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CREATING A SUSTAINABLE FUTURE

THE DECADE OF OCEAN SCIENCE

EDITORIAL

Towards a sustainable ocean economy

As the recent analysis of the High Level Panel for a Sustainable Ocean Economy shows, humankind can sustainably produce six times more food from the ocean, generate 40 times more renewable energy, and close around 20 per cent of the carbon gap towards the Paris Agreement's more ambitious goal of keeping global warming to a maximum of 1.5 °C.[1] However, all these imperatives are ocean-science intensive.

Can the present ocean science rise to the challenge? Not quite yet. Our ocean observation system is largely able to *describe* the physical state of the ocean, but we are only just embarking on *quantifying* our knowledge of ocean biogeochemistry, biology and ecology. The ocean economy produces trillions of pounds of wealth annually, but we have barely mapped its societal interactions and impacts. The benefits stemming from ocean science seem to be significant but they are not yet part of national accounting systems. Ocean science is acquiring a stronger voice when sounding the alarm for ocean health, so that we all know, for example, that in 2050 the mass of plastic in the ocean may exceed the mass of fish. But along with a diagnosis of the problems, we need systematic solutions.

The realisation of the need to transform, strengthen and mainstream ocean science was behind the 2017 proposal by the Intergovernmental Oceanographic Commission (IOC) of UNESCO to the 72nd Regular Session of the UN General Assembly to consider the need for a UN Decade of Ocean Science for Sustainable Development. The Assembly proclaimed the Decade from 1 January 2021, for 10 years.

In 2018–20, an enthusiastic community of several thousand individuals, hundreds of organisations and dozens of countries joined under the leadership of the IOC to co-design the framework of the Decade. The Ocean Decade Implementation Plan[2] calls on us to achieve, by 2030, the seven societal outcomes of the Decade, representing the desired qualities not only of the ocean but also of people. The 10 initial challenges of the Decade are the domains where efforts will be concentrated. They are aimed at addressing pollution, restoring ocean ecosystems, sustainably generating more food and wealth from the ocean, resolving the host of issues in the ocean–climate nexus, reducing the risk of disasters, observing the ocean and representing its state digitally, developing capacity and changing our behaviour towards a more harmonious relationship with the ocean.

This is why the Ocean Decade is a once-in-a-lifetime opportunity to gather our forces, intellect and goodwill, and move ocean science to a new level of readiness for the delivery of 'the ocean we need for the future we want'. For that reason, I am very grateful to the Institution of Environmental Sciences for dedicating its March 2021 issue of the environmental SCIENTIST to the Ocean Decade. The seventh societal outcome of the Decade is 'an inspiring and engaging ocean'. I am sure this issue will be a step towards achieving that outcome.

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Dr Vladimir Ryabinin is an oceanographer, marine engineer, climatologist, and emeritus meteorologist in Russia. As the Executive Secretary of the IOC, he started the process that ultimately resulted in the proposal for the UN Decade of Ocean Science for Sustainable Development (2021–2030).

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

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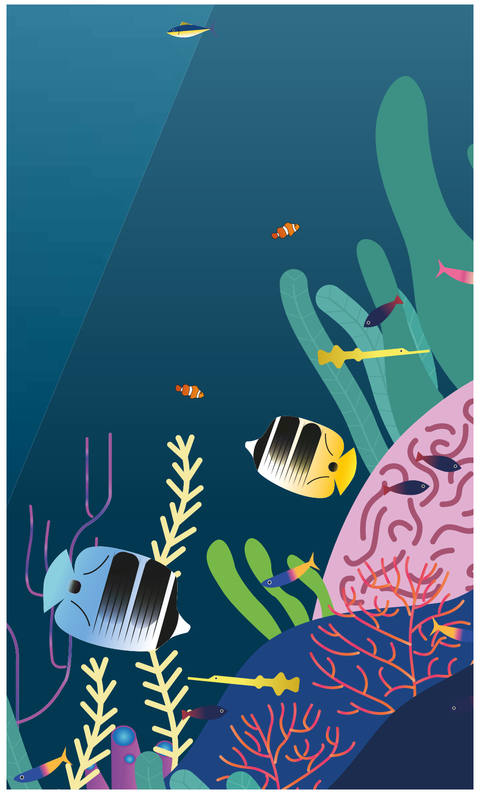

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INTRODUCTION

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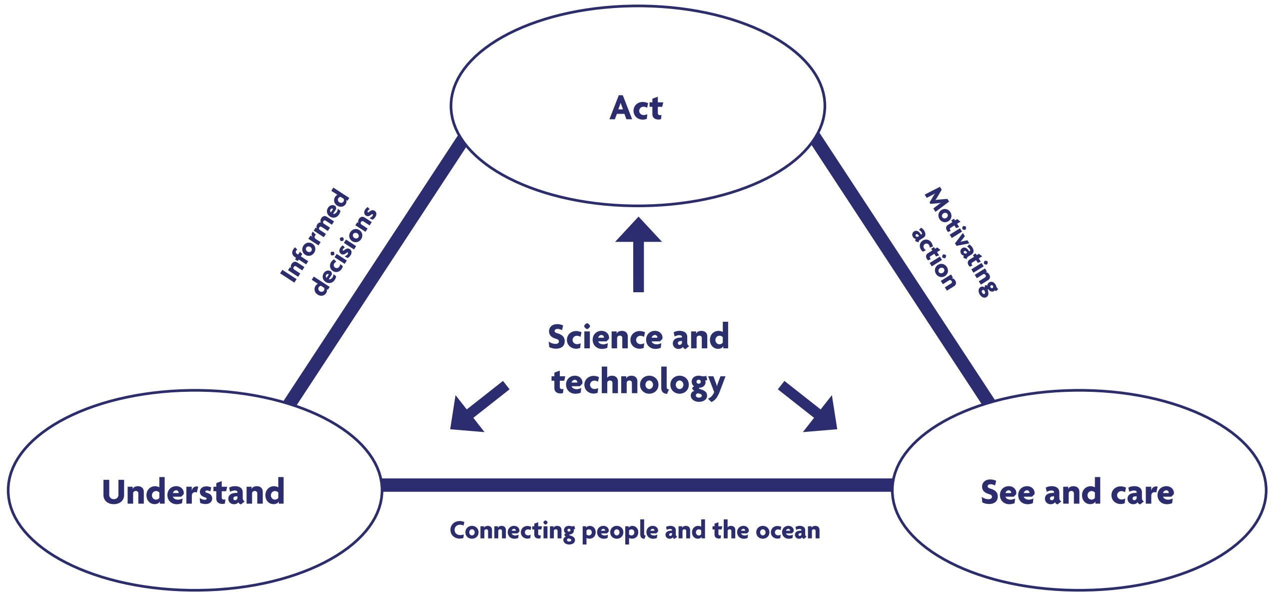
The Decade of Ocean Science for Sustainable Development 2021–2030

Edward Hill provides an overview of one of the most important ocean initiatives of the 21st century.

The Decade of Ocean Science for Sustainable Development 2021–2030 has a powerful and urgent motivation. There is only one ocean, a vast interconnected body of water covering 70 per cent of the Earth, and is its largest ecosystem. It is divided in to large basins and shallow seas, teaming with life everywhere. Less than 400,000 km away, the Moon (our nearest neighbour, ocean-less and lifeless) experiences daily temperature swings of between +120 °C and -170 °C. Life on Earth would be impossible without the ocean. It regulates climate and provides many other hidden services to humanity – half the oxygen we breathe and much of the protein for more than a billion people, many in the poorest countries of the world.



▲ **Figure 1. The interaction between science and engagement.**

The wellbeing of people and the ocean is intertwined. The single biggest cause of uninsured losses and misery to countless people by natural disasters is flooding from the sea – a risk growing year on year as sea level rises and the human population grows, most rapidly in low-lying coastal plains and cities. The ocean economy[1] is growing with the output of ocean-dependent industries equivalent to the world's seventh largest economy and underpinned by the natural capital of healthy ecosystems, worth at least US$24 trillion.[2] But that capital is under threat from the cumulative impacts of human activities worldwide – habitat destruction, over-exploitation of living resources, pollution and the impacts of climate change, warming, acidification and oxygen depletion.

THE NEW NARRATIVE FOR THE OCEAN

Something needs to change. A new narrative has been proposed for the ocean.[3] We used to think the ocean was too big to fail. When it became apparent this was not true – it cannot dilute everything put into it and its resources not unlimited – some came to despair that the ocean was too big to fix. However, what is now certain is that the ocean is too big to ignore.

While 40 per cent of the area of the oceans is under the jurisdiction of coastal states as territorial waters and exclusive economic zones, and is therefore where the sea and people most closely interact, the remaining 60 per cent – an area greater than the entire land surface of the Earth – is especially prone to being ignored. Being beyond national jurisdictions does not mean it belongs to no one; it means it belongs to everyone, and it can drive some of the biggest changes felt in coastal waters. As humans turn with increasing urgency to the sea for resources being depleted on land, the ocean has become an economic, geopolitical, technological and scientific frontier.

Because people live on land, what goes on beneath the waves is an unfamiliar world that is out of sight and out of mind for most. We are 'sea blind'. It is hard for us to care about what we cannot see. We do not manage what we do not care for and, in any event, we cannot properly manage what we cannot measure and understand (see **Figure 1**). The Decade of Ocean Science grasps all dimensions of this problem, seeing science as central to informing a new relationship between people and the sea, to reverse the decline in the health of ocean ecosystems upon which we all depend.

THE OCEAN WE WANT

The ambitious vision for the Ocean Decade[4] calls for 'the science we need for the ocean we want' where the ocean we want is spelt out in terms of seven clear outcomes:

1. A clean ocean where sources of pollution are identified and reduced or removed.
2. A healthy and resilient ocean where marine ecosystems are understood and protected.
3. A productive ocean supporting a sustainable food supply and a sustainable ocean economy.
4. A predicted ocean where society understands and can respond to changing ocean conditions.
5. A safe ocean where life and livelihoods are protected from ocean-related hazards.
6. An accessible ocean with open and equitable access to data, information, technology and innovation.
7. An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development.

THE SCIENCE WE NEED

It is obvious that greater knowledge is needed to manage the ocean and its resources. Less than 20 per cent of the shape of the seafloor (the ocean's basic anatomy) is mapped by modern methods – we have better maps of the surfaces of Mars, the Moon and Venus. There are almost no continuous observations of most essential ocean variables below 2 km depth. But on its own, more knowledge is not enough.

Crucially, the Decade's mission recognises that the science we need has to go beyond traditional confines – in how we conduct science and engage more diversely in how it is designed, conducted and used. For science to inform action, it needs to be oriented towards solutions that in turn critically rely on the motivation and social licence that comes from a greater sense of connection between people and the sea. Science has a key role to play in fostering that connection by making visible the unseen ocean world and illuminating why it matters to us all – helping us become 'ocean literate'.

That is why the Ocean Decade's mission is described as 'transformative ocean science solutions for sustainable development, connecting people and our ocean'. For these reasons too, the Ocean Decade sets clear expectations for the science we need:

- Framed within the Sustainable Development Goals of the 2030 Agenda;
- Co-designed between scientists and those who need and implement solutions;
- Reaching across disciplines and actively integrating natural and social sciences; and
- Embracing local and indigenous knowledge, including those in less-developed and developed countries, and striving for generational, gender and geographic diversity.

These approaches are encapsulated in 10 specific challenges (see **Box 1**) that, if addressed, will make concrete progress towards achieving the Ocean Decade's vision and outcomes. The other articles in this issue offer perspectives on these challenges.

SOME KEY TRANSFORMATIONS NEEDED

The success and legacy of the Ocean Decade will be measured in progress towards achieving the outcomes described. An especially important part of that legacy

BOX 1. DECADE CHALLENGES

Knowledge and solutions challenges

- **Challenge 1:** understand and map land and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems, and develop solutions to remove or mitigate them.
- **Challenge 2:** understand the effects of multiple stressors on ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions.
- **Challenge 3:** generate knowledge, support innovation, and develop solutions to optimise the role of the ocean in sustainably feeding the world's population under changing environmental, social and climate conditions.
- **Challenge 4:** generate knowledge, support innovation, and develop solutions for equitable and sustainable development of the ocean economy under changing environmental, social and climate conditions.
- **Challenge 5:** enhance understanding of the ocean–climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services, including predictions for the ocean, climate and weather.

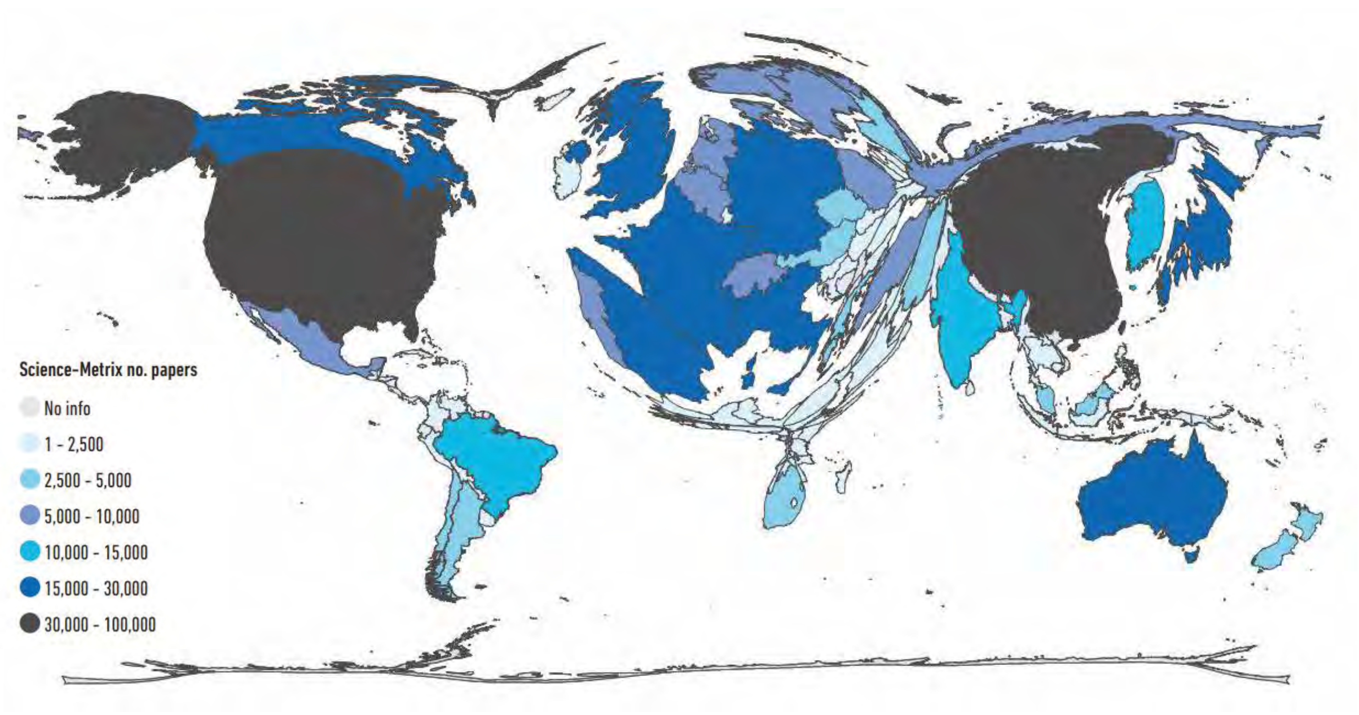
Essential infrastructure challenges

- **Challenge 6:** enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience.
- **Challenge 7:** ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users.
- **Challenge 8:** through multi-stakeholder collaboration, develop a comprehensive digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering, and visualising past, current, and future ocean conditions in a manner relevant to diverse stakeholders.

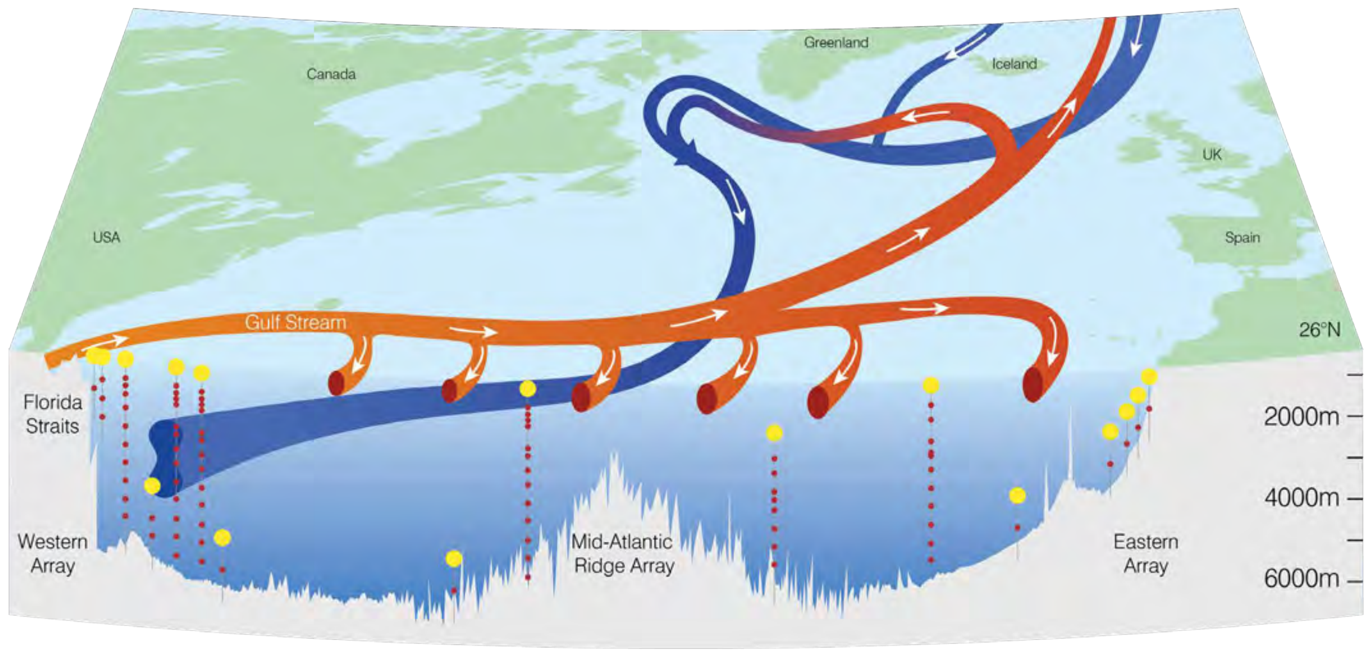
Foundational challenges

- **Challenge 9:** ensure comprehensive capacity development and equitable access to data, information, knowledge and technology across all aspects of ocean science and for all stakeholders.
- **Challenge 10:** ensure that the multiple values and services of the ocean for human wellbeing, culture, and sustainable development are widely understood, and identify and overcome barriers to behaviour change required for a step change in humanity's relationship with the ocean.

INTRODUCTION



▲ **Figure 2. Country size scaled by number of global ocean science publications.[5] (© UNESCO. Global Ocean Science Report, ISBN 978-92-3-100226-7. Licensed under the terms of the Attribution-ShareAlike 3.0 IGO [CC BY-SA 3.0 IGO] license: https://creativecommons.org/licenses/by-sa/3.0/igo. No changes were made to this material.)**



▲ **Figure 3. The continuous surface-to-bottom, continent-to-continent movement of the Atlantic overturning circulation is part of the global ocean heat conveyor belt that regulates climate and weather. (© National Oceanography Centre)**

will lie in progress with the enabling foundational and infrastructure challenges.

For example, the *Global Ocean Science Reports* in 2017[5] and 2020[6] starkly demonstrate the large disparity in the capacities to undertake ocean science across the world. The ocean respects no borders and this disparity will become an ever-more important obstacle to progress if allowed to persist (see **Figure 2**).

Timely and open access to ocean information, and the ability to visualise and interpret it through big-data digital representations and simulations, provides huge opportunities for inspiring us to see and imagine the ocean in new ways, and as tools for informing and enabling targeted actions. However, these possibilities must ultimately be grounded in real measurements of the ocean that chart its continually unfolding changes (see **Figure 3**). Indeed, we risk deluding ourselves if merely content to live with a typically human, but now big-data-enabled, biased picture of the ocean – one that is skewed by data concentrated mainly in the near surface ocean, the part we can already see. The ocean is a vast three-dimensional world with an average depth of 4 km, and major processes driving change – such as the ocean's conveyor belt circulation[7] – happen in the deeper subsurface layers, where there are major gaps in knowledge and probably surprises waiting.

The bedrock of the value chain that produces necessary ocean information, such as forecasts and status assessments, is effectively a system of coordinated measurements of essential ocean variables and other ocean indicators in the subsurface ocean – not just those from satellites. These will be expensive to collect, possibly costing US$1 billion or so per year – but not that expensive compared with the economic implications of the actions needed and the consequences of not getting them right. Instead, enormous effort is being consumed by many institutions figuring out how to avoid paying for ocean observations. Some even ask why we need them at all – are they not just telling us in ever-more detail about problems we already know about, and should not investment instead focus on solutions? This false narrative about 'science for solutions' misses the point that observations and solutions go hand in hand.

For example, it would be medical negligence to treat a sick patient in the hospital emergency room without first following basic procedures to wire them up to monitor their vital life signs – temperature, pulse rate, blood pressure, oxygen saturation – and regularly take blood samples to test biochemical signatures. These observations are not just used to diagnose the problem. They alert to sudden changes or complications, inform the treatment plan and evaluate whether the treatment is working. Monitoring alone does not save the patient – but it helps those who will. It is the same for the ocean – more so, because the change is unprecedented with no case histories. It is not a choice between observing and treating: they go together and are integral parts of the solution.

That is why infrastructures that produce sustained ocean information, and the human capacity to develop and use them, are such an important challenge for the Ocean Decade. Innovations and reform in governance arrangements, institutions, funding and business models that enable access to ocean information now need to step up to match the technological innovations that have made these infrastructures possible in the 21st century in ways not possible only 20 years ago.

The Decade of Ocean Science comes at a pivotal moment – it challenges the scientific community to focus on the science needed now to make a difference and to galvanise our efforts. It is an exciting opportunity to be a part of it. **ES**

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FEATURE

Marine pollutants and contaminants

Michael Elliott explores marine problems, solutions and the role of the UN Decade of Ocean Science for Sustainable Development.

'The Decade aims to catalyse the human behaviour change required for the successful implementation of these solutions. Guided by the United Nations Convention on the Law of the Sea (UNCLOS), the Decade will generate the data, information and knowledge needed for more robust science-informed policies and stronger science-policy interfaces at global, regional, national and even local levels, leading to improved integrated ocean management and development of a sustainable ocean economy.'[1]

The greatest challenge of the UN Decade of Ocean Science for Sustainable Development is to enable science to help create: 'clean, healthy, safe, productive, biologically diverse marine and coastal environments, managed to meet the long-term needs of people and nature'.[2] This article considers the scale of the problem to be tackled by the Ocean Decade with regard to contamination and pollution as indicated in the first of its 10 challenges: understanding and mapping land and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems. Challenge 1 then leads to Outcome 1: 'a clean ocean where sources of pollution are identified and reduced or removed'. Most importantly, both the natural and social sciences are required in order to address this Challenge and deliver this Outcome.

The Ocean Decade should promote science to tackle the one big challenge facing our oceans: 'how to protect and maintain the marine ecology while at the same time enable the oceans to create the ecosystem services which can be used to provide the goods and benefits required by society'[3] – i.e. the sustainability in the Ocean Decade's full title. For example, suitable waves, tides, sediments, etc. will create the right conditions for

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▲ **Figure 1. Industrial discharge from a petrochemical plant. (© Mike Elliott)**

the marine microbes, plants, invertebrates and higher animals. These physical and biological structures and processes can then ensure the oceans provide ecosystem services, such as sustainable populations, recycling and storing carbon and nutrients and pleasant seascapes, to name but a few. Following this, human capital and complementary assets (money, energy, skills and time) can then be used to obtain societal goods and benefits (for food, recreation, clean air and water, etc.).[4]

MARINE CONTAMINATION AND POLLUTION

It is important to distinguish between contamination, which is the presence of a human-derived material in the environment, and pollution, which is the biological effect of those contaminants which, if unchecked, will reduce the health of one or more levels of biological organisation, from the cell to the ecosystem. There are various types of contaminants and pollutants – materials, which can be 'large' or small solids, dissolved substances or energy. They can be 'unnatural' materials, such as synthetic chemicals, for which organisms have not evolved coping mechanisms, or they can be 'natural' materials in 'unnatural quantities' that exceed the assimilative capacity of the oceans to be stored, sequestered, detoxified or degraded.

Classically, pollution concerns have focused on microorganisms (e.g. from sewage) and agro- and industrial chemicals (**Figure 1**), such as heavy metals, organohalogens, radionuclides and phosphate compounds. However, increasingly they include macro- and microplastics (**Figure 2**), sediment (from erosion or seabed disturbance), gases (CO_2), energy (light, noise and vibration[5]) and macroorganisms such as non-native species[6] – all of which can cause ecological damage. Indeed, if large structures (such as wind turbines, bridges, oil and gas rigs) are placed in the sea then they also meet the above definitions for contaminants and pollutants – they undoubtedly disturb the marine system and are demonstrated or assumed to harm nature and the way we use the seas. This can be, for example, by changing the habitat and hydrodynamics, inputting or resuspending contaminants in the bed sediments, affecting food chains and by preventing us from exploiting fish and shellfish. The Ocean Decade has 10 years in which to focus on the science needed to tackle all of these types of contaminants and pollutants.

The input of the materials mentioned above comes from human activities, usually on land, but also at sea. Each of those activities has a footprint and leads to pressures defined as 'the mechanism of effect', which

▲ **Figure 2. Fishing, household and industrial litter washed up on the strandline. (© Mike Elliott)**

are impacts both on the natural system and on humans. Those pressures and impacts also have footprints of their own, so there is the need to separate activity-footprints, pressures-footprints and effects-footprints, which may be but are often not in the same place.[7] For example, the activity-footprint of an offshore windfarm may be relatively small but it exerts pressures and effects over a larger area by affecting the migration of species, emitting noise and electromagnetic waves, and disturbing hydrographic and sediment patterns. The Ocean Decade science is needed to determine the scale of those footprints in both space and time – from a hectare to globally and from a few hours to millennia.

As indicated above, pollution implies adverse effects on one or more levels of biological organisation in the sequence from cells and tissues, through whole organisms and their populations, to communities and ecosystems.[8] Within this, environmental managers have long adopted the precautionary principle, in which it is assumed, unless proven otherwise, that human activities will have an adverse effect and that those effects, unless stopped, will be transmitted from individuals to ecosystems. For example, discharging polychlorinated biphenyls (PCBs) into the sea may generate cellular detoxification mechanisms leading to cancers and eventually whole organism, population and community effects. However, the natural marine system is complex and variable, and such complexity and variability have an ability to absorb some of the effects of stressors (what may be termed environmental homeostasis), without leading to whole-system effects.[9] All of this requires detailed science and, despite the study and management of marine pollution since the 1960s, the Ocean Decade is even more required as an impetus for fit-for-purpose, well-coordinated and well-funded science.[10]

Tackling marine contamination and pollution is essentially a process of Risk Assessment and Risk Management, in which the causes and consequences need to be determined and management responses need to be enacted.[11] However, although this is the Ocean Decade, we need to know what are land-based problems, such as nutrients, plastics and industrial contaminants, and what are their synergistic, antagonistic or cumulative effects. The history of marine science for management has passed through many phases, from the first studies on oil spills (**Figure 3**) and metal pollution in the 1960s, through synthetic chemicals and an awareness today of overfishing to marine debris and the loss of habitats.[12] Hence, we have a large knowledge on which to base our management actions.

▲ **Figure 3. Pollution from shipping accidents leading to oil pollution. (© Mike Elliott)**

SCIENCE, POLICY AND MANAGEMENT

Managing and controlling the problems over the coming decade and linking these to the required science has to be underpinned by a solid causes, consequences and response approach, such as the DAPSI(W)R(M) (pronounced *dap-see-worm*) problem-solving framework[3] (**Figure 4**). In this, the **D**rivers of basic human needs, such as for food, security and clean water, are satisfied by our **A**ctivities which, in turn, result in **P**ressures. These pressures lead to **S**tate changes on the natural ecology and to **I**mpacts (on human **W**elfare) and both the ecological state changes and impacts on society need to be addressed by **R**esponses (using management **M**easures). Hence the management addresses the drivers, activities and pressures to prevent the adverse effects on the natural and human systems. Each of these elements then needs the appropriate science to create indicators (as shown in **Figure 4**) to measure and monitor the direction of trends and to determine whether or not the management measures have been successful. In the case of contaminants and pollutants, for example, urbanisation and industrialisation lead to the production, use and discharge of materials that eventually reduce the health of organisms and humans. We then need the laws, economic instruments, technological devices and societal attitudes to control the resulting problems.

