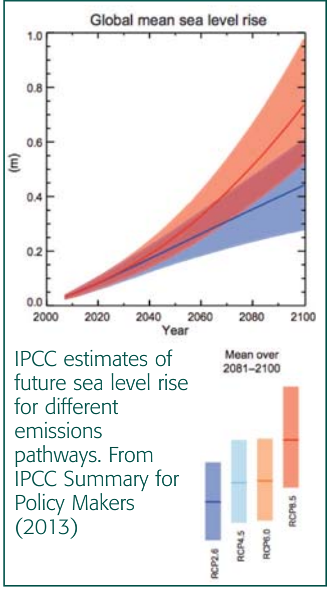
We now have a sophisticated network of 42 tide gauges around our coastline to support coastal flood forecasting but there are fewer data from 1953, so making a direct comparison of the two events is difficult. Water levels on north east coastlines (at North Shields) were approximately 0.5m higher in December 2013 than in 1953, and the December 2013 water level at the Hull Barrier was the highest ever recorded. On the other hand, water levels in the Thames estuary on 5th December were about 0.5m lower than those seen in 1953. The emerging picture is of a storm surge in 2013 very similar to that of 1953 but with greater severity in the northern part of the North Sea, most likely due to the December 2013 storm tracking in a more northeast-wards direction. Those who study our highly variable weather know that no two storms are identical, which is why complex statistical methods have been devised to estimate extreme water levels around the UK



Schematic diagram of the components of the UK Coastal Flood Forecasting System

coastline. These *joint probability techniques* estimate the likelihood of extreme storm surges coinciding with higher than average tides, and they are the basis of coastal defence design standards.

Any worldwide change in coastal flood frequency or amplitude could significantly affect coastal populations and the global economy. In studies based on tide gauge data, any observed trends in extreme sea level have been shown to be controlled by changes to mean sea level rather than changes in storminess; and for the UK there is no observational evidence of any long-term trend in storm surges[4]. The latest generation of climate models provide no significant evidence for future changes to storm-related extremes (due to low confidence in their ability to simulate extreme winds). Of course, the natural variability of our climate system makes it possible that we may experience more consecutive wet and windy winters like the most recent. There is a wealth of historical information[5] to suggest that European climate in the 17th century was dominated by several decades of cool, wet and windy weather, with 1628 dubbed a "year without summer". Whilst the winter of 2013/14 saw an unusual number of severe, consecutive storms and was exceptional in terms of record breaking rainfall for some parts of the UK, it was not unprecedented in a climatic context. Since it is not possible to predict accurately future changes to mid-latitude storminess we must assume that changes in extreme water levels around Europe will be governed by mean sea level rise.



IPCC estimates of future sea level rise for different emissions pathways. From IPCC Summary for Policy Makers (2013)

The Intergovernmental Panel on Climate Change (IPCC) is unequivocal in its assessment of the gradual rise in mean sea level[6]. The projected rise in globally averaged sea level for the year 2100 is in the range 0.29-0.82m, depending on greenhouse gas emissions. On the basis of observed data over the past century, sea level rise around the UK is consistent with global averages. Even with no change to the storm climate of northern Europe the rise in mean sea level will increase the frequency of extreme water levels (since storm surges and waves will be superimposed on a higher mean sea level); any particular threshold (eg a sea wall) will – on average – be exceeded more often. This will place greater demands on flood warning systems to deliver more accurate forecasts and with longer lead times, in order to protect lives and property. It follows that sustained investment in flood warning mechanisms and coastal defences would be wise.

References

1 McRobie, A., Spencer, T. and Gerritsen, H. (2005) The Big Flood: North Sea storm surge, Philosophical Transactions of the Royal Society of London A, 363, 1263-1270

2 Environment Agency (2009) Flooding in England: A national assessment of flood risk. Environment Agency, Bristol, UK. http://publications.environment-agency.gov.uk/pdf/GEHO0609BQDS-E-E.pdf.

3 http://www.environment-agency.gov.uk/research/policy/116129.aspx

4 http://www.mccip.org.uk/media/18620/2013arc_backingpapers_4_slr.pdf

5 Geoffrey Parker (2013) Global Crisis: War, Climate Change and Catastrophe in the Seventeenth Century, 904pp, ISBN: 9780300153231

6 IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US