future ocean
KIEL MARINE SCIENCES

The research network Future Ocean harnesses the collective knowledge of marine scientists, economists, medical scientists, mathematicians, IT experts, legal scholars and social scientists in pursuit of the study of oceanic and climate change. A total of more than 250 scientists working at Kiel University (CAU), GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design join forces to develop options for sustainable marine conservation and use.

IOI International Ocean Institute

The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

mare

The bimonthly German-language magazine *mare*, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. *mare's* mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

KDM
Konsortium Deutsche Meeresforschung
German Marine Research Consortium

The German Marine Research Consortium combines the broad expertise of German marine research. Its membership comprises all of the research institutes that are active in marine, polar and coastal research. A primary objective of the KDM is to collectively represent the interests of marine researchers to national policymakers and the EU as well as to the general public.

world ocean review

The Ocean, Guarantor of Life – Sustainable Use, Effective Protection

7

world ocean review

Living with the oceans. 2021

7

The Ocean, Guarantor of Life – Sustainable Use, Effective Protection

Published by
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future ocean KIEL MARINE SCIENCES
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Preface

It is 14 years since I began to develop the concept for the *World Ocean Review*. The first *WOR* – a comprehensive report on the state of the world's oceans – was published a little more than ten years ago. Subsequent reports have explored topics such as fisheries, marine resources, sustainable use of the oceans, coasts, and the Arctic and Antarctic. So it is the right time to publish another *World Ocean Review (WOR 7)* on the general state of the oceans and seas. One decade on, a retrospective is called for.

The four basic pillars which, in combination, make the *World Ocean Reviews* unique have not changed:

- Scientific relevance (the partnership with the Cluster of Excellence "The Future Ocean" and the German Marine Research Consortium KDM);
- Independence (maribus gGmbH is an independent, non-profit organization with no agenda or vested financial interests);
- Distribution free of charge: thanks to the Ocean Science and Research Foundation (OSRF), which was founded by Elisabeth Mann Borgese 20 years ago, secure funding is available to cover printing, mailing and staffing costs, among other things;
- Easily accessible content (due to mareverlag's journalistic style, reflected in the text, images and overall design, the content is clear and comprehensible and can be used by schools, the media and decision-makers).

The concept has proved its worth to a quite remarkable extent. On average, the reports on the website are accessed 65,000 times a month and more than 12,000 printed copies were requested and sent out at no charge in 2020 alone. The *World Ocean Review* now appears not only in German and English but also in Chinese, Thai and Japanese. Members of the European Parliament and German politicians alike rely on it for guidance, schools use it in lessons and journalists know that it is an indispensable source that they can rely on in their work.

Ten years ago, a science-based yet clear and comprehensible ocean review that was available free of charge and identified the complex threats to the seas, as well as potential solutions, appeared to be both a necessity and long overdue, for at that time, the oceans were mainly viewed as a transport route and holiday destination. However, the problem of plastic litter focused the attention of a wider section of society on the state of the world's oceans for the first time and helped to raise awareness of our own behaviour. But it was the climate debate – and, not least, the initiative of one young schoolgirl – that led to a broader public, and therefore also political, focus on the oceans. Throughout this process, however, we invariably observe that the complexity of topics such as the carbonate balance, global warming or overfishing increasingly requires fact-based explanations.

One decade on, *WOR* has thus become more important than ever.

Nikolaus Gelpke
Managing Director of maribus gGmbH, mareverlag publisher and Patron of IOI

Marine research across scientific disciplines, and intensive cooperation between the natural and the social sciences for responsible use of the ocean: these were the objectives which the marine scientists in Kiel set themselves more than ten years ago. They may have sounded somewhat esoteric at the time, but today, they are embedded as an integral part of countless marine research projects. It has long been recognized that it takes basic and applied knowledge in more than one discipline to mount an effective response to the challenges faced by society. As was the case more than ten years ago, what is needed today is an interdisciplinary publication to serve as the basis for knowledge-sharing with society.

In 2021 – the first year in the UN Decade of Ocean Science for Sustainable Development – a further insight is important: the crisis affecting the oceans can only be solved if all stakeholders worldwide – from governments and local decision-makers to businesses and private individuals – are actively involved in building our knowledge of marine science. Clear, comprehensive and sound knowledge is the essential basis for transformative action, away from overexploitation towards sustainable ocean governance. And that is exactly what this seventh *World Ocean Review* has to offer. It provides a broad overview of the role of the seas in relation to our climate, our food security, global trade, the energy supply and new pharmaceuticals. This latest publication maps the essential direction of travel towards more sustainable conservation and use of the ocean in future, including the interaction with land-based inputs, biodiversity loss and climate change. It is a mammoth task. Pollution, global warming, sea-level rise, overexploitation of coastal zones, extreme weather events – the headlines suggest that the tipping point may have been reached some time ago and that the international targets, such as carbon emission reductions, will be difficult to achieve.

Nevertheless, we would certainly encourage our readers to remain confident and to embrace innovative, transformative and collective approaches in engaging for the health of the oceans. Why is this worthwhile? At the international level, the world's largest contiguous ecosystem is attracting unprecedented levels of attention. The UN Decade of Ocean Science will connect large numbers of people, organizations and countries. Topics on the agenda will include what can be done to ensure unrestricted universal access to innovative technologies, resources, data and education. The willingness of large sections of society, research and politics to work on an interdisciplinary basis for sustainable solutions and to implement these solutions at national, regional and local level is higher than ever before. This new edition of *World Ocean Review* makes a valuable contribution to the UN Decade of Ocean Science. We wish you an inspiring read.

Prof. Dr. Martin Visbeck
GEOMAR Helmholtz Centre for Ocean Research, Kiel, Co-Spokesperson of Future Ocean

Prof. Dr. Nele Matz-Lück
Kiel University (CAU) Co-Spokesperson of Future Ocean

Prof. Dr. Ralph Schneider
Kiel University (CAU) Co-Spokesperson of Future Ocean

The seas are the cradle of life on our planet. The species richness of marine organisms, their capacity to adapt to changing environmental conditions and their constant ability to develop new ways of producing energy never cease to amaze. We humans are only gradually becoming aware of the services provided by marine biota in the Earth system through these organisms' metabolic processes. It has long been recognized that oxygen production via photosynthesis prepared the Earth's atmosphere to support more advanced forms of life. Sulphide oxidation under anoxic conditions and energy generation from methane combustion are services provided by microorganisms; without them, the chemical balance in the marine ecosystem would be impossible. Complex chemical compounds are produced as substances that provide protection or support communication processes. Their benefits to humans in pharmacological and medical applications are now being recognized, albeit slowly.

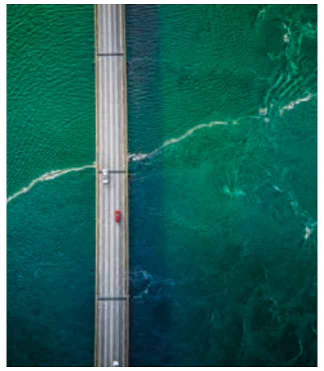
The oceanic ecosystems have adapted and to some extent helped to shape the climatic phases of the Earth's history. So I am confident that life in the ocean will adapt to the current climatic changes as well. Examples of changes from the polar regions and the tropical seas are described in detail in *WOR 7*. These changes will not only be felt along the coasts. Global cycles such as the weather, the distribution of rainfall and temperatures on our planet are regulated to a crucial extent by the oceans. The entire planet will be affected, and it is likely that the ecosystems will not remain in the form that is familiar to us.

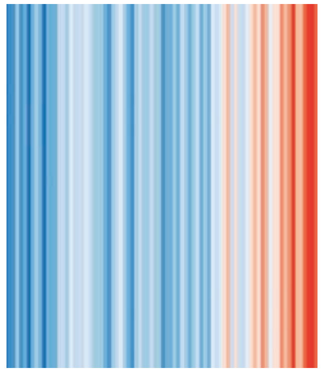
Healthy food from the sea is becoming ever more important for a balanced diet for the global population. The challenges associated with our future food security are increasing as other forms of use of the seas develop. Shipping and resource extraction are just two of the examples discussed in *WOR*, showing which risks the oceans face without proper management. It is better to take precautionary measures now than to have to compensate for the damage later. In some areas, such as microplastics, it is doubtful whether it will be possible to repair the damage at all.

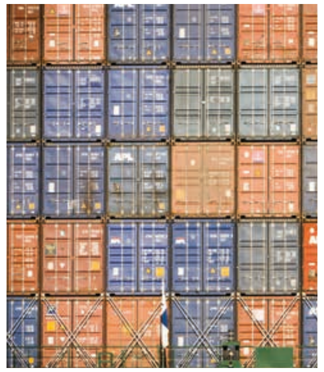
Germany's dynamic marine science community is facing up to the challenge of identifying and understanding interconnections in the ocean system. The Forum Future Ocean think tank, which is organized by the German Marine Research Consortium (KDM) in which all the marine research institutes are represented, is identifying the key challenges. The German Marine Research Alliance (DAM) has set itself the goal of answering the big questions and developing possible solutions through its research projects.

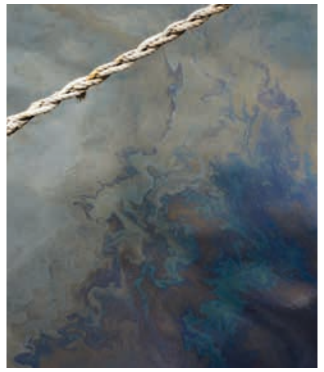
Marine management has a great responsibility: to put scientific findings into practice so that the numerous claims on the oceans from society, business and nature conservation are harmonized in a way which ensures that the Earth's greatest natural asset – our oceans – is preserved for the long term.

Prof. Dr. Ulrich Bathmann
Director, Leibniz Institute for Baltic Sea Research (IOW), Warnemünde, and Chair of the German Marine Research Consortium (KDM)



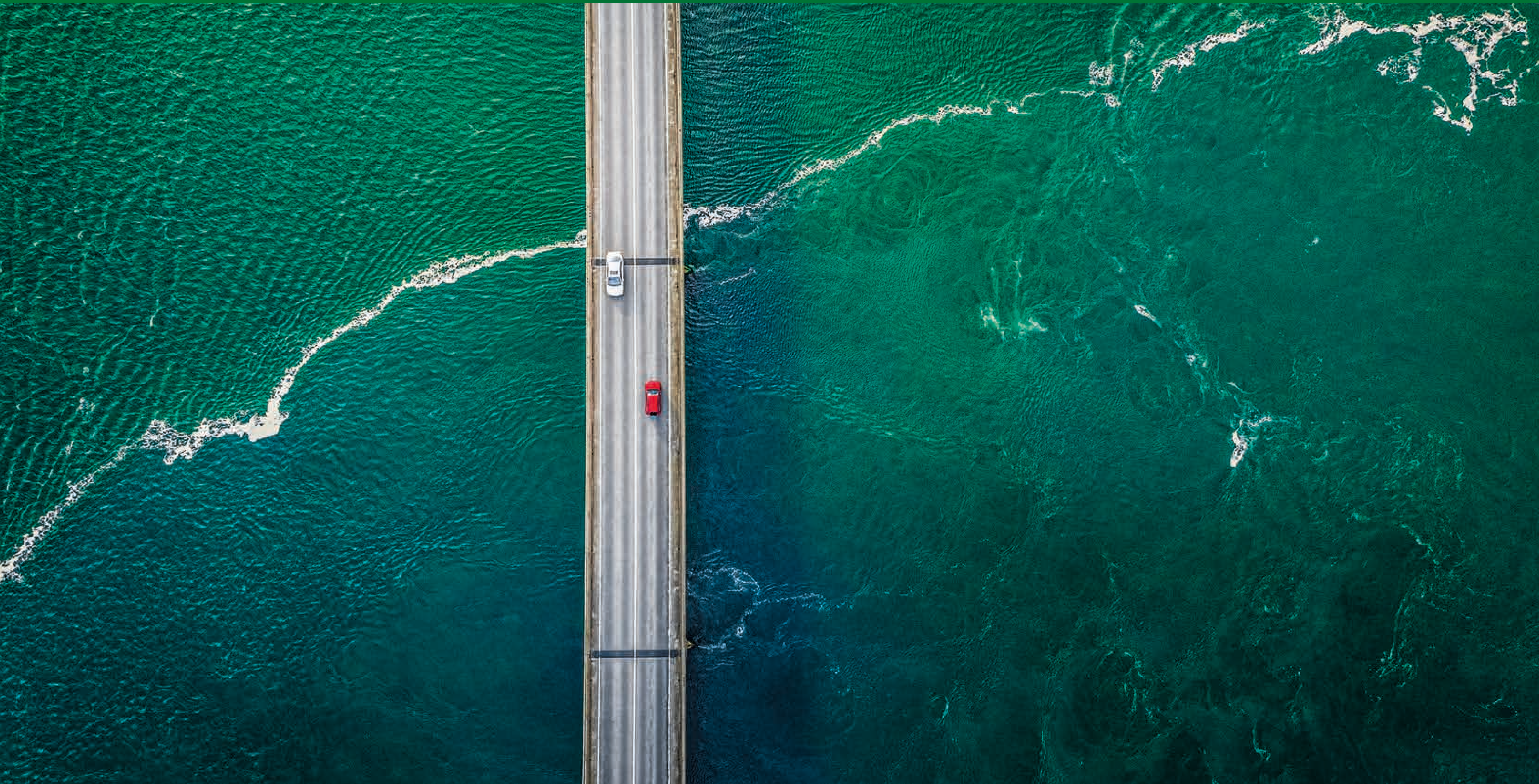






1 Our oceans – source of life

> The oceans and seas supply much of the oxygen we breathe and are a source of food for over a third of the world's population. They provide livelihoods for millions of people and have a place in the hearts of many more as a haven of dreams, a spiritual home, or as a playground for sports and adventure. The seas also regulate the weather and climate and curb anthropogenic warming of the Earth. For all these reasons, the future of humankind is directly connected to the fate of the oceans.