Just as the implementation plan for the Ocean Decade mentions human behaviour, the Ocean Decade needs a concerted scientific effort to understand the fate and effects of pollutants – what may be regarded as 'behaviour' at many levels. This needs interdisciplinary research that covers the physical and chemical sciences (i.e. the 'behaviour' of the physical and chemical marine system) leading to an understanding of the 'behaviour' of the contaminant in the environment. Such behaviour, in turn, leads to contaminant uptake by organisms depending on their behaviour and biological traits; for example, whether they will filter polluting particles out of the water or ingest them from sediments. Following this is the 'behaviour' of the pollutants inside organisms – whether they will be sequestered, stored, detoxified and/or excreted and whether any of these will lead to

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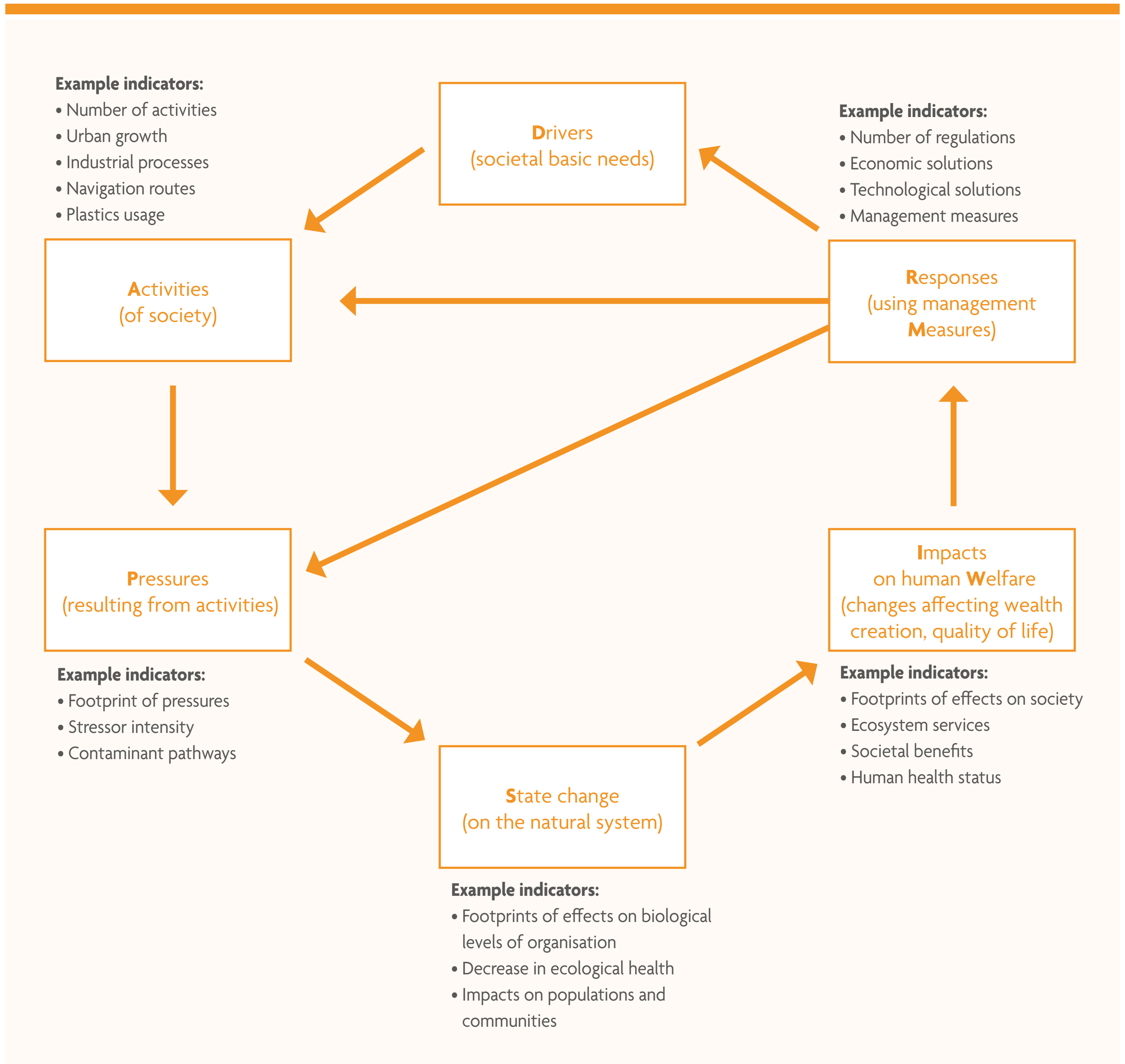
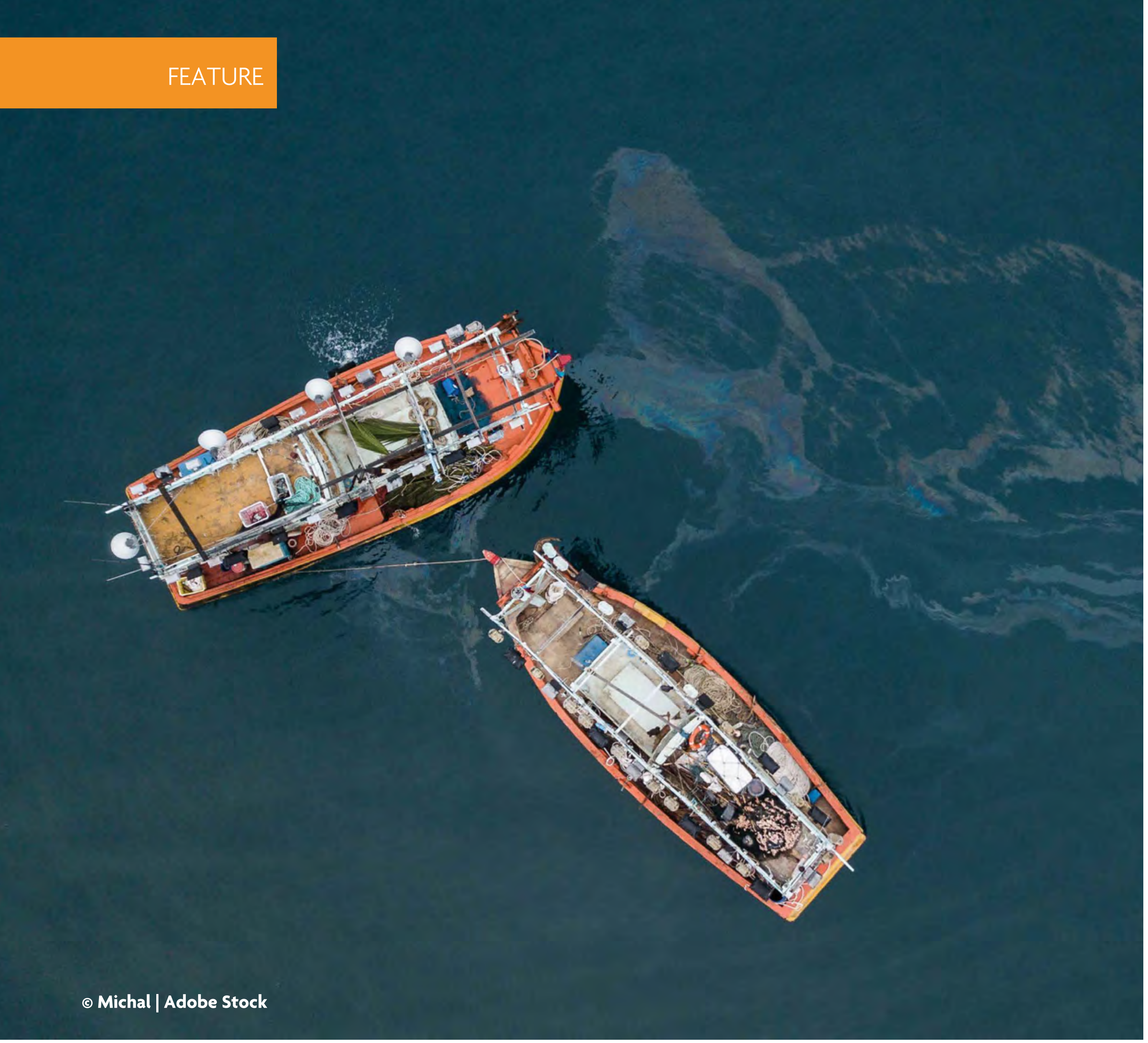


▲ **Figure 4. The DAPSI(W)R(M) cause, consequence and response framework with indicators (modified[3]).**

them being accumulated throughout food chains, i.e. passed on to predators or progeny. As a consequence, the control, management and policy of marine pollution must be based on good science in the sequence of research – knowledge – policy – management.

The Ocean Decade is intimately linked, and over the same timescale, to the global Sustainable Development Goals (SDGs) and especially SDG 14 ('Life below water'), with its focus on the oceans. The SDG 14 targets are mostly related to wider management and fishing, and may be insufficiently quantitative to know if they are achieved by management.[13] In particular here, and notably as the first target, SDG 14 Target 14.1 has an especially ambitious (and perhaps unattainable!) target: 'By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution'. Arguably, other types of pollution are also important and, again it could be argued, that marine debris (litter) and plastics are a land-originating problem that requires land-based rather than marine solutions. At present there is an excessive effort on microplastics research but one questions whether this is looking mostly at contamination (i.e. the presence) rather than pollution *per se* (i.e. the effects).[14]



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Of increasing further concern, and as a problem exacerbated by global climate change, are biological pollutants – non-native, invasive species with a potential for ecosystem consequences.[6] This requires us to retain international maritime transport but without moving species around the globe, and of coping with the effects of one type of pollution (climate change, ocean warming, loss of ice caps, ocean acidification) exacerbating another (non-native species deposited in an area leading to ecological and economic consequences). To prevent species being moved by shipping requires control and management of ballast water; however, perhaps more insidious is the movement of non-native species with warming seas and with the opening up of sea routes through the thawing of ice caps.

SOLUTIONS FROM THE OCEAN DECADE

The Ocean Decade aims to focus on the science for healthy oceans but also gives importance to education and communication for sustainable solutions, for indicating not only obvious problems (such as litter) but also the hidden concerns such as noise and dissolved pollutants. There is the need to determine the size and context of the problem, and bring to bear the legislative, economic and technological means of controlling pollutants and contaminants. As emphasised by Outcome 1 of the Ocean Decade, 'it will be critical to fill urgent knowledge gaps and generate priority interdisciplinary and co-produced knowledge on the causes and sources of pollution and its effects on ecosystems and human health. This knowledge will underpin solutions codesigned by multiple stakeholders to eliminate pollution at the source, mitigate harmful activities, remove pollutants from the ocean, and support the transition of society into a circular economy'.[1]

Unfortunately, society still has an 'out of sight, out of mind' attitude – throwing our waste into the nearest watercourse and allowing it to be carried downstream takes it away from being a local problem. This leads to a few major river systems worldwide being the source of most plastics, eventually contributing to the huge plastics gyres in the major oceans. But in allowing contamination and pollution are we also wasting resources? The American architect and theorist Richard Buckminster Fuller commented that 'pollution is nothing but resources we're not harvesting. We allow them to disperse because we've been ignorant of their value'. This has been misquoted as 'pollution is the wrong type of materials, in the wrong place and at the wrong time'. Hence, we need a change to the mindset so that these valuable resources can be harvested in a circular economy.

In closing, it is important to return to Challenge 1 of the Ocean Decade: 'understanding and mapping land and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems'. The understanding, monitoring and assessment are a good start but only if accompanied by management and solutions. We also have to remember that the Ocean Decade goes hand in hand with the UN Decade on Ecosystem Restoration 2021–2030, which should also include solutions for the marine environment.[15] Taken together, these give us two decades of additional effort to achieve seas restored to health.

ES

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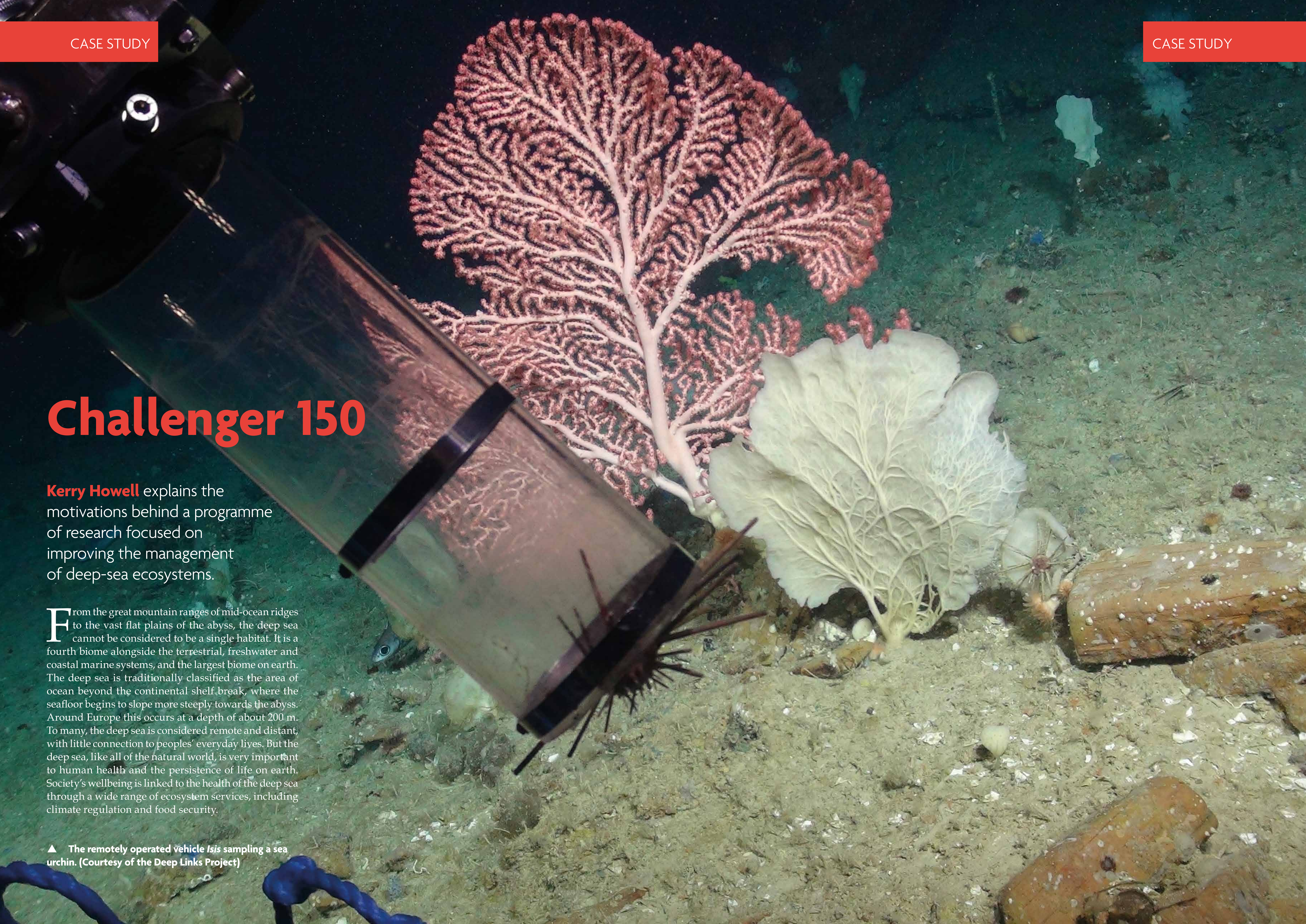
CASE STUDY



Challenger 150

Kerry Howell explains the motivations behind a programme of research focused on improving the management of deep-sea ecosystems.

From the great mountain ranges of mid-ocean ridges to the vast flat plains of the abyss, the deep sea cannot be considered to be a single habitat. It is a fourth biome alongside the terrestrial, freshwater and coastal marine systems, and the largest biome on earth. The deep sea is traditionally classified as the area of ocean beyond the continental shelf break, where the seafloor begins to slope more steeply towards the abyss. Around Europe this occurs at a depth of about 200 m. To many, the deep sea is considered remote and distant, with little connection to peoples' everyday lives. But the deep sea, like all of the natural world, is very important to human health and the persistence of life on earth. Society's wellbeing is linked to the health of the deep sea through a wide range of ecosystem services, including climate regulation and food security.

▲ **The remotely operated vehicle *Isis* sampling a sea urchin. (Courtesy of the Deep Links Project)**

THE HUMAN FOOTPRINT

Human use of deep-sea ecosystems is increasing. Since the 1950s, when exploratory fishing began, the human footprint in the deep sea has been growing. Fishing activities occur down to 2,000 m and the effects are felt at even greater depths than this.[1] Oil and gas activities have been pushing into waters more than 3,000 m deep, with rare but well documented catastrophic consequences,[2] and a new mining industry is taking its first steps in the exploitation of deep-sea resources.[3]

On top of this, our changing climate is affecting all of the natural world and the deep sea is no exception. The shallowing of the aragonite saturation horizon, a result of the ocean absorbing atmospheric CO_2, will have consequences for all organisms that use this form of calcium carbonate in their structures. Changes in the timing and composition of surface phytoplankton blooms will disrupt the food supply of deep-sea organisms that rely on a continuous rain of marine snow (organic material from the surface) to sustain them. The effects on deep-sea ecosystems of pressures arising from human use are poorly known, and cumulative effects are only just beginning to be considered.

Given the importance of the deep sea to human wellbeing and the increasing pressures this biome is facing, it is imperative that we develop the tools to inform more effective and coordinated management of human activities if we wish for human use to be considered sustainable. Underpinning these tools is the fundamental knowledge of the biome, including its organisms and ecosystems, and their connections and functions.

When people speak about the deep sea, you will often hear the phrase 'we know more about the surface of the Moon (or Mars) than we do about the deep sea'. This is true from the perspective of high-resolution topographic/bathymetric mapping, but does a disservice to the last 150 years of scientific investigations. We do know a lot about the deep sea, but our knowledge is spatially biased towards areas near economically wealthier nations and limited by the technology available for use. The biological data archived in the Ocean Biodiversity Information System tells that the South Atlantic, South Pacific, Indian Ocean and high seas are very poorly studied, and that sampling effort decreases with depth. If our knowledge of terrestrial ecology was based largely on observations from the top of northern European and north American mountains, it is easy to see how this would impact our view of the terrestrial biome. The technology required for sampling and observation in the deep sea has improved dramatically over the last decade, but our ability to conduct controlled experiments is still very limited, and technology has been slower to develop. This has restricted our understanding of organism physiology and behaviour, and with that ecosystem function.

There is a need for coordinated scientific effort to fill gaps in our knowledge of the deep-sea biome, with a very clear line of sight on how that knowledge might support the sustainable use of the deep sea. The UN Decade of Ocean Science for Sustainable Development represents an incredible opportunity to mobilise the global scientific community to put their collective efforts into this task. A new 10-year programme of study focused on delivering the fundamental biological and ecological data to populate ecosystem models, including spatial and temporal models, and linking to similar developments in environmental data modelling, such as oceanographic, geochemical and hydrographic models, could provide a much-needed leap forward in the development of solutions for the management of deep-sea ecosystems.

CASE STUDY

▲ The royal research ship *James Cook* deploying the Autosub6000 autonomous underwater vehicle. (Courtesy of the Deep Links Project)

BROADENING KNOWLEDGE OF THE DEEP SEA

In response to the Ocean Decade, members of the deep-sea science community have recently published a blueprint for such a programme: Challenger 150[4,5] has developed as a grass-roots initiative by working groups of the Deep-Ocean Stewardship Initiative (DOSI), and the Scientific Committee on Oceanic Research (SCOR), building on initial discussions in the Challenger Society for Marine Sciences' Deep-Sea Ecosystems Special Interest Group.

Challenger 150 follows in the footsteps of another global 10-year programme, the Census of Marine Life (CoML). The Census, as it is fondly known, took place from 2001 to 2010 and was an international effort undertaken to assess the diversity, distribution and abundance of marine life. During the decade of the Census, more than 6,000 potential new ocean species were discovered by the roughly 2,700 participating scientists from more than 80 countries. Of the 17 recognised CoML projects, five were focused on the deep sea and two on the polar regions. These projects considered different habitats, including the continental slope, abyss, seamounts, mid-ocean ridges and chemosynthetic systems. They significantly advanced our understanding of these ecosystems and built individual, institutional, national and regional capacity for deep-sea science. However, at the end of the CoML, large data gaps remained, and the number of nations engaged in deep-sea science was still relatively small.

Challenger 150 will build on the achievements of the Census but will seek to move beyond standard habitat silos by working at basin and/or biogeographical levels, recognising the connectivity of ecosystems. Regional science committees (RSCs) will bring together researchers active in specific ocean basins to coordinate research, prioritise areas for study, support

▲ **Large bubble gum corals projecting from a coral reef in the north-east Atlantic. (Courtesy of the Deep Links Project)**

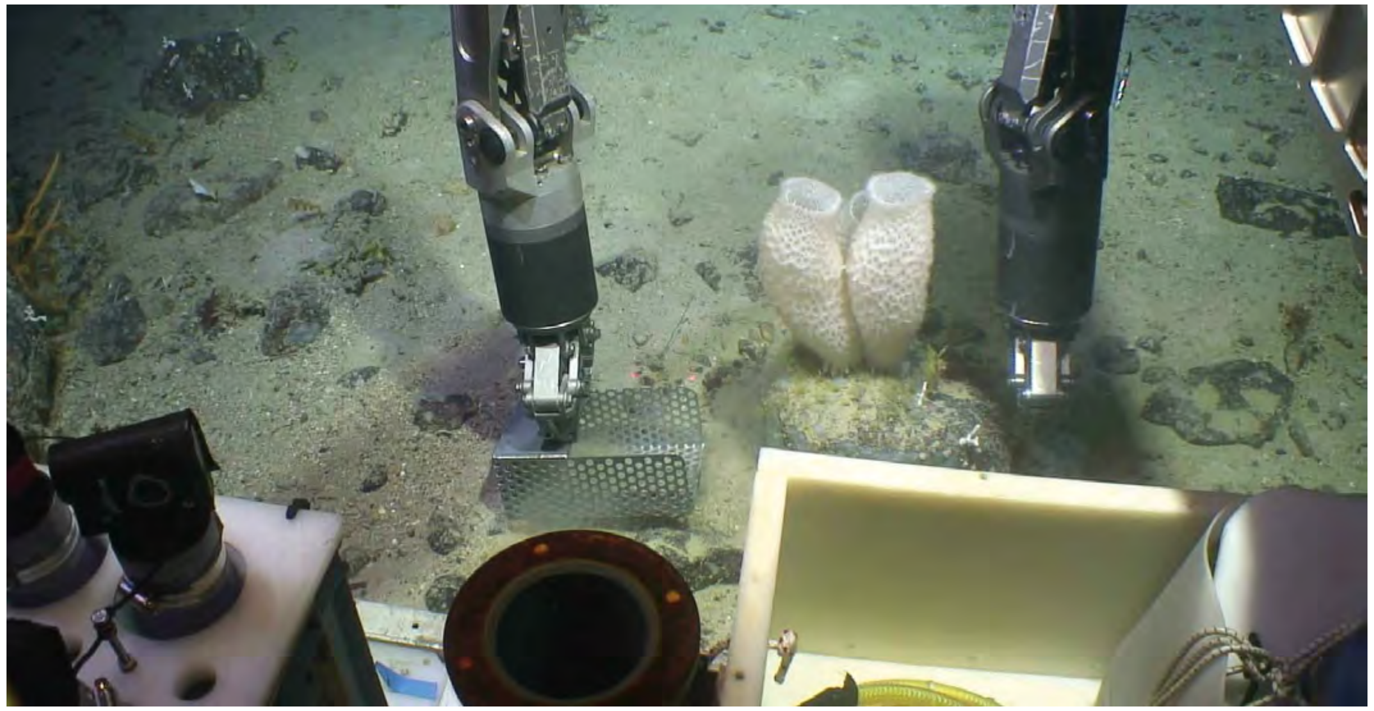
the development of new funding bids, and ensure the data gaps are filled. This regional structure will facilitate another important aim of both Challenger 150 and the Ocean Decade, which is to build capacity in deep-sea science globally, particularly among nations that have had a more limited presence in this field, including economically developing nations and large ocean states (also called small island developing states).

RSCs will also work to identify and liaise with regional stakeholders on research needs and support the development of science-to-end-user pathways. Technical science committees (TSCs) will support the development of standards in methods and measurements, which are critical to delivering a dataset that will form the basis of the development of ecosystem models to assess cumulative impacts. The CoML programme began this process, and Challenger 150 will continue to move researchers closer to each other on standards in working practices. In addition, these TSCs will assess the potential of new technologies to support deep-sea science to make it more accessible, through either lower cost or by opening up of novel lines of enquiry.

However, the programme will go beyond data collection, and actively work with stakeholders to understand science needs and ensure science informs policy. While the programme's initial focus will be natural sciences, there is recognition that engagement with the social sciences, law, arts and education will be critical to effecting change and achieving sustainable management practices. Regional conventions and

▲ **The Challenger 150 Programme has been submitted to the International Oceanographic Commission for endorsement as an official programme of the Ocean Decade. (© Plymouth University)**

associated bodies, such as the Abidjan Convention and the Benguela Current Convention, will be important pathways for moving science into policy. Expert bodies, such as the DOSI network of more than 1,900 experts



▲ **The remotely operated vehicle *Holland I* sampling sponges. (Courtesy of the DeepMap project)**

from 93 different countries, will help to support the integration of science, technology, policy, law and economics to advise on ecosystem-based management of resource use in the deep ocean.

The Decade of Ocean Science for Sustainable Development is a call to action for all ocean-focused researchers. Challenger 150 has the potential to deliver management-relevant ecological data in an accessible format, bring the deep sea into global models as more than just a black box, and provide the tools to sustainably manage this vast biome in the future. In so doing the programme will help fulfil five of the Ocean Decade's six societal outcomes. For deep-sea science it really could provide a significant leap forward in our knowledge and management of this biome. ES

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ANALYSIS

A source of nutritious food

Colin Moffat considers current marine food production and the necessary actions for the ocean to continue to provide us with good-quality food.

The seven societal outcomes of the United Nations Decade of Ocean Science for Sustainable Development 2021-2030 that describe the 'ocean we want' (see **Box 1**) summarise, indirectly, the challenges to delivering high-quality protein, whether from wild or cultivated marine sources. Increasing direct human pressures on the marine environment (e.g. the removal of target and non-target species, contaminants, impulsive noise) coupled with climate-driven changes (e.g. increasing water temperatures and deoxygenation of the ocean) and ocean acidification are perturbing marine ecosystems globally. Climate change and environmental degradation present an existential threat to the ocean and, consequently, humankind. However, the seven societal outcomes can be delivered, including having a productive ocean supporting a sustainable food supply, if transformative and varied solutions are created through the Ocean Decade, including in the area of large-scale human behaviour change.

BOX 1. THE OUTCOMES FOR THE 'OCEAN WE WANT'[1]

1. A clean ocean where sources of pollution are identified and reduced or removed.
2. A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed.
3. A productive ocean supporting sustainable food supply and a sustainable ocean economy.
4. A predicted ocean where society understands and can respond to changing ocean conditions.
5. A safe ocean where life and livelihoods are protected from ocean-related hazards.
6. An accessible ocean with open and equitable access to data, information and technology and innovation.
7. An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development.

OCEAN DECADE CHALLENGE 3

Challenge 3 in the Ocean Decade focuses on how innovative science will 'generate knowledge, support innovation, and develop solutions to optimise the role of the ocean in sustainably feeding the world's population under changing environmental, social and climate conditions'. The key objective is in respect of the ocean's contribution to sustainably feeding the world's population. This is against a backdrop of the changes already outlined above. The knowledge required to deliver the solutions to optimise the role the ocean will have in providing a nutritious supply of food must be identified. The data, knowledge and information must then be generated and, finally, the information must be used to implement processes and procedures. This will allow major steps forward to be made with respect to achieving societal outcome 3 – a productive ocean.

CURRENT PRODUCTION

Globally, the marine production of fish, crustaceans, molluscs and other aquatic animals amounted to 115.2 million tonnes in 2018 (see **Table 1**). This included 84.4 million tonnes from capture production and 30.8 million tonnes from aquaculture.[2] Between 2012 and 2018 (the most recent year for which data are available) marine capture and aquaculture increased steadily (see **Figure 1**). The percentage increase in the marine production between 2012 and 2018 was 13.3 per cent.

In 2018, catches of anchoveta (*Engraulis ringens*) were the highest, at more than 7.0 million tonnes per year. Alaska pollock (*Gadus chalcogrammus*) was second, at 3.4 million tonnes, while skipjack tuna (*Katsuwonus pelamis*) ranked third for the ninth consecutive year, at 3.2 million tonnes. Atlantic herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*) and Atlantic mackerel (*Scomber scombrus*) were fourth, ninth and 11th, respectively, with more than 1 million tonnes each caught in 2018. The top seven capture producers, China, Indonesia, Peru, India, the Russian Federation, the USA and Viet Nam, accounted for almost 50 per cent of total global capture.

Aquaculture also produces high-quality marine-based food. A range of fish and shellfish are cultivated which is generally geographically determined. Aquaculture production also faces challenges, including from the changing climate. However, there are many viral and bacterial infections that can thrive in an intensive aquaculture environment that is typical of, for example, Atlantic salmon (*Salmo salar*) production. This is important when it is appreciated that salmon and trout have been the most important aquaculture commodities traded in value terms since 2013, and accounted for about 18 per cent of the total value of internationally traded fish products in 2018.[2]

Globally, in addition to the recognised fish and shellfish products, various other foods are obtained from the ocean that are not included in the Food and Agricultural Organization of the United Nations (FAO) data. For example, fermented food products that include seabird and seal as the primary material are consumed in the Arctic region, as is smoked seabird. These represent a key source of protein and are traditional marine food products. In terms of aquatic plants, 33.3 million tonnes, mostly seaweeds, were produced in 2018, of which 32.4 million tonnes (97.1 per cent) were harvested from aquaculture.[2]

A GLOBAL ISSUE

Marine capture fisheries is a global activity (see **Figure 2**). In 2018, the Pacific marine fisheries were the largest for capture fisheries, at 49,165,173 tonnes (58.2 per cent), while the Arctic, at 113 tonnes, was the smallest. Atlantic marine fishing yielded 22,951,792 tonnes, while in the Indian Ocean, marine fishing amounted to 12,294,902 tonnes (see **Figure 2**). This makes the delivery of Ocean Decade's challenge 3 a genuinely global issue.

Although marine production has continued to increase (see **Figure 1**) there is a continuing awareness that the removal of target species requires management. The resource *is* finite. The question is not only about how to remove the target species in a way that avoids bycatch and other non-target species, but also concerns how much of this highly nutritious food supply, that is an excellent source of highly polyunsaturated fatty acids, including all-*cis*-5,8,11,14,17-eicosapentaenoic acid (EPA), can be removed from marine areas that are experiencing increasing demands from renewable energy production together with the need to maintain biodiversity.

Achieving the balance between the multiple uses of the marine environment and maintaining a fully functioning ecosystem that can deliver the various ecosystem services in the future requires transformational science from the Ocean Decade. This is especially critical given the rapid changes that are occurring in the ocean due to the increasing concentrations of greenhouse gases in the atmosphere. Furthermore, the ocean continues to be the repository for microplastics, heavy metals, persistent organic pollutants, and pharmaceuticals and personal care products. Some of these are concentrated in fish and apex predators such as seals.

TOWARDS SUSTAINABLE FISHERIES

Overfishing has been recognised for many years and has resulted in various management measures being introduced. Taking the north-east Atlantic as an example, these management measures are evaluated each year by the International Council for the Exploration of the Sea (ICES). Fishery and survey data from appropriate countries are used to estimate fishing mortality (*F*), spawning stock biomass (*SSB* or *B*) and recruitment (*R*). These metrics are used to conclude whether a fishery of a discrete stock is sustainable and the stock healthy by comparing these metrics to pre-defined reference points.[4] The reference points can be categorised as maximum sustainable yield (MSY), a limit value that should not be exceeded (lim), and a precautionary value (pa). In this context:

- *F*(MSY) is the fishing mortality estimated to result in the maximum sustainable yield over a long time period;
- *F*(lim) is the fishing mortality that should not be exceeded; and
- *F*(pa) is a lower buffer value that ensures that *F*(lim) is not exceeded.

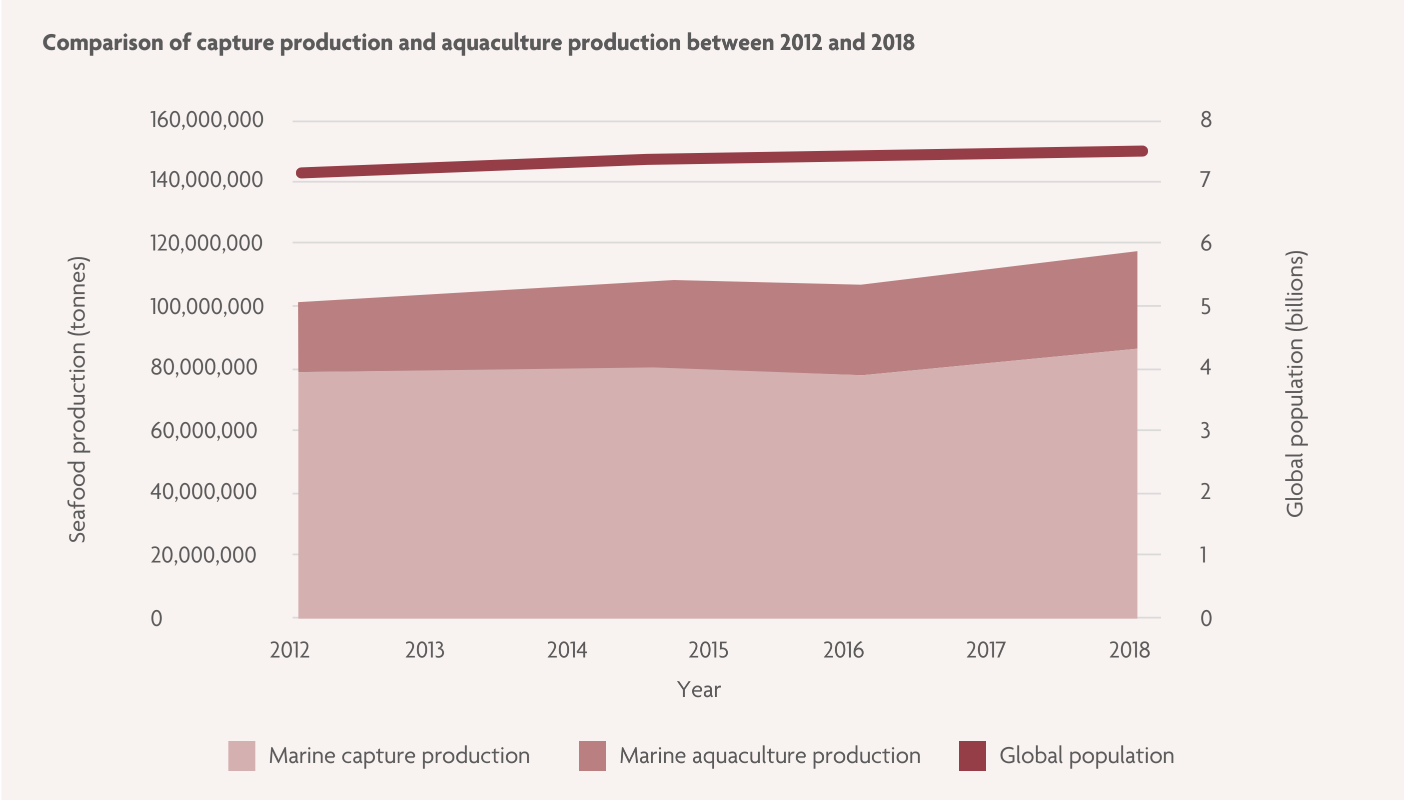
By plotting the fishing mortality over time (see example in **Figure 3**), the amount of fish that can be caught from a given stock can be determined and agreements made between states that have an entitlement to fish in the area.

The process used in the north-east Atlantic is not universal. The South Pacific Regional Fisheries Management Organisation (SPRFMO) Conservation and Management Measures (CMMs) define the regulatory framework for the SPRFMO fisheries in the high seas areas of the South Pacific Ocean. They detail various provisions, such as the application of technical measures or output and input controls, requirements for data collection and reporting, and regulations for monitoring, control and surveillance and enforcement. This includes the requirement to use a vessel monitoring system (VMS), the proportion of days that must include an observer and the provision of data to the Executive Secretary of the SPRFMO. The data submitted under a CMM is provided to the Scientific Committee, which conducts the necessary analysis and assessment in order to provide advice on stock status.[6]

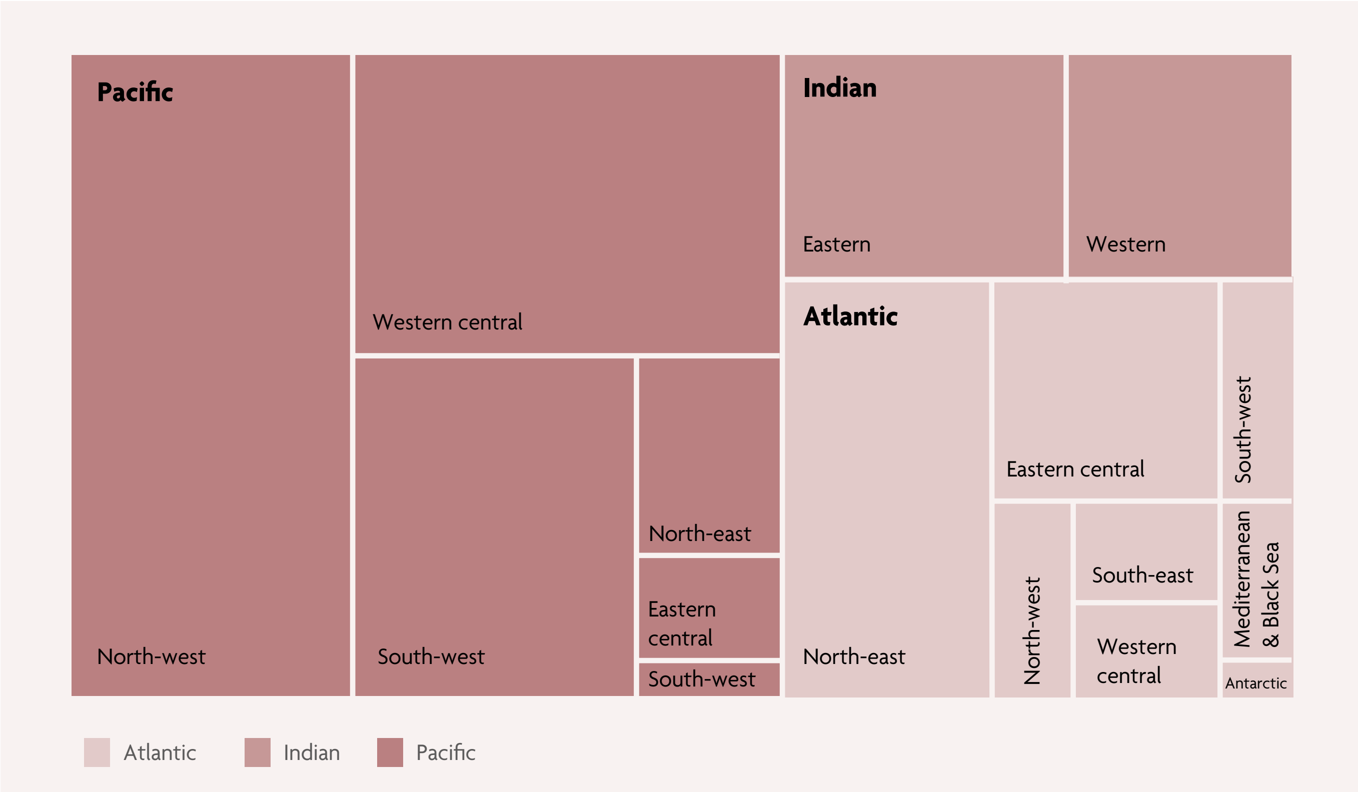
There are a significant number of international fisheries management organisations that facilitate international cooperation to achieve effective, responsible marine stewardship and ensure sustainable fisheries management covering the Atlantic, Pacific, Indian and Southern oceans. Some are species specific, such as the Indian Ocean Tuna Commission (IOTC), which is

▼ **Table 1. Global marine capture and marine aquaculture production of fish, crustaceans, molluscs and other aquatic animals for 2012 and 2018[2]**

Category	2012		2018	
	Production (tonnes)	%	Production (tonnes)	%
Marine capture	77,753,302	76.48	84,412,380	73.29
Marine aquaculture	23,906,018	23.52	30,756,189	26.70
Total marine	101,659,320	-	115,168,569	-



▲ **Figure 1. Global marine production of fish, crustaceans, molluscs and other aquatic animals from capture production and aquaculture production, 2012–2018.[2] There was a small shift from capture production to aquaculture production during this period. Total marine production increased from 101,659,320 tonnes to 115,168,569 tonnes, an increase of 13.3 per cent. In 2018 a significant proportion was used for direct human consumption.[2] Over the same period, the global population increased from 7.13 billion to 7.63 billion (7.0 per cent).[3]**



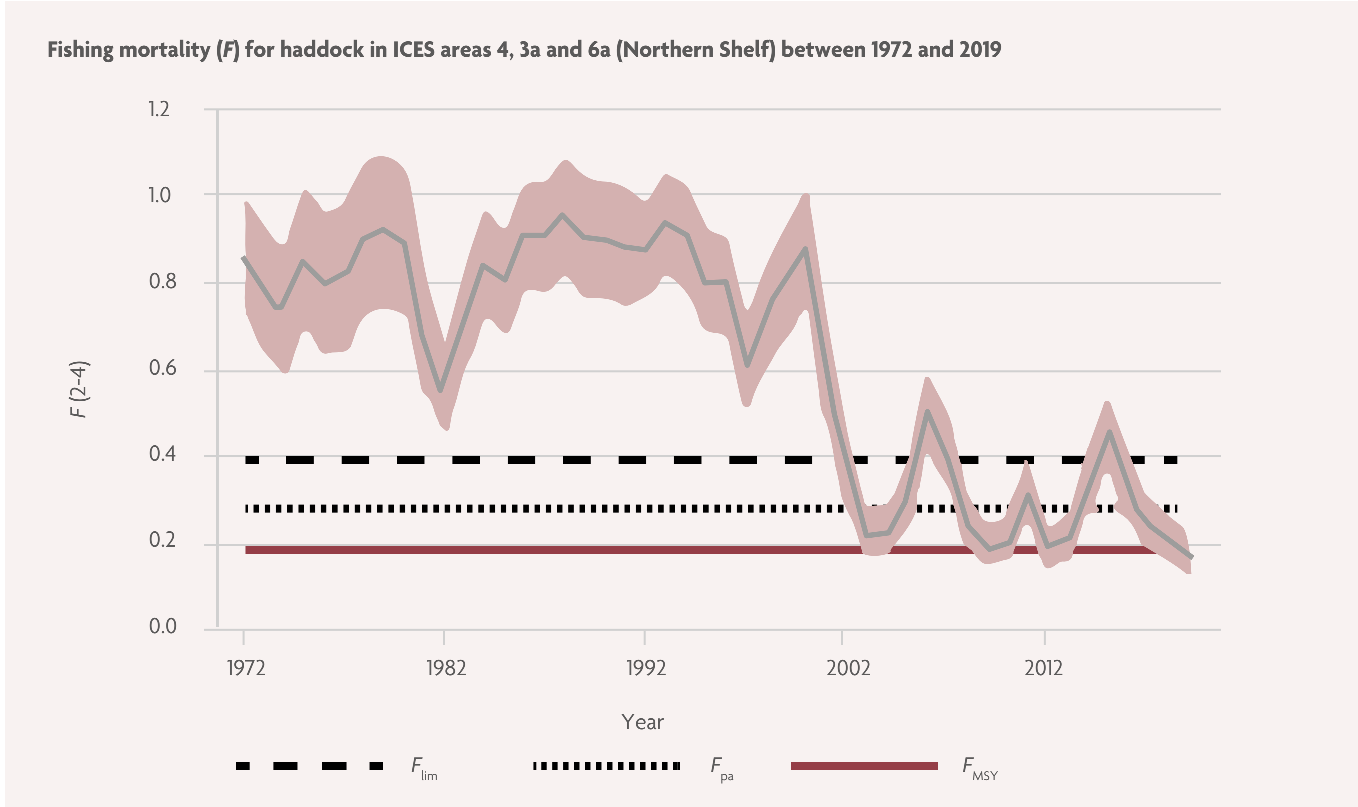
▲ **Figure 2. Global marine capture production by marine fishing area for fish, crustaceans, molluscs and other aquatic animals based on the 2018 data.[2] Although there are year-on-year variations, the general pattern over the period 2012–2018 is the same. The seven Pacific areas combined give a capture value of 49,165,173 tonnes. The seventh area, the Pacific Antarctic, contributes only 3,405 tonnes (0.01 per cent) and is therefore too small to be visible on the figure. Capture production from the Indian Antarctic, although greater than that from the Pacific Antarctic at 11,339 tonnes, is also too small to be shown. The total capture production for the Atlantic marine fishing area was 22,951,792 tonnes. The capture production for the Arctic is not included, as it was only 113 tonnes in 2018.**

an intergovernmental organisation responsible for the management of tuna and tuna-like species in the Indian Ocean. In contrast, the Northwest Atlantic Fisheries Organization (NAFO) Convention on Cooperation in the Northwest Atlantic Fisheries applies to most fishery resources of the north-west Atlantic except salmon, tunas/marlins, whales and sedentary species (e.g. shellfish). What this illustrates is that there is a significant amount of effort and expenditure invested in managing capture fisheries and that it is conducted on a regional basis. However, data and information are key, regardless of species or location.

CONCEPTS FOR THE OCEAN DECADE

As highlighted earlier, marine ecosystems globally are changing. This is because of the increasing direct human pressures on the marine environment, together with the consequences of changes to the global climate as a result of increasing concentrations of atmospheric greenhouse gases. Light pollution of the sea, which has only become a really significant issue over the last 50–80 years, continues to increase in some regions, contaminants continues to be an issue, and in the coastal zone where aquaculture takes place, there is competition for space. As renewable energy devices develop, these will be more numerous and therefore located across a larger area.

In this context, the Ocean Decade must look to develop methods that deliver genuine ecosystem assessments that are able to take account of the various processes affecting a recognised area and, from this, provide the information that will ensure that decision-makers are able to balance the need for nutritious food (capture and aquaculture), energy, genetic resources, novel drugs, sand and gravel, a tourist industry, accessibility to the marine environment for spiritual reasons and health and wellbeing, nature-based solutions to coastal protection, carbon storage and the maintenance of habitats that ensure the existence of a diverse range of species. Genuine ecosystem assessments have been elusive, but through transformational science, focused on how to merge different types of indicators and assess the cumulative (or otherwise) impacts of multiple stressors, marine planning will be undertaken on a much firmer footing, ensuring that the balance between use and



▲ **Figure 3. Fishing mortality (*F*) for haddock in ICES areas 4, 3a and 6a (Northern Shelf). The lowest fishing mortality reference point is *F*(MSY) and the highest (the value that should not be exceeded) is *F*(lim). *F*(pa) is higher than *F*(MSY) but lower than *F*(lim).[5] The '2–4' in '*F*(2–4)' is the age range over which the mean fishing mortality is calculated. This needs to be representative of the main fished population, so it does not include the youngest or oldest fish. The shaded area indicates the 95% confidence intervals.**

protection is always optimal. This will help to deliver a functioning ocean for future generations. **ES**

Colin Moffat was, until recently, the Chief Scientific Advisor Marine for the Scottish Government and over the last 25 years, he has focused on assessing the state of the marine environment and the impacts that human activities have on the ocean. He initially concentrated on contaminants and their effects, then broadened his interests to understanding the consequences of the many and varied human activities that have direct impacts on the marine ecosystem, as well as the consequences of climate change and ocean acidification. This work will continue in Colin's roles as Visiting Professor at Robert Gordon University and Honorary Professor at Heriot-Watt University.

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CASE STUDY

Industry engagement with the Ocean Decade

David Millar outlines the advantages of input from industry for the equitable and sustainable development of the ocean economy.

Calling all ocean businesses: after three years of planning and consultation, the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) is at last underway. A multifaceted initiative, the Ocean Decade aims to build a common, global framework for ocean science that will help reverse the cycle of decline in ocean health and create improved conditions for sustainable ocean development worldwide. Its success will require the involvement and collaboration of stakeholders from diverse disciplines and sectors, across all geographies, so the private sector truly has an opportunity to help save the planet.

THE GLOBAL OCEAN ECONOMY

The global ocean economy encompasses a wide range of businesses, including defence and security, shipbuilding, oil and gas, offshore wind, fisheries, aquaculture, shipping and tourism. While this list represents the largest and most obvious components of the global ocean economy, there are many more businesses that support their respective supply chains. Examples include manufacturing, warehousing, cables, connectors, software, sensors, research, education and geodata (information about geographic locations that can be stored in and used with a geographic information system [GIS]), to name but a few.

▲ **Figure 1. The UN Ocean Decade Action Framework. (© Intergovernmental Oceanographic Commission – UNESCO)**

Before the Covid-19 pandemic, the Organisation for Economic Co-operation and Development (OECD) projected that the ocean economy would reach US$ 3 trillion by 2030, effectively doubling its size in 2010 and potentially outperforming the growth rate of the global economy in terms of generated value and employment.[1]

It is no surprise that this momentum has slowed over the past year, given the negative impacts of Covid-19 on ocean business.[2] A rebound is expected, however, as the primary drivers for economic growth that existed before the pandemic still remain: food, climate and decarbonisation.[3] As business builds back post-pandemic, there is a growing expectation that it will do so with an increased focus on sustainability. This emphasis would provide many opportunities for industry to engage with the Ocean Decade via mutually beneficial scenarios. After all, sustainable development is only possible through ocean science.

THE PRIVATE SECTOR'S ROLE

The Ocean Decade provides a participative and transformative process for developing 'the science we need for the ocean we want'. Its framework comprises four components: actions, the tangible initiatives and endeavours to be managed by stakeholders; objectives, the steps in the process towards achieving the ocean we want; challenges, the most immediate and pressing needs; and outcomes, the qualities that will ensure a safe and sustainable ocean (see **Figure 1**).

Within this framework, the actions will fulfil the objectives and achieve the challenges. The challenges will in turn contribute to one or more outcomes, which ultimately will support the United Nations Sustainability Agenda and regional and global policy frameworks.[4]

While the private sector can play a role in achieving all 10 challenges, challenge 4 is particularly relevant to industry given its association with the sustainable development of the ocean economy. Challenge 4 calls on stakeholders to 'generate knowledge, support innovation, and develop solutions for equitable and sustainable development of the ocean economy under changing environmental, social and climate conditions'.[4]

GENERATING KNOWLEDGE

Generating knowledge starts with the collection and sharing of ocean science data and information. To facilitate this process, the Ocean Decade is establishing a digital ecosystem that will catalyse cooperation between knowledge generators and knowledge consumers.[4] Some organisations, such as Fugro, do both. As the world's largest geodata specialist, Fugro supports a wide range of ocean businesses with data acquisition, analysis and advice. The company also uses ocean science to support its own operations. For example, ocean mapping and ocean observation data is used to perform desktop studies, fuel models and forecasts, and support project planning and scheduling.

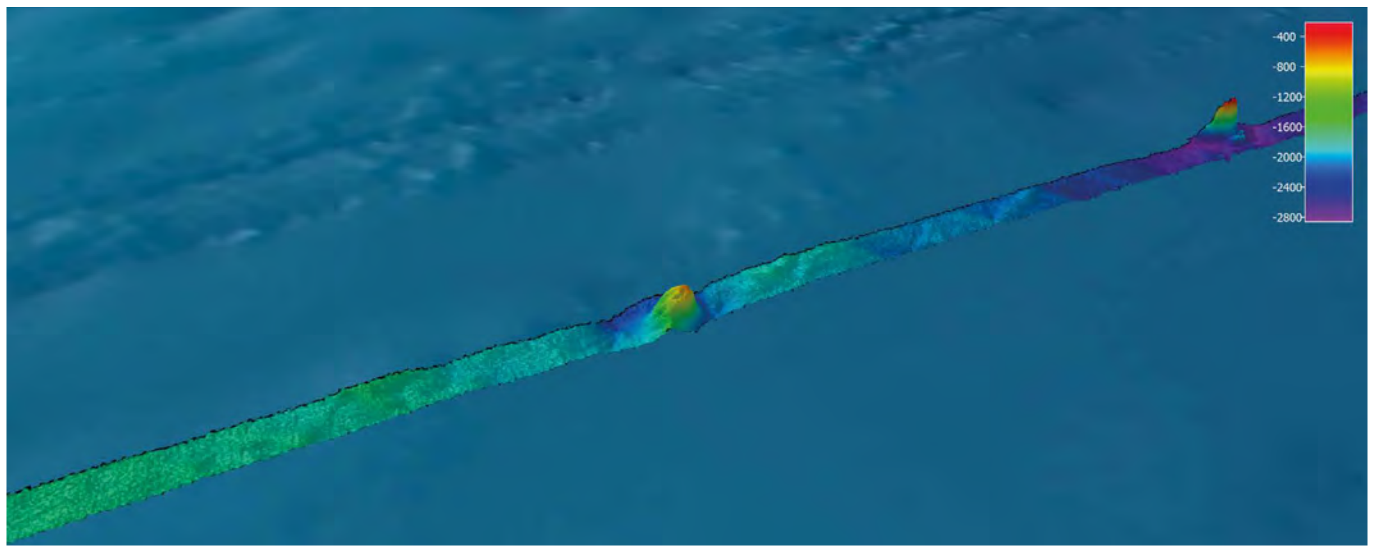
In 2016, Fugro began supporting a nascent global ocean mapping initiative that sought to address ocean science data gaps, specifically related to bathymetry. That initiative has since become known as the Nippon Foundation-GEBCO Seabed 2030 Project. A collaborative effort between The Nippon Foundation and the General Bathymetric Chart of the Oceans (GEBCO), Seabed 2030 aims to inspire the complete mapping of the world's oceans by 2030 and the compilation of all bathymetric data into the freely available GEBCO ocean map. The project supports United Nations Sustainable Development Goal 14 and is recognised as an important initiative in line with Ocean Decade objectives. Since its launch in 2017, Seabed 2030 has increased its available bathymetry holdings by 13 per cent.

One of the primary ways Fugro supports Seabed 2030 is through the contribution of high-resolution bathymetry data collected by company vessels while in transit between project locations (see **Figure 2**). Since the start of Seabed 2030, approximately 1,450,000 km^2 of survey data collected by Fugro has been contributed to the project. In addition, the company has facilitated the contribution of bathymetry and metocean data (meteorological oceanographic data from ocean locations) acquired by Fugro but owned by its clients. Building on these successes, Fugro is now implementing similar strategies around other types of ocean observation to benefit the Ocean Decade.

It is important to note that geodata expertise is not required to support knowledge generation. Businesses that own and operate ocean-going vessels and/or infrastructure can also participate. The commercial shipping, fishing and cruise-ship industries have a tremendous opportunity to participate in this process at very little cost to their businesses. Fugro and other companies can support these activities through their systems, sensors and software, which facilitate the collection, management and distribution of ocean science data and information. As such, virtually any ocean business can make impactful contributions to the Ocean Decade.

SUPPORTING INNOVATION

Transformative ocean science requires transformative technology solutions. It is not enough to simply



▲ **Figure 2. An example of Fugro's in-transit bathymetry data collection for Seabed 2030. (© Fugro)**

CASE STUDY

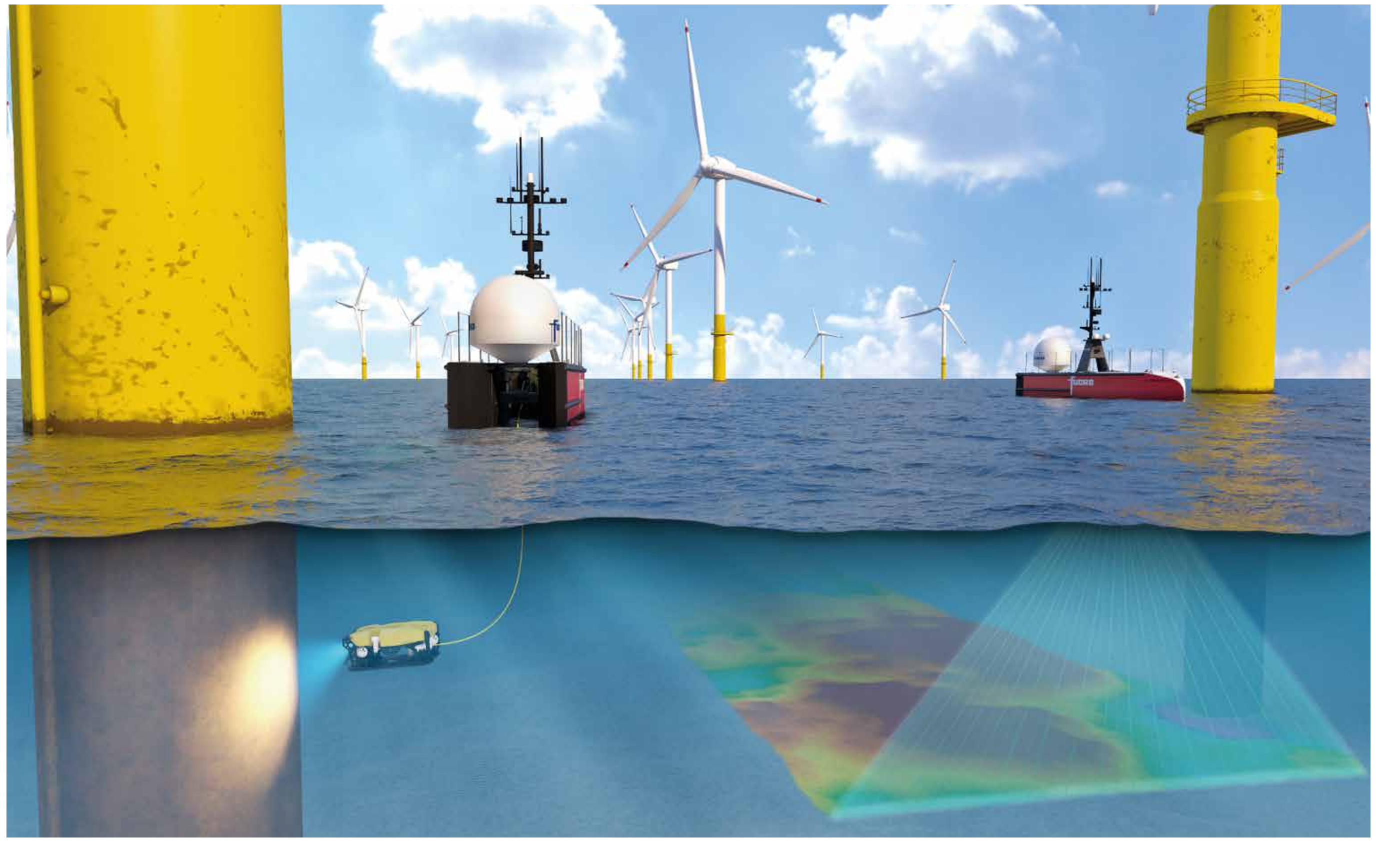
generate knowledge; the way knowledge is created and disseminated must advance to increase quality, access and efficiency. To this end, knowledge generators and users are expected to co design Decade Actions that facilitate the update of science knowledge for policy, decision-making, management and/or innovation, providing yet another avenue for private-sector engagement with the Ocean Decade.[4]

Geodata technologies and solutions that support ocean mapping and ocean observations are now advancing at an unprecedented pace, driven primarily by innovations in core technologies, such as remote operations, autonomy, robotics, analytics and cloud automation. These core technologies are already starting to change the way ocean science data and information are collected and shared, leading to safer and more efficient, cost-effective and sustainable solutions. There is no doubt that the solutions being deployed to support Seabed 2030 and the Ocean Decade in five years' time will be very different from those being used today.