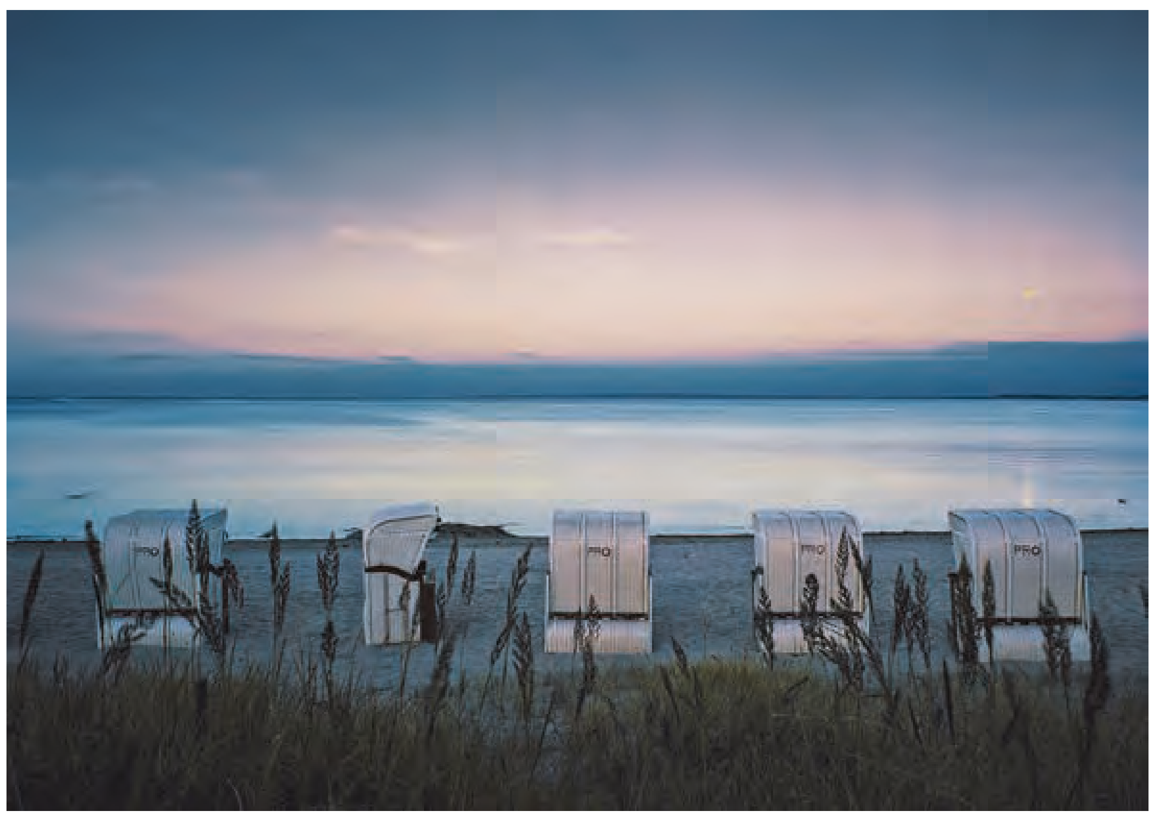
Vital yet finite seas

> For thousands of years, humankind lived with and from the ocean – all this time seeing it as infinite, boundless in its ability to provide food and resources, inviolable against every human encroachment. Today, the consequences of this human error are more visible than ever: reefs are dying, coasts collapsing, and in many places, fisherfolk are pulling in empty nets. This much is clear: if we wish to benefit from the ocean's bounty, we must treat it with respect and recognise that even the planet's largest habitat has its limits.

Water – the dominant elixir

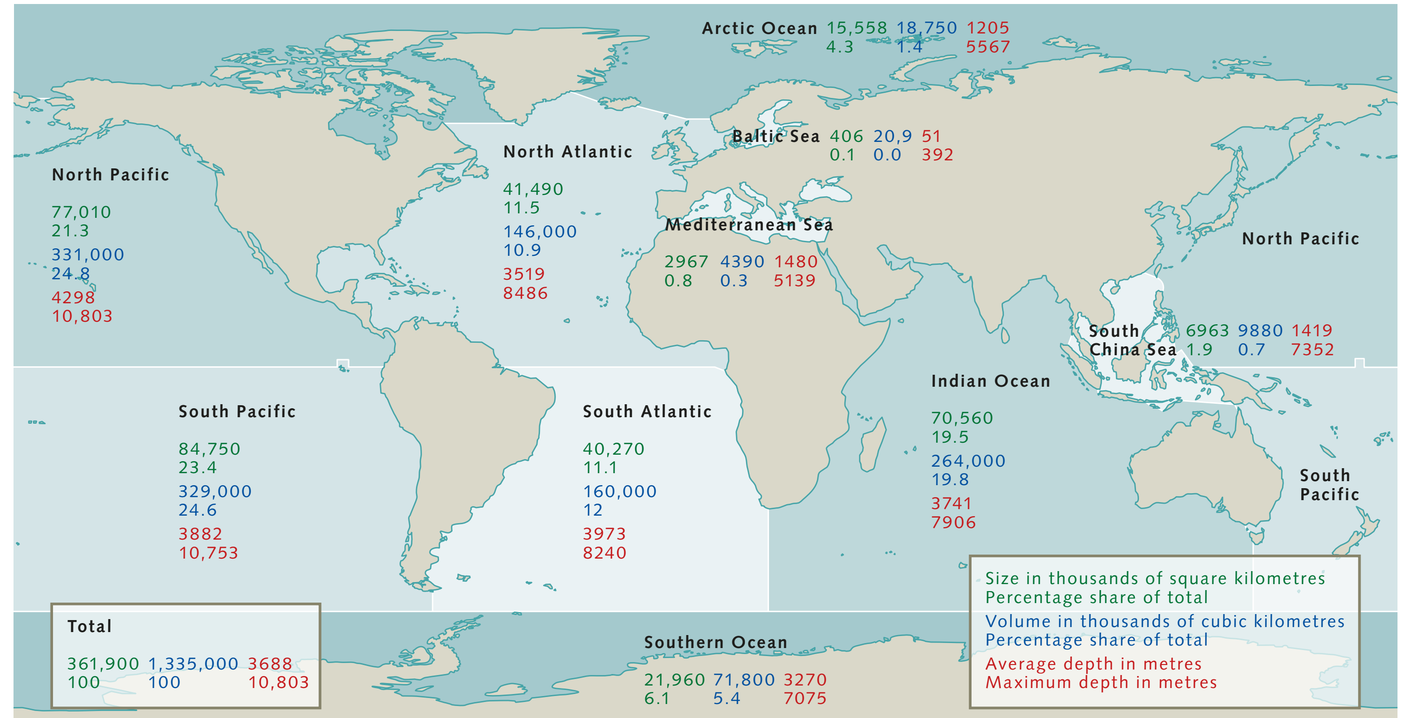
Earth is the watery planet. Its oceans and seas extend for 362 million square kilometres, covering 71 per cent of the Earth's surface. Unimpressed by these figures? Then consider this: the Pacific Ocean alone is large enough to cover the entire landmass of all the world's continents and islands combined. And that's not all: the world's four major ocean basins have an average depth of approximately 3700 metres below sea level and together hold a total volume of 1.3 billion cubic kilometres of water – enough to fill the largest lake in Germany, Lake Constance (water volume: 48 cubic kilometres) to the brim more than 27 million times. Roughly 97 per cent of all the water on Earth circulates in the oceans.

These figures are almost beyond human comprehension. And yet if these 1.3 billion cubic kilometres are divided by 7.9 billion – the world's approximate population in 2021 – it works out at just one-sixth of a cubic kilometre of water, or 160 million cubic metres of seawater, for everyone. It is a vanishingly small amount if we consider that this must supply us with all the services we take from the



1.1 > A longing for the sea: People are often drawn to the sea to switch off for a moment, to forget their cares and concerns and let their thoughts and ideas roam free.

Ocean
The term "ocean" refers to the major bodies or volumes of saltwater which fill the Earth's huge deep-sea basins. These include the Arctic Ocean, the Atlantic Ocean, the Indian Ocean, the Pacific Ocean and the Southern Ocean.



1.2 > The ocean covers 71 per cent of the Earth's surface. It is divided into the ocean regions shown here. Areas and volumes are based on calculations by the US National Oceanic and Atmospheric Administration (NOAA).

sea. For example, the ocean produces half of the oxygen we breathe and provides a nursery and habitat for all the marine fish and shellfish we eat. Every drop of water we drink over the course of a lifetime comes from the world's seas, for it is here, on the ocean's surface, where most of our water evaporates before falling as rain or snow elsewhere.

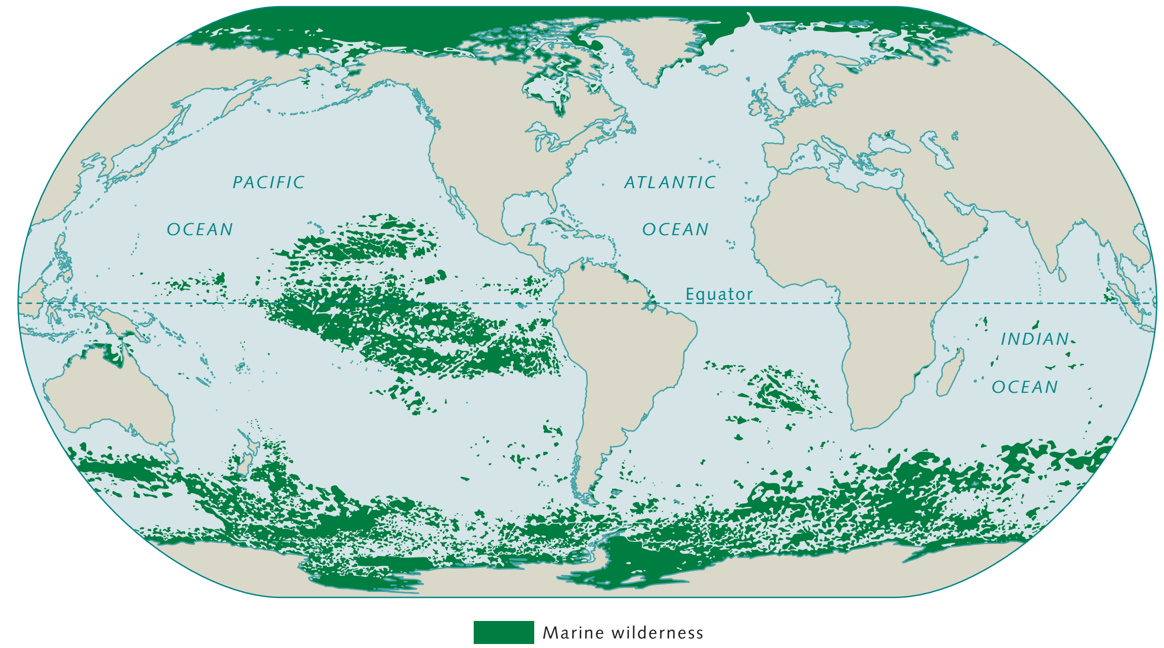
The sea acts as a brake on climate change by absorbing heat and carbon dioxide (CO_2), a greenhouse gas, and locking it away in its watery depths for centuries. It provides sea routes for our freight and connects continents located thousands of miles apart. It is a repository of resources in or on the sea floor, some of which we are already using today or plan to use in future; it is a source of renewable energy – and besides all of this, it is a place where we can relax and recharge, if necessary even online. At the height of the coronavirus pandemic in 2020, for example, people all over the world were posting seascapes on social media – an expression of their desire to switch off for a moment and forget about the stress of the pandemic.

The oceans and seas are also our planet's largest continuous habitat, containing 99 per cent of habitable space for much of the great diversity of organisms that thrive on Earth – from microscopic single-cell algae and deep-sea microbes to the world's largest mammal, the gigantic blue whale *(Balaenoptera musculus)*, which can grow to 30 metres in length.

In some cases, human communities make direct use of these marine organisms. Others benefit us indirectly, such as phytoplankton: these single- or multi-cell algae not only absorb carbon dioxide and produce around half the oxygen in the Earth's atmosphere; they also serve as a forage base for many of the zooplankton and fish species that we ultimately consume as food.

As these few introductory examples show, the fate of humankind is bound up with the world's oceans in countless ways. They are the cradle and the engine of life on our planet and, as such, they gain in significance with the dawn of each new day and the birth of each new citizen of our Earth. It is projected that by 2050, the world's population will have swelled to around nine billion. This

1.3 > The giant of the deep: This blue whale, seen foraging off the Californian coast, has an estimated body length of 25 metres. Researchers recently discovered that the heart of a blue whale can slow to just four to eight beats per minute on a deep dive, when it is searching for food. Its heart rate then accelerates to as high as 37 beats per minute after it has returned to the surface to breathe.



1.4 > "Marine wilderness" means areas of water whose habitats and biotic communities are mostly undisturbed by humans. In 2017, the term applied to just 13.2 per cent of the global ocean. Most of these ecologically intact spaces are located in open ocean regions, remote from overexploited coastal areas.

means that by then, the per-capita share of the ocean and its services – oxygen, food and water, and many more – will have shrunk to around one-seventh of a cubic kilometre of seawater.

Growing demands on the ocean

It is already apparent that our demands on the ocean will increase at the same time, and this applies particularly to food production. The fact is that onshore, our scope to produce sufficient food by conventional means is limited. Competition for fertile land is intensifying; water and fertilizer are in short supply in many parts of the world, and extreme events – such as heatwaves, droughts, heavy rainfall or pest infestations – are occurring more frequently in many regions as a result of climate change, with negative impacts on crop yields.

In order to assuage the hunger of an ever-growing world population in the long term, we need new strategies for sustainable land use and resource-efficient food production, which must include a return to mainly plant-based foods. But according to some scientists, the ocean too should make an even greater contribution to our food supply – and has the capacity to do so, provided that this more intensive use is based on sustainable, near-natural expansion of marine aquaculture and improved conservation and management of natural stocks and habitats.

Other scientists doubt that the ocean can fulfil this ambition. They point out that according to statistics compiled by the FAO, 34.2 per cent of natural fish stocks in the world's marine fisheries in 2017 were overfished, and that maximally sustainably fished stocks accounted for a further 59.6 per cent. The experts are also critical of plans to expand aquaculture in coastal areas, seeing this as ecologically unsustainable in many instances.

Barely a place without a human trace

In truth, human activity has been impacting on the health and welfare of the seas and oceans for decades. In its *Global Assessment Report on Biodiversity and Ecosystem Services*, published in 2019, the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)** (also known as the World Bio-

Sea
The term "sea" has two meanings. Firstly, it is synonymous with "ocean" and means the expanse of water that surrounds the continents and covers most of the Earth's surface. But it also means bodies of water that are smaller than the oceans, are located on their periphery, or are separated from them by chains of islands, deep-sea trenches, ridges or straits.

1.5 > A sharp-edged stone tool discovered in a cave on the Portuguese coast. Other finds from the site – crab and clam shells, scraps of fish and the fossilized bones of seabirds – provide evidence that Neanderthals, in their day, assuaged their hunger with food from the sea.

diversity Council) concludes that marine ecosystems worldwide, from coastal to deep sea, now show the influence of human actions, with 66 per cent of marine habitats experiencing significant human impacts. In plain language, this means a proven deterioration in their condition. Coastal marine ecosystems are in a particularly poor state, with the majority showing rapid ongoing decline.

The researchers note that this decline in marine biodiversity and deterioration in habitat condition are driven mainly by the growth of fishing and intensive use of coastal land (including coastal construction, expansion of urban area, start of production at oil and gas installations, pollutant and nutrient inputs from rivers). These two main drivers account for more than 50 per cent of the observed changes over the past five decades. Climate change, marine pollution and the arrival of invasive alien species appear lower down in the ranking; however, the IPBES experts emphasize that the influence of these three drivers is steadily growing.

According to ocean researchers, genuinely unspoilt marine wilderness, meaning biologically and ecologically intact marine habitats mostly undisturbed by humans, still exist in some open ocean regions in the southern hemisphere and in the still largely inaccessible polar seas. These unspoilt ocean regions extend for approximately 55 million square kilometres in total – roughly three times the size of Russia, but just 13.2 per cent of the global ocean.

In physiographic regions that are heavily frequented by humans, the pressure on natural biotic communities (biocoenoses) has become so intense that some species are now showing more rapid biological evolution. This is happening in the ocean as well. Some commercial fish populations, for example, have evolved to reach maturity earlier under intensive harvesting. Rising air and water temperatures favour the evolution of seasonally earlier reproduction in some species and disrupt established patterns of life in the ocean. The impacts of this rapid evolution on species diversity and marine biotic communities may be positive or negative, according to the IPBES experts, and must certainly be considered in all relevant marine conservation and management planning.

Taken together, it is apparent from all the various changes observed and listed by the IPBES that humankind now poses the greatest threat to the ocean and that this often unchecked exploitation of the marine environment is steadily depriving humankind of its own future.

How do people profit from the sea?