As with knowledge generation, Fugro and other businesses that develop data collection, management and distribution technologies can support innovation that will meaningfully contribute to the Ocean Decade. Citing Fugro's Seabed 2030 experience again, Fugro has developed and deployed remote command-and-control capabilities that allow it to efficiently and cost-effectively acquire bathymetry data during transits without the need for surveyors onboard vessels.

The next step in this technological evolution is to acquire bathymetry and other ocean science data from uncrewed and/or autonomous vehicles operating over the horizon for extended periods (see **Figure 3**). Such an approach was proven during a demonstration project in August 2020, when Fugro's partner SEA-KIT used an uncrewed surface vehicle to successfully complete a 22-day trial mission to map the seabed in the North Atlantic for Seabed 2030 and, by extension, the Ocean Decade.

While these examples are focused on ocean mapping, it is easy to see how similar solutions can be developed and used to support the collection and sharing of other ocean science data and information. To further accelerate innovation and the development of new technology, the Ocean Decade is actively promoting cross-sectoral partnerships that bring together innovators from government, academia, philanthropy, non-government organisations and the private sector.



▲ **Figure 3. An illustration of Fugro's remote and autonomous vehicles performing ocean mapping and ocean observations at an offshore windfarm development. (© Fugro)**

DEVELOPING SOLUTIONS

Human health and wellbeing that include sustainable and equitable economic development depend on the health and safety of the world's ocean.[5] In fact, one of the Ocean Decade outcomes envisioned is an accessible ocean with open and equitable access to data, information and technology, and innovation.[4] Equally important is the equitable access to the benefits generated by the ocean.

Policies that facilitate the equitable and sustainable development of the ocean economy are largely a government responsibility. However, the private sector also has an important role to play, by simply supporting and participating in the Ocean Decade, as described above through knowledge generation and technology innovation, the private sector is contributing to an accessible ocean with open and equitable access to data, information and technology, and innovation. However, these actions can and should be amplified to ensure that all nations, especially developing nations, not only have access to data, but also to the skills and infrastructure to maximise their use over the long term. Collaborations between government, industry, universities and local communities, as endorsed by the UN Ocean Decade, will help facilitate progress in this regard, leading to much-needed diversity, equity and inclusion in the use of ocean science for sustainable development.

Fugro's vision is to help create a safe and liveable world, so the company is very focused on working with its global clients and partners to develop exactly these types of partnership. As an example, Fugro is working to advance the concept of public–private partnerships that would expand the scope and scale of data being generated in support of offshore development projects such as offshore windfarms. Here, the initial private-sector investment in ocean science would be augmented by public-sector funding, generating greater access to ocean science knowledge among a wider user base, including the communities living and working in the region. Traditionally, ocean science data has been acquired solely to support the project at hand. In a world with increased emphasis on ocean stewardship through initiatives like the Ocean Decade, more equitable and sustainable approaches to developing the ocean economy are within reach.

WHY ENGAGE?

The private sector has much to gain from a healthy ocean, and much to lose from a depleted one. Understanding the ocean and oceanic processes is critical to mitigating development risks and recognising societal benefits in a sustainable ocean economy. Since industry is one of the beneficiaries of the ocean's shared resources, it has a responsibility to help ensure its longevity.

From Fugro's perspective, advancing ocean science through participation in the Ocean Decade is not just the right thing to do, it is the smart thing to do. The company has included support for the Ocean Decade and Seabed 2030 in its corporate sustainability programme with widespread approval from its employees, shareholders and customers. The company's involvement in these initiatives not only helps to improve ocean sustainability, it also highlights the value of the geodata, thus increasing demand for Fugro services. For other businesses, such as those involved in infrastructure development or resource management, participation will lead to improved scientific knowledge that can help reduce operating risks and open doors to new sustainable development opportunities.[4]

Theoretically, a tipping point in terms of private-sector support for the Ocean Decade will be reached if the number of industry leaders who prioritise ocean stewardship continues to grow. The result will bring new paradigms for responsible private-sector involvement in the growing ocean economy, along with opportunities to inform new ocean governance frameworks and influence the next generation of ocean professionals.[4,6] **ES**

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ANALYSIS

Climate-change impacts on coastal systems

Daniela Schmidt considers the synergies and tensions between mitigation, adaptation and resilience.

The ocean provides services to millions of people and is home to a vast number of species on our coastal sea bed. Over the last few decades, changes to the physical and chemical properties of the ocean have become measurable, indicating the profound impact that climate change is having on the ocean.[1,2] In addition to increasing warming and surface ocean density stratification (driven by temperature and salinity), marine heatwaves exert extreme pressures on marine ecosystems that often result in irreversible changes, as seen in the 2010–11 marine heatwave off Western Australia. Additionally, sea-level rise in coastal systems reduces habitat area for a wide range of benthic species if the change in sea level reduces the available habitat and is faster than the ability of the species to migrate or grow in the reduced light levels of the deeper waters. These physical changes are combined with changes in ocean chemistry, notably the decrease of ocean pH and dissolved oxygen.

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▲ **Figure 1. Diversity of the coastal systems exemplified by the kelp sub-canopy in Orkney showing a kaleidoscope of colour generated by kelp, encrusting and foliose red algae, and orange soft corals (dead man's fingers). (© Martin Sayer, Tritonia Scientific)**

Coastal areas display considerably higher environmental variability compared to the open oceans. For example, UK shelf waters have been warming by around 0.3–0.6 °C per decade over the last 30 years, with total global warming forecast to be in the range of 1.5–4 °C by 2100.[3] High increases in sea level are projected for the southern North Sea and the Atlantic coasts of the UK. Coastlines are also affected where large river systems discharge into coastal areas, and where cities and populated areas impact the coasts via effluents, water extraction (leading to subsidence) and infrastructure. River fluxes into coastal regions are projected to significantly change both seasonally (in response to wetter winters and drier, hotter summers) and in extreme weather conditions.[4] Changes in hydrology will impact riverine and sediment fluxes into coastal systems, which may be amplified by changes in catchment management upstream, and these will impact water clarity, ocean chemistry, primary productivity and habitat composition. Climate change threats are exacerbated by marine pollution, unsustainable use of marine resources, competing spatial claims and conflicts among a varied set of resource users. Given the current projection for CO_2 emissions – combined with habitat fragmentation and human-induced disturbances – these changes in the ocean environments are projected to accelerate in the coming decades.[2]

CLIMATE CHANGE AND MARINE ECOSYSTEMS

Climate change impacts are not an impending problem – they are currently altering our marine systems. A future loss of marine and coastal ecosystems – including their biodiversity and the ecosystem goods, functions and services they provide (see **Figure 1**) – is projected by the middle of this century, impacting coastal livelihoods including food, trade and sustainable energy production.[1]

Marine organisms are responding in many ways, including by phenotypic plasticity, acclimation and adapting to the novel environment. They may also have to evolve in the face of local extirpation or global extinction. The changes seen in marine organisms depend on habitat type, temperature gradient, thermal affinity (i.e. whether a species is adapted to warmer or cooler habitats) and the mobility of the species. Thus, it varies across regions, taxa and ecological groups as well as at the level of local environmental changes. The strongest current example of changes to individuals, populations and ecosystem is the redistribution of organisms. Range shifts along the leading edge of over 70 km per decade have been estimated across a wide range of taxa, though trailing-edge contractions have been significantly slower.[5] The fastest expansion is documented for highly mobile organisms such as plankton. These changes in plankton distribution have repercussions higher up the food chain and, combined with changes in fish distributions, are altering food webs and catch potentials.

Such local or global declines in abundance are combined with the often-overlooked degradation of ecosystem engineers, habitat-forming species and foundation species. The capacity to respond to climate change in many of these species is limited compared to mobile species, due to lower dispersion and hence lower ability to relocate. Dredging of the sea floor has impacted these systems over recent decades. Additionally, there is growing evidence that environmental changes also impact the shells and skeletons these organisms are made of, thereby threatening their stability, with the risk of loss of complexity of a population or ecosystem. Morphological responses within skeletal organisms can affect the ability to maintain structural integrity and form habitats for other species. These structural changes are hidden vulnerabilities that are often not well assessed[6] (see **Figure 2**).

ADAPTATION IN SOCIO-ECOLOGICAL SYSTEMS

Given the importance of marine systems for biodiversity, what kind of adaptation options are available to reduce the impacts of climate change? How are these interacting with mitigation options that focus on protecting human systems? Autonomous adaptation to climate change is clearly evidenced: migration, the spread of species that become invasive and local loss of abundance. However, the capacity of autonomous adaptation as a response to future climate change is not clear, nor are the resulting the limits of adaptation.[2]

MARINE PROTECTED AREAS

Importantly, there are barriers to autonomous adaptation. Marine protected areas (MPAs) are designed to ensure conservation and safeguard ecosystems and their services. Migration of species in response to climate-change challenges set the boundaries of MPAs that are defined by the species living in them. However, MPAs were not planned with climate change in mind, so we lack an assessment of which adaptation options work where, when and how. We also lack information about whether habitats and species will relocate in response to warming and how much habitat will be lost due to sea-level rise. Expected future migration needs to be part of the planning for such protected areas. These migrations do not consider national boundaries, thereby necessitating complex international agreements of protection.[7]

The number of MPAs is increasing rapidly but they are still fragmented and have differing levels of protection. Networks of protected areas, which use climate-change projections of habitat relocations, need be considered in the global goal to protect 30 per cent of the ocean by 2030, as they would facilitate the relocation of species and species interactions.

The largest power of MPAs is their ability to reduce secondary stressors, such as infrastructure development, sea-bed dredging, resource extraction and pollution. While MPAs cannot reduce the climate-change impacts that are global, they can provide frameworks to rebuild populations, increase structural complexity in habitats, and reduce the impacts of pollution. Regrettably, the management of MPAs in most countries is restricted to the marine environment, even though these coastal systems are highly dependent on the river fluxes into the ocean. Changes in land use along the river catchment can have impacts on sediment loads, for example.[8] Local action can reduce the impacts of acidification and oxygen loss by changing nutrient runoff into the coastal system, providing respite for these ecosystems and increasing resilience to heat and other stressors.

Any MPA, though, is only as strong as its own protection and the implementation of these measures. Many MPAs do not have clear governance and management plans that set out how local and national stakeholders will contribute to the management and support of the MPA. For effective climate-change adaptation of new and existing MPAs, it is important to understand what interventions are feasible and effective in response to particular climate-change scenarios in the light of technological, institutional, governance, economic, sociocultural and environmental factors.[9]

PATHWAYS TO RESILIENCE

UN Sustainable Development Goal (SDG) 14 focuses on 'life below water' with the aim to 'conserve and sustainably use the oceans, seas and marine resources for sustainable development'.[10] Functioning ecosystems are essential for meeting SDG 14 and supporting human wellbeing. It is important, however, to understand that SDG 14 is intimately linked to most other SDGs, most notably SDG 13 on combating climate change and its impacts; it will also benefit from SDG 12 on sustainable consumption patterns. In the past, the link between climate change, human health and the ocean focused on increases of harmful algal blooms of pathogens (such as vibrio) and their impacts on fisheries, tourism and human health. More recently,

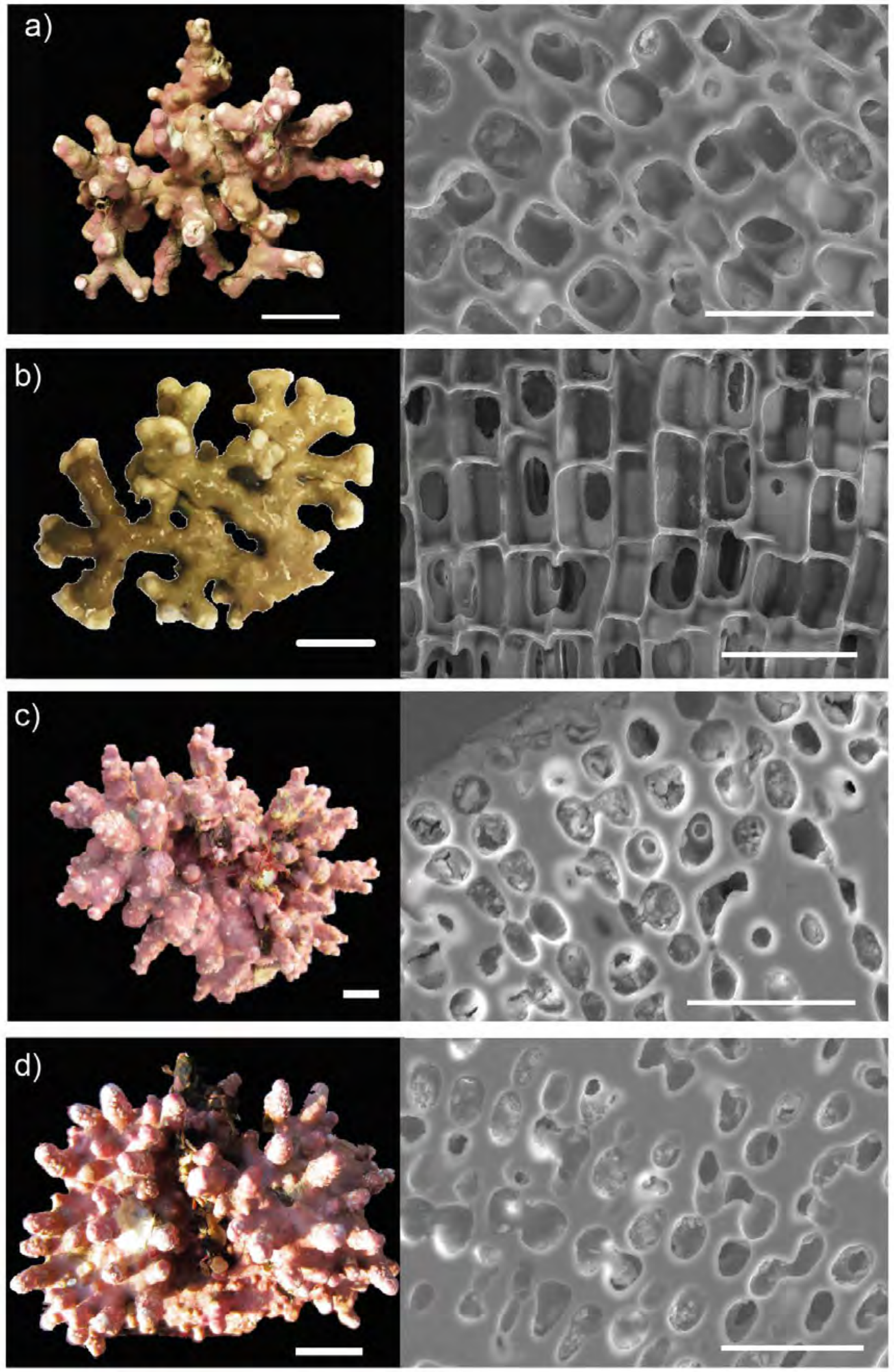

Figure 2. External and internal complexity of coralline algae from the UK coastal shelf: (a) *Phymatolithon calcareum* and (b) *Lithothamnion corallioides* from the south of the UK; and (c) *L. glaciale*; (d) *L. erinaceum* from Scotland. Note the strong differences in internal structure, with thin walls and open cells in the southern species resulting in a lower ability to withstand stress despite similar external growth. Scale bar: gross morphology 1 cm; cellular structure 30 µm. (© Leanne Melbourne, University of Bristol)

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the benefits of the ocean systems for humans are increasingly considered much more holistically, so there is more recognition of the benefits to human health and wellbeing, particularly to those who are deprived socio-economically.[11] Consequently, many other SDGs will benefit if we understand the coasts as socio-ecological systems with sustainable cities and communities (SDG 11), good health and wellbeing (SDG 3) and good-quality education (SDG 4).

Natural systems can also reduce the impacts of climate change as they provide coastal flood protection and reduce coastal erosion if the sea-level rise is slow enough for the ecosystem to respond. Coastal blue-carbon ecosystems, such as seagrass meadows, kelp forests, marshes, mangroves and coral reefs, are effective as natural carbon sinks. Diverse ecosystems also bring other benefits, such as tourism and fisheries.

Successful protection needs to include legal and economic considerations of how any adaptation or mitigation options impact on the local social and ecological resilience. This is especially important as the coming decades will bring decisions between mitigation actions to support human systems and ecosystems. There will be many difficult decisions, such as whether renewable energy systems should be built in coastal systems or whether infrastructure development against rising sea level should be allowed to remove habitats and their functions. Therefore, at any given location, the specific socio-ecological system needs to be understood to give the right balance of so-called 'soft' versus 'hard' solutions for adaptation and climate mitigation. ES

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Where warming land meets warming sea

Katharine R. Hendry and **Christian März** give an overview of the complexities of biogeochemical processes in polar coastal regions.

There is by now ample evidence, and scientific as well as societal and political recognition, that Earth's climate has been changing over the past decades. These changes are particularly pronounced in the Arctic and Antarctic land masses and oceans, where the trend of average global warming is amplified. As increasing temperatures affect the land, the ocean, ice sheets and sea ice in multiple ways, it is the nexus between these different environmental systems – the polar coasts and continental shelf seas – where changes are most rapid, direct, multilayered and least understood.

It is also in the polar coastal and shallow marine areas where environmental changes have the biggest and most immediate effects on society, including human livelihoods, infrastructure and essential resources. Many of these plainly visible and complex effects of rising temperatures are born out of invisible interactions between physical, chemical and biological processes in the soils, sediments, water and ice of the polar regions, collectively termed biogeochemical processes.

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FEATURE

PAST, PRESENT AND FUTURE BIOGEOCHEMISTRY

The discipline of biogeochemistry studies the complex interactions and feedbacks that exist between living organisms, dead organic material and inorganic chemical compounds in waters, soils, sediments and rocks. Biogeochemical processes are an intricate part of the global climate system. They operate everywhere and have done so for billions of years. In fact, an often overlooked aspect of modern climate change is that human resource extraction, and especially oil and gas burning, is linking biogeochemical processes that occurred in long-lost oceans to modern ones. In the Arctic region, vast amounts of atmospheric carbon dioxide originally locked up in organic material, then transformed into hydrocarbons tens of millions of years ago, are now being released as Arctic oil and gas exploration intensifies and increasingly moves offshore. This is just one example of a human-induced 'shortcut' within our planet's complex biogeochemical feedback systems, and such shortcuts disproportionately affect polar coastal regions.

Another prominent example is the accelerated thawing of permafrost that has existed around the Arctic Ocean for thousands of years.[1] Here, the multifaceted nature of Arctic warming is evident yet again: while permafrost thawing can lead to the release of methane (a potent greenhouse gas previously locked into the frozen soil) to the atmosphere, the coastal erosion of permafrost by warming and rising seas transfers huge amounts of organic material into the adjacent ocean, with a yet poorly understood effect on the global carbon cycle.

Lastly, the muddy deposits underlying polar coastal and shallow shelf seas hold huge stores of organic material (part of blue carbon, the carbon stored in coastal and marine ecosystems), derived from photosynthetic organisms like algae that extracted carbon dioxide out of the atmosphere decades to millennia ago. And while we know little about the different ways in which climate change can affect this carbon store just beneath the seafloor, it is certain that fishing by trawling ploughs up the seafloor, with a lasting negative effect on both carbon storage and seafloor ecosystems.[2] The risks of increasing trawling and offshore hydrocarbon exploration in polar coastal regions are exacerbated by the ongoing disappearance of summer sea ice, warming seas, ocean acidification and ecosystem shifts that make offshore economic activities more viable and affordable.[3] However, it needs to be recognised that such activities, while financially attractive in the short term, will further disturb biogeochemical systems and carbon stores that have been stable for long periods of time, leading to further environmental changes in the mid- to long-term that might be irreversible.

Besides such human-induced shortcuts in the long-term carbon cycle of polar coasts and shelf seas, there are many effects of ongoing climate and biogeochemical changes with more immediate societal relevance.

THE CLIMATE–OCEAN NEXUS: ARCTIC SOCIETY

High Arctic coastal regions mark not only the transition between land, ice and water, but are the focus of – often starkly direct – interactions between climate, ocean and society.[1] Landfast ice (ice that forms in shallow coastal waters) is becoming thinner and breaking up earlier in the boreal spring due to oceanic and atmospheric warming. Polynyas (stretches of open water) form naturally in sea ice and are essential for biogeochemical cycling through impacts on ocean circulation and sediment transport. With polar warming, polynyas are widening where sea ice is thinning, and vanishing as the sea ice disappears entirely.

Such coastal ice structures are essential for Indigenous communities, which rely on them for travel and hunting. Polynyas, for example, are rich in fish, birds and marine mammals, so any change in polynya physical and biogeochemical cycles will have bottom-up impacts on these ecosystems and natural resources. Several Arctic communities rely on icebergs and multiyear ice for drinking water, and are finding their supplies dwindling. On land, permafrost thawing results in rapid coastal erosion (**Figure 1**), and glacier retreat impacts river water and sediment transport, leading to changes in littoral biogeochemical cycling.[4] More directly, this erosion is resulting in widespread collapse of infrastructure, including housing, municipal buildings and communications networks, impacting communities that often lack resilience to such damage.

Despite being perceived as remote and pristine environments, Arctic coastal regions are highly susceptible to pollutants, the sources of which exhibit diverse and complex interactions with climate change. Run-off from rivers and melting permafrost and land ice can enhance the flux of natural chemicals past the shoreline that can cause imbalances in biogeochemical cycling, and can transport human-made pollutants from local communities.[5] For example, run-off from a wastewater system in Nunavut, Canada (**Figure 2**), has been shown to add excess nutrients to a coastal bay, leading to algal blooms and potentially resulting in future eutrophication and water deoxygenation.[6] International shipping is on the rise in the Arctic, in part because of the opening up of seaways as a result of thinning and shrinking sea ice. In addition to direct disruption of ecosystems through noise pollution, the presence of more ships adds more polluting hydrocarbon fuels and heavy metals into coastal waters.[7] Sources of Arctic pollutants can be far from local. Melting sea ice can dump atmospheric contaminants, such as volatile persistent organic pollutants (POPs), and POPs and microplastics are also transported vast distances in sea ice and ocean currents. To add to this complexity,

▲ **Figure 1. Eroding permafrost cliff in the Russian Lena delta. (© Jens Strauss [top] and Guido Grosse, Alfred Wegener Institute [bottom])**

▲ **Figure 2. Aerial view of Nunavut, Arctic Canada (top) and Cambridge Bay, Nunavut (bottom), both in early summer. (© Kate Hendry)**

melting Arctic sea ice can also be a source of atmospheric pollutants, acting as a feedback on aerosol distribution in lower latitudes.[8]

Impacts at the climate–ocean nexus are acting as multiple stressors on Arctic communities with severe consequences for human health, more often than not due to the actions of industrialised countries or regions south of the Arctic Circle. Direct impacts on human health, from changes in food and water supply to bioaccumulation of heavy metals and POPs, are exacerbated in areas where there is a lack of medical services. The resilience of such communities could be reduced even further through indirect climate impacts if infrastructure, communications and supplies are disrupted due to permafrost thaw, landslides and coastal erosion (**Box 1**).

However, it is crucial to remember that all of these impacts from biogeochemical changes in coastal Arctic regions are occurring in the context of other societal transformations, including drivers to enhance the development, connectivity, access and self-determination of Indigenous communities. These complex, interacting factors have severe implications for Indigenous culture and knowledge, education and mental health, and are inherently linked with environmental justice and sustainable development.

BOX 1. THE IPCC ON IMPACTS OF ARCTIC COASTAL EROSION

'Harvesters of renewable resources are adjusting timing of activities to changes in seasonality and less safe ice travel conditions. Municipalities and industry are addressing infrastructure failures associated with flooding and thawing permafrost, and coastal communities and cooperating agencies are in some cases planning for relocation (*high confidence*). In spite of these adaptations, many groups are making decisions without adequate knowledge to forecast near- and long-term conditions, and without the funding, skills and institutional support to engage fully in planning processes (*high confidence*).'[1]

WHAT DO WE NEED TO KNOW?

The achievement of the Sustainable Development Goals in the High Arctic must consider resilience to climatic and oceanographic change as well as access of rights holders to healthy resources. Marine science and biogeochemistry play an important role in improving our understanding of the critical processes underlying the cycling of carbon, nutrients and pollutants, and the implications for local communities of complex and multiple stressors on natural systems.

Currently, we have limited understanding of how several Arctic biogeochemical processes function, and low confidence in our predictions of how these

BOX 2. THE IPCC ON ARCTIC KNOWLEDGE GAPS

'There are clear regional gaps in knowledge of polar ecosystems and biodiversity, and insufficient population estimates/trends for many key species. Biodiversity projections are limited by key uncertainties regarding the potential for organisms to adapt to habitat change and the resilience of foodweb structures. Relatedly, knowledge gaps exist concerning how fisheries target levels will change alongside environmental change and how to incorporate this into decision making. Similarly, there are knowledge gaps on the extent to which changes in the availability of resources to subsistence harvesters affects food security of households...

There is limited understanding concerning the resources that are needed for successful adaptation responses and about the effectiveness of institutions in supporting adaptation. While the occurrence of regime shifts in polar systems is both documented and anticipated, there is little or no understanding of their preconditions or of indicators that would help pre-empt them.'[1]

processes will continue to respond to climatic change and impact ecosystems into the future (**Box 2**). We need a better grasp of the cycling of carbon and natural nutrients between surface waters and shallow seafloor sediments (called 'pelagic–benthic coupling'), and how contaminants are recycled or stored within continental shelf systems. We need to understand and quantify the impacts of changes relating to glacial ice melt and glacier dynamics on the quality of drinking water and the supply of nutrients and pollutants to shorelines. And we need to understand the risks to ecosystem and human health of eutrophication and algal blooms, microplastics, heavy metals and POPs.

Biogeochemists cannot answer these timely questions alone, and need to work with other scientific fields, such as medicine and engineering. Biogeochemists must also embrace opportunities to engage more broadly with sociologists, economists, legal experts, historians and policy-makers. Such wide-reaching and cross-discipline research will only be possible with buy-in from funding organisations, preferably via bi- or multilateral international collaborations that last longer than a few years. Lastly, and most critically, future scientific and political decision-making surrounding the coastal realm must be co-produced with representatives of Indigenous communities, integrating traditional knowledge to mitigate, adapt and build resilience against future changes at the climate–ocean nexus. ES

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FEATURE

Multi-hazard early-warning services

Steve Hall assesses what is needed for a complex mix of ever-changing risks.

According to the United Nations, some 40 per cent of all people live within 100 km of the coast, with a very high proportion living and working on land that lies at less than 10 m above present-day sea level. There are many reasons why humans want to live near coastlines, ranging from access to trade and commerce to availability of resources, suitable level building sites for factories, houses and infrastructure, availability of marine food, minerals and energy – and the pleasure of living in a beautiful coastal location.

While living near the coast offers many benefits, it also places people and infrastructure in harm's way for natural hazards such as flooding, coastal erosion and storm surges. In those parts of the world that have the right geological conditions for earthquakes and offshore landslides, inundation from tsunami is also a threat. Global warming adds to the mix, giving us new extremes – heavier rainfall, higher waves, more powerful and frequent storms, and a steadily rising sea level. Not all coastal hazards are driven by wind and water – oil spills, pipeline failures, harmful algal blooms, nuclear accidents and pollution incidents all pose threats to human and animal life, requiring detection and response at the earliest possible stage.

The UN Decade of Ocean Science for Sustainable Development offers a once-in-a-generation opportunity for the global marine science, policy and industry communities to apply their collective knowledge, research and outreach skills to help address and mitigate the risks and maximise the benefits of living near the coast.

MULTI-HAZARD ASSESSMENT SYSTEMS

Given this rich and complex mix of threats, we have an ongoing requirement to develop and install appropriate, reliable and affordable early-warning services for geophysical, ecological, biological, weather, climate and anthropogenic ocean and coastal hazards. These are needed for communities, industry and emergency services to have sufficient warning to preserve life, property and infrastructure, and restore safe functionality as quickly as possible after an event.

With limited resources, systems that offer utility across several different kinds of hazard offer the most value – this is what is termed a multi-hazard approach. The Ocean Decade will help a variety of organisations from many nations work together to build these systems, based on best practice and lessons learned in previous years.

The World Meteorological Organisation describes a four-stage approach to multi-hazard response:

- Hazards are detected, monitored and forecast, and hazard warnings are developed;
- Risks are analysed and this information is incorporated into warning messages;
- Warnings are issued (by a designated authoritative source) and disseminated in good time to authorities and public at risk;
- Community-based emergency plans are activated in response to warnings so as to reduce impact on lives and livelihoods.[1]

The last two points are important – having superb sensors and procedures is pointless if the public cannot receive the warnings, or do not know how to react to them, so a key part of multi-hazard warning is training the local population on how to react and ensuring that they receive warnings in time to react (see **Figure 1**). Here the experience gained by the global tsunami warning networks coordinated by the Intergovernmental Oceanographic Commission (IOC) will greatly assist during the Ocean Decade period and beyond.

▲ **Figure 1. The author with multi-hazard warning staff from the Turks and Caicos and British Virgin Islands at an IOC tsunami-warning training session. (© Steve Hall)**

FEATURE

▲ **Figure 2. Anguilla in the Caribbean – a typical low-lying community vulnerable to storm surges and tsunamis. The jetty is a robust structure potentially suitable for mounting sensors such as a tide gauge for storm-surge and tsunami warnings. (© Steve Hall)**

DETECTING THE HAZARDS

Coastal states require networks of sensors, supported by scientists, technicians and trained citizen-scientists able to receive, understand and react to the data that warns us of encroaching threats. For example, tide gauges at coastal locations are relatively inexpensive, do not require constant human supervision and can be easily networked into early-warning systems. A tide gauge not only senses changes in sea level caused by tides, but also by changes driven by variations in atmospheric pressure or an approaching tsunami. With the right density and spacing of observations, entire coastal regions and groupings of neighbouring countries can be given several hours' warning, allowing the local authorities and population time to act (see **Figure 2**).

Larger regions, indeed whole ocean basins, can be protected by satellite remote sensing, which transmits weather updates and hurricane warnings, and warns of oil spills, harmful algal blooms, storm surges and extreme wave fields.

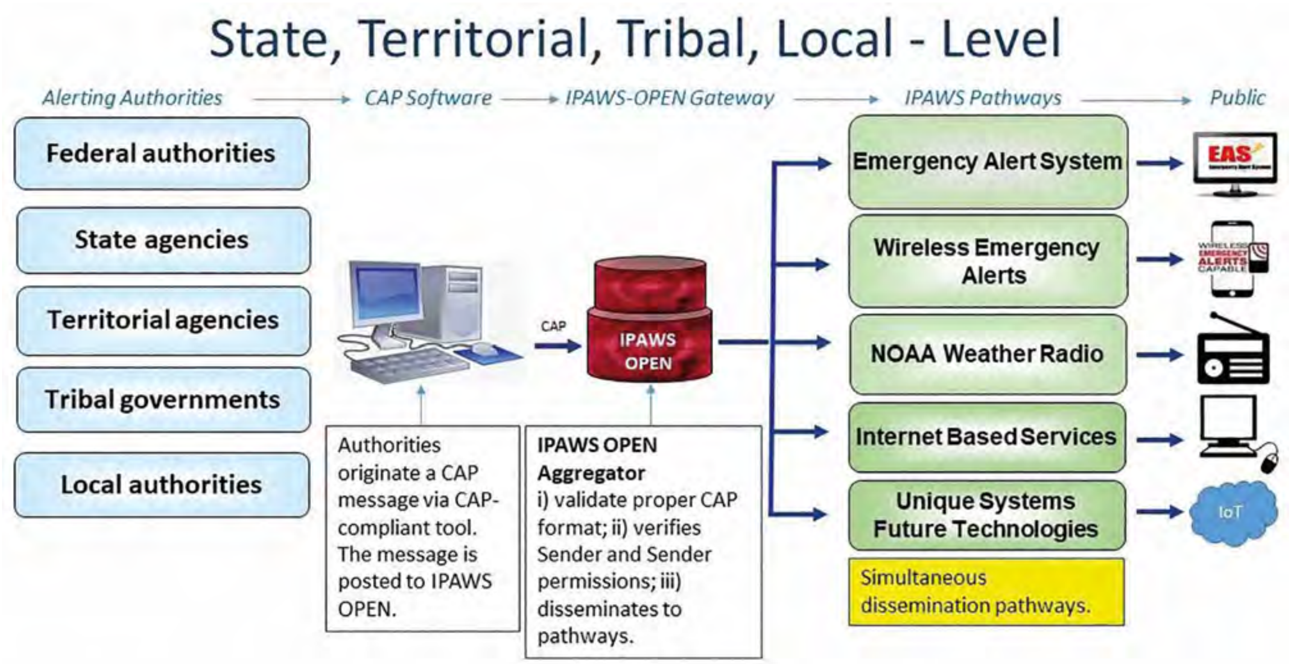
RISK REGISTERS

Many nation states have a national risk register, a regularly updated document compiled by experts that lists all the threats a nation may face – warfare, terrorism, pandemics, earthquakes, volcanism, organised crime, nuclear accidents, even asteroid strikes. Risk registers list the nature of the threat, the consequences of it occurring, any possible mitigation measures and the likelihood of it happening at all. A storm surge is not a rare event, so would be classified as a high-risk, high-probability event, whereas an asteroid impact would be high risk, low probability so might not have any mitigation measures attached to it. For low-lying coastal states, or those with rapidly eroding coastlines, there will be a section dedicated to coastal issues, often with detailed emergency response plans.

Having identified which hazards apply to a particular location, such as tsunamis, storm surges, flood risks or toxic algal blooms, suitable early-warning devices are developed, selected, purchased and installed, sometimes with aid money in nations with limited resources.

TELLING THE PUBLIC

Once the sensors have detected that a hazard is imminent or developing, the warning needs to be



▲ **Figure 3. Flowchart of the US IPAWS system.[4]**

spread as fast as possible to the target audience. At the simplest level, warnings can be given by siren, klaxon or bell, but these methods obviously only work within hearing distance. If they are manually operated they need someone to be available to receive the warning message by phone, text, fax, email or pager who can then set off the warning, this leads to considerable variability in the speed of response – if any! Also, that kind of response, while appropriate for a tsunami, is not needed for a hazard such as a harmful algal bloom or even an oil spill, which does not pose the same urgent risk to life, though the authorities and the public still need to be informed and able to respond in the best way.

The early-warning community learned that 'reaching the last mile' was a major problem when the Indian Ocean tsunami of 2004 happened:[2] warnings were received by the authorities even in quite remote coastal locations, but they had no means of getting the warning to coastal communities in time. Since then, the widespread availability of mobile telephones and smartphones even in the least-developed nations has allowed authorities to use new kinds of information and communication technologies as the most effective tools for multi-hazard early-warning system communication.

Mobile phone messaging has many advantages over a siren in that more information can be conveyed, and there is the versatility to address several different kinds of hazard or impact. It is also possible to address multiple simultaneous hazards that might require different kinds of reaction by the public. A text message might be able to state the nature of the emergency, the time available to react and action to be taken. Multilingual instructions can be used, and pictograms and locational data added for smartphone users.

Recognising that the technology is now so widespread across the world, the common alerting protocol[3] has been adopted by the International Telecommunications Union (ITU, the United Nations specialist agency for telecommunications and information and communication technologies) as the common international telecommunications format for exchanging multi-hazard emergency alerts and public warnings over all kinds of networks. This allows simultaneous emergency messaging over many different warning systems, increasing warning effectiveness while simplifying the warning task.

The common alerting protocol works with mobile and landline telephones, the internet (including email), Google, Facebook, Twitter, WhatsApp, smartphone apps, online advertising, Internet of Things devices, in-home smart speakers such as Alexa, indoor and outdoor sirens, broadcast radio and television, cable television, emergency radio, amateur radio, satellite direct broadcast, digital signage networks such as motorway signs, billboards and road and rail traffic controls. This ensures that the maximum possible number of people can be alerted before the hazardous event places them at risk of death or injury. The common alerting protocol is also appropriate for less lethal hazards that people still need to know about, such as instructions to avoid entering a situation such as an ongoing terrorism incident.

Common alerting protocol capabilities include:

- Geographic targeting using three-dimensional geospatial representations;
- Multilingual and multi-audience messages;
- Message update and cancellation functions;
- Template support to frame complete and effective warning messages; and
- Digital encryption support and signature.

A good example of use of the common alerting protocol is the system used in the USA, the Integrated Public Alert & Warning System[4] (IPAWS; see **Figure 3**), which provides authenticated emergency and life-saving information to the public through mobile phones using wireless emergency alerts, radio and television via the emergency alert system, and on the National Oceanic and Atmospheric Administration's weather radio.

The Ocean Decade will include initiatives that roll out these capabilities to regions of the world that have poor coverage at present, taking advantage of constantly improving access to telecommunications equipment, the internet and smartphone ownership.

THE SENDAI FRAMEWORK

As indicated in the previous section, despite the advances made in technology, there are still gaps in multi-hazard warning, especially in reaching the 'last mile'. There are also gaps in the ability to reach the most vulnerable and remote populations, or those who may lack the physical or mental capacity to understand or react to warnings.

To help address this, the United Nations Office for Disaster Risk Reduction and such partners as the IOC and World Meteorological Organisation established the International Network for Multi-Hazard Early Warning Systems (IN-MHEWS). This was one of the outcomes of the Third UN World Conference on Disaster Risk Reduction at Sendai, Japan in 2015 to support the Sendai Framework on Disaster Risk Reduction 2015–2030.[5] IN-MHEWS facilitates the sharing of expertise and good practice for multi-hazard early-warning systems for disaster risk reduction, climate-change adaptation, and building resilience. In addition, it aims to guide and advocate the implementation and/or improvement of multi-hazard early-warning systems, share lessons learned regarding early warning, and increase the efficiency of investments in such systems for enhanced societal resilience. The 'last mile' remains a challenge, but the IN-MHEWS partnerships help to ensure that local populations are trained to know what that particular warning signal or text alert means, so that they know how to respond.

▲ **Figure 4. Tsunami hazard zone signage near a low-lying beach on the island of Anguilla in the Caribbean. (© Steve Hall)**

An example of a good training system that makes good use of IN-MHEWS best practise is the one used within the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE-EWS) IOC Caribbean grouping of coastal and small island states, for warning of tsunamis or storm surges.[6] Exercises are held on an annual basis: local social media, television, newspapers and radio alert the population to the date and time of the test, common alerting protocol messages are sent (with 'test' shown prominently!) and schools, factories and workplaces all take part in practise sessions where people rehearse how to respond by moving to higher ground or climbing to upper levels of robust buildings, followed by the all-clear signal. Simple warning signs help the population remember their training and indicate safe evacuation routes (see **Figure 4**).

THE FUTURE

The world remains on track for population growth to more than 9 billion humans by the middle part of this century, with many of the new arrivals expected to live in countries or regions that are already densely populated, are vulnerable to flooding, and have limited infrastructure for disaster prevention and relief. Advanced economies may be less vulnerable in some respects, but still need warning systems for major hazards. The Ocean Decade will help address some of the shortfalls in multi-hazard early warning to vulnerable coastal communities and remote regions, especially as fast internet connections become available across the planet.

Common alerting protocol messages, fed with accurate data by sensors, human operators and satellite remote sensing systems, are able to provide sufficient warning to allow many to survive who might otherwise have been killed or injured. However, even the best systems cannot entirely eliminate the consequences of major natural disasters. The IN-MHEWS and the Sendai Framework will contribute to risk reduction and adaptation, and improved digital interconnectivity will help individuals and communities to receive appropriate safety alerts in ways that are constantly improving, with near-real-time warning of hazards for almost all coastal communities. ES

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USEFUL LINK

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FEATURE

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Building resilience to coastal hazards using tide gauges

Angela Hibbert describes the instrumentation that helps to warn of tsunamis and tidal surges.

The loss of life and physical devastation caused by the Indian Ocean tsunami of 2004 demonstrated that while large tsunamis may be infrequent, their impact can be disproportionately high when compared to other natural hazards. Tsunamis are a type of long wave, whose speed is proportional to the square root of water depth, meaning that they can rapidly propagate through the deep ocean. On reaching shallower coastal areas, the wave slows down and its kinetic energy is converted to potential energy, heightening the wave crest, sometimes by several tens of metres. So, while tsunamis may be barely detectable in the open ocean, they are highly destructive at the coast – indeed the Indian Ocean tsunami attained heights of up to 30 m and, in some places, extended 3 km inland.[1] This notable event galvanised governmental cooperation to mitigate such disasters in the future. Under the coordination of the Intergovernmental Oceanographic Commission (IOC), dedicated tsunami warning systems soon developed in the Indian Ocean, north-east Atlantic, Mediterranean and Caribbean regions.

TIDE GAUGES IN EARLY-WARNING SYSTEMS

Today, these warning systems generally comprise an array of seismic sensors to detect earthquakes, together with computer models that calculate the likely magnitude, direction of travel and arrival time of tsunamis that might be generated by these seismic disturbances. Within minutes of a seismic event, model-based tsunami alerts are released to member states. The authorities invoke emergency measures, so the reliability of these alerts is vital. Unnecessary evacuations are costly and can reduce the credibility of tsunami alerts, causing them to be largely ignored.

Therefore a network of sea-level monitoring stations is a third vital component of a tsunami warning system and mainly comprises tide gauges (although there are also open-ocean tsunami-detection moorings, known as DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys. These tides gauges are coastal instruments that continuously monitor the height of the sea surface at a particular location (see **Box 1**). Their observations are transmitted in near-real time to warning centres where they are used to either confirm an alert or cancel it when the danger has passed. Their data are also used to improve numerical tsunami models, and thereby minimise the number of false alerts.

It is important to note that tsunamis can also be generated by processes other than submarine earthquakes – the three Storegga landslides that occurred in the Norwegian Sea around 8,200 years ago induced such large tsunamis in the North Atlantic Ocean that they are believed to have deposited oceanic sediments many kilometres inland.[2] Tsunamis caused by volcanic eruptions, such as Anak Krakatau, Indonesia in 2018, can also have devastating impacts. These days, tide gauges are likely to be the first means of detecting landslide and volcano-driven tsunamis (since seismic networks are not geared to their detection), so tide gauges are doubly important to tsunami mitigation efforts. Consequently, since 2004, the development of resilient tsunami-capable tide gauge networks was a central focus of programmes such as the IOC's ODINAfrica (Ocean Data and Information Network for Africa),[3] which installed and upgraded tide gauges around Africa.

While the Sumatra tsunami may have provided the impetus to enhance and expand tide gauge networks, these are also used increasingly for storm surge early-warning purposes, via real-time monitoring of individual surge events and validation of storm surge model alerts. In the hurricane-prone Caribbean region, for instance, the operational role of tide gauges is clearly implied by the name of the regional network: the Intergovernmental Coordination Group for Tsunamis and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE-EWS). Although they are slower-moving than tsunamis and therefore allow for greater preparedness, storm surges are persistent and often as destructive as tsunamis – tropical cyclone Bhola, for example, led to the loss of an estimated 500,000 lives on the northern Indian Ocean coast in 1970.[4]

MULTI-HAZARD TIDE GAUGE SYSTEMS

Sadly, while the value of tide gauges to early-warning systems is now well established, their scientific importance is often overlooked. If sea-level monitoring is sustained over several decades, these records become even more useful, for example, in evaluating the combined statistics of the probability of both extreme tides and storm surges to improve predictability. These statistics, in turn, inform coastal engineers in the design of sea defences and, of course, lengthy tide gauge records allow scientists to estimate the long-term trends in mean sea level that are associated with climate change. Long-term change is particularly important, as coastal inundation becomes increasingly likely if hazards such as storm surges and high tides are superimposed upon increased mean sea levels, meaning that short-term hazards become exacerbated by long-term trends.[5] So these days, tide gauge networks are increasingly viewed as multi-hazard warning systems.

However, a good understanding of *all* sea-level hazards demands high-quality sustained observations. This can only be assured through dedicated long-term funding and skilled local operators to maintain instruments and fully use data. These are key challenges even for well-established tide gauge networks, let alone for small island developing states and lesser developed countries, which, coincidentally, are so often vulnerable to coastal hazards, due to low elevation, hurricane activity or tsunami threat. As a result, fledgling tide gauge networks risk falling into disrepair or may be little used beyond satisfying their international early-warning obligations. National activities, such as the provision of basic tidal information to assist in port operations and safety at sea, are often ignored.

The Intergovernmental Coordination Groups of the IOC, such as ICG/CARIBE-EWS, have sought to address these challenges by identifying funding gaps and lobbying governments accordingly for financial support. For example, since 2005, ICG/CARIBE-EWS has worked with international and regional partners, donors and

BOX 1. TIDE GAUGE TECHNOLOGY

Automatic tide gauges have been around in one form or another for 200 years. Earlier mechanical models were known as float gauges and consisted of a disc-shaped float contained within a large vertical tube (the stilling well) with an opening to the sea. The stilling well removed much of the wave action, and the float would rise and fall with the tide, its movements being recorded on a paper chart on a clock-driven chart recorder by a pen that was connected to the float via a pulley system.

Although some float gauges remain in place, modern sensors are predominantly underwater pressure transducers (which measure sea-level height from the hydrostatic pressure of the overlying water column) or above-water systems such as radar or acoustic sensors (which calculate the distance to the sea surface using reflected radar or acoustic pulses). Tsunami-capable tide gauges often use a combination of the two technologies (see **Figure 1**) for added resilience: while surface-mounted systems are easier to maintain and therefore less likely to fall into disrepair, underwater systems cannot be overtopped during extreme events such as tsunamis.

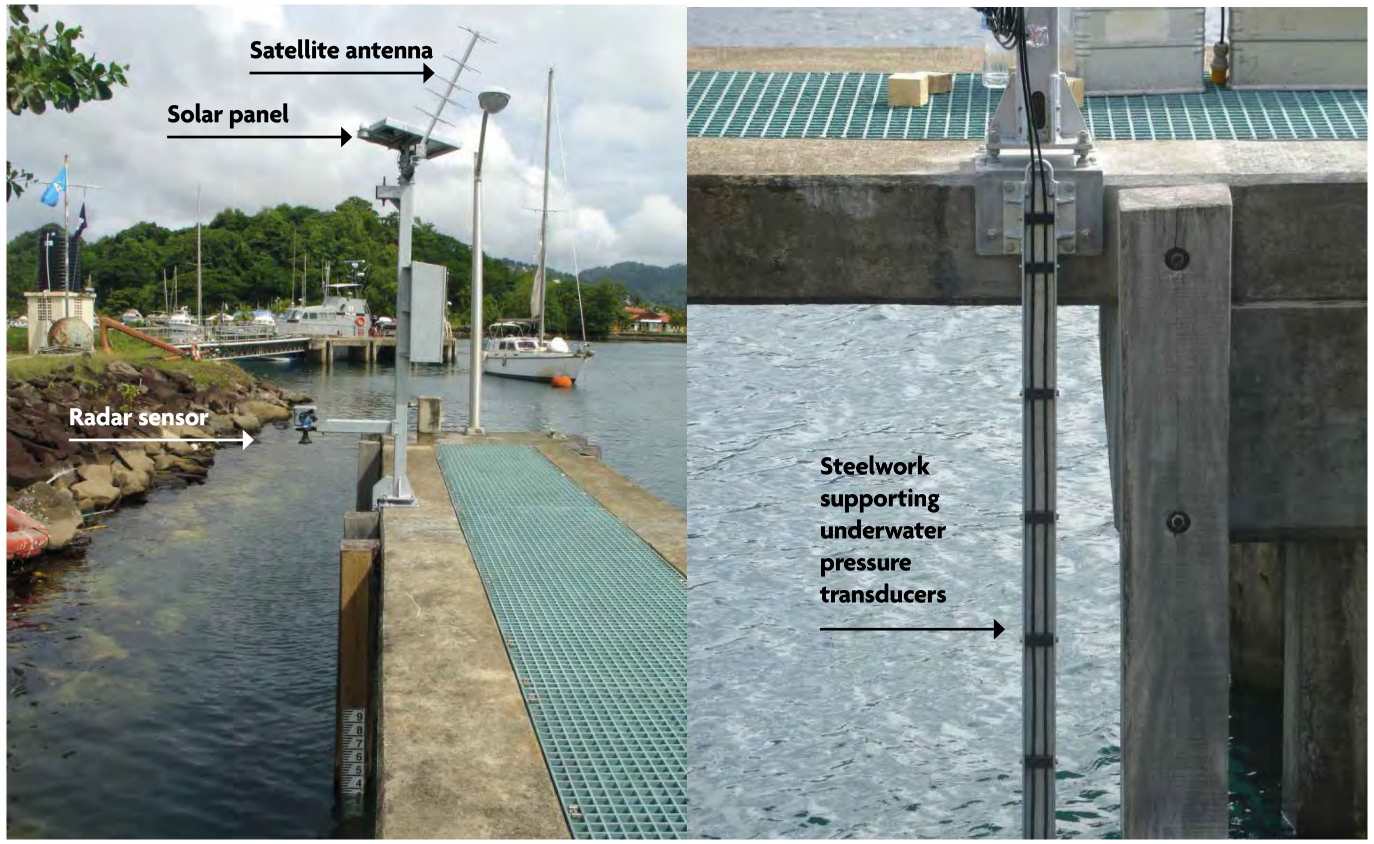


Figure 1. A solar-powered tsunami-capable tide gauge at Ganters Bay, St Lucia, with dual measurement technologies (radar and pressure sensors) and satellite telecommunications. The right-hand panel shows a side view of the supporting steelwork and power lines to the underwater pressure transducers. The gauge was installed by the NOC through the Commonwealth Marine Economies Programme. (© Jeff Pugh, NOC)

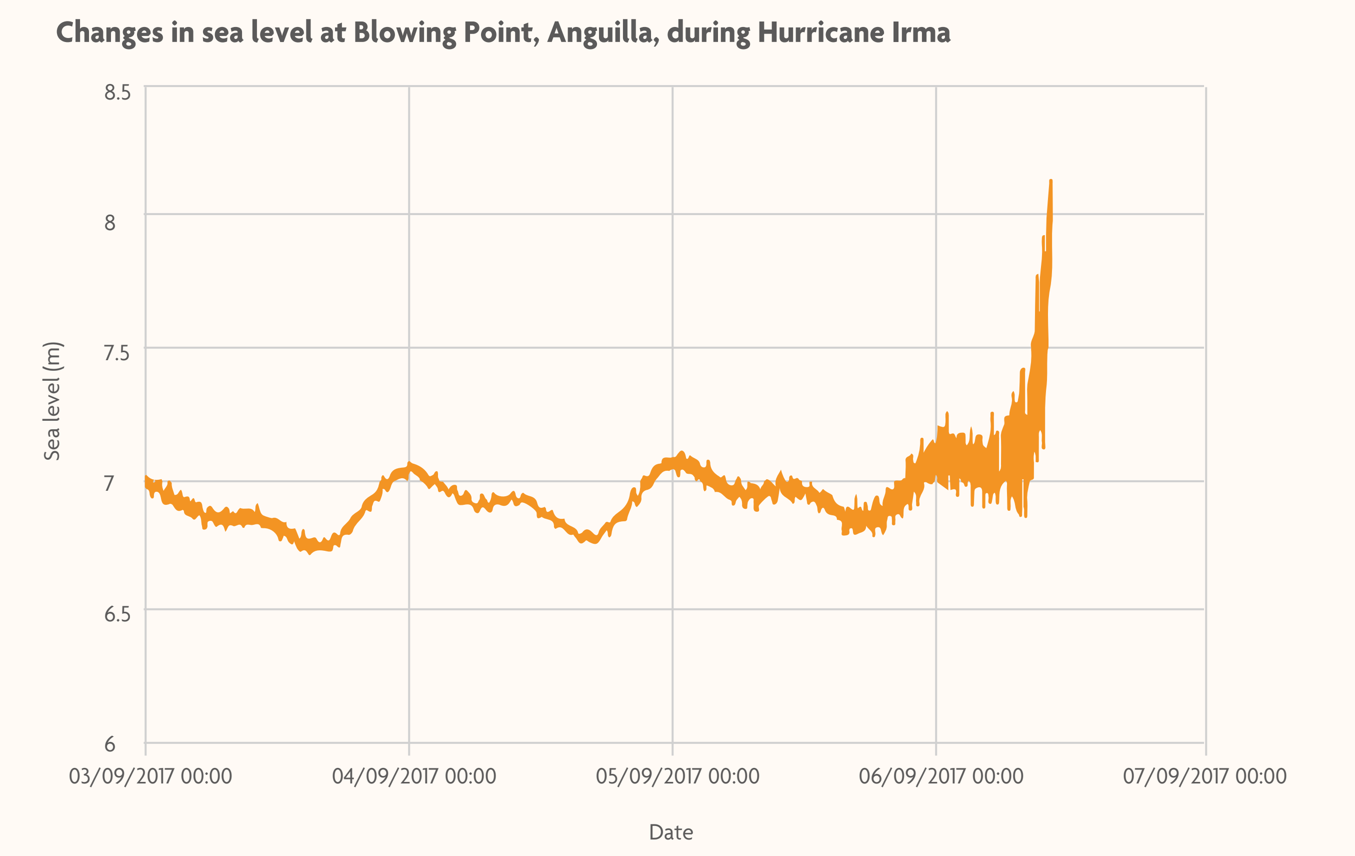
Figure 2. Delegates and trainers at the 6th ICG/CARIBE-EWS Short Course on Sea Level Station Installation, Maintenance and Levelling, Quality Control and Data Analysis 26 February–2 March 2018, Mexico City. The author is seated third from left. (© IOC)

its 48 member states and territories and succeeded in increasing the number of tide gauges sharing data in real time from a handful in 2005 to 80 prior to the 2017 hurricane season. Even so, funding often remains sporadic, prompting the development of tide gauge technology that is low maintenance and has minimal operating costs, while still offering the resilience required to withstand harsh hurricane conditions. Tide gauges such as those installed by the National Oceanography Centre (NOC) in St Lucia, Belize (see **Box 2**) and Dominica between 2016 and 2018 have combined solar-powered technology and free-to-use geostationary satellite communications systems in order to minimise utility costs to local operators, while robust marine-grade steel stanchions have been used to mount tide gauge sensors and supporting electronics (**Figure 1**).

At the same time, ICG/CARIBE-EWS (alongside international partners) has promoted the longevity of the regional tide gauge network by delivering annual or biennial training courses to local tide gauge operators in tide gauge maintenance and early-warning systems (**Figure 2**). More recently, this capacity-building work has been extended to upskilling local tide gauge operators to quality control tide gauge records and produce tidal information, which is a significant step along the path to increasing local capacity to use these data to address their scientific and societal needs.

Autumn 2017 saw the arrival of two powerful hurricanes, Irma and Maria, which swept through the north-eastern Caribbean. Hurricane Irma developed in the Western Tropical Atlantic in late August, intensified as it moved westwards and attained category 5 status by the time it arrived in the Leeward Islands and Virgin Islands on 5 September. The tide gauge at Blowing Point, Anguilla recorded a 1 m surge before it was obliterated (**Figure 3**). Irma continued westwards in the three days that followed, causing inundation in Cuba, Haiti and the Dominican Republic, before making landfall over Florida. Just two weeks later, the category 5 Hurricane Maria hit Dominica, damaging or destroying 90 per cent of the buildings on the island before moving through the Leeward Islands and arriving in Puerto Rico as a category 4 event.

In all, hurricanes Irma and Maria were recorded by 30 and 32, respectively, of the ICG/CARIBE-EWS tide gauges. While the majority withstood the hurricane conditions, nine tide gauges were damaged or destroyed, serving as a timely reminder that work to improve tide gauge resilience is by no means complete. For ICG/CARIBE-EWS, 'hardening' their stations has now become a key priority and a number of their members and supporters have worked to develop and install more robust tide gauge equipment (**Figure 4**).



▲ **Figure 3. Data from the tide gauge at Blowing Point, Anguilla, during Hurricane Irma. The time series ended when the tide gauge was swept into the sea. (Courtesy of Jerard Jardin, Jardin Sea Level Systems)**

BOX 2. BELIZE – A CASE STUDY

Coastal inundation poses a significant threat to Belize, as around 40 per cent of the population resides in the coastal zone and offshore reef areas, while the population centre, Belize City, has an elevation of only about 50 cm above sea level. The combination of Belize's low elevation, together with its location in a region of both hurricane and seismic activity, means that it is particularly vulnerable to coastal hazards such as tsunamis, storm surges and the longer-term impacts of sea-level rise associated with climate change. This was exemplified by the impact of Hurricane Hattie in 1961, which destroyed about 75 per cent of buildings in Belize City, leaving more than 300 people dead and 10,000 homeless, and leading to the relocation of the Capital City 80 km inland to Belmopan.[8]

An acoustic tide gauge was installed in 1998 in Belize City and was upgraded in 2007, but by 2011 it had fallen into disrepair. A donor organisation had subsequently supplied the local meteorological service with radar sensors but they lacked the capacity and supporting equipment to install these. In late 2017, funded by Commonwealth Marine Economies Programme (which is funded by the UK government), the NOC installed a low-cost, low-maintenance radar-based tide gauge, training local operators in installation and maintenance procedures. Ongoing technical support is provided jointly by the NOC and ICG/CARIBE-EWS.

▲ **Dual radar sensors installed by the NOC at Belize City beneath a jetty walkway, where they are safe from damage by shipping. (© Jeff Pugh, NOC)**

TECHNOLOGY INNOVATIONS

One potential route to improving tide gauge resilience harnesses global navigation satellite system (GNSS) technology to monitor the sea surface from buildings and higher ground, thus minimising the risk of damage to the tide gauge. GNSS receivers (**Figure 5**) are more conventionally used to measure changes in land elevation by the detection of positioning and timing information from a constellation of navigational satellites such as GPS (USA), GLONASS (Russia), BeiDou (China) and GALILEO (Europe). Their observations are a valuable means of detecting land motion trends to help understand the long-term sea-level trends derived from tide gauge records, so they are often sited alongside tide gauges.

Over the last decade, it has become apparent that the strength of the GNSS signal at a receiver (and therefore the quality of the positions) can be affected by the local surroundings as a direct GNSS signal and its reflection off a nearby object will interfere. It turns out that where the signal is reflected off a relatively flat surface, such

▲ **Figure 4. Post-hurricane remains of the Blowing Point tide gauge shown alongside the newly installed 'hardened' replacement system. (© Jerard Jardin, Jardin Sea Level Systems)**

▲ **Figure 5. A GNSS receiver installed at Ruperts Bay, St Helena. (© Alan Hudson)**

FEATURE

as the sea, the combination of the direct and reflected signal (the signal-to-noise ratio) will exhibit a periodic variation, with a frequency that varies according to the elevation of the satellite and the level of the sea surface; this allows sea-level height to be inferred. Currently, this emerging technology, known as GNSS interferometric reflectometry (GNSS-IR) does not afford the frequency of sampling (<1 minute) or latency of communications (<6 minutes) that is ideal for tsunami-capable systems, but it is a promising technique for locations where conventional tide gauges might be unsuitable or where the tsunami risk is lower. GNSS-IR is also currently being incorporated into a number of prototype European tide gauge systems as a secondary technology.