There is only one way out of this downward spiral: through the sustainable management of the marine environment and protection of major ecosystems that perform key functions. The latter, however, presupposes that there is a clear definition of what the terms “valuable” or “worth protecting” mean. The scientific community has been discussing the value of nature and its services to humankind since the 1970s, when researchers were beginning to gain a better understanding of the functions of nature and its biocoenoses – ecosystems, in other words. It was also becoming increasingly apparent, at the same time, to what extent humankind was degrading nature and, in consequence, losing many of the services provided by the natural world.

In order to assess the benefits that nature provides to humankind and the harm caused by its degradation, economists and ecologists developed the concept of ecosystem services in the 1990s. This refers to the functions and processes within an ecosystem that contribute directly or indirectly to human wellbeing. Examples are the provision of drinking water, fresh air or food in the form of fish or crops.

Natural phenomena that have destructive or harmful impacts, such as storms, diseases, earthquakes, floods or droughts, are termed “disservices” and, for a long time, did not count as ecosystem services. Almost 20 years on, the IPBES, among others, took this conceptual weakness as an opportunity to rethink and expand the analytical approach. Guided by the recognition that humankind not only dominates but is also exposed to the dynamic forces of nature, its broader notion of “nature’s contributions to people” goes beyond the ecosystem services approach and takes the harmful aspects of dynamic nature into account, such as pest infestations, parasites and viral or bacterial diseases.

The ecosystem services concept was presented in a scientific paper for the first time in 1997 and was subsequently used by the United Nations as the basis for its *Millennium Ecosystem Assessment (MEA)*, published in 2005. According to this model, the ecosystem services provided by nature and hence by the marine environment are divided into four categories:

Provisioning services

Provisioning services include marine functions and processes which form the basis for human communities, using labour and technical aids, to provision themselves with products such as food and raw materials. These services also include the spaces and areas in the marine environment that can be used for shipping or generation of renewable energies, for example. The utility or profits yielded by provisioning services can often be measured directly and are traded in the marketplace. In other words, they generally have a market value which can be precisely quantified. For example, according to the FAO, the market value of all global fish production – edible fish, shellfish, crustaceans and aquatic plants – harvested from seas, lakes and rivers or produced in aquaculture is estimated to have reached USD 401 billion in 2018.

Fish and shellfish provide 3.3 billion people with around 20 per cent of their average per capita intake of animal proteins, albeit with regional variations in fish consumption. The ocean is an indispensable source of food and livelihoods for coastal communities in many developing countries. In countries such as Indonesia, Sri Lanka and many smaller island states, fish provides more than 50 per cent of the average per capita intake of animal proteins.

Regulating services

This category refers to the benefits and utility that humankind derives from the regulating effect of the sea. It thus comprises services such as climate regulation (heat transfer and exchange) by the sea; coastal protection by mangrove forests, dunes, seagrass beds and reefs; the production of oxygen by phytoplankton and other marine flora; and natural water purification through the breakdown of nutrient and pollutant inputs. Monetizing these services has proved to be extremely difficult: for many of them, a market, i.e. a trading place in the conventional sense, does not exist. In lieu of this, attempts have in some instances been made to capture their value using comparative cost accounting, for example by seeking to determine the level of investment that would be required if humankind were to provide these services itself using technological solutions. Scientists have also attempted to identify and analyse the economic or financial harm that would ensue without the protective functions of nature.

Overview of marine ecosystem services

The advantages and benefits that the oceans provide from the human perspective are referred to as ecosystem services. Ecosystem services can be both material and non-material, and are grouped into four categories.

SUPPORTING ECOSYSTEM SERVICES

can be regarded as the indispensable basis for the other categories of services

- Maintenance of intact habitats (by supplying food, oxygen, clean water etc.)
- Maintenance of food web dynamics (functioning predator-prey relationships)
- Water cycle (evaporation and rainfall; exchange between land, atmosphere and sea)
- Safeguarding biodiversity
- Primary production (production of biomass)
- Nutrient cycles (formation of nutrients through primary production, degradation of nutrients by bacteria and biochemical conversion on the sea floor or in water)
- Maintenance of the resilience of marine habitats

PROVISIONING ECOSYSTEM SERVICES

encompass products and goods for direct human sustenance, on the one hand, and spaces and areas that the sea makes available, on the other

- Fish and seafood from wild catch and aquaculture
- Transportation routes
- Renewable energies (tides, waves and wind)
- Drinking water from seawater desalination plants
- Areas for pipelines and sea cables
- Pharmaceutical ingredients and other biochemical substances, e.g. for the food and cosmetics industry
- Goods for jewellery or souvenirs
- Areas suitable for military use
- Non-renewable resources (natural gas, oil, gravel and sand)
- Genetic resources from bacteria, sponges, and other organisms, e.g. for the development of new medicines

CULTURAL ECOSYSTEM SERVICES

comprise diverse functions which serve the non-material wellbeing of humankind

- Contribution to science and to natural history education
- Aesthetic value beautiful marine landscapes
- Religious and spiritual value of marine landscapes and places near and in the sea
- Inspiration for folklore, art, architecture etc.
- Recreation and tourism
- Cultural heritage (culturally significant landscapes and places near and in the sea, culturally significant sea creatures for traditional jewellery etc.)

REGULATING ECOSYSTEM SERVICES

comprise the advantages and benefits that humankind gains from the regulating effect of the sea and its ecosystems

- Climate regulation through the transportation of heat by ocean currents and heat exchange between water and atmosphere
- Coastal protection by dunes, coral reefs and mangrove forests
- Maintenance of water purity by breaking down nutrients from wastewater and agriculture which enter the sea
- Maintenance of air quality through algal production of oxygen or ocean uptake of carbon dioxide
- Maintenance of water purity by breaking down pollutants by means of dilution, chemical modification into harmless substances, or sinking and burial in the sediment

In a recent study, for example, researchers in the US showed that mangrove forests, salt marshes, seagrass beds and wetlands along the USA's Atlantic coast and the Gulf of Mexico avoided billions of dollars in storm and flood damage costs between 1996 and 2016. They found that one square kilometre of wetlands saves an average of USD 1.8 million per year in property damage caused by storms (wind and flooding). In densely populated coastal areas, the protective effect of coastal forests and wetlands is valued at nearly USD 100 million per square kilometre per year.

Cultural services

Cultural services comprise many diverse functions that serve human wellbeing in a non-material sense. They may have a particular social, religious or spiritual significance or form part of a nation's traditions. They include services such as the aesthetic appeal of a seascape, the marine environment's recreational function and leisure value, or the inspiration that artists, academics, architects and many other social groups draw from the sea.

The utility of the cultural services provided by the sea is also difficult to measure and almost impossible to monetize. What we do have available, however, are the turnover figures for the ocean tourism industry, whose business model is based to a large extent on the cultural services provided by the sea. With global direct value-added in marine and coastal tourism an estimated USD 390 billion and some seven million full-time equivalent jobs, it was the second most important branch of the ocean economy in 2010, surpassed only by the oil and gas industry, and is projected to become the leading marine industry by 2030. Whether this prediction from 2016 will come to fruition is debatable, however, given that the 2020/2021 coronavirus pandemic has led to the collapse of the travel industry.

Supporting services

This means the basic biological, chemical and physical processes which occur naturally in the environment and sustain life on our planet. In the marine environment, they include biomass production by algae and aquatic plants, nutrient cycles, the sea's contribution to the global water cycle, predator-prey relationships, and species and habitat diversity. Humankind generally benefits from all these supporting services indirectly, as they form the basis for the cultural, regulating and provisioning ecosystem services described above.

It is important to bear in mind that some services provided by the sea can be assigned to more than one category. With their abundant fish stocks, coral reefs, for example, often play a significant role in food production, which falls into the category of provisioning services. But they also provide regulating services – for example, by dissipating wave energy and thus protecting coastlines on their leeward side from erosion.

To this day, one of the great strengths of the ecosystem services concept is that it allows scientists to investigate and describe to what extent our human wellbeing hinges on nature. Some scientists note that the concept helps to strengthen the commitment to the environment by highlighting the vital role that ecosystems and species diversity play in sustaining human life. These services, they point out, are the foundation of life, contribute to our wellbeing and are a key pillar of our economy. Other experts extol the fact that the ecosystem services approach has helped to promote social dialogue on environmental and marine conservation and has thus enhanced communication between interest groups such as environmental campaigners, scientists, businesses and policy-makers.

There has been criticism as well – and not only of the failure to take account of harmful natural phenomena such as earthquakes. One point of criticism is that application of the concept is tantamount to putting a price tag on nature's bounty, turning it into products and services that can be traded or even privatized. Environmental ethicists also complain that it is often unclear who is performing this valuation of ecosystem goods and services and which criteria are being applied. In their view, this vital task should not be entrusted solely to scientists and policy-makers, for the value of nature is measured differently for each person and often cannot be quantified in monetary terms at all. This is the case, for example,

1.6 > A winter storm rages on France's Atlantic coast, demonstrating the terrifying power of the sea.

1.7 > The ocean has bestowed great wealth and power on coastal cities like Hong Kong. Port cities are important fishing and trading centres, but they are also at particular risk from global sea-level rise.

in relation to the aesthetic, cultural or symbolic value of nature to the individual or the personal value that a person assigns to a tree, a river or an ocean region to which they feel a special connection. An Indonesian spear-fisher who, every day since childhood, has dived on the coral reef along the coast near his village will have a very different connection to the reef and will value it very differently than a government official in Jakarta who decides on the allocation of funds for its conservation. Focusing solely on natural goods and services that can be quantified and given a price tag also diverts attention from the non-material ecosystem services, ethics experts say.

A Decade of Ocean Science for Sustainable Development

Despite all these justified criticisms, the ecosystem services concept has been widely applied by scientists in order to demonstrate the vital importance and value of natural physiographic regions such as the ocean and their need for protection. Reports such as the *World Ocean Assessment II* (2021) and the IPCC's *Special Report on the Ocean and Cryosphere in a Changing Climate*, published in September 2019, provide abundant evidence that the ocean is struggling under the weight of harmful human-induced impacts, that marine biodiversity is decreasing and the range of functions that it performs is shrinking and becoming more monotone. There is much to suggest that this downward trajectory will intensify, particularly against a backdrop of ongoing climate change and world population growth.

Based on this recognition, the United Nations came up with the idea of designating a Decade of Ocean Science for Sustainable Development, commencing in 2021 and ending in 2030. According to the project brief, the aim is to mobilize the scientific community and other social groups, during this period, in major efforts to connect the wealth of existing ocean-related scientific knowledge more effectively across disciplinary and national boundaries. This will make it possible, inter alia, to feed scientific knowledge about the seas and oceans more directly into decision-making processes and to improve forecasting, enabling potential policy impacts to be assessed more accurately.

The United Nations also sees it as the task of interdisciplinary ocean research to boost international cooperation and foster technological innovations that would, for example, enable polluted seawater to be purified, valuable habitats such as reefs and seagrass beds to be mapped and protected, and predicted changes in the ocean modelled with sufficient accuracy that humankind has time to adapt.

The Blue Economy – business and ocean in harmony

In a best-case scenario, researchers might even succeed in developing recommendations for action that would enable the world's oceans to be utilized in accordance with Blue Economy principles. This concept, often known by its synonym "ocean economy", was first introduced at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012. A precise and universally valid definition of what is meant by the term does not yet exist. Nevertheless, the broad objective is clear: the world's oceans should be used in a way which achieves maximum economic and social benefits without putting the health and sustainability of marine habitats and biotic communities at risk. In an ideal scenario, it would even be possible to restore degraded habitats such as seagrass beds, reefs and mangrove forests so that they regain the functions that they have already lost.

The ocean economy is now considered to encompass all the human activities that have a connection to the sea and generate revenue, provide employment or offer other benefits of a financial or non-financial nature. They thus include fishing and marine aquaculture, extraction of raw materials and resources, and the use of the seas as a source of renewable energies, as well as shipping and shipbuilding, marine tourism, safety technology and newly emerging business sectors such as marine biotech, large-scale marine protected area management, and CCS and blue carbon markets.

CCS stands for carbon capture and storage, a process whereby waste carbon dioxide – a greenhouse gas – from

1.8 > Unlike hard corals, soft corals do not form a hard, calcium-based skeleton, but they too provide many reef-dwellers with protection and food and are therefore essential for species diversity on coral reefs.

power plants or industry is captured before it reaches the atmosphere and then placed in underground storage or processed into synthetic fuels and other products. Blue carbon means the quantity of carbon dioxide that the world's coastal ecosystems, such as seagrass beds, mangrove forests, salt flats and salt marshes, capture naturally from the atmosphere and lock in their biomass or the substrate on which they grow.

In 2010, the ocean economy provided full-time jobs for around 31 million people, with industrial fishing and tourism the largest employers at that time. The value of the products and services generated annually by the ocean is an estimated USD 2.5 trillion. If the ocean were classified as a country, it would rank as the world's seventh largest economy. If non-marketed services – cultural or regulating services, for example – are included as well, the ocean would be right at the top of the leaderboard. Although there is much discussion among academics about the right way to value non-marketed ocean services, the experts are broadly in agreement: the total value of the ocean's regulating and cultural services exceeds the value of its marketed products and services many times over.

Gross domestic product
Gross domestic product (GDP) is a measure of a national economy's performance during a specific period. It is a monetary measure of the market value (value added) of all the final goods and services produced by the country during this period, excluding inputs used to produce other goods and services.

The Organisation for Economic Co-operation and Development (OECD), in its 2016 report *The Ocean Economy in 2030*, states that economic activity in the ocean will continue to expand to 2030 – and even has the potential to outperform the growth of the global economy as a whole. The economists also predict the emergence of new industries and greater use of the oceans.

The drivers that they identify include world population growth, increased trade, global resource consumption, new technological developments and climate change. At the same time, however, the OECD draws attention to the numerous complex risks associated with increased use. These risks, it says, must be minimized, as degradation of the marine environment also worsens the development prospects of the ocean economy.

In order to avert potential financial losses and guarantee a healthy, sustainable future not only for the ocean economy but also for the ocean itself, the OECD puts forward a number of recommendations, some of which also feature in the goals for the United Nations Decade of Ocean Science for Sustainable Development. They include the following tasks:

- Foster greater international cooperation in marine science and technology as a means to stimulate broad-scale innovation and the establishment of expert networks;
- Strengthen integrated ocean management, including improved governance structures, better economic and social stakeholder engagement, and more efficient management and decision-making processes;
- Improve the statistical and methodological base for measuring the scale and performance of oceanbased industries, with optimized methods for forecasting the future of this branch of the economy.

By applying this approach – analysing the multitude of services provided by the ocean and assessing their material or non-material value – there is now a growing recognition, not only among marine conservationists and affected communities, that the disappearance of individual ecosystem services constitutes a loss in real terms. It is also widely accepted nowadays that a change of mindset is needed in politics and the ocean industry itself in order to ensure that in future, human use or consumption of marine products and services is kept within the bounds of sustainability.

For that end – according to the pioneers of the ecosystem services concept – a new economic paradigm is needed, based on ecological principles: in other words, an economic model that is centred around nature. However, they also point out that achieving this is likely to be a long and arduous process, for political debate and decision-making in most countries are still dominated by traditional economic thinking. Nevertheless, the recognition that a nation's wealth and prosperity cannot be captured accurately using gross domestic product alone is a major step forward, say the experts. Instead, various indicators relating to the environment and the nation's health and social prosperity should be factored into the equation.

Proposals on how this new measure of prosperity might be applied successfully have been made by the

1.9 > Mangrove forests like the Sundarbans along the border between India and Bangladesh are a habitat and nursery for countless species of fish. They are of great benefit to local fishers, who put out their nets on the flats while the tide is out and wait for the incoming tide to bring in the bounty.