It is important to emphasise that funding challenges are not peculiar to newly emerged tide gauge networks such as ICG/CARIBE-EWS. Some British Overseas Territories, including Montserrat and Pitcairn Island, lack any form of sea-level monitoring,[6] while a 2016 survey of European tide gauge operators by the European Global Ocean Observing System (EuroGOOS) indicated that 23 of the 40 respondents faced an uncertain funding scenario.[7] This has led some institutions to adapt to their own needs the low-cost, low-maintenance technology solutions that were originally designed for developing countries. However, such technology upgrades themselves demand significant investment.

It is unsurprising, then, that the United Nation's Decade of Ocean Science for Sustainable Development aims, as one of its key challenges (challenge 6) to 'Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience'. This is a most welcome and timely development for those working in the coastal hazards community towards achieving the Ocean Decade outcome of 'a safe ocean'. ES

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FEATURE

Ocean data, information and knowledge systems

John Siddorn outlines the observing system value chain we need to have the ocean we want.

We depend on the ocean for so much of what we do, from essential marine industries and transport to the vital role the oceans have in moderating weather and climate (including the water cycle, which has a direct impact on our daily lives). Despite the fact that some regions of the ocean feel so remote from our day-to-day worlds, we all recognise the vital life-supporting services provided by the ocean, and the increasing importance in understanding what is happening to and in it.

To ensure the safety of those in and around our marine environments, to support economic activity in our marine environment (often termed the 'blue economy') and to manage the health of our marine systems, ocean monitoring and prediction services are becoming increasingly important. These prediction services generally rely on observations of the marine environment combined with modelling to give the service providers a picture of the state of the oceans that can be used in their decision-making processes.

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GATHERING DATA

These ocean predictions and their use in providing services for public good are not new. Early operational forecasts of water levels around UK coastlines were implemented in response to a devastating surge event in 1953, when there was widespread coastal flooding across the East of England that prompted the installation of tide gauges around the UK. Such events can not only have significant economic impacts but also have catastrophic consequences for coastal communities if they are not well predicted. The deadliest storm surge on record was the 1970 Bhola cyclone, which killed up to 500,000 people in the area of the Bay of Bengal. Thankfully, forecasting services now mean that there is generally forewarning of such events, and if integrated well with emergency response such loss of life can be avoided; subsequent storms of comparable magnitude have not had the same catastrophic impact.

Soon after these early surge systems, wave models were introduced to forecast the sea state for mariners and commercial operators. Today, they are also used in combination with surge modelling to forecast coastal flooding and provide a well-established part of the armoury for predicting and monitoring extreme weather events. More recently, ocean forecasting and monitoring services have expanded from solving essentially two-dimensional wave equations for storm surges and surface waves to include the fully three-dimensional state of the ocean. A number of ocean forecasting services were developed in the late 20th century, initially largely driven by the requirements from navies to understand the depth-resolved currents (for diver operations, mine hunting and vessel operations) and the depth-varying density and optical properties (for submarine operations and detection).

A number of other users also use ocean analysis and forecast services, most notable (for the UK at least) being the renewable and oil and gas industries, which have huge infrastructure programmes in areas like the North Sea and other, deeper waters. To operate safely (and within the law) they require an understanding of the physical environment in which they are working, including the particularly challenging need to have accurate historical information about, and predictions of, currents. Additionally, the increasing emphasis on monitoring the marine environment under legislation such as the Marine Strategy Framework Directive (MSFD) is driving the need to monitor the marine environment at levels not presently achievable.

Alongside these statutory drivers, other users of the marine environment, such as the aquacultural industry, also require good-quality marine information that goes beyond the physical information (currents, waves and temperature) to environmental information (for example nutrients and plankton blooms) that are harder to measure and to model. This creates significant challenges for service providers and increases the need for the marine community to invest in an increasingly all-encompassing marine observation and monitoring programme.

USES OF DATA

Observations of the marine environment are fundamental to the ocean prediction community in a number of ways. Without observations, we would not have the underpinning scientific understanding of the ocean, and the marine environment, that allows us to provide information and advice. Moreover, once we have provided a prediction or information product, we need to be able to provide some analysis about the uncertainty in that product to help in the decision-making process. Fundamental to understanding uncertainty are the processes of validation and verification that rely upon comparing observations with models.

Finally, and increasingly, we make use of observations to constrain our predictions through a process called data assimilation, a mathematical discipline that seeks to optimally combine theory (usually in the form of a numerical model) with observations, using an understanding of the relative errors in both. Using data assimilation, many millions of individual pieces of information collected that day from diverse sources and with diverse characteristics – from ships, moorings, autonomous platforms (robots collecting data) and from satellites – are combined with computer models to produce a coherent (in space and time), actionable picture of the ocean.

To do this effectively we not only need observations, but we need observations at sufficient time and space resolution, and with well-described error characteristics. Presently, timeliness, coverage and the ancillary error information could all be improved upon, even for those types of observation that are readily available. When it comes to predictions of marine health, where the observing capability is far less mature (and more difficult), this is particularly limiting.

DATA GATHERING IN THE MARINE ENVIRONMENT

The marine environment is a challenging one for those of us who wish to predict it: it is wet, deep and remote. It is therefore expensive and difficult to obtain information from, especially the remote ocean interior. However, recent decades have seen significant advances in observing capability. Satellite oceanography has made a dramatic difference since the 1990s, when we started receiving measurements of the sea level from space. Shortly afterwards the Argo programme[1] resulted in thousands of profilers being deployed to drift with the ocean currents 2 km below the ocean surface. Every 10 days, floats come to the surface, transmitting the data they collect via satellite. These data are used, critically, by operational service providers, within hours of being transmitted. This has unmasked the ocean interior in a way previously unimaginable to oceanographers. These, and many other observing campaigns, are the backbone of the services critical to the health, wealth and wellbeing of coastal nations. Of course, we always want more and as services become more sophisticated the need for more, and many different kinds of, observations of the ocean grows.

As scientists, we are also conscious of, and striving to better represent, the interconnectedness of our world. Changes in our seas on one side of the world have an impact on the weather days, weeks and months later elsewhere. Rain that falls upon the mountains on our continents flow through rivers, picking up pollutants and nutrients on their way through estuaries into our seas, impacting upon fisheries that sustain our coastal communities. This interconnectedness is driving an increased interest in the states of our oceans by our meteorological services, with, for example, the Met Office soon to release their first weather predictions that incorporate dynamic modelling of the world's oceans.[2] This broadening of the scope of ocean information also provides added impetus to the need to better understand and monitor our oceans and seas.

IMPLICATIONS OF THE UN OCEAN DECADE

For those of us involved in studying and predicting the oceans with a view to providing services to the public and industry, the UN Decade of Ocean Science for Sustainable Development has the potential to fundamentally change what we are able to do. The Ocean Decade implementation plan makes clear that we are aiming for a transformative change to the stewardship of our oceans:

'The Decade will support ocean data, information, and knowledge systems to evolve to a much higher level of readiness, accessibility, and interoperability. The scale of such efforts will need to be exponentially greater than anything seen to date.'[3]

Particularly important for ocean prediction services is challenge 7: 'Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users.'[3]

Challenge 7 speaks to improving the end-to-end value chain for ocean observations, from collection to quality control, incorporation into an information service, and distribution. This ambition to make tangible changes to the availability of observations, and to their usability, will dramatically enhance the quality of the information and the range of marine services possible. An improvement in the number, availability and usability of observations is particularly timely for the ocean community, given that a lot of the ocean-observing network is sustained through research programmes and is therefore less integrated and well-coordinated than is often true in other disciplines.

The Ocean Decade provides a framework in which ocean observation and the services it underpins can be put on a much more sustainable footing, and we must make sure this opportunity is not missed. However, it is also critical for those of us in the ocean sciences community to recognise the far-reaching social and economic impacts of the Covid-19 pandemic and how that may affect investment in ocean research and observation.

While advocating for the need to invest in our oceans, we must demonstrate that any investment is having maximal impact and is providing an outcome of significant societal benefit. That means ensuring that the data we produce, and the information we derive from it, is usable, and reusable, so that society really sees value in the work we do. The Ocean Decade challenges our community to make sure that future generations have the oceans they want, and frames these challenges to ensure we really do demonstrate this societal impact and value. It is therefore particularly timely and provides an opportunity that we cannot afford to let slip.

ES

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FEATURE

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The Global Ocean Observing System

Emma Heslop advocates for fit-for-purpose ocean observing as a foundational step towards the success of the Ocean Decade.

The Ocean Decade is a major opportunity for society to halt long-term decline in the marine environment and to ensure that future ocean decisions are based on solid foundations. It has the full backing of the United Nations, and will be highlighted this year throughout the UK's G7 presidency and hosting of COP26. Attaining a fit-for-purpose ocean observing and forecasting system will be a fundamental step towards success in the Ocean Decade – we cannot make sound decisions without information, and cannot manage what we cannot measure.

Long-term ocean observations allow us to better understand climate change and variability, and improve our forecasting of climate, weather, ocean status, and environmental hazards and their impacts. Achieving sustainability at global, regional and local scales will require a comprehensive understanding of the current and projected state of our ocean, seas and coasts, across interlinked physical, biogeochemical and biological realms. Ocean information provides an evidence base for real-time decision-making, tracking the effectiveness of management actions, and guiding adaptive responses on the pathway to sustainable development. Enhancing our ability to provide relevant information is vital to addressing societal needs, and building resilience and climate adaptation strategies. It is also the foundation for sustained and vibrant marine ecosystems. Ocean knowledge and information also have the power to generate jobs and profits in a sustainable marine economy. By 2030, the ocean economy is predicted to be a much larger component of many national economies.[1]

THE ROLE OF OBSERVATIONS

Today, observations provide the backbone for ocean and weather forecasts; they also deliver understanding of the ocean's role in the global climate system and the climate's impact on the ocean. However, it is clear that to meet the growing demands of policy-makers, private-sector users and the general public, we need a step change in the breadth and extent of the ocean observing system.

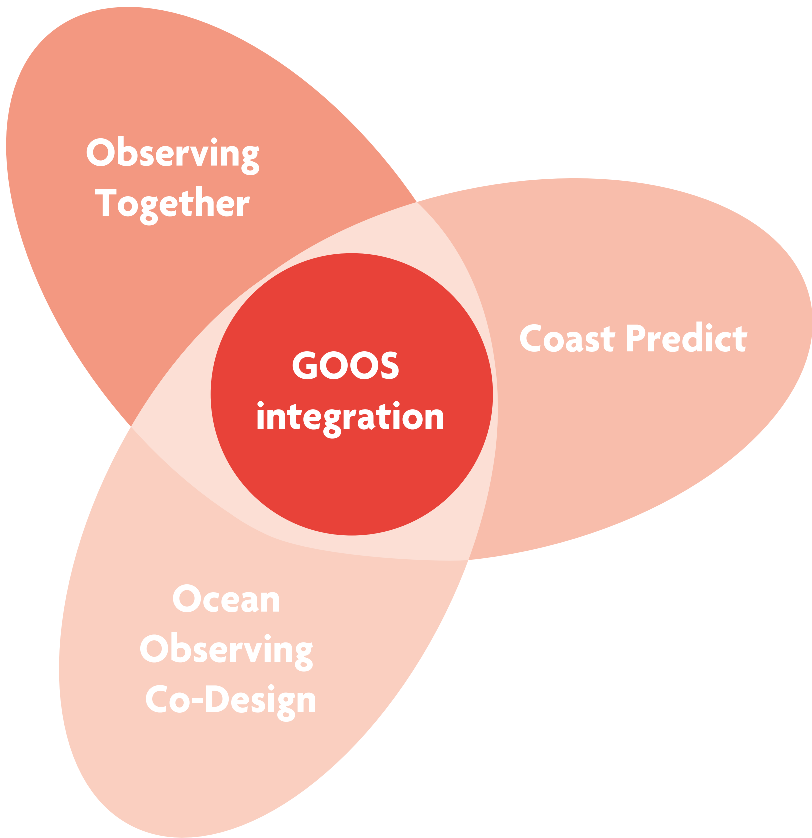
The Ocean Decade outcomes of a healthy and resilient ocean, a productive ocean, a predicted ocean, a safe ocean and a clean ocean will all rely on fit-for-purpose observations flowing from an integrated observing system connected to prediction, assessment, science and information services. These will deliver information to those who need it in a timely manner. The Ocean Decade is delivering the opportunity for the ocean community to take a long view and think big about what is needed, and with a decade perspective we can achieve this transformation, starting with the foundational steps.

The need for the expansion of a global ocean observing system, designed to meet the requirements of a broad suite of users, is clear and urgent. It was outlined in the Global Ocean Observing System 2030 Strategy,[2] which identified a vision for a truly integrated global ocean observing system that delivers the essential information needed for our sustainable development, safety, wellbeing and prosperity. It also identified that GOOS cannot achieve this vision alone, and that it will take partnership to grow an integrated, responsive and sustained observing system.

KEY AREAS FOR ACTION

The Global Ocean Observing System (GOOS) took up the transformational challenge of the Ocean Decade and identified three key areas for action, where bridging gaps will have a significant impact on the Ocean Decade outcomes: connecting the open ocean to the coast, integrated system design, and connection from observing through to communities. With strong partnership, three linked GOOS Ocean Decade programmes have been developed (see **Figure 1**), all with a focus on transforming the observing system through integration:

- **Ocean Observing Co-Design (ObsCoDe):** creating the process, infrastructure and tools for the co-design of a fit-for-purpose GOOS;
- **CoastPredict:** will transform the science of observing and predicting the global coastal ocean, from river catchments to the urban ocean (where the coastal ocean is markedly influenced by the human presence) to the oceanic slope waters; and
- **Observing Together:** supporting communities to bring needed observations and forecasts to users and into global data streams, making every observation count.



▲ **Figure 1. The three GOOS programmes are focused around the core theme of integration – integration down the value chain to users, with the modelling community, from open ocean to coast, across the physical, biogeochemical and biological realms, and as many nations and communities into the global system as possible.**

The programmes are united in being transformational for the Ocean Decade and the GOOS 2030 Strategy. These programmes intersect and it is anticipated that elements will converge to one integrated system by the close of the decade. **Box 1** details the high-level objectives of all three programmes.

We cannot achieve the ambition of the Ocean Decade with a business-as-usual approach and here the Ocean Decade is, again, having a beneficial effect. It has been the stimulation for a kind of speed dating across organisations and programmes, creating new connections and partnerships that have strong potential for progress towards an integrated system.

THE GOOS DECADE PROGRAMMES

ObsCoDe aims to transform the ocean observing system assessment and design process, creating a system co-designed with observing, modelling and key user stakeholders. The programme will work with existing and new observing networks, and closely couple with the modelling community across assessment, assimilation and prediction, to support the development of an integrated and agile ocean observing system with linked prediction capabilities. Readily available and fit-for-purpose ocean information is a foundational element in achieving the ocean we want by 2030. Through integrated observation and modelling capability, we can track the current state and future variability of the ocean, enable skilful predictions and warnings, manage ocean resources, empower society to adapt to change, and ultimately, assess the impact of action towards a sustainable ocean. The programme aims to build the process, infrastructure and tools for co-design, creating an international capacity to evolve a truly integrated ocean observing system, matching agile observing and modelling capability with requirements. By 2030 this programme will advance the maturity and robustness of the global ocean observing and forecasting enterprise, moving towards an integrated system that will raise permanent support and increase the impact of investment.

Key to this is a broad partnership with the modelling community, the observing community and user stakeholders. The programme will assess fitness for purpose through the use of observing system exemplars – examples of end-user need areas – to drive synthesis of requirements, and diagnostics on observing system status. The process, infrastructure, and tools for co-design will be created through building on existing infrastructure and developing innovation through projects and partnership, for example with other Ocean Decade initiatives: ForeSea, which will contain common project elements with ObsCoDe, CoastPredict, Marine Life 2030 and the Digital Twins of the Ocean (DITTO).

CoastPredict[3] will transform the science of observing and predicting the Global Coastal Ocean, from river catchments, including urban scales, to the oceanic slope waters. It will integrate observations with numerical models to improve prediction, with uncertainties, from extreme events to climate, for coastal marine ecosystems, and for biodiversity; co-designing a transformative response to science and societal needs in the coastal zone.

BOX 1. GOOS PROGRAMME HIGH-LEVEL OBJECTIVES

ObsCoDe:

- Integrate observing and modelling to support a sustainable ocean and society in ways that are measurably better;
- Make ocean observing and information appreciably more impactful through transformative co-design with the modelling community and key user stakeholders;
- Establish the international capacity and modular infrastructure to co-design and regularly evaluate the observing system; and
- Entrain new observing and information technology across all elements of the programme.

CoastPredict:

- A predicted global coastal ocean;
- The upgrade to a fit-for-purpose oceanographic information infrastructure; and
- Co-design and implementation of an integrated coastal ocean observing and forecasting system adhering to best practices and standards, designed as a global framework and implemented locally.

Observing Together:

- Equitable and practical access to ocean observations enabled by engagement and co-design with local observation and stakeholder communities;
- A truly global ocean observing system that makes a greater number of global and local observations available, integrated, interoperable and comparable;
- Strengthened connections, mutual understanding and improved knowledge sharing between ocean observers and the stakeholder communities they serve, at the global and local scales;
- Increased evidence that ocean observations are applied to solve problems and inform decision-making at community, national, regional and global levels; and
- Efficient design and use of ocean observations to maximise return on investment.

CoastPredict will re-define the concept of the global coastal ocean, focusing on the many common worldwide features, to produce observations and predictions of natural variability and human-induced changes in the coastal areas. It will upgrade the infrastructure for the exchange of data with standard protocols. By the end of the decade observations and modelling will be integrated in the coastal ocean. The programme anticipates projects across key societal impact areas and will require new observing and new modelling technology to be developed.

Observing Together aims to transform ocean data access and availability by connecting ocean observers and the communities they serve, through enhanced support to both new and existing community-scale projects. Globally, many communities are unable to access ocean data in decision-ready formats and so cannot see the value of investment in ocean observations. Co-design will broaden equitable access to and relevant application of ocean knowledge by a myriad of stakeholders. It will leverage the GOOS's network of expertise to bring needed observations and forecasts to community users and into global data streams, making every observation count.

This multi-year programme will provide a platform for connecting inter-disciplinary projects under the Ocean Decade that seek a deeper understanding of regional ocean issues and will build partnerships across the value chain – from observing networks through data and forecasting systems to scientific analysis and assessments, and service providers and users. The programme will assist ocean observers to work within the GOOS Framework for Ocean Observing (FOO) and enable the observations to be integrated into end-products designed to meet specific stakeholder needs. GOOS expertise, resources, partnerships and networks will be applied to deepen engagement throughout the ocean data ecosystem to advance the application and impact of observations, and to demonstrate benefits and increase return on investment. By assisting such efforts to enhance their practices and contribute to the GOOS, there will be considerable added value to the projects, the Ocean Decade, and the global stakeholder community.

See **Box 2** for more information about GOOS.

A GROWING CLUSTER OF ACTIONS

There are also many exciting ocean observing actions dedicated to supporting the closing of specific gaps in our ocean observing and forecasting system coming up from within the observing community, such as: Marine Life 2030, focused around biological monitoring; Observing Air-Sea Interactions Strategy (OASIS), focused around improving air–sea flux monitoring; the Biomolecular Ocean Observing Network (BOON), focused around genetic monitoring; Odyssey, focused around enabling new observing contributors from recreational or working users of the ocean; Deep Ocean Observing Strategy (DOOS), focused around deep-sea observing; OceanPractices, supporting ocean stakeholders in sharing and collectively advancing ocean methodologies across the value chain; OneArgo, focused on expanding biogeochemistry, deep monitoring and high-latitude Argo float monitoring, MegaMove, focused on using animal tracks and behaviour for spatial management and conservation; and GO-SHIP Evolve, focused on developing global ocean ship-based hydrographic investigations (GO-SHIP) biological and ecosystem monitoring, and enabling more nations to participate.

In addition, there are actions beyond observations that will also have strong links to the GOOS programmes, including ForeSea, where modelling and observational objectives are supported through collaboration between ForeSea, Ocean Observing Co-Design, CoastPredict and DITTO, which will enable users to explore and understand the consequences of specific interventions within a digital ocean.

This is just to mention a few. The first call for actions in the Ocean Decade has received over 200 submissions, a significant proportion of which have been identified as related to ocean observing. This perhaps indicates the foundational role of observations in meeting the Ocean Decade challenges.

BOX 2. ABOUT GOOS

Since 1991, we have been leading the development of a truly global ocean observing system that delivers the essential information needed for our sustainable development, safety, wellbeing and prosperity. GOOS is led by the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and co-sponsored by the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP) and the International Science Council (ISC). We lead and support a community of international, regional and national ocean observing programmes, governments, UN agencies, research organisations and individual scientists. There are seven elements to the GOOS core team:

- **The GOOS Steering Committee:** a multinational body that provides direction to the GOOS core team in implementing its strategic objectives and building outside partnerships;
- **Expert Panels:** the Physics and Climate, Biochemistry and Biology and Ecosystems Panels are vital for identifying user needs and evaluating the system;
- **The Observations Coordination Group:** the OCG strengthens GOOS implementation by coordinating the system through 12 global observing networks and the monitoring, metadata and visualisation activities of OceanOPS (part of the monitoring infrastucture);
- **The Expert Team on Operational Ocean Forecast Systems:** ETOOFS guides initiatives to improve the capacity, quality and interoperability of ocean model forecast products;
- **GOOS regional alliances:** GRAs identify, enable and develop GOOS ocean monitoring and services to meet regional and national priorities;
- **Projects:** advancing innovation and expanding the observing system, services and product delivery by expanding into new areas and capabilities; and
- **The GOOS office:** the GOOS core team works full time to enable the GOOS core to function, and to enable connection across the observing enterprise.

Through these components GOOS supports a community encompassing all those playing a role in the observing system: international, regional and national observing programmes, governments, UN agencies, research organizations and individual scientists. By working together on observing tools and technology, the free flow of data, information systems, forecasts, and scientific analysis, this global community can leverage the value of all these investments.

GALVANISING FOR THE DECADE

There has already been a positive impact from the Ocean Decade in galvanising the community to look at long-term goals and form the partnerships that will be needed to reach them. This year will see the Ocean Decade meeting its first real test as these programmes will begin to seek investment. The base for this investment has the potential to be broad – encompassing philanthropy, governments, NGOs and industry. With the establishment of national decade committees, there are promising signs that the UK and other nations are taking the challenge of the Ocean Decade seriously, and understand that strategic investment now, across Ocean Decade actions, can have a major impact on human and ocean wellbeing.

We cannot pretend that the outcomes for the ocean and society are disconnected. The Ocean Decade offers a wealth of initiatives for long-term beneficial change, and careful investment will reap big rewards for society. ES

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FEATURE

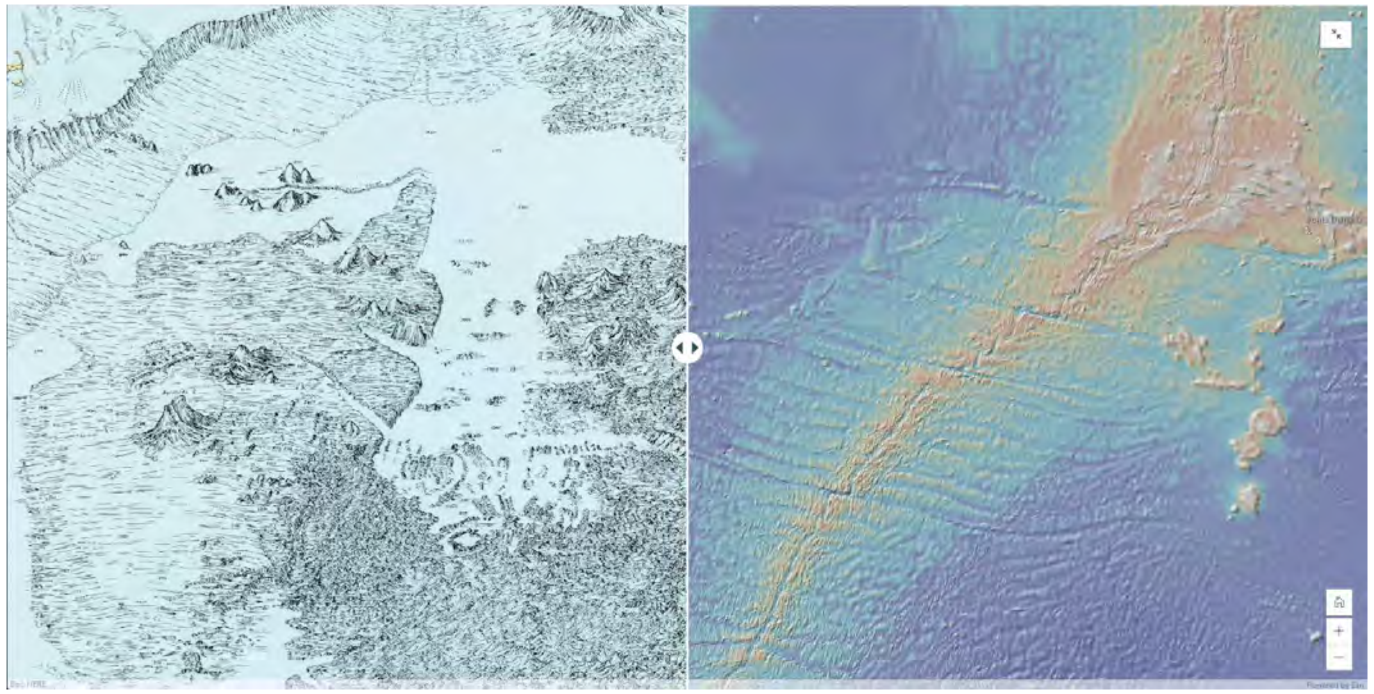
Mapping the world's ocean

Helen Snaith describes the technology and partnerships required to achieve the Seabed 2030 project.

When we view maps and travel routes on our phones and computers, we take for granted that we know the surface that is being portrayed: the shape of the coastline, the height of the hills and the width of the valleys. This has been achieved through generations of dedicated surveyors using theodolites and levelling staffs, often driven by the need to plan roads or other transport routes, or for military planning. More recently, large areas have been mapped from space using satellite techniques. The Shuttle Radar Topography Mission[1] was one such major mapping initiative that gave us an almost-global view of the shape of our land surfaces. Similar techniques have been applied to the Moon and Mars. But for more than two-thirds of the Earth, we have a serious problem when trying to determine the shape of the surface: it is covered by water. And water is incredibly effective at hiding what lies below. This means that we are restricted to either direct *in situ* measurements of the ocean floor, or inferred measurements from space or airborne sensors.

HOW DO WE MEASURE OCEAN DEPTH?

As with much land-based mapping, the primary drivers for mapping the ocean floor have been transport or military related. Almost every nation with a sea border has some form of hydrographic mapping service dedicated to providing charts and other information for safety of navigation at sea. Clearly, the focus has been on the dangerous shallow waters, with measurements of bathymetry (water depth), by depth-pole and plumb lines common for hundreds of years. Deep-ocean measurements came along much later, in the early 20th century, when acoustic sensors were developed to take advantage of the propagation of sound through water. These acoustic sensors were able to detect the seafloor even in the open ocean. The early single-beam sensors have now developed into highly accurate multibeam systems, able to accurately map swaths of the ocean seafloor. But even these modern sensors have to contend with the physics of transmission through water, limiting the spatial resolution they can obtain and the rate at which data can be collected.



▲ **Figure 1. Heezen and Tharp's 1959 map of the North Atlantic, determined from sparse acoustic transects (left) and the GEBCO 2020 grid (right). The slider view of these maps in the story map[5] highlights the remarkable skills of Marie Tharp in interpolating sparse data using geological knowledge, but also demonstrates the complexity and detail of the seafloor now observed through modern measurements. (© LDEO/V. Ferrini)**

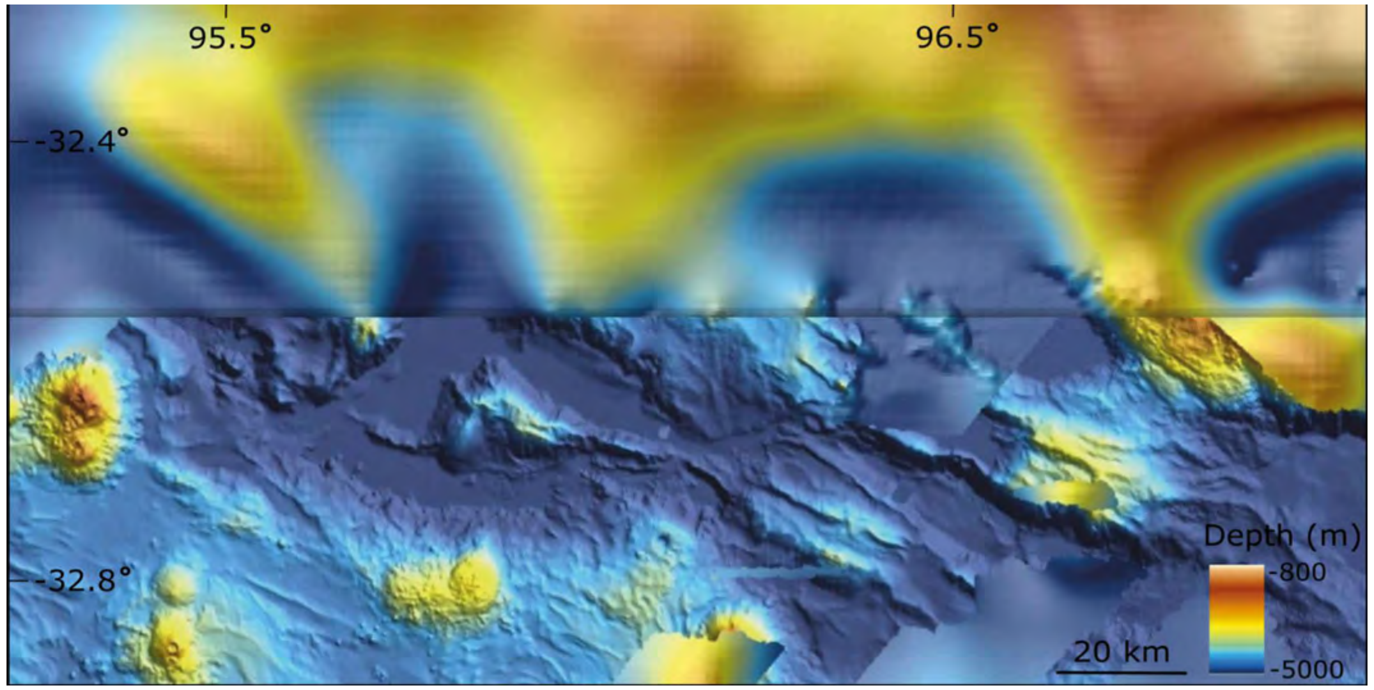
Lidar (light detection and ranging) was developed in the 1970s, and uses airborne laser to determine the difference in return from the seafloor and the sea surface. But these systems can only penetrate to depths of around 70 m even in clear waters,[2] and typically less than 30 m, limiting the depth range they can apply to. Other satellite or airborne instruments can be used to infer water depth from surface properties. The relative absorption of different wavelengths of light by water with depth can be used to infer water depth from surface 'colour', specifically the surface-leaving radiance of different wavelengths of light, and this is used in satellite-derived bathymetry.[3] This technique is limited to relatively clear, shallow waters and should be calibrated to particular water and seafloor characteristics to obtain accurate measurements. But it is an excellent method of mapping some remote areas, for example around atolls or coral reefs.