Changing perspective: one instead of five

How many oceans exist on Earth? Nowadays, there are two possible answers to this question. The first is five: this is the answer given in encyclopaedias and on knowledge platforms. It is usually accompanied by a world map of the type familiar to most of us from our school days, showing the continents as great land masses that separate four of the five oceans from each other. On the left- and right-hand margins of the map, there is the vast Pacific. The Atlantic takes pride of place in the centre, while the Indian Ocean is shown on Africa's eastern seaboard and the Southern Ocean encircles the Antarctic. That just leaves the Arctic Ocean, squeezed in right at the top.

But this is not the only way to think about the Earth's basic geography. There are other, very different options, such as that described by American geophysicist and oceanographer Athelstan F. Spilhaus in an article for *Smithsonian Magazine* in November 1979. In it, Spilhaus published a world map in the form of a square, with the five oceans and their respective seas depicted as one collective body of water, one ocean, in the centre, framed and delineated by the continental coastlines.

Spilhaus's world ocean map fell into oblivion for almost four decades after its publication, known only to a handful of ocean enthusiasts, who dusted it off whenever they wanted to show that a change of perspective and a new holistic understanding were required for effective marine conservation. Nowadays, however, Spilhaus's concept has the backing of ocean researchers and is steadily gaining in appeal. International organizations such as the United Nations increasingly refer, in their special reports, to one ocean whose water masses circulate in four ocean basins. Manufacturers of geographic information systems now offer the Spilhaus projection as a map template and the latest specialist publications on ocean management urge their readers, from the first chapter onwards, to think differently about the world, away from their preconceptions formed by life on land.

The rationale is as follows: the structure and functions of the ocean are so unique that attempts to manage the ocean with the same, often small-scale, methods and strategies that work on land are bound to fail. Unlike the land masses, the ocean has virtually no boundaries or barriers. When a tsunami inundated the Fukushima nuclear plant in Japan in March 2011, radioactive water escaped into the sea. Over the next three years, ocean currents carried this water from the coast of Japan all the way across the northern Pacific, with nothing – neither an army nor a deep-sea trench – to stand in their way. Likewise, plastic litter and other debris are transported freely around the world on the ocean currents. And of course, human-defined boundaries between areas pose no obstacles to shoals of fish or migrating whales.

As its name suggests, the *World Ocean Review* sees the world's oceans and seas as a single entity, the ocean. Nevertheless, as before, this latest edition uses a variety of terms – ocean, oceans and world's seas – interchangeably.

1.10 > The world map in the form of a square (left): Designed by American geophysicist and oceanographer Athelstan F. Spilhaus, this depicts the five oceans as one collective body of water, one ocean, with the Antarctic in the centre. Most people are more familiar with the conventional type of world map (right), which shows the continents as great land masses separating the Pacific, Atlantic and Indian Oceans.

World Bank, the United Nations and the OECD. However, academics have voiced criticism of these methodologies too, on the grounds that they fail to capture the extent to which economic processes impact on nature and society. Scientists are also calling for a shift away from the concept of limitless growth. A new common objective is required, they say: to safeguard adequate prosperity for all in such a way that the impending ecological crisis and the associated social crisis can be averted. To both these ends, the interests of the natural environment must become an integral component of global economic policy, with more frequent and more nuanced discussion of this topic across broader sectors of global society.

The need for such a transformation of our thinking and action towards sustainable development becomes ever more urgent with the onward march of climate change. As a result of anthropogenic greenhouse gas emissions and the consequent global warming, the basic pillars of life in the ocean are changing. But that's not all: the ocean itself is losing the ability to perform some of its key regulating functions to which we humans owe the – previously stable – conditions of life on our planet.

Conclusion

An end to the infinity illusion

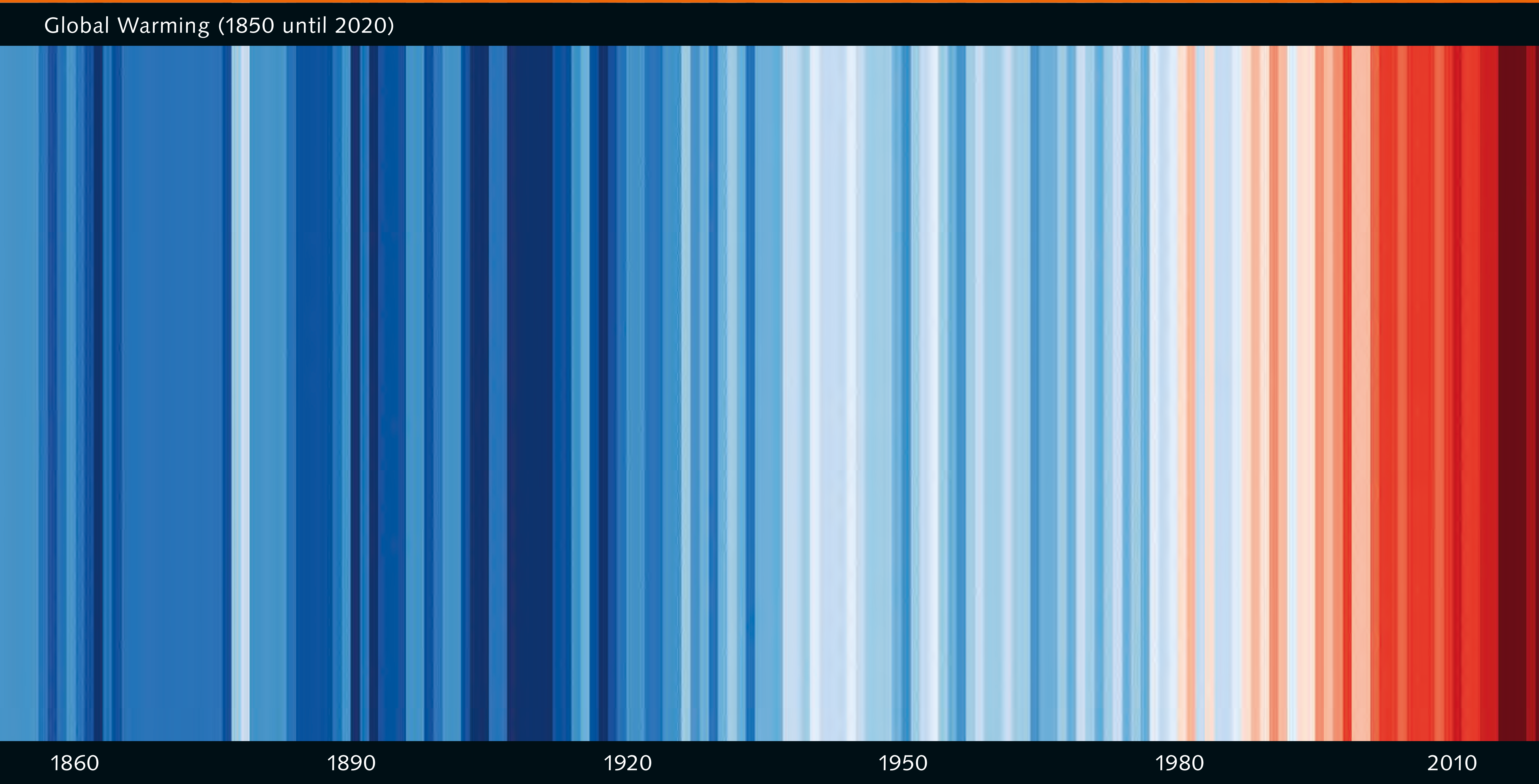
The ocean covers 71 per cent of the Earth's surface and is more vital for human wellbeing than ever. It provides people and the global economy with goods and services, material and non-material, whose monetary value is often impossible to quantify. According to the ecosystem services concept, they can be assigned to four categories: researchers distinguish between provisioning, regulating, cultural and supporting services from the sea.

Although the ecosystem services approach has sparked controversy among scientists, it has, over the past 25 years, done much to reveal the major extent to which human wellbeing depends on the ocean, as well as the likely adverse impacts if the condition of the oceans and seas were to deteriorate. The state of the world's ocean is regularly investigated in international studies by bodies such as the IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). In its recent *Global Assessment Report*, the IPBES concludes that 66 per cent of marine habitats are experiencing significant human impacts and that the ocean's functional diversity is therefore decreasing. The world's largest habitat, once seen as vast and infinite, has long reached its limits.

International policy-makers and the ocean economy therefore face a challenge: to develop new and sustainable strategies for the use of the ocean. One possible solution is the blue economy model. The international ocean research community is also committed to more intensive cooperation and, during the United Nations Decade of Ocean Science (2021 to 2030), will help to build a shared information system, based on science-based data from all parts of the world's ocean. The aim is to be able to predict the possible impacts of political or economic decisions on the ocean more effectively and discuss them in advance. Campaigners against the reckless exploitation of the ocean, however, are calling for a total renunciation of conventional economic models and a shift towards ecological concepts that would enable the ocean, in future, to fulfil all the demands made of it by human communities.

2 Oceans under climate change

> The oceans provide an invaluable service to humankind: They regulate climate and curb global warming by absorbing much of the heat that is trapped in the Earth System due to anthropogenic greenhouse gas emissions. This, however, also sets large-scale chain reactions in motion. On the one hand, water temperatures and sea levels rise. On the other, the physics and chemistry of the oceans are altered so dramatically that marine life is thrown out of sync.



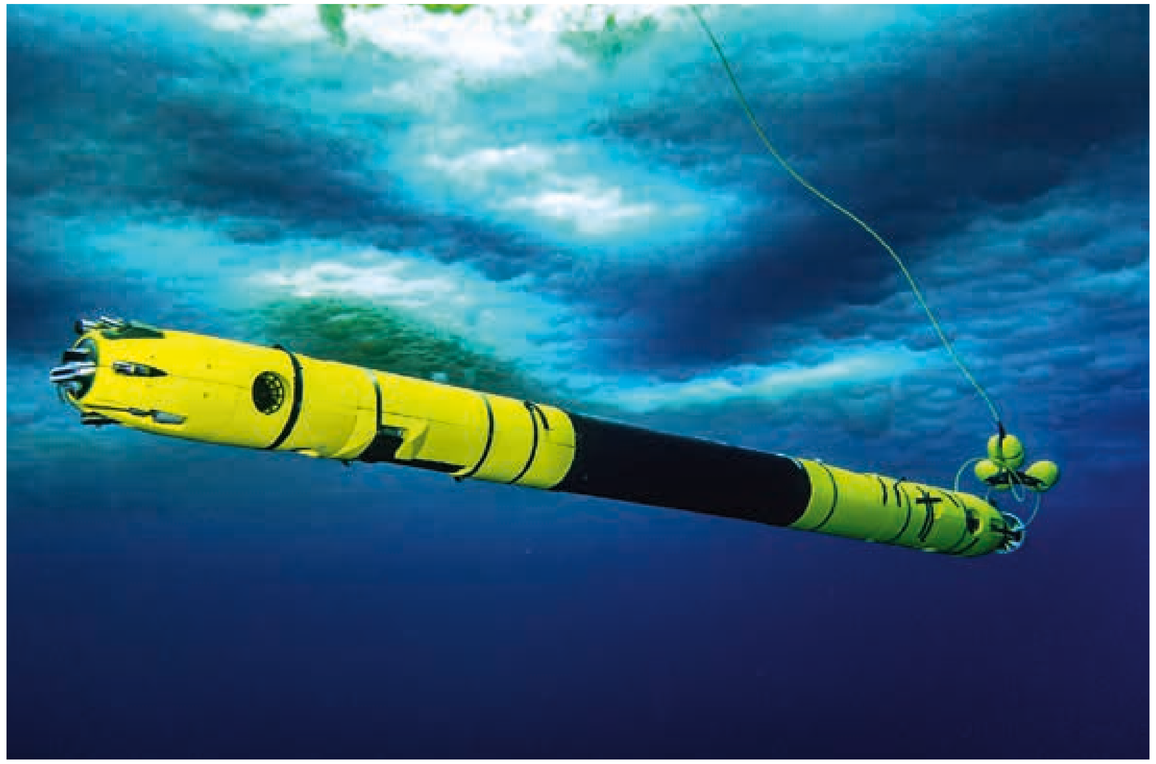
The fatal consequences of heat

> A great tragedy is playing out in the world's oceans. As humankind continues to release more greenhouse gases into the atmosphere every year, resulting in one high-temperature record after another, the oceans are countering the otherwise disastrous warming. They are absorbing more than 90 per cent of the excess heat and are storing it at increasingly greater depths. There is a high price for this service to the climate. The oceans themselves are warming! They are expanding and, in the process, losing their most valuable elixir of life – oxygen.

Old role, new attention to detail

For many reasons the world's oceans are and will remain key regulators of climate on Earth. In the summer they store the sun's energy in the form of heat, and in the winter they release it into the atmosphere. At the same time, ocean currents are continuously transporting heat from the tropics to the high latitudes, and in this way distribute it around the globe. Both of these processes act to moderate the climate. Moreover, the oceans remove the greenhouse gas carbon dioxide from the atmosphere. A portion of this is stored in the deep sea, which helps to buffer global warming. They also feed the global water cycle through the evaporation of large amounts of water from their surfaces.

Scientists have known about these large-scale relationships for a long time, but what is new is the level of detail at which researchers now comprehend the complex interactions between the ocean, the atmosphere, the sun, ice and snow, and the land surface. The foundations for this knowledge are provided by modern observation systems, which are deployed today in space, in the air, on land and in many regions of the world's oceans. Satellites record the growth and shrinking of ice sheets and glaciers. They measure the surface temperatures of the ocean, changes in sea level, the area and thickness of sea ice in the Arctic and Antarctic regions, and can also document the salinity, colour and chlorophyll content of surface waters. Sensors attached to ships' hulls, along with submersible vehicles, buoys and moorings, record seasonal and long-term changes in key water parameters such as temperature, salinity, pH values, oxygen, nutrient concentrations and chlorophyll content. A good example is the ARGO network of independently operating profiling drifters, comprising more than 3700 measuring devices. These robots measure the water temperature and salinity, and in some cases even pH values, oxygen and nitrogen content, down to depths of 2000 metres.



2.1 > With this one-metre-long and 23-centimetre-diameter submersible vehicle called *Icefin*, scientists have succeeded for the first time in penetrating beneath the floating ice tongue of the Thwaites Glacier in West Antarctica to study on a large scale how warm the water is on the underside of the ice.

In addition, there are ultra-modern submersible vehicles that are either propeller-driven or glide through the ocean for months at a time, allowing scientists to steadily advance into previously inaccessible ocean areas. In West Antarctica, for example, British and American researchers were able for the first time, in the winter of 2019/2020, to obtain measurements in the water masses beneath the floating ice tongue of the Thwaites Glacier using an underwater robot. The scientists drilled a 40-centimetre hole through more than 600 metres of ice shelf and lowered the torpedo-shaped measuring tool down on a rope. Upon reaching the underside of the ice, the vehicle, called *Icefin*, began an hours-long exploratory tour documenting the temperature and conductivity of the water, among other properties. The data revealed that the water was two degrees warmer than the melting point of the glacier ice, which explains why the Thwaites Glacier is losing ice so rapidly.