The shape of the seafloor has a direct impact on the shape of the sea surface, through local variation in gravity. For example, a seamount has a greater mass and therefore higher gravitational attraction than the same volume of seawater, so it will pull the sea surface into a bulge over the top of the mount. Similarly, a trench will have lower gravity and the sea surface will form a matching trench. Satellite altimetry allows the surface of the ocean to be measured and the gravitational slopes inferred can be used to predict the sea floor. The first global maps using this technique[4] enabled a huge step forward in our understanding of global bathymetric features. Until this time, global bathymetry maps were effectively interpolated from incredibly sparse data points, maybe hundreds of kilometres apart. In fact, the sparsity of data makes the accuracy of the early ocean basin maps, such as that of Marie Tharpe in 1959 (see **Figure 1**), really remarkable.

But only seafloor features with wavelengths (horizontal scales) of four times the water depth will have a signal in the sea surface and hence in predicted bathymetry. And all the fine-scale detail is lost. So this view is very blurred when compared to the high resolution view we can obtain from modern multibeam sensors, as shown in **Figure 2**.

WHAT DO WE KNOW SO FAR?

By 2014, the most complete ocean bathymetric maps, such as the General Bathymetric Chart of the Ocean (GEBCO) 2014 grid, were being created as a mix of satellite-predicted bathymetry and the best available observational data. That dataset was produced on a global grid with a spatial resolution of 30 arc seconds (1/120 degree) in latitude and longitude, and only 16 per cent of values were based on actual observations rather than predicted bathymetry.



▲ **Figure 2. Curtain view of the seafloor around Broken Ridge (top) and Diamantina Trench (bottom) in the Southeast Indian Ocean. The image shows a comparison of the resolution in bathymetry data between satellite-derived bathymetry (top) and multibeam bathymetry that was acquired to assist the search for Malaysia Airline flight MH370 (bottom). (Image modified from the MH370 storymap; Australian Government, 2017)**

With the adoption of the UN Sustainable Development Goals (SDGs) in 2016, and particularly SDG 14 Life below water, it became clear that our understanding of the seafloor was going to be critical to underpinning the science needed to support many of the targets – how do you identify key conservation targets if you don't understand the seafloor you need to conserve?

SEABED 2030

The recognition in the mid-2000s that so little of the world's ocean had been mapped led to the Forum for Future Ocean Floor Mapping. The Forum was held in June 2016 and brought together over 150 senior representatives, scientists and scholars from major ocean-related and international organisations to discuss the importance of understanding the shape of the ocean floor.

The Forum led to the creation of The Nippon Foundation-GEBCO Seabed 2030 Project, which has the ambitious vision of facilitating the complete mapping of the ocean floor by the year 2030. It aims to bring together all available bathymetric data to produce the definitive map of the world ocean floor and make it freely available to all. The project was launched at the UN Ocean Conference in June 2017.

Since then the project has established four Regional Centers and a Global Center, and is managed by a project director. The Regional Centers are responsible for championing mapping activities; assembling and compiling bathymetric information and collaborating with existing mapping initiatives in their regions. The Global Center is responsible for producing and delivering centralised GEBCO products, such as bathymetric grids.

▼ **Table 1. Seabed 2030 resolution targets at different depth ranges[6]**

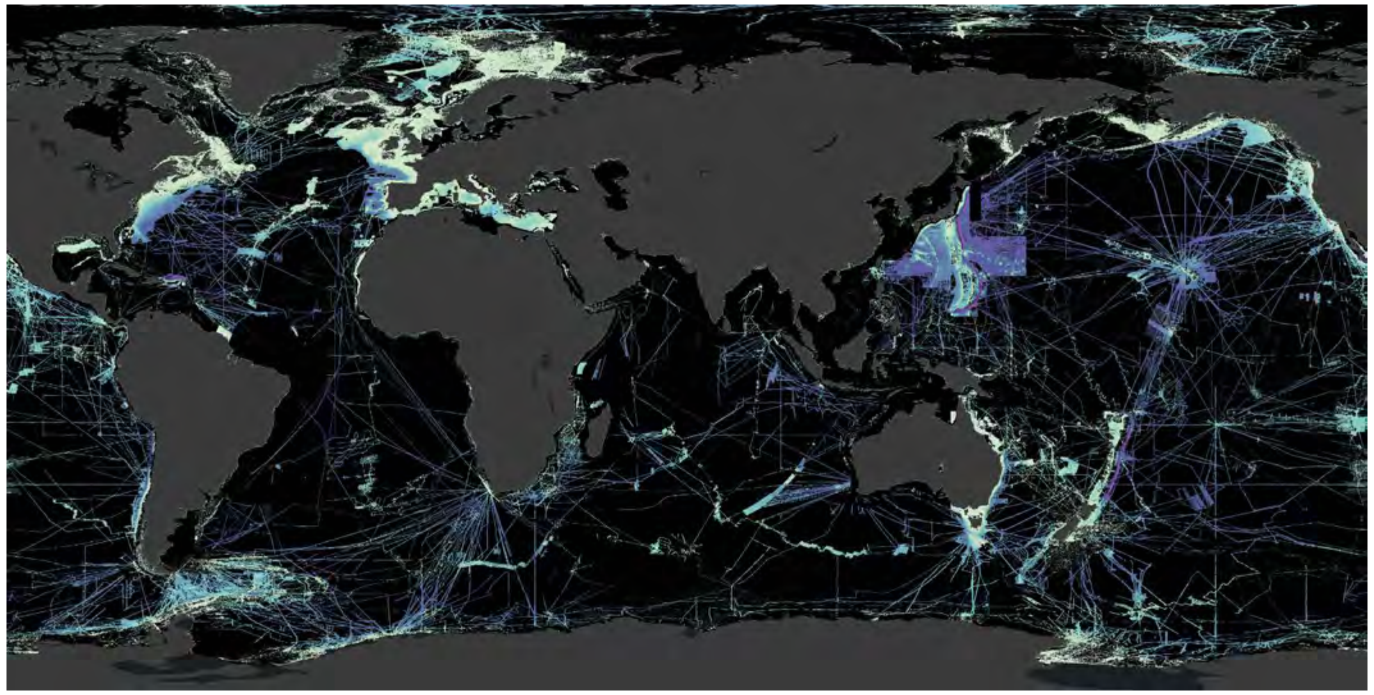
Depth	Grid cell size
0–1,500 m	100 × 100 m
1,500–3,000 m	200 × 200 m
3,000–5,750 m	400 × 400 m
5,750–11,000 m	800 × 800 m

DETERMINING WHAT IS MAPPED

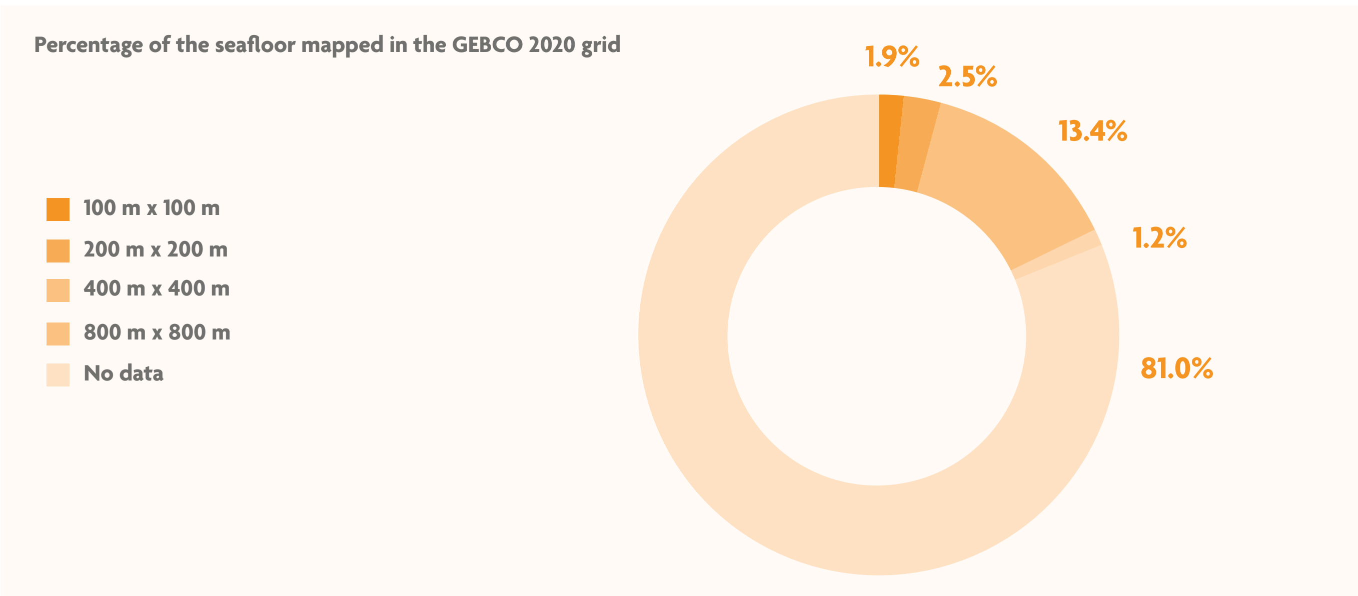
To reach the project goal of 100 per cent of the world ocean mapped by year 2030, the first task was to define what was mean by 'mapped'. While satellite-derived bathymetry is capable of mapping undersea features of the order of several kilometres or more in spatial extent, a range of applications need bathymetric grids that resolve smaller features on the order of tens of metres in scale.

To help to quantify what is mapped, the project has specified a set of target mapping resolutions (see **Table 1**). These are based on the assumption that the mapping will largely be done using surface vessels and the capabilities and limitations of existing multibeam echo-sounding technology. Using this new definition of 'mapped', the data included in the GEBCO 2014 grid only accounted for 6.7 per cent of the global grid cells.

Early priorities of the project have included identification of existing data that are not yet available for GEBCO products. Seabed 2030 is working at building relationships with the survey companies and their customers to release the data they hold, or own, for use in generating the next generation of GEBCO products. Furthermore, it is critical that a concerted effort is made to identify other available sources and how they can be accessed. The



▲ **Figure 3. Global bathymetry from GEBCO 2020 using only those grid cells where the data are from an actual observation. All areas with no direct observations are masked in black. (© V. Ferrini, LDEO)**



▲ **Figure 4. Percentage of the seafloor mapped in the GEBCO 2020 grid per target grid resolution. (© NOC)**

early years of the project have successfully led to the identification and addition of some significant existing resources that are now included in the grid (see **Figure 3**), giving us 19 per cent coverage for the second Seabed 2030 release – the GEBCO 2020 grid – split between the grid resolution areas as shown in **Figure 4**.

WORKING IN PARTNERSHIP

However, we know that these existing sources will not provide the full coverage we need. Absolutely key to the project's ability to deliver a completely mapped ocean is working in partnership with the wider bathymetry community to develop strategies for effective mapping. Through existing partnerships, such as the International Bathymetric Chart of the Arctic Ocean[7] and the International Bathymetric Chart of the Southern Ocean,[8] exploration effort is already being concentrated on those areas with no swath bathymetry coverage.

The Seabed 2030 project is not able to fund large-scale mapping projects. Existing mapping initiatives will need to be extended and new mapping initiatives kick-started, funded by national states and the international survey community. The US National Strategy for Mapping, Exploring and Characterizing the United States Exclusive Economic Zone is an example of one such programme already working to support Seabed 2030 objectives, but more are needed. Engaging with local communities, through crowd-source bathymetry initiatives such as the crowdsourced bathymetry on the Great Barrier Reef[9] project, will help us to reach a wider stakeholder group.

The UN Decade for Ocean Science for Sustainable Development gives the Seabed 2030 project an additional focus and impetus. Seabed 2030 has been proposed as a Decade Programme through the recent UN Call for Decade Actions, and anticipates providing fundamental underpinning for one of the core deliverables: a comprehensive digital atlas of the ocean. The Ocean Decade Executive Planning Group makes the call clear: 'The seabed remains one of the least studied and most poorly understood biomes on the planet. Until these vast areas are better known, exploitation and management processes will not be properly informed nor will they be effective in reducing impacts and risks associated with potentially threatening uses'.[10] Together, we can build the networks and communities needed to make the Seabed 2030 vision a reality. ES

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CASE STUDY

The coastal based approach

Natasha Bradshaw, Bob Earll, Peter Barham, Amy Pryor and **Mark Everard** analyse a way of enabling systematic collaboration and integrated delivery.

This article outlines a proposed approach to coastal governance in the UK that brings together public bodies, private-sector interests and coastal communities to offer better oversight and stewardship of coastal and marine resources. Governance of the coast is quite unlike the terrestrial environment because it requires the management of both marine and terrestrial environments and activities within them, many crossing this conceptual boundary and providing connections between people and the sea.

OCEAN AND COASTAL CONNECTIONS

People's appreciation and respect for the ocean depends upon their realisation of their connection to and benefits from it. For most people, this means being able to access, enjoy and understand it from the coast. The coast is a highly interconnected landscape and seascape, with a diverse mix of land ownership and governance. Coastal ecosystems contain valuable habitats and species and provide important ecosystem services. At the same time, the coastal zone often has a high population density and is visited and enjoyed by many more people, providing health and wellbeing benefits. Coasts often attract intensive investment in development, such as housing, ports, recreational and transport infrastructure. Estuarine systems in particular are often heavily encroached and converted for development.

CASE STUDY

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Economic competition for space between diverse and legitimate interests places multiple stressors on the coastal and ocean ecosystem. If these pressures are not well balanced, public access and enjoyment can be compromised and ecosystem health can deteriorate. At the same time, social deprivation is also an issue in many coastal towns: their dependence upon tourism often results in a high proportion of seasonal work and lack of stability. Coastal communities are on the frontline of climate change, facing increased risks from the impact of storms and sea-level rise, with some serious challenges and choices about future management priorities to be faced.

CHALLENGES AND OPPORTUNITIES

The management of coastal issues poses a set of interconnected challenges quite unlike those on land. The number and diversity of public- and private-sector interests is often highest in the coastal zone, with a proportionate increase in the complexity of planning and management in this highly contested space. It is increasingly recognised that the sustainable management of our coastal infrastructure and natural assets is required alongside improving coastal community resilience to natural hazards, posing complex systemic challenges. Frequently, management approaches are dominated by either inland or offshore perspectives, with the coast often lacking a specific focus and the resources and capacity to be effectively managed.

Despite these challenges, there are huge opportunities for improvement. Seasonal revenue from recreation and tourism could be better managed alongside the potential for blue (maritime industry) growth, with revenues retained locally to provide better services for deprived coastal communities. At the same time, nature-based solutions to shoreline resilience could offer multiple benefits for coastal recreation and tourism, bringing health and wellbeing benefits to coastal populations and visitors – quality-of-life benefits from being near water are increasingly known as 'blue health'. Coastal regeneration and coastal habitat restoration could go hand in hand to offer mitigation and adaptation opportunities to climate change. A new approach that focuses on the land–sea interface, encouraging coastal communities to take a real role in how the coast is managed, will help to ensure the longer-term resilience of the coastal ecosystem and the socio-economic benefits derived from it.

GOVERNANCE BEYOND SILOS

A plethora of organisations and designations have arisen in an *ad hoc* way over many years to govern different coastal resources. Many organisations operating conventional land and sea management policies are set up in a historical context, operating in top-down, discipline-specific silos. These traditional approaches originate from a command-and-control paradigm that has led to decision-making being top-down, expert-driven and imposed. This is often combined with the consideration of issues in isolation, which tends not to take full account of: the complexity of natural systems; the interactions, opportunities and trade-offs across different sectors and scales; and the range of values and needs of the coastal community. Hence, opportunities may be missed that could otherwise positively impact all members of communities and maximise budgetary efficiencies through integrated approaches.

Coordination and collaboration are needed across scales, sectors and levels of government. A flexible and enabling approach is needed to transition and influence understanding and management of complex natural systems while taking into account local and regional scales. A more inclusive approach that recognises differing stakeholder groups as well as the spatial scales of impact can grow shared capability, better informing a more flexible, adaptive management. A transition away from the current narrowly discipline-bound and top-down norms would impose a shift from government to governance: public, private and civil-society sectors would work in partnership to establish more collaborative governance. Importantly, this would not require any changes to the current legislation, but would require measures, potentially including incentives, to facilitate changes in approach and the growth of collaborative partnerships.

COLLABORATIVE GOVERNANCE

Collaborative governance is an arrangement where one or more public agencies directly engage non-state stakeholders and citizens in informal, cooperative decision-making, also linking with other agencies likely to be affected by management decisions. Collaborative governance provides opportunities for identifying how to:

- Bridge the gaps in the overlaps of existing legislation and policy;
- Capture synergies and minimise trade-offs; and
- Promote cross-sectoral alignment in a forum for deliberation by interdependent stakeholders.

The UN 2021–2030 Decade on Ecosystem Restoration recognises coastal ecosystems as a foundational resource vital for the achievement of outcomes across linked policy areas. There are many practical examples of effective partnerships and models of collaboration networks in different sectors. They can enable collaborative action on a project basis or local place-based issues, which generate a wide range of benefits enabling an integrated, values-based and cross-sectoral approach. If well delivered, these types of collaboration can also be particularly effective at breaking down barriers between organisations and delivering effective communications between stakeholders and communities. Current examples include catchment partnerships, marine planning partnerships, local enterprise partnerships, coastal/estuary partnerships and natural capital pioneers.

THE COASTAL BASED APPROACH VISION

The coastal based approach (CoBA) is a simple idea: to establish local and regional partnerships collectively covering the entire English coast that will support integrated place-based delivery for coastal ecosystems and communities. It offers a vision to strengthen and provide a systematic and flexible approach to enable leadership through collaborative, integrated, place-based and inclusive governance. It offers a solution to support the monitoring, management and restoration of coastal ecosystems and adaptive management under changing climate conditions.

CoBA is based upon the experience of UK coastal partnerships over recent decades, and supported by evidence from the catchment based approach (CaBA) over the past decade. CaBA is an approach facilitated by the Environment Agency that host partners for the delivery of catchment partnerships, with action plans for every English river catchment to address land use and water issues. It has shown that, for every £1 directly invested by the government, CaBA partnerships have mobilised over £3 from other sources.

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Both coastal and catchment partnerships provide a supportive framework for collaborative working at the scale of the catchment, or with a focus on the coast around locally identified issues and potential multi-beneficial solutions. CoBA would assist government with the delivery of legal and policy responsibilities and related programmes in a locally nuanced and integrated manner better supported by local communities. CoBA partnerships would have no legal duties or executive role – those would remain with statutory partners.

BUILDING ON COASTAL PARTNERSHIPS

To address local needs, there is already an array of community-based coastal partnerships in over 50 locations around the UK coast. These coastal partnerships support statutory agencies with policy delivery and encourage the engagement of coastal communities in decision-making. Their coverage is fragmented and some are financially fragile, but there is a huge amount of experience within them that can benefit the wider roll-out of CoBA. They demonstrate significant local impact, delivering benefits to society, the environment and the economy. Consequently, they provide a platform to support the delivery of CoBA. Their geographical remit could be extended and, with a secure base, they will stimulate more funding to enable delivery of a wide range of initiatives. This will realise interconnected benefits to coastal communities and deliver government objectives around the whole coastline.

BENEFITS TO GOVERNMENT

CoBA will deliver collaborative governance for the entire English coast, strengthening existing coastal partnerships and filling the gaps where no partnerships currently exist. Full coverage of this approach will ensure that communication and joint working is strengthened between government agencies, local authorities, non-governmental organisations and all sectors: port/harbour authorities, utility companies, the renewables industry, tourism associations, fishing clubs, recreation user groups, etc. It will ensure that every coastal community is better connected into governance, and develops a stronger sense of stewardship. It offers a consistent national delivery framework with regional and local flexibility according to need, and provides an umbrella for delivering cross-government policy at the local level.

By providing a platform for collaboration, CoBA partnerships will provide clear benefits to government and its agencies in the delivery of a wide variety of policies and programmes. Direct local input will help to ensure effective and long-lasting delivery, as will working with local authorities and bridging the links across community networks through a place-based approach to decision-making.

At the time of writing, in England the government (and its arm's-length bodies) have a range of ambitious coastal/marine initiatives. CoBA will assist in the delivery of green recovery, net zero targets, the restoration of marine biodiversity and the levelling-up agenda on jobs and resilience. This will include the 25 Year Environment Plan targets, the National Flood and Coastal Erosion Risk Management Strategy, marine plans, shoreline management plans and the achievement of good environmental status, amongst others. Strengthening communication between stakeholders and within coastal communities will provide a unified voice to support the delivery of government policies and programmes, maximising opportunities for multiple benefits. By investing in local capacity, it will mobilise cooperation between stakeholders, communities and government.

DELIVERY

To deliver CoBA across the entire English coast, it is proposed that the UK government champion the launch and trial of CoBA (as they did with CaBA in 2011). For a modest investment, the government could leverage a large return for the economy, the environment and society. The proposal for a CoBA across England will help to ensure that the benefits of partnership working are harnessed, sustained and strengthened. A CoBA Steering Committee has been established, with membership from the public sector, industry, charity and academic interests, to promote the proposal widely.

Mapping is proposed to evaluate the gaps in the overlaps between existing partnerships, policy areas and existing collaborative initiatives. A call for trial locations has been issued, with interest expressed from all regions. Suggested match funding of local partners' contributions by central government would lever stronger local engagement in many areas of policy delivery, by supporting local partnership officers to facilitate engagement. The returns on investment would be monitored through a new evaluation scheme and by facilitating the sharing of best practice across the UK through the national Coastal Partnerships Network. This would also strengthen skill sharing and training to improve coastal knowledge amongst practitioners and policy officers. Importantly, it would also strengthen the next generation of decision-makers to embed resilience into coastal communities and protect people's connectivity to and respect of the ocean.

LOOKING AHEAD

There is a need for a more coherent approach to coastal governance based on our extensive understanding of collaborative working. CoBA would provide flexible, inclusive and effective leadership for some of the most challenging, complex and often neglected areas at the coast. It would support the delivery of government policy while building resilience into pre-existing community-led structures, providing local capacity to cover areas that are currently not represented. It will assist existing and new local coastal partnerships, many of which have grown organically, to achieve their full potential and provide national consistency along the entire English coast. CoBA will set out the need for defined coastal units so as to fill the gaps. The benefits of collaborative working will be quantified, along with the value of resourcing local co-ordinators and mobilising national coordination.

As we approach COP26 in November 2021, and begin to respond to obligations under the 2021–2030 UN Decade on Ecosystem Restoration, the UK's partnership approach to managing the coast can demonstrate the cutting edge of coastal management globally. Furthering the UK's experience through the coastal based approach will provide a mechanism for local engagement and delivery of national and global objectives to support climate adaptation and ocean recovery.

The full CoBA proposition paper outlines the vision for CoBA and further information on how it would support delivery of government policy and programmes. For further information and contact see www.coastalbasedapproach.org ES

Natasha Bradshaw is a doctoral researcher at the University of the West of England (UWE Bristol) who collaborated with co-authors working in public policy from government bodies, academia, industry, environmental charities, trusts and coastal networks for the preparation of the CoBA proposition.

Bob Earll is a consultant specialising in coastal and marine environmental issues, with emphasis on communications, marine wildlife and individual action for the environment. He has over 50 years of experience of working in research, marine conservation, environmental management and organisational development (www.cmscoms.com).

Peter Barham MBE is chair of the Solent Forum and the Welland Rivers Trust, which was one of the original 11 pilot catchments when CaBA was launched. Although largely retired, he is still chair of the Seabed User and Developer Group (www.sudg.org.uk) and continues to work closely with government on issues such as net gain.

Amy Pryor is a marine and estuarine scientist with over 20 years of experience in marine and coastal management. She is the Technical Director at the Thames Estuary Partnership, London's coastal partnership covering the tidal Thames, and chairs the UK Coastal Partnerships Network (www.coastalpartnershipsnetwork.org).

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CASE STUDY

The Plover Rovers

Scott Xavi Gudrich explains how bringing together marine professionals and coastal residents increases ocean literacy.

The UN Decade of Ocean Science for Sustainable Development puts a strong emphasis on communication and education. It aims to foster a participative and transformative process to ensure that ocean science will deliver tangible benefits for marine and coastal ecosystems as well as for human society. The empowerment of local communities plays a central role in this vision. By taking the needs of coastal communities into consideration and fostering a culture of dialogue in science and policy (rather than a traditional top-down knowledge-deficit approach), citizens are supposed to feel invited to actively shape their natural and intellectual environment rather than feel that they are being subjected to random decisions made by far-away policy-makers and scientists who are unaware of local issues and needs.

For this participative vision to become reality, it is imperative that the marine scientific community come together to raise ocean literacy among coastal communities in order to enable them to take an active part in these transformative processes.

ENABLING COMMUNICATION

To empower local communities to do just that, I founded the marine science communication charity the Plover Rovers in April 2020. By bringing together the scientific and professional marine community with coastal communities all along the English coast, our Talking the Coast project will increase ocean literacy and play a part in the urgently needed transformation of our relationship with our seas and coasts to benefit people and nature, thereby addressing Challenge 10 of the UN Decade of Ocean Science for Sustainable Development.

We aim to improve access to marine science and conservation, especially for people who would not normally engage with science and/or conservation activities, thus hopefully diversifying the marine science community of the future.

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We want to cultivate an understanding and appreciation for the role the ocean plays in all our lives. As the coast is the gateway to the ocean, coastal communities are intrinsically linked to both sea and land. Increasing knowledge of the marine and coastal environments means that communities will be better suited to face the sea and act as catalysts for transformative change, so that coastal communities can be part of the solution.

One of our volunteers, when asked why she believed that working with coastal communities was key to achieving the SDGs and the aims of the UN Ocean Decade, replied: 'Communities that border the oceans are on the front line of society and change – they should be equipped to use their local knowledge and understanding of the coastal environment to inspire change in others and raise awareness of current issues.' We want our work to be part of the UN Ocean Decade's formulated goal of shifting peoples' values towards a more sustainable interaction with the ocean and turning local communities into ambassadors for their seas and coasts. This ambitious goal of a value shift, a 'deep' leverage point for systemic change,[1] must be underpinned by a huge concerted effort by the marine community to empower local people to take ownership of their coasts and seas and develop a sense of stewardship (in the sense of activism-based planetary stewardship[2]). As another of our volunteers pointed out: 'Marine communities know their local area best – both for social needs and environmental changes. To not put them in the focus as a catalyst of change wouldn't result in successful solutions and futures – these communities are the frontier that can help or hinder initiatives to improve ocean health.'

With the Plover Rovers, we want to add our grain of sand by making marine science more accessible to a broad segment of society. We strongly believe in the power of positive messaging, of giving people a sense of empowerment and purpose rather than scaring them into apathy with doom-and-gloom messages.[3] We also recognise, that ocean literacy is much more than just knowledge and that the concept should also encompass awareness, attitude, communication, behaviour and activism.[4]

THE FOUR-LEVEL APPROACH

Communicating on the subject of the ocean in ways that enhance and increase awareness, concern and connection, and ultimately foster positive behaviours requires an understanding of how different people and communities think about, and value, the ocean.[5] We want to focus on understanding what people's current values are and to then explore how these can be used to develop effective communication around pressing coastal and marine issues. To achieve this, we use a four-level approach to enhancing ocean literacy:

1. **Science communication:** present relevant science with a focus on active dialogue between participating scientists and members of coastal communities, rather than top-down knowledge transfer. We take the view that the situation around Covid-19, which likely will not allow for large groups to congregate this summer, is an opportunity to foster a more personal connection between local citizens and scientists, bringing them together on a level playing field, enabling person-to-person conversations that are potentially transformative for both sides.