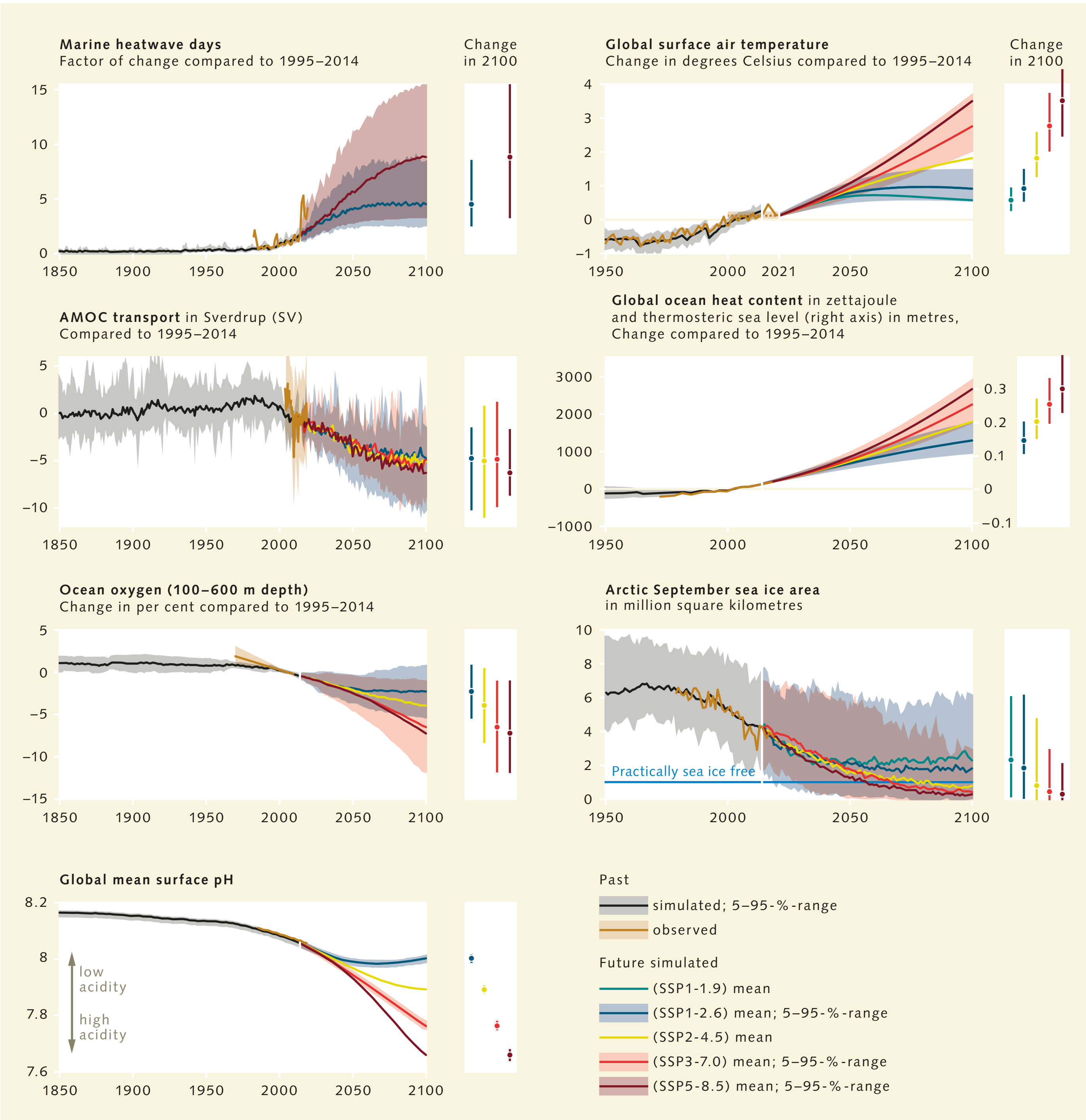
Also contributing to our better understanding of the role of the ocean in the climate system, however, are a plethora of historical, mostly handwritten weather records (ships logs, marine weather reports, etc.) that have now been digitized and fill some of the gaps in long-term observation series. Progress has also been made in deciphering past weather and climate data extracted from coral reefs, ice cores, lake and marine sediments, fossils and other natural climate archives.

Furthermore, climate research now has the benefit of high-performance computers with much greater storage and calculating capacities. These supercomputers are enabling researchers to develop new generations of climate and Earth System models that either have a much higher spatial resolution than previous generations, or that take into account many more components (for example, ocean, ice, snow, vegetation) and interactions in their calculations, and can thus better represent the complexity of climate.

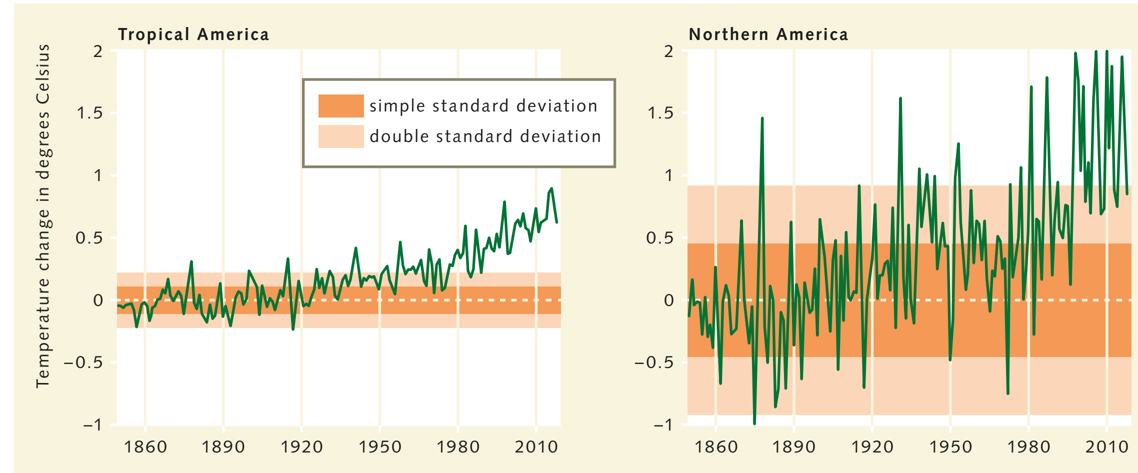
2.2 > The Thwaites Glacier is one of the fastest flowing ice streams in West Antarctica. It transports ice from a region as large as the US state of Florida toward the sea. Its melting ice masses alone are responsible for four per cent of the current sea-level rise.

For example, the ocean component of the latest model generation is capable of representing ocean eddies with diameters only slightly larger than 100 kilometres. In addition, the fast-moving ocean-margin currents are more realistically simulated. Because of these two advances, the heat transport in the ocean can be much better represented. The resolution of earlier models was not sufficient to reproduce transport processes on such small scales and to account for them in climate simulations. The same is true for biogeochemical processes in the ocean or the depiction of overlying clouds. Their existence, as well as their many associated interactions can now be modelled in much greater detail.

Based on this abundance of new observational data and climate simulations, science today is much better able to describe how the Earth's climate has changed over the past 800,000 years, and especially since the beginning



2.3 > The physical and chemical properties of the world's oceans are changing. Modelling conducted for the IPCC's *Sixth Assessment Report* simulates future development trajectories for a set of possible Shared Socioeconomic Pathways (SSPs) – green shows the scenario for a world with very low greenhouse gas emissions (SSP1-1.9), blue a world with low emissions (SSP1-2.6), yellow intermediate (SSP2-4.5), red high (SSP3-7.0) and maroon very high (SSP5-8.5) emissions.



2.4 > Although temperatures have risen more in northern America than in the tropics, the northern temperature curve still drops regularly into the former range of variations. In the tropics, on the other hand, it has long since departed from the previous levels.

of the industrial era about 150 years ago (1850 to 1900). There is also greater certainty about the causes of these changes, how climate change is affecting the oceans and seas, and what predictions can be made for the future and their degree of confidence, both on global and regional scales.

Beyond all doubt

The most important finding of climate research is that the world is warmer today than at any other time in the past 2000 years, and probably far beyond that. Since the period of 1850 to 1900, the average global temperature of our planet has risen by 1.1 degrees Celsius, whereby the warming over the continents has been significantly greater than over the oceans.

The greatest warming trend over land as documented by researchers has been in the Arctic region. The temperatures in recent decades have increased three times as fast in the northern polar region than in the rest of the world, with average temperatures varying widely from year to year. The differences are sometimes more than one degree Celsius, which is a lot. This fluctuation range, or temperature variability as meteorologists call it, makes it difficult for scientists to clearly distinguish the signal of climate change from the natural fluctuations of climate, which are referred to as climate noise.

To date, the smallest temperature increases over land have been observed in the tropics. This knowledge alone, however, is not a cause for optimism because, unlike in the Arctic region, the interannual differences here are much smaller. This means that the temperature is rising more slowly, or in smaller steps, but it is then remaining permanently above the former upper limits.

Looking closely at the curves from the equatorial regions, we see that temperatures have been above the former range of fluctuations since the 1980s. Those regions have effectively moved into a new, higher temperature regime. In other words, people living in the tropics now experience a hotter climate than their ancestors did 100 years ago. Climate researchers thus conclude that global warming is particularly evident in the tropics even though the temperature increase expressed in pure numbers is actually lower there than in the Arctic region.

Globally rising surface temperatures, however, are not the only evidence of the Earth's changing climate. Researchers are now observing numerous indicators. The air masses in the troposphere, the lowest layer of the atmosphere, are warming and therefore able to store more water vapour, which is leading to more precipitation in many parts of the world. Smaller temperature differences between the poles and the tropics are causing changes in air-mass flow and thus a shift of the important wind belts in the temperate latitudes. At the same time, the subtropi-

ARGO drifters
ARGO profiling drifters are measurement platforms that, when deployed in the sea, sink to a depth of 2000 metres and record the most important parameters of the surrounding water. Every ten days they return to the sea surface and transmit their data via satellite. The data is made freely available to the public within a few hours. Research institutions representing more than 40 countries are currently involved in the ARGO observation network.

cal arid zones are expanding, and in the Arctic region the area of Arctic sea ice has shrunk by 40 per cent over the past 40 years.

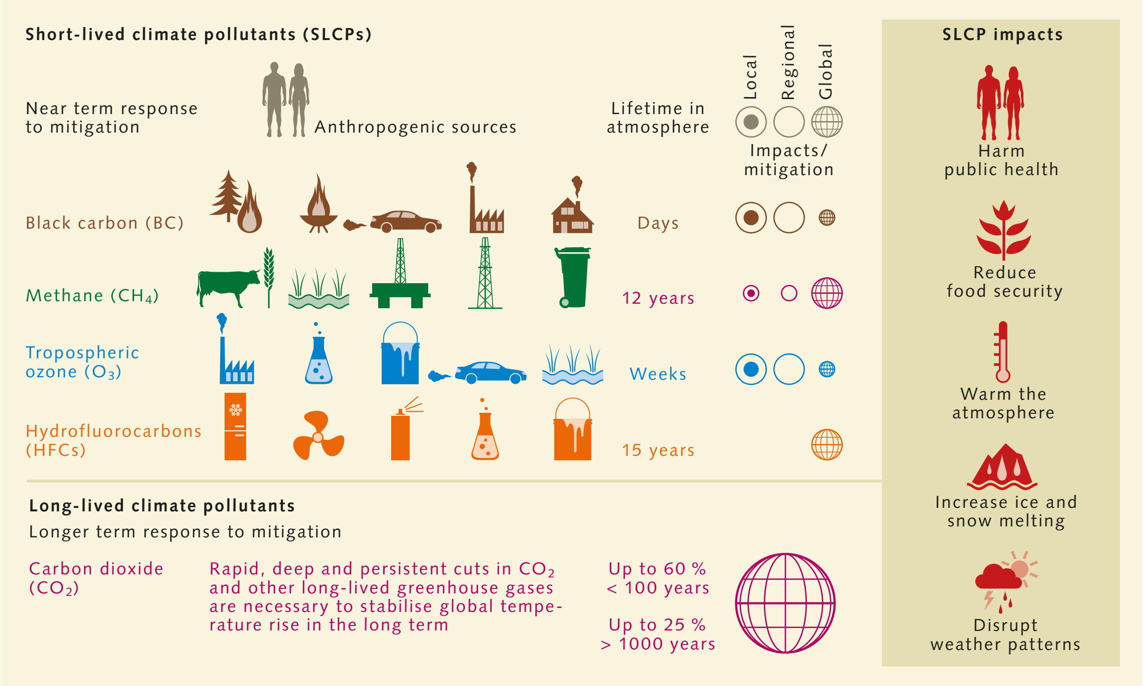
Humans are primarily responsible for these changes. This statement can be made beyond any doubt today. Important natural climate factors such as the brightness of the sun or the cooling effects of large volcanic eruptions fade into relative insignificance in view of the effects of human activity on Earth. By burning coal, oil and natural gas, humankind is releasing such great quantities of greenhouse gases such as carbon dioxide, methane and nitrous oxide (laughing gas) every year that their concentrations in the atmosphere are increasing and the greenhouse effect is intensifying.

For the regularly published IPCC Assessment Report, researchers repeatedly produce new evidence and construct increasingly better climate models to calculate the extent to which the world would have warmed with and without human activity. For some time now, the results have been telling a clear story. If the models only take into account natural climate drivers such as the sun, volcanoes, vegetation, the ocean and others, they are not able to account for the amount of warming since the beginning of the industrial era. A realistic simulation of the current climate situation can only be obtained if the researchers include the data related to human greenhouse gas emissions.

Over the past 170 years humans have released an estimated 2430 billion tonnes of carbon dioxide into the atmosphere. Of this amount, 70 per cent was produced by burning coal, oil and natural gas. The remaining 30 per cent was due to changes in land use, which include deforestation and the draining of wetlands and marshes, but also the intensification of agriculture.

Furthermore, it is notable that, throughout this time period, increasing amounts of carbon dioxide have been released by human activity with every advancing decade. In the past, financial and economic crises have at best only led to lower rates of increase or, as in the exceptional case of the financial crisis of 2008, only to a short-term

2.5 > Energy produced by burning coal, oil and natural gas is an important factor worldwide that is continuing to drive climate change.



2.6 > Around 40 to 45 per cent of global warming is caused by short-lived climate pollutants. Unlike carbon dioxide, these only remain in the atmosphere for a short time, from a few days (particulates, soot) to a few years or decades (e.g. methane and hydrofluorocarbons).

decline in emissions. Afterwards, the global economy has always recovered and carbon dioxide emissions have increased again, so that the overall long-term increase has continued. It is therefore not surprising that until corona year 2020 statisticians have been reporting new record levels of emissions with each subsequent year. The current highest value, from the year 2019, was a global total of 43.1 gigatonnes (billion tonnes) of carbon dioxide emitted. In the pandemic year 2020, emissions from fossil fuel combustion decreased by seven per cent compared to the previous year.

Of the amount of emitted carbon dioxide meanwhile 46 per cent remains in the atmosphere. The ocean absorbs 23 per cent, and another 31 per cent is absorbed from the atmosphere by land plants during their growth.

The world ocean as a heat repository

For the year 2020, due to global emissions, the annual average carbon dioxide concentration in the Earth's atmosphere rose to a value of 413.9 ppm (parts per million). For comparison, in the year 1750, two decades before the Scotsman James Watt laid the foundation for the industrial era by optimizing the steam engine, the carbon dioxide concentration is estimated to have been 277 ppm. The more carbon dioxide there is in the Earth's atmospheric shell, the more impenetrable it becomes to the heat energy that our planet is constantly radiating outward again due to the accumulation of incoming solar radiation. Instead of allowing the heat to escape into space, the greenhouse gases trap it in the atmosphere, so to speak, thus causing temperatures on the Earth to rise.

Thanks, first and foremost, to the world ocean, average global warming has so far been limited to a value of 1.1 degrees Celsius. Since the 1970s, the oceans have absorbed more than 90 per cent of the excess heat trapped in the Earth System due to human activities.

The enormous amount of energy involved becomes evident when one considers that, during the period from 2018 to 2019 alone, the oceans removed around 44 times more energy from the atmosphere in the form of heat than all of humanity had used in the same time period for transportation, industry, heating and in their households. The oceans are clearly the most effective

Methane – the unexpected rise of "younger brother"

In the past, the greenhouse gas methane has appeared much less frequently in the public spotlight than its "big brother" carbon dioxide. This is largely due to the fact that methane degrades chemically in the atmosphere, and only remains there for about twelve years. Carbon dioxide, on the other hand, does not break down easily. It must be extracted from the atmosphere, either by plants, the ocean or through the weathering of rocks. These natural extraction processes proceed much more slowly than the rate of carbon dioxide emissions, so newly released carbon dioxide will continue to impact the climate as a greenhouse gas for millennia.

But for more than ten years now, researchers have been observing the increase in the methane content of the atmosphere with great concern. Since 2014, they have been referring to it in terms of a strong increase. The concentration of methane is still significantly lower than that of carbon dioxide, but it possesses a much greater heat potential. Calculations indicate that it retains about 30 times more heat in the atmosphere than carbon dioxide. This leads to the estimation that methane is responsible for around 30 per cent of the warming observed on Earth to date.

It is not yet precisely known why methane emissions have increased so sharply in recent years. Methane is released by natural processes as well as by human activities. Around two-fifths of the emissions originate from natural sources such as moors and wetlands. Three-fifths of the emissions can be attributed to human activity. They escape from oil and gas production facilities or from old coal shafts, or are released from waste dumps and by the burning of organic material. But they can also be released through agricultural activity, for instance in rice farming or by cattle herds.

Population growth in the tropical regions may be one explanation for the rise in methane concentrations. Where there are more people, more agriculture has to be carried out to produce sufficient amounts of food. Through the use of improved observation technology such as drones and satellites, however, researchers are gaining much better insights into the enormous amounts of methane that are being released by waste dumps and oil production facilities.

The one ray of hope in the present situation is the short-lived nature of methane. If humans are able to drastically reduce their methane emissions within a short period of time – and the knowledge to achieve this goal is available – the concentrations will decline noticeably within a decade.

With carbon dioxide, however, there would be a wait of centuries to millennia before extensive reductions in emissions could result in a measurable decline in the atmospheric concentrations.

component of the Earth's climate system for storing heat.

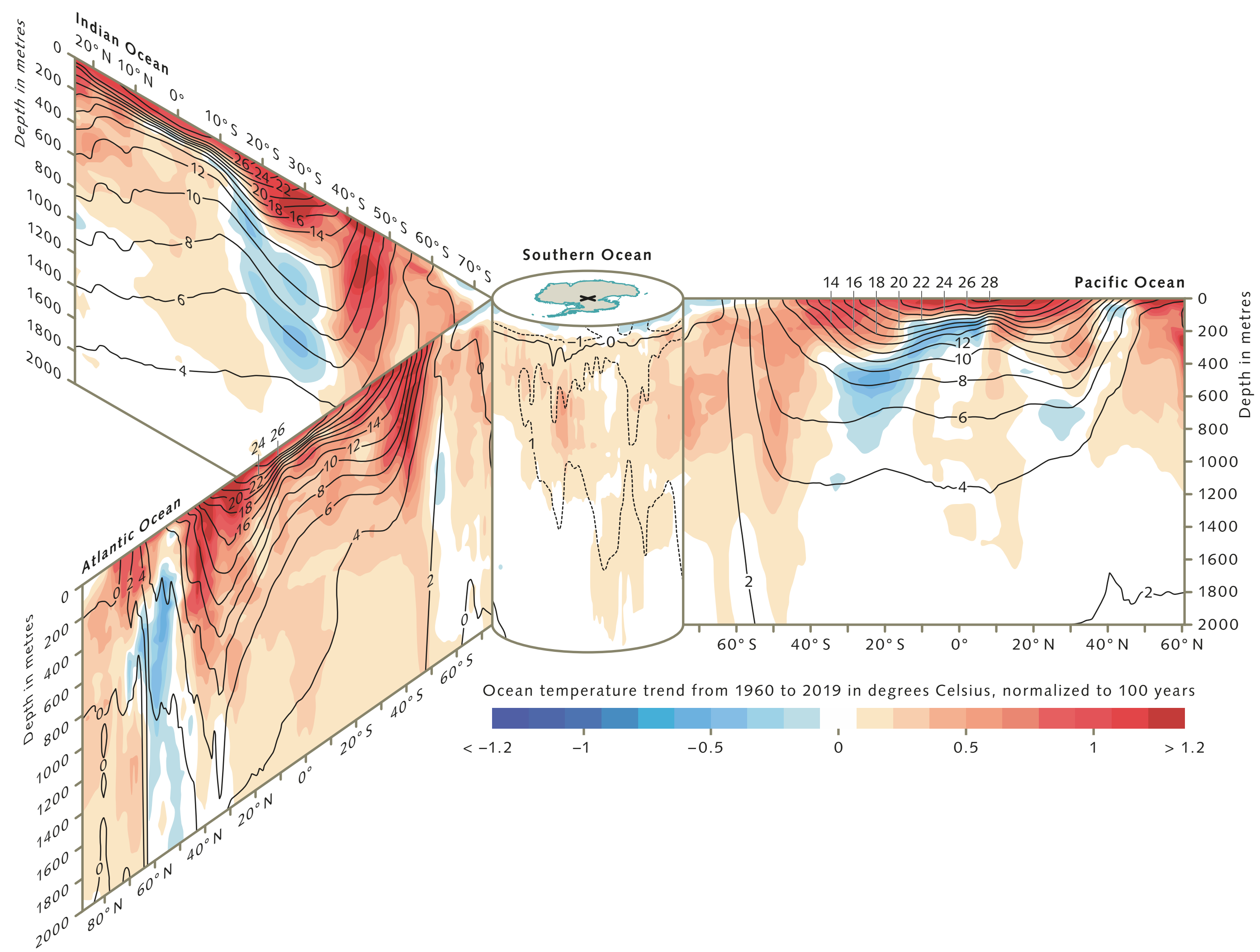
The fact that the ocean can extract so much heat from the atmosphere is primarily due to the extremely high heat capacity of water. This means that, compared to other substances, a comparatively large amount of thermal energy is needed to heat water by even one degree Celsius. To put it another way, the sea is capable of absorbing large amounts of heat without becoming significantly warmer itself. Conversely, however, this also means that the oceans are able to store a great deal of heat, a property that becomes particularly important considering that they will also release that heat energy back into the atmosphere when the water masses cool down.

Because the heat capacity of water is four times greater per kilogram than that of air, the oceans are able to store over 1000 times more heat than the Earth's atmospheric shell. The absorption of heat occurs at the sea surface. Winds, tides and ocean currents act to mix the water masses and keep them in constant motion, so that the heat is transported vertically to substantial depths as well as horizontally from the warmer regions toward the poles.

Heat absorbed by the sea, however, does not simply disappear. It is only stored temporarily. The ocean can therefore be compared to a gigantic thermal battery that, by the emission of greenhouse gases, we humans have been constantly charging with heat since the beginning of industrialization, thereby forcing climate change.

The heat energy stored in the sea eventually has an impact on climate again by contributing to the melting of sea ice or floating glacier tongues in the Arctic and Antarctic regions, by enhancing the evaporation of seawater, or by warming the air directly above the sea surface.

In this case, the ocean releases its heat energy back into the atmosphere and causes air temperatures to rise, especially in the temperate and higher latitudes. The time frame in which this occurs is difficult to predict. Once it is absorbed, the heat in the ocean can significantly influence the Earth's climate for decades. In order to make scientific climate predictions, therefore, it is crucial to



2.7 > The oceans absorb heat at their surface. Currents then transport it to greater depths. This pattern is observed in all oceans, as illustrated here by the changing temperatures to a depth of 2000 metres.

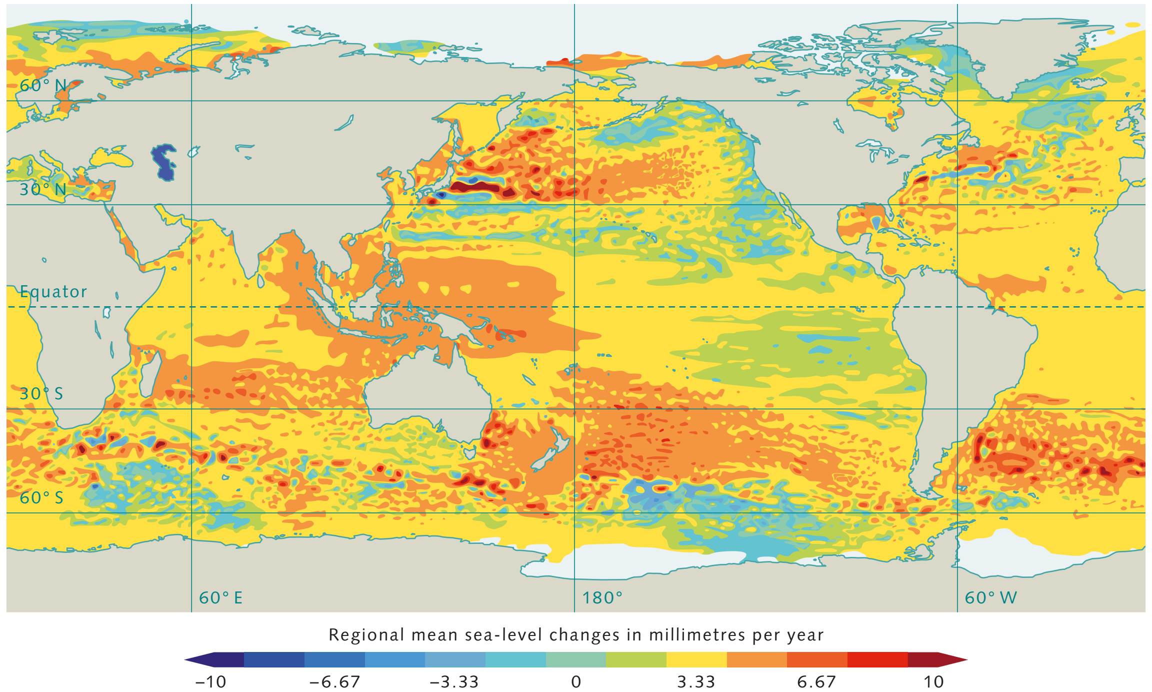
know the heat content of the world ocean as accurately as possible.

The ocean temperature curve through time also serves scientists as an important monitoring tool. Data that describe changes in the heat content of the oceans are the best indicators of how global warming is progressing – whether it is abating (stable or declining water temperatures) or advancing (rising water temperatures). Data from the air are actually not particularly useful for such analyses because they are influenced by too many different factors. Nevertheless, they are still often used to make assertions about the development of global warming.

Temperature increases at great depths

As the ocean continues to absorb heat, the increase in water temperatures becomes more evident, initially at the sea surface, but eventually also to greater depths. Since the beginnings of the 20th century, the mean surface temperature of the oceans has increased by 0.88 degrees Celsius.

However, scientists are also now observing substantial changes in the deep sea as well. Looking at the heat distribution at various depths, up to the year 2020 about 40.3 per cent of the absorbed heat had remained in the



2.8 > Sea levels do not rise uniformly as they do in a bathtub. Satellite observations from 1993 to 2017 reveal significant regional differences.

upper 300 metres. 21.6 per cent had reached depths of 300 to 700 metres, and another 29.2 per cent had accumulated in the water layers between 700 and 2000 metres. The remaining 8.9 per cent of the heat was transported to depths below 2000 metres, especially in the Atlantic and Southern Oceans.

Climate researchers therefore conclude that the large-scale warming of the ocean is one of the most convincing signs of global climate change. The oceans are warmer today than they have been at any time since the beginning of continuous observations. All signs point to a continued increase in water temperatures throughout the 21st century, even if humankind succeeds in reducing its greenhouse gas emissions.

Life-threatening consequences

As a result of warming there are changes in several key physical properties of seawater. Some of these changes have a direct impact on climate, while others have a more pronounced impact on life in the sea and near the coasts. The most important effects are:

- the rise in sea level,
- increased stratification of the water masses and the associated decrease in ventilation and oxygen content of the inner ocean,
- intensified evaporation of seawater,
- amplified danger of extreme weather events such as storms, and
- increased occurrence of heatwaves in the ocean.

Rising water level with no end in sight

Water expands with warming. This basic law of nature also applies to the oceans, of course, and in recent decades this process has contributed to a mean global sea level that was 20 centimetres higher in 2018 than it was in the year 1900. And, according to predictions, the level will continue to rise by another 18 to 23 centimetres by 2050. Until the beginning of the 21st century, the increasing ocean temperatures and accompanying expansion of water masses were the main reason for the long-term rise of global mean sea level. From 1901 to 1990 the rise averaged 1.4 millimetres per year.

2.9 > The highest point on the Philippine island of Batasan is less than two metres above sea level. The island is thus one of the low-lying coastal regions of the world that will soon be uninhabitable because of the rising water levels. During high tides, water already routinely enters the houses.

Since then, however, the rise in sea level has been accelerating noticeably. From 1971 to 2018 the global level rose by an average of 2.3 millimetres per year, whereby values as high as 3.7 millimetres were measured during the second half of this time period (2006 to 2018). This means that the rate of rise has more than doubled when compared to the past century.

This acceleration, however, cannot be attributed to ocean warming alone, even though the share due to density changes in the water now stands at 1.4 millimetres per year. Rising sea levels can be caused by a variety of processes. In the past two decades the amounts contributed by the worldwide melting of glaciers and of the ice sheets in Greenland and Antarctica have increased drastically. The constant influx of new meltwater means that there is actually more water circulating in the ocean, and this increase in mass is also contributing to sea-level rise. According to the **Intergovernmental Panel on Climate Change (IPCC)**, over the past 15 years ice loss from glaciers and ice sheets accounted for 1.62 millimetres of rise per year. This is around 44 per cent of the total rate of increase.

Furthermore, changes in water-usage practices on land also have a measurable influence on global sea levels. For example, if streams and rivers in numerous regions of the world are dammed to form reservoirs, it can actually have the effect of lowering sea level. The reverse effect occurs when large amounts of water on land are removed from groundwater sources or lakes, and this water is then discharged into the ocean through sewers, streams and rivers after its use.

At this point, it should be noted that the water levels in the world's oceans do not rise uniformly like the water in a bathtub. The surface is also not level, as one might first think when looking out to sea from the beach. Satellite observations confirm that there are significant regional differences in sea level, as well as in the rise of water levels over time. These can be attributed, for example, to the influences of ocean currents and winds, or the variability of water-mass expansion due to heat. Rising or falling water levels, however, can also be affected by uplift or subsidence of the land areas in coastal regions that were covered by huge glaciers during the last glacial period. Expressed quantitatively, these differences can account for as much as plus/minus 30 per cent of the present global increase.

For this reason, scientists commonly refer to sea levels in the plural sense. In addition, experts frequently point out that when assessing the risk of local flooding, it is not the global trend alone that matters, but that local conditions in particular must be taken into account. A striking example of this is seen in the water-level trends along the coasts of North America. While sea levels along the west coast have remained almost unchanged or have even fallen in recent years, they are still rising for the most part on the east coast.

Rising water levels are one of the most impactful effects brought about by climate change. They threaten countless atolls and small island nations as well as extensive, often densely populated coastal regions around the world. But it is still extremely difficult for scientists to make precise predictions about the future development of regional and local sea levels. This is because of the great uncertainties connected with the crucial influencing factors. For example, accurate future melting rates of the ice sheets in Greenland and Antarctica are still difficult to predict, and it is not certain whether they will eventually reach a tipping point, beyond which their collapse will be unstoppable and irreversible.