2. **Art and emotion:** we collaborate with artists to provide an additional, more emotive access to the topic, making our events interesting to an audience beyond the usual bracket of the academic white middle class. We believe that art can aid science communication by providing both an active and immersive way of discovering nature. It can also enhance emotional connectivity with the natural world. While there is still a need to better understand the role of emotions in decision-making and behaviour,[6] a large-scale emotional reconnection with the natural world is an obvious necessity if we want to successfully work for transformative behaviour change on a societal level.[7]

3. **Activism:** we collaborate with local organisations to provide people with options for local engagement. As stated above, we believe knowledge should not be separated from activism and we therefore want our events to double as volunteer recruitment for locally active community groups. This direct pathway from an informative setting to active engagement will help consolidate the acquired theoretical knowledge and build a sustained connection with the natural environment.

4. **Heritage and storytelling:** we will collect stories from local people to explore and understand their connection to the sea, their concerns, hopes and visions, acknowledging that we need to understand how our audiences connect with a particular topic, place or issue in order to deliver science communication that can elicit behaviour change.[8] This active listening approach is key to achieving the UN Ocean Decade's goal of 'identifying and overcoming barriers to behaviour change required for a step change in humanity's relationship with the ocean'.

▲ **Figure 1. The Plover Rovers volunteers are dedicated to increasing ocean literacy along the English coast and beyond.**

CURRENT PROJECTS

Our project is deeply committed to creativity, to a transdisciplinary approach to science communication and to inclusiveness. Our charity is shaped by our volunteers, many of them young, early career marine scientists, who are invited to contribute their vision to our mission (see **Figure 1**). I would like to mention just four projects we are currently working on to illustrate the four-level approach mentioned above. Firstly, an example of a physical event designed to raise awareness of a local stretch of coastline. In front of the Portbury Wharf Nature Reserve (and between Portishead and the Port of Bristol) lies a small salt marsh that often goes unnoticed. We are teaming up with the Friends of Portbury Wharf Nature Reserve and local artists to create a digital pack about the salt marsh with some accessible scientific background information on the important ecosystem services provided by the marsh. We are also hosting an interactive event for the local community with art workshops and two scientific talks, one on the local geology and one on salt marsh ecosystem services.

Secondly, in the sphere of heritage and storytelling, we are cooperating with an artist and seagull rehabber on the Gull Tales project, which is designed to explore and improve human–gull relationships along the English coast.

Thirdly, one of our immersive art projects is a bespoke coastal-themed choir piece (currently being arranged for us) that we will make available to choirs that can either perform it at one of our events, be it physical or online, or just sing it for their own enjoyment. We believe that the positive power of singing, of feeling the musical vibrations in one's own body, creates a positive emotional bond with the natural world one is singing about and envisioning while performing the piece.

Fourthly, in our 'Talking the Coast' project, we aim to include groups that would not normally have easy access to such events to help them to create new pathways of integration by giving them a voice. One such group we want to focus on are refugees. Our storytelling project, My Coast – Your Coast – Our Seas, focuses on the narrative that the sea is the big connector between us all, rather than being a divide, and that marine and coastal issues are similar across the world, so the route to their solutions knows no country boundaries. We are looking for refugees who come from a coastal region and would like to talk about what life is like by the coast in their home country. Refugees and local people will find common ground through this shared coastal narrative.

We are still looking for members of the marine/coastal scientific community to join us on this journey as Walker-Talkers and bring their relevant exciting research into coastal communities all along the English coast. If you would like to volunteer for this initiative, please get in touch. **ES**

Scott Xavi Gudrich is a marine environmental scientist with a background in classics, linguistics and punk rock. Passionate about science communication and transdisciplinary work, he is the founder and director of the marine science communication charity the Plover Rovers. He lives with his Latin-obsessed husband and three cats in Hampshire.
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CASE STUDY

Blue Communities in Southeast Asia

Victoria Cheung, Andy Bell, Lota Creencia, Lora E. Fleming, Hong Ching Goh, Carya Maharja, Karyn Morrissey, Isabel Richter, Amy Yee-Hui Then and **Melanie C. Austen** describe how the Blue Communities programme is growing interdisciplinary marine research capacity and application in Southeast Asia.

The global ocean and its marine resources play an important role in the livelihoods, food and general well-being of humanity. This is especially relevant to the coastal communities in Southeast Asia where almost all the countries have extensive coastlines and a long and rich history of marine-related activities that are key contributors to their economies, social structures and human health.

The Southeast Asian seas link the Pacific and Indian Oceans and are characterised by high diversity habitats including coral reefs, mangroves and seagrass meadows, favoured by the tropical climate and heavy precipitation that transports nutrients to the sea. These factors make the Southeast Asian seas some of the most resource-rich on the planet, providing many goods and services that support the human population. With increasing coastal development and expanding population levels, the demands on those goods and services from fisheries, oil and gas extraction, shipping and transport, the armed forces, mining, tourism, recreation and conservation are greater pressures than ever before.

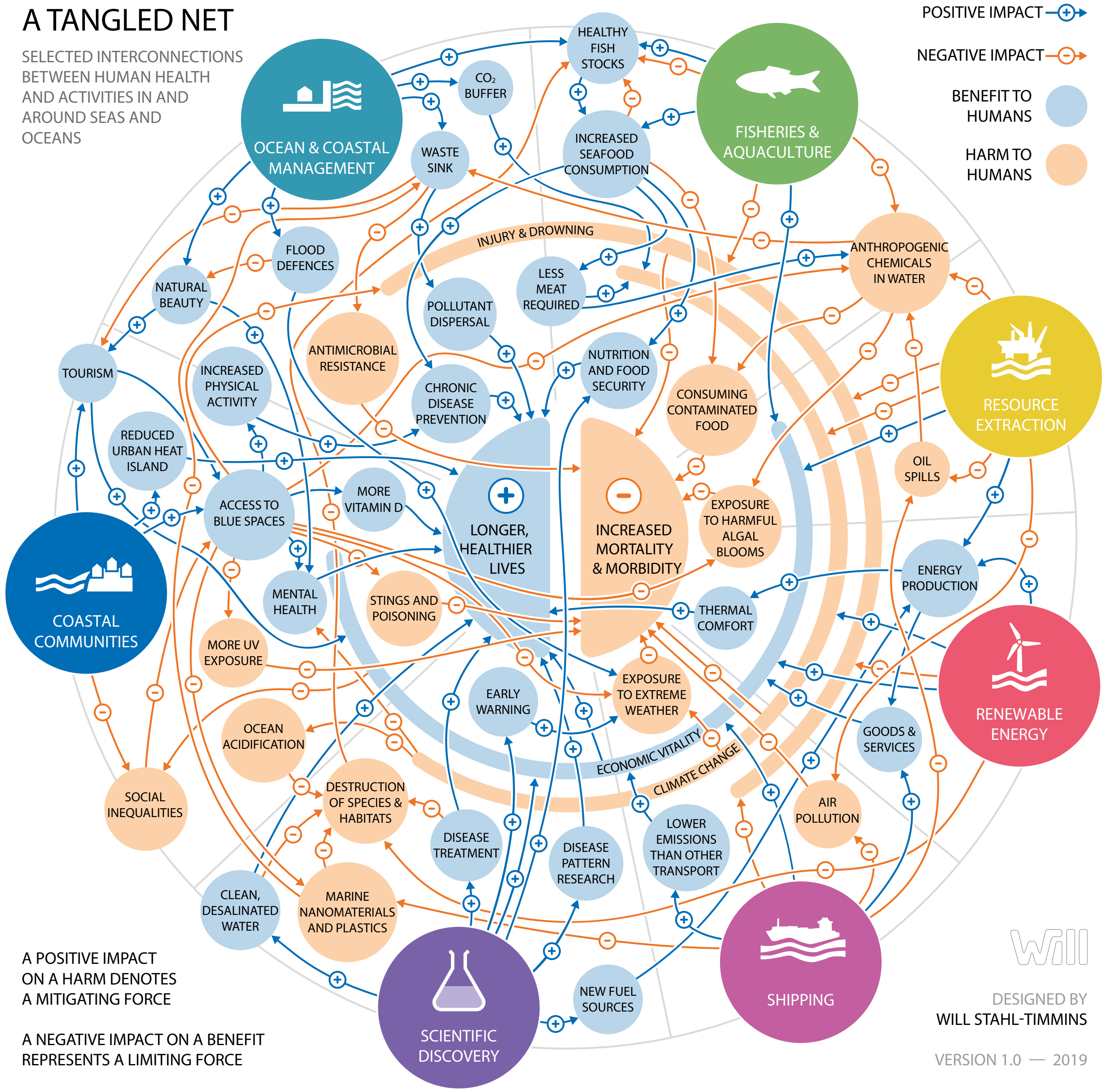
More than 80 per cent of those globally involved in the fisheries and aquaculture sector are in Asia, where they generate billions of pounds for the region's GDP.[1] Southeast Asian countries are among the top countries globally for seafood consumption per capita. However, overfishing coupled with destructive fishing practices (including cyanide and blast fishing as well as trawling) greatly affect the rich resources, in particular the coral reef ecosystem. Concurrently, tourism has been one of the fastest-growing economic sectors in Southeast Asia, with beaches and coral reefs amongst the most popular destinations. This includes conventional tourism as well as ecotourism (which aims to conserve the environment and sustain the well-being of local people). The exponential growth of tourism has both economic and social effects, creating jobs and generating revenue, but also having negative impacts on the environment, culture, society and human rights in the region. Overfishing and tourism are just two examples for the multiple pressures that create conflicts between users (user–user conflicts) and between users and the environment (user–environment conflicts), especially among the most vulnerable and in regions where the waters are highly exploited.

CASE STUDY

On a regional scale, initiatives such as the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI-CFF) are guided by principles of integration, inclusive stakeholder participation and multilevel governance mechanisms. Typically, they use spatial planning tools such as marine protected areas (MPAs) to help preserve marine and coastal resources. At the same time, they address food security, climate change and marine biodiversity. To support systematic conservation planning, guidelines have been formulated for designing marine reserve networks within broader spatial planning and management frameworks. This is to address biodiversity conservation, fisheries management, climate change adaptation and coastal management.[2]

HUMAN HEALTH LINKED TO PLANETARY HEALTH

Recent research has highlighted the multitude of ways that human health and well-being are directly and indirectly linked with the coasts, seas and ocean (see **Figure 1**). These range from culture, history and livelihoods to protein and other nutrients from seafood and, more recently, evidence of physical health and mental well-being benefits.[3] Evidence for the latter comes primarily from studies in the Global North, but the findings point towards people from all over the world benefitting from high-quality marine environment interactions.[4]



▲ **Figure 1. A tangled net. There are a multitude of interconnections between human health and the coasts, seas and ocean. (© Dr Will Stahl-Timmins)**

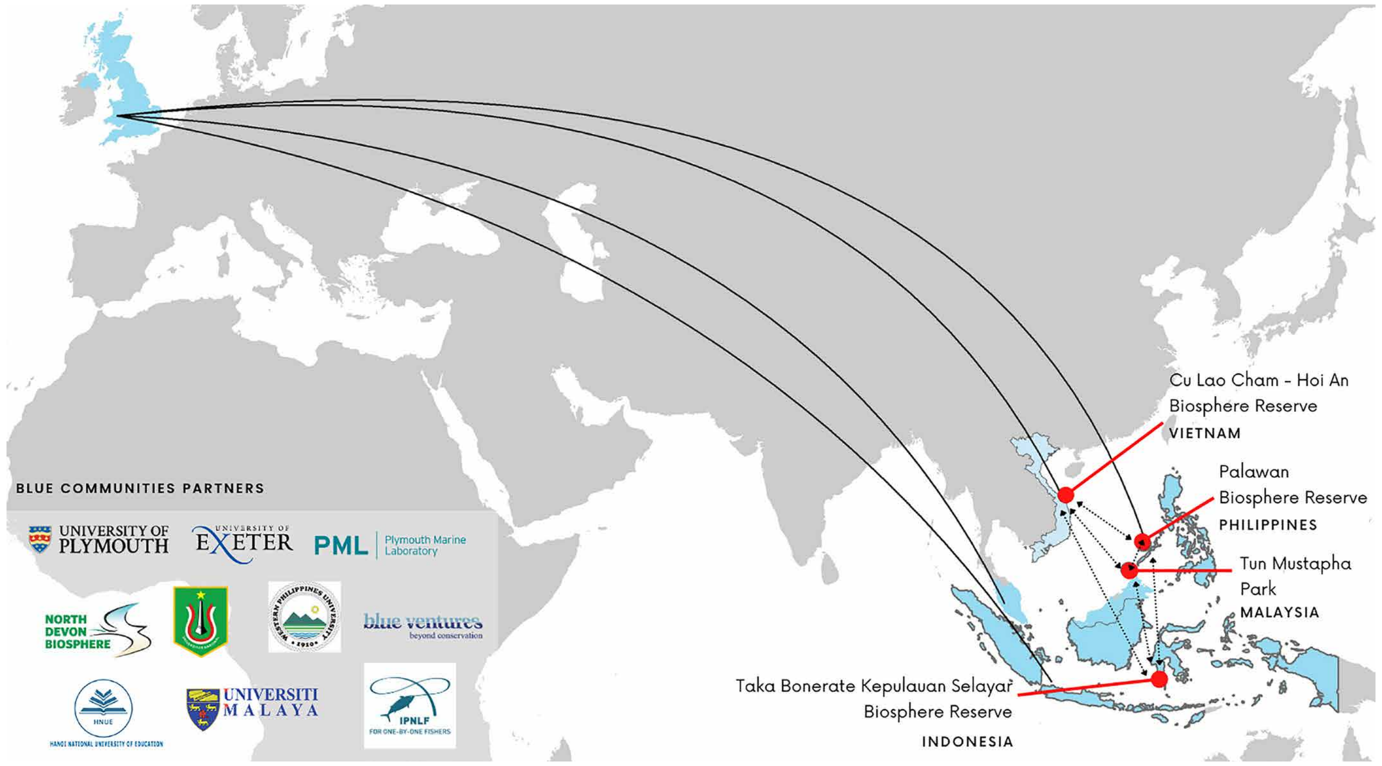
However, potential human health benefits from the marine ecosystem have not been well researched for coastal communities in Southeast Asia, which are experiencing the very real and negative impacts from the ocean due to climate change (including extreme weather and sea level rise), pollution (chemicals, including plastics), harmful algal blooms and increasing environmental degradation.

Planetary health joins other framings of the interactions of humans with the natural environment (including One Health and Ecological Public Health) in stressing the inextricable linkages between the health of humans and the planet. Over the past 50+ years, with increased understanding of the causes and impacts of global pollution, climate and other environmental change, biodiversity loss and general ecosystem degradation, we have become aware of the negative impacts of humans on the planet, and how these impacts come back to haunt us. At the same time, there is an increasing appreciation that when humans can live sustainably with natural environments, our own health and well-being are improved and we flourish.

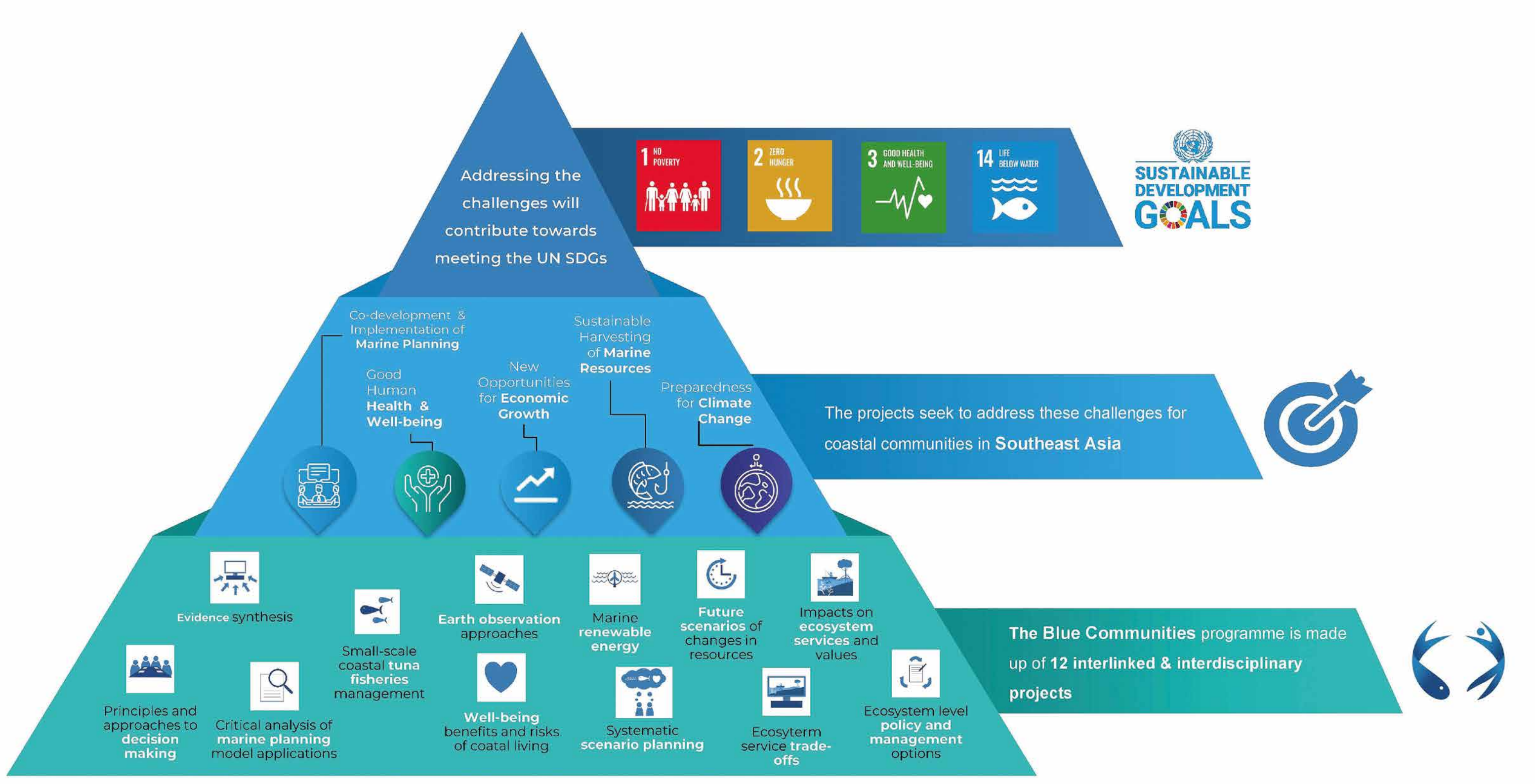
GCRF BLUE COMMUNITIES

The Blue Communities project is one of 37 projects funded by the UK's Global Challenges Research Fund (GCRF) to grow interdisciplinary and international research capacity. The aim is to strengthen and broaden skills and expertise in developing regions and countries, enabling them to address specific challenges and generate long-lasting partnerships, ideas and knowledge. The project is led by the University of Plymouth in partnership with four universities in Southeast Asia (Hanoi National University of Education, Viet Nam; Universitas Nasional, Indonesia; University of Malaya, Malaysia; and the Western Philippines University, Philippines), the University of Exeter and Plymouth Marine Laboratory, UK, and three non-governmental organisations (Blue Ventures, International Pole and Line Foundation, and the North Devon Biosphere Foundation). The Blue Communities project is building capacity for sustainable interactions with marine ecosystems for the benefit of the health, well-being, food security and livelihoods for coastal communities in Southeast Asia (see **Figure 2**).

There are currently 714 UNESCO biosphere reserves in 129 countries that belong to the World Network of Biosphere Reserves. These have been identified



▲ **Figure 2. Blue Communities is building research capacity through partnerships between 10 organisations in five countries. The research focuses on four case study sites, three of which are UNESCO biosphere reserves and one of which is a designated marine park. (© Blue Communities)**



▲ **Figure 3. Through 12 interlinked and interdisciplinary projects, Blue Communities is addressing challenges for coastal communities in Southeast Asia and aims to meet the SDGs. (© Blue Communities)**

as sites for testing interdisciplinary approaches to understand and manage changes and interactions between social and ecological systems. They are also a means of testing and developing policy and practice for wider use. From this network, Cu Lao Cham–Hoi An Biosphere Reserve in Vietnam, Palawan Biosphere Reserve in the Philippines, Taka Bonerate-Kepulauan Selayar Biosphere Reserve in Indonesia, and Tun Mustapha Marine Park in Malaysia have been selected as case studies for the GCRF Blue Communities project. As aligned with UNESCO's Man and Biosphere Programme's objectives, they are providing a focus for the promotion of north–south and south–south collaboration, and represent a unique platform for international cooperation through sharing knowledge, exchanging experiences, building capacity and promoting best practices. For example, the work in the North Devon Biosphere Reserve with the UK's Department for the Environment, Food and & Rural Affairs' marine pioneer has been a focus for exchange of practice between the sites.

HOW BLUE COMMUNITIES' RESEARCH HELPS

To promote the sustainable use of marine resources, Blue Communities has 12 highly interlinked, interdisciplinary sub-projects that provide:

- Training, resources and tools to researchers, such as systematic methods, data, GIS maps, reports and models;
- Many (but not all) of the resource requirements for a holistic approach to marine planning;
- Access to Earth observation data that facilitate understanding of marine habitat distribution and aquaculture distribution;
- Co-creation of ecosystem models and fish models that project the outcomes of climate change in the region;
- Identification of future opportunities for the development of marine renewable energy;
- A deeper understanding of marine ecosystem services and their benefits in the region, as well as of the activities that cause pressure on these services and goods, and how they might be reduced;
- Information on the key and strategic governance issues concerning the use and management of coastal resources, as well as the trade-offs that are inevitable, when there are conflicting uses and users; and
- A deeper understanding of the perceptions and expectations of the local communities with regard to their environment, and how it affects their health and well-being.

These approaches are being developed while engaging with diverse stakeholder groups. At the same time, data and evidence are being gathered to inform policy-makers and enable them to make informed decisions about the management of their coastal areas that would benefit both their communities and the environment.

By building research capacity via the 12 sub-projects, Blue Communities addresses a series of six challenges that will in turn feed into the United Nations Sustainable Development Goals (SDGs) for a better and more sustainable future for all (see **Figure 3**).

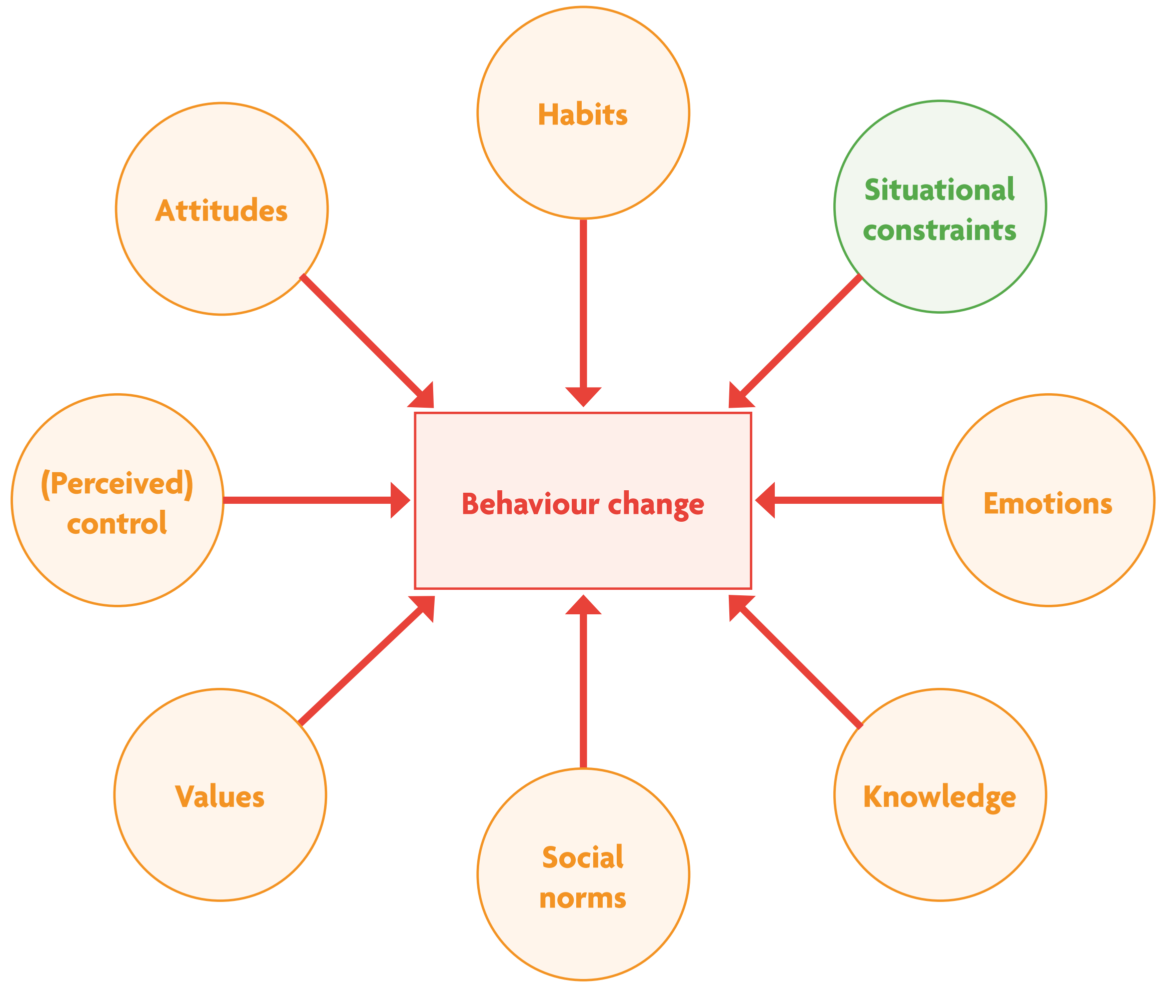
> **"Ocean science, supported by capacity development, is essential not only to inform SDG 14 but also other SDGs that have an ocean dimension."**
>
> **Peter Thomson, UN Special Envoy for the Ocean**[7]

BEHAVIOUR CHANGES REQUIRED

It is a common misconception that telling people what the problem is is enough for them to change their behaviour. However, human decisions and behaviour are complex and influenced by a variety of factors such as emotions, norms, values, attitudes, habits and situational constraints (see **Figure 4**).

To develop a strategy for behaviour change, we need to identify the barriers, benefits and motivators of people's actions. By understanding what drives behaviour, we can tailor our strategy; this is called community-based social marketing.[5]

Strategies for sustainable behaviour change can be context-based (such as nudging or legislation) or communication based (such as education programmes or campaigns). Nudging and legislation often require infrastructural changes. They have proven to be successful for some behaviours relevant to sustainable development. These are, however, top-down approaches that can lead to low community acceptance. There is also the question



▲ **Figure 4. Human decisions and behaviour are complex, and affected by a variety of factors.**

of whether policies designed to nudge people towards desirable actions are ethical. It has also been argued that, as ever with any top-down approaches, delineation of what could be considered to be coercion, manipulation, incentivisation or persuasion should be made transparent to ensure their efficacy and ethical status.[6]

In contrast, the act of communicating reasons or ideas for why changes are important or desirable is an important part of a bottom-up approach, where behaviour change arises from the communities themselves. To communicate effectively, messages should be tailored to the audience (in terms of language and personal relevance) and kept simple (ideally using visuals or local narratives). Emotive messaging has been found to encourage action. Integrating co-developed solutions and a shared vision into the communication strategy can maximise people's self-efficiency and feelings of ownership.

By working with coastal communities living in and around UNESCO biospheres and marine parks in Southeast Asia, the Blue Communities project is focusing on an overall case study for the future of humans and the planet, since these sites are rich in natural resources with communities that live in overt and daily interdependence. By co-developing strategic communication techniques together with the communities, their livelihoods, health and the sustainable use of the coastal environments can be improved. Researchers have much to learn from these communities: they face the increasing pressures of climate and other environmental change as well as economic and political forces, while trying to live sustainably and in ways that are good for their health and the natural world around them.

NEXT STEPS FOR GCRF BLUE COMMUNITIES

According to the Sustainable Development Solutions Network, more than two-thirds of the SDG agenda cannot be fully achieved if the global goals are not translated to a local scale, which relies upon the involvement of urban and local actors. Therefore, local actors are needed to co-create and co-define strategies and policy implementation towards the SDGs and monitor them against the global targets. Local success stories can be up-scaled and shared between regions and countries and thereby create a feedback circuit between global and local resource management.

The scientific community around the world shares the responsibility of bringing disciplines, projects and communities together to develop evidence-based solutions for sustainable marine stewardship, integrating human and natural systems. By doing this, we can build greater understanding of the complexity of marine systems in a planetary health context, and identify common issues and share solutions.

In addition to reinforcing cross-disciplinary communication, it is paramount to integrate local stakeholders and communities as equal collaborators and discussion partners. Truly involving local populations can not only offer insights into indigenous knowledge to policy-makers and resource managers but also elicit strong commitment, ownership and support from the communities themselves to protect their environment.

Through the collaborations and partnerships built through Blue Communities' activities, the co-creation and continuous development of research tools and new ways of working have evolved. By engaging with stakeholders from the outset, they have been empowered with new knowledge to make decisions that affect their own futures, improve their coastal environments and consider alternative livelihoods. All Blue Communities' researchers (from early-career stages and beyond) have been encouraged to increase their capacity through interdisciplinary approaches and to engage with the local stakeholders. As a result, they have become empowered with better understanding and new skills and experiences. The research community has been able to learn lessons from the stakeholders as well as sharing the knowledge they have gained from their research. This has enabled the research team to take a holistic view of coastal communities' challenges and how to address them using a systematic, informed and sustainable approach. ES

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Melanie C. Austen is Principal Investigator for the GCRF Blue Communities project. She is Professor of Ocean and Society at the University of Plymouth, a title that reflects her belief that collaboration across the disciplines is essential for the sustainable management of our seas and oceans so that they can underpin both good environmental stewardship and the needs of coastal communities and global populations.

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