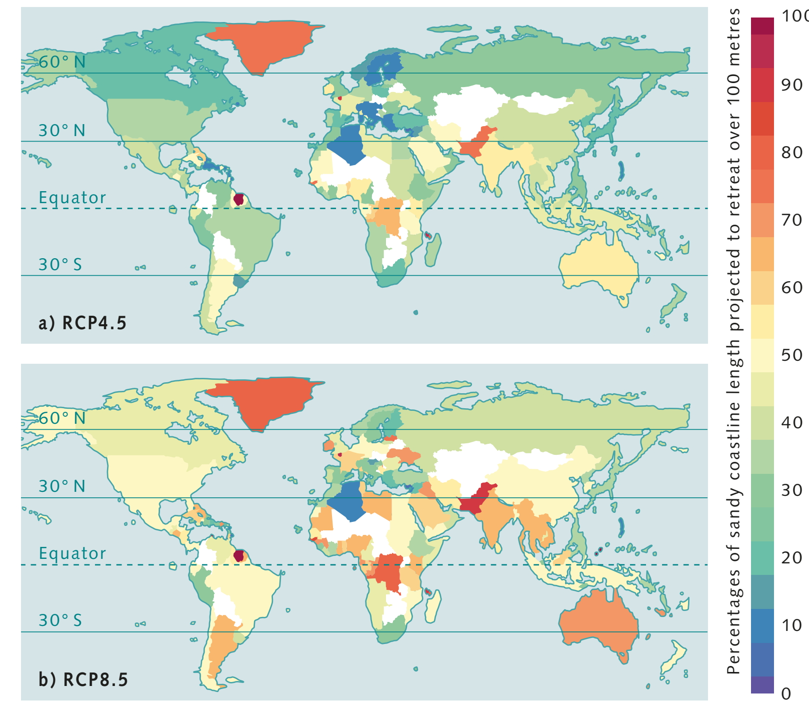
In its *Sixth Assessment Report*, published in 2021, the Intergovernmental Panel on Climate Change projected that the rise in global sea level will continue to accelerate, even if the international community is successful in reducing greenhouse gas emissions to the levels agreed to in the **Paris Climate Agreement** of 2015. According to present predictions, the mean global sea level will rise by 38 to 77 centimetres by the year 2100, depending on the amount of greenhouse gases humankind continues to emit.

As water levels rise, the danger of flooding becomes greater, especially in coastal regions that are less than ten metres above sea level. Statistically, many of these, in the past, were hit by exceptional flooding events related to storm and spring tides or extremely high waves only once every 100 years. According to the Intergovernmental Panel on Climate Change, by the year 2050 these events will be occurring every two to 50 years in the high and temperate latitudes. In the lower latitudes, the coastal areas of the tropics and subtropics, the experts expect several extreme high-water events every year. This means that cities with millions of inhabitants, such as Calcutta, could be regularly inundated by the sea in the future.

Flooding will be particularly severe when a generally high sea level is combined with spring tides in an area of storms, where winds pile up seawater off the coast. Under these conditions, high waves are able to penetrate especially far inland and flood large coastal areas. Coastal protection experts estimate that the danger of severe flooding increases by a factor of about three with every decimetre of sea-level rise. This steep increase is mainly due to the fact that the coastal zones in many regions of the world are only slightly higher than the current local sea levels. So, if the regional level rises by about ten centimetres, the high-water line shifts landward by around 30 to 40 metres, depending on the amount of slope. During storms, the waves roll in much further over the coastal area unless steep cliffs or structures such as coastal protection walls block their path.

Discounting all high-water protection measures and considering only the land elevation in the coastal regions, around 360 million people presently live in low-lying regions that would be regularly flooded by the year 2100, even if the two-degree climate target were to be met. Most of these people are in Asia. In Vietnam, for example, almost one-fourth of the population would be affected under these conditions. In Bangkok, the capital of Thailand, large portions of the city would be permanently under water, and a similar situation would be seen in Shanghai.

This number, however, is only one among many, because scientists have proposed many quite different definitions of the conditions under which coastal populations are considered to be threatened by sea-level rise. More accurate prognoses are also difficult because the future population growth in coastal regions can only be approximated, and due to the fact that many coastal metropolitan regions are subsiding as a result of large quantities of groundwater being pumped out of the subsurface aquifers. Where local sea level is rising at the same time, the flooding risk is greatly multiplied.



2.10 > Rising sea levels are threatening the world's sandy beaches. For all coastal countries, these two maps show the calculated percentage of sandy beach coastline length with a loss in breadth of more than 100 metres by the year 2100. Above (a) shows a world that warms by 2.5 degrees Celsius by 2100; below (b), a world that is around 4.3 degrees Celsius warmer by the same time.

But researchers are in full agreement in their overall assessment of the threat that the global rise in sea level presents. They leave no doubt that minimizing the impacts on coastal populations is one of the greatest societal challenges of our time.

Oceans running out of oxygen

The warming ocean water is not only expanding, it is also losing oxygen, which is vital to marine life. Between 1960 and 2010, the world's oceans lost more than two per cent of their oxygen content (around 77 billion tonnes of O_2). One reason for this was eutrophication, a process that mainly affects coastal waters. Another factor, which scientists can now clearly demonstrate is responsible for most of the oxygen loss, is ocean warming due to climate change.

Oxygen enters the ocean in two ways: either through gas exchange processes between the atmosphere and sea at the water surface, or as a by-product of photosynthesis, which is carried out by algae and aquatic plants in the upper part of the water column penetrated by light. Still, on average, a litre of seawater contains about 30 times less oxygen than a litre of air, which is why breathing underwater is such a difficult task. To obtain one gram of oxygen, fish, mussels, starfish and other animals have to pump around 152 litres of water through their gills or respiratory organs. By contrast, land organisms have to inhale only 3.6 litres of air to get the same amount of oxygen.

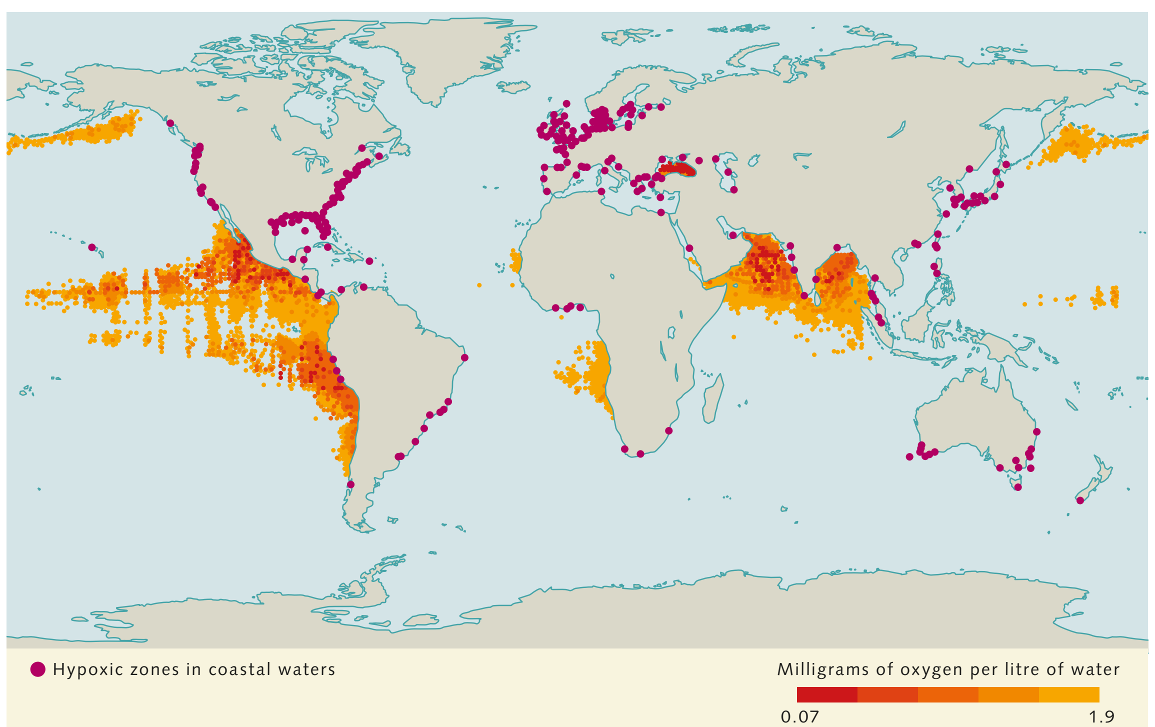
Oxygen in the ocean is not only used by fish and other highly developed marine organisms. It is needed mainly by microbes and multi-celled organisms that break down plant and animal remains (organic material) at great depths, whereby oxygen is consumed. The more biomass that is produced in the zone penetrated by light and the more algae and animals that die and sink, the more organic material there is available for the microbes and, accordingly, the greater the amount of oxygen they consume. The case is similar for rising water temperatures. As the ocean becomes warmer, the large and small marine inhabitants require more oxygen to maintain all of their vital processes.

From this knowledge, scientists can draw two main conclusions.

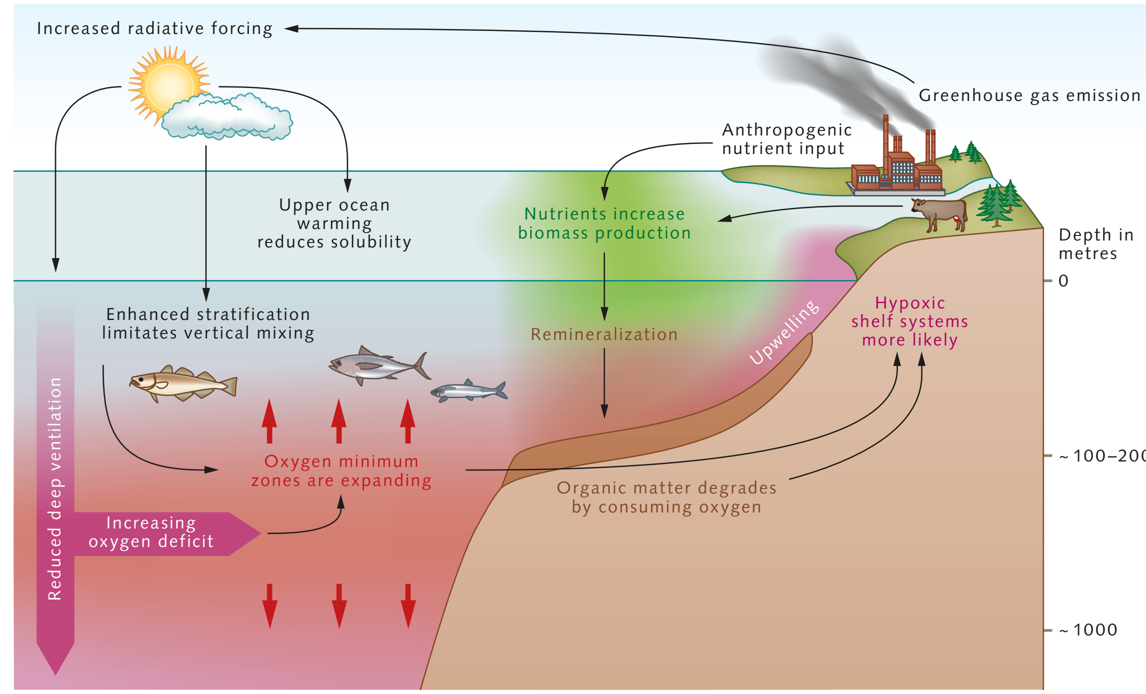
Firstly: Changes in the basic chemical or physical conditions within a water layer – for example, the amount of nutrient input, the temperature, or the amount of incident light – influence biomass production and thus, in the long term, the amount of oxygen-consuming decomposition of the biomass that sinks into the depths.

Secondly: When ocean circulation transports oxygen-rich surface water to greater depths, its oxygen concentration is initially comparatively high. But the longer this water remains in the deep, the more time the microbes and other organisms have to break down the sinking particles and thereby consume the oxygen contained in the water. For this reason, the deep water, as a rule, is relatively oxygen-poor.

But let us return to the sea surface. The amount of oxygen that the ocean can absorb from the air depends on the temperature and salinity of the surface water.



2.11 > Low or declining oxygen concentrations are a global problem that is present both in coastal waters and in the open ocean. This map shows coastal regions marked in purple whose waters contain less than two milligrams of oxygen per litre of water (< 63 micromoles per litre). The distribution of the oxygen minimum zone at a depth of 300 metres is shown in orange.



2.12 > Oxygen depletion in the open ocean is caused primarily by rising water temperatures. These have the effect of inhibiting the dissolution of oxygen in the water and preventing adequate mixing between the surface and deep waters. In coastal areas, on the other hand, a high influx of nutrients enhances algae growth, and their degradation by microorganisms eventually consumes all of the oxygen.

These two factors significantly determine the solubility of gases in water. Less oxygen can be dissolved in a warmer and saltier ocean. If the temperature of the surface water increases from four to six degrees Celsius, for example, its oxygen content automatically decreases by five per cent.

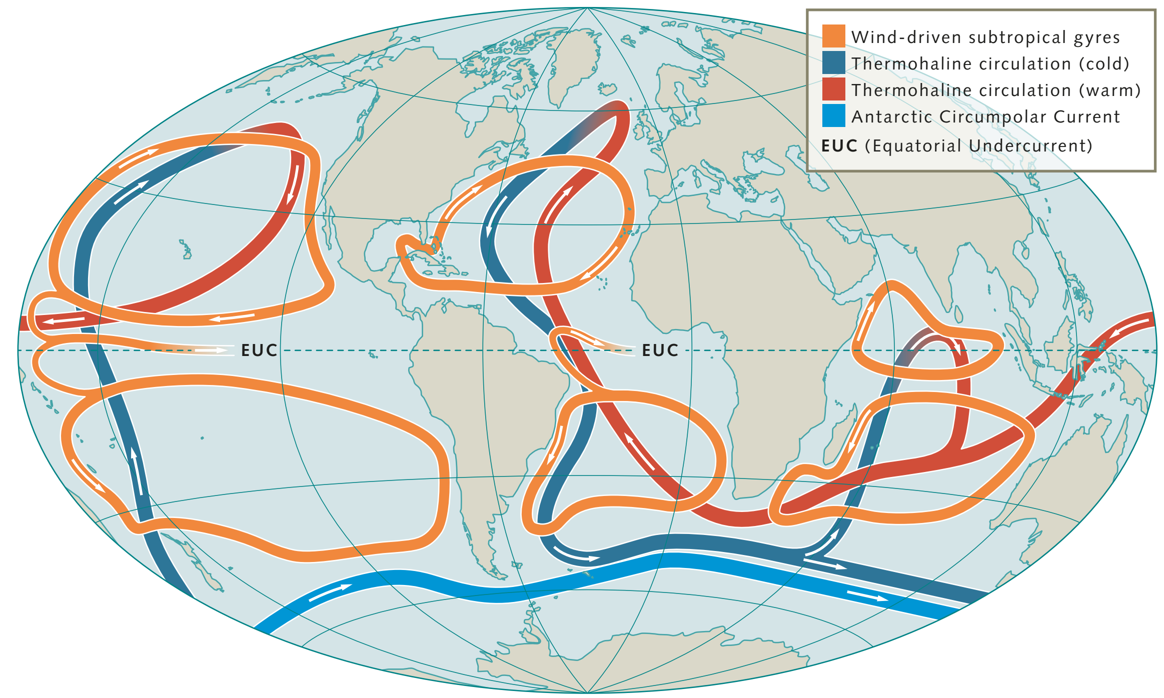
Scientists have studied how great the respective influences of temperature and salinity changes have been on the oxygen content of the oceans through recent decades. They have concluded that the decrease of oxygen in the upper 1000 metres of the water column is primarily due to the increasing levels of heat and the consequential lower solubility of gases in the ocean. Changes in salinity, on the other hand, have been found to play only a minor role.

Calculated for the entire water column, however, the oxygen losses related to heat and solubility account for only 15 per cent. The remaining 85 per cent are caused by the fact that the ocean currents as well as the mixing depths of the surface water are changing.

The water masses at the sea surface are aerated by direct gas exchange with the atmosphere. This process is so efficient that the surface water is practically always oxygen-saturated with respect to its temperature. This means that it has the maximum possible oxygen concentration and, in this regard, is in equilibrium with the atmosphere. The depth to which this condition exists depends on the wind as well as the air and water temperatures, both of which vary depending on season and latitude. In the summer, when the surface water is warmed strongly by the sun and by higher air temperatures, it expands and becomes significantly lighter than the underlying, mostly cooler water layers. Fundamentally, the colder and saltier a water mass is, the greater its density, and the deeper it lies within the stratigraphy of the ocean. As a result of this density contrast with the deep water, the warm surface water lies like a stable, warm blanket on top of the ocean, and even a strong wind is no longer able to mix the upper layer with the underlying water masses. The oxygen-rich water remains near the sea surface, and is not transported to the deeper layers.

Scientists refer to the layering of water masses due to density differences as stratification. Because the ocean warms from the top down, stratification of the layers is

2.13 > Temperature-defined boundaries between water masses can sometimes be seen with the naked eye. In this picture, jackfish and yellowtail fusiliers are swimming just above much colder deep water.



2.14 > The location, size and distribution of oxygen-poor zones are closely related to ocean currents. This map shows the wind-driven currents of the subtropical gyres and the Antarctic Circumpolar Current, as well as the density-driven conveyor belt of thermohaline circulation.

intensifying as a direct consequence of ocean warming, and the amount of water exchange between the surface and the underlying layers is decreasing at ever greater rates. In some regions of the world, the temperature-related stratification of the upper water layer is further amplified. For example, in the polar regions, the snow cover, glaciers and ice sheets are melting at increasing rates, and their meltwater is freshening the ocean at the surface. Scientists are observing the same effect in those ocean and coastal regions where there is more precipitation as a result of climate change. Like the meltwater, rain is pure freshwater, which dilutes the surface water of the ocean, making it less saline and therefore lighter.

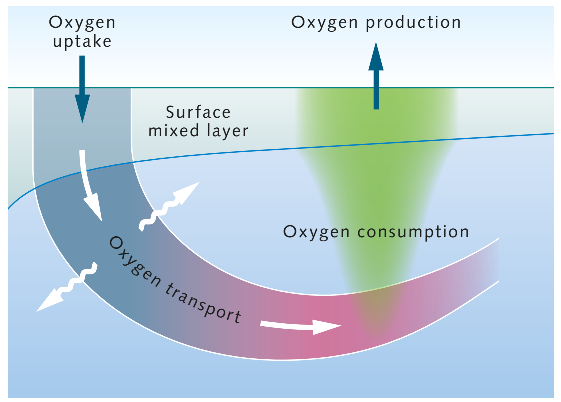
The thermohaline conveyor belt of ocean currents is responsible for ventilating the levels below the wind-mixed surface layer. It transports the water masses of the ocean like a kind of conveyor belt through all of the major ocean basins. This conveyor belt moves because of temperature and salinity differences between the water masses, which is why scientists refer to it as thermohaline circulation (*thermo:* driven by temperature differences; *haline:* driven by differences in salinity).

However, its operation is impeded by climate change, because when the water masses at the sea surface become warmer and lighter, the overturning by thermohaline circulation proceeds more slowly. This process entails the cooling and sinking of enormous masses of water, both in the middle latitudes where the intermediate water originates, and in the Arctic and Antarctic regions where heavy, oxygen-rich deep water is formed. The latter flows from the polar regions back toward the equator, thus ventilating the deep ocean. The intermediate water, on the other hand, supplies the middle layers of the ocean with oxygen.

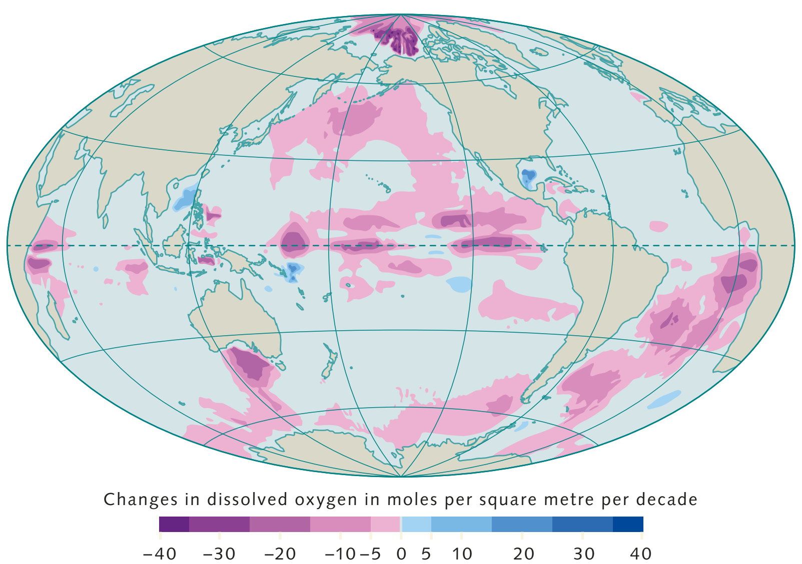
There is now evidence from many parts of the world that the conveyor belt of thermohaline circulation is slowing down as a result of climate change. It indicates not only that less oxygen-rich surface water is reaching greater depths, but that the individual water masses, on their journey through the oceans, are also spending more total time within the middle and deepest layers of the ocean. But in these two levels, microbes and other small organisms are continuing to decompose organic particles and consume oxygen, which is leading to a further depletion of the oxygen content of the intermediate and deep waters.

German scientists, using climate-ocean models, have calculated how these processes will play out. Their results indicate that the deceleration of global ocean circulation due to warming will be responsible for half of all the oxygen loss in the upper 1000 metres of the water column in the future. And in the deeper ocean, below 1000 metres, as much as 98 per cent of the loss will be attributable to the slowdown of thermohaline circulation.

Over the past 50 years in the open ocean, the total area of the oxygen minimum zone, in which fish no longer have enough oxygen to breathe, has expanded by around 4.5 million square kilometres. This increase is roughly equivalent to the land area of the European Union. During the same time period, the amount of anoxic water, completely void of oxygen, has quadrupled. The ocean is literally running out of air because of climate change. The catastrophic aspect of this development, however, is that the heat-induced loss of oxygen in the ocean cannot simply be stopped and reversed. Even if humans were able to successfully reduce their greenhouse gas emissions by amounts that are in accordance with the Paris Climate Agreement and live with net-zero emission levels in the future, it would take several centuries for greenhouse gas concentrations to decline, for the atmosphere and the world ocean to cool down, and for the oxygen content of the oceans to return to pre-industrial levels.



2.16 > In the open ocean the oxygen content of the water decreases with increasing depth. This is due to oxygen consumption by microorganisms.



2.15 > Since 1960 the total oxygen content of the ocean has decreased by more than two per cent. This map shows the regions in which the oxygen concentrations have declined most strongly.

Fuel for hurricanes and heavy rains

Ninety-seven per cent of all liquid water on Earth circulates in the oceans and their marginal seas, which makes them the most important reservoir in the global water cycle. An estimated 420,000 cubic kilometres of water evaporate above the oceans each year. Around 90 per cent of this moisture then returns directly to the sea in the form of rain or snow. The remaining ten per cent, however, drifts over the continents in the form of water vapour or clouds and precipitates there. On its way back to the sea, it often makes temporary stopovers – for example, in the form of water droplets that help a plant to grow, or to seep through the soil and help replenish a groundwater reservoir. But eventually, this water too returns to the sea.

The amount of water that evaporates above the ocean to take up this journey depends greatly on the air and water temperatures. The more the atmosphere warms, the more water vapour it can hold (seven per cent more moisture per one degree Celsius of warming). And the warmer the seawater is, the more readily it evaporates at the surface. As a result, significant patterns of water distribution within the hydrological cycle are changing in the

wake of climate change. Higher evaporation rates, for example, amplify the intensity of heavy rainfall events that mostly build up over the ocean. This means that during this kind of extreme weather event much more rain will fall today than it would have in the past.

A good example of this was tropical storm Imelda, which struck the south-eastern region of the US state of Texas in mid-September 2019 and triggered large floods because of its unusually high amounts of rainfall. On the second and third days of the storm, up to 500 litres of rain per square metre fell in the storm centre, an amount of rainfall that is normally only seen in this coastal region every 50 years. Around 1000 people had to be evacuated, five people died, and more than 10,000 cars were damaged by the rainfall and flooding. A state of emergency was declared for 13 counties with a total population of 6.6 million.

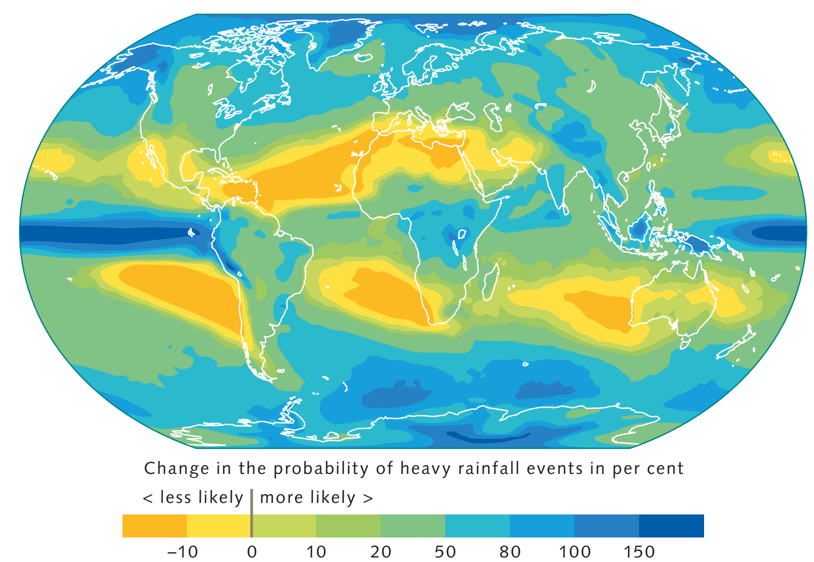
After this extreme event, climate researchers collected all of the available meteorological data from the region – current weather data as well as historical records going back at least 80 years. Using climate models, they then calculated the degree to which climate change had increased the probability of the storm and its intensity of precipitation. Their analysis showed that, compared to the year 1900, the risk of this kind of two-day heavy rainfall occurrence had risen by a factor of 1.6 to 2.6. The intensity of the rainfall had increased by nine to 17 per cent. Researchers concluded that the study was further evidence that climate change along the US Gulf Coast is leading to increasing amounts of rain during extreme weather events.

These kinds of studies, referred to as extreme event attribution research, belong to a still relatively young research field within climate science. For almost 20 years researchers have been trying to identify the proportion of the contribution of human-induced climate change to extreme events such as droughts, heatwaves, storms and floods. They often compare the observational data from an extreme event to two kinds of climate simulations – one in a world without greenhouse gas emissions from humans, and a second which realistically reflects our present climate.

Over 350 individual studies have now been reviewed by experts and published in professional journals. Most of them provide new indications that human activity increases the probability of occurrence or the intensity of extreme weather events. In an overview study published in 2020, experts showed that man-made climate change had increased the probability or intensity of 78 per cent of the extreme events studied. In most cases, the triggers were rising temperatures resulting from high greenhouse gas emissions. When considering only the studies on heavy rainfall events and flooding, the results were not quite as conclusive. For these cases, a clear link to climate change could be detected in only 54 per cent of the studies.

In its most recent report, the Intergovernmental Panel on Climate Change similarly anticipates that precipitation patterns will change in many regions of the world. Exceptional events such as heavy rainfall or prolonged drought will occur more frequently and will be more intense. Moreover, the seasonal differences in amounts of precipitation will increase. In some regions this will mean less frequent rainfall. But when precipitation does fall, the sky will open its floodgates and more water will rain down within a short time than the local population has been accustomed to. The danger of flooding is increasing because tropical and extratropical storms are carrying much more moisture.

2.17 > The warmer the atmosphere and ocean are, the more water evaporates and the greater the danger of heavy rainfall becomes. The map illustrates the increased probability of heavy rainfall events in a world that is three degrees Celsius warmer than in pre-industrial times.



Oxygen distress in eutrophic coastal waters

Every year in June, scientists from the US National Oceanic and Atmospheric Administration (NOAA) publish a prediction of the size of the dead zone that will form in the northern part of the Gulf of Mexico during the summer. Dead zones refer informally to near-coastal marine areas where the water is hypoxic. These are areas where the oxygen content is so low that fish and other breathing aquatic organisms experience respiratory distress and are forced to greatly reduce their metabolism or, if that is not possible, to migrate or to die.

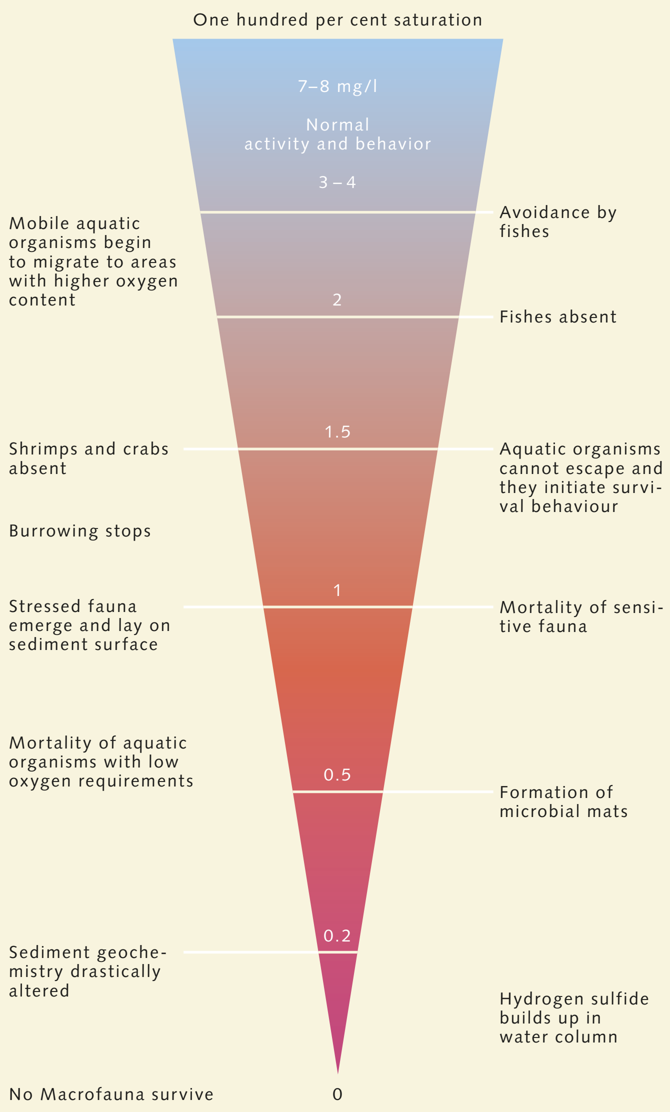
Exactly when this point is reached differs from species to species. Scientists simply use guideline values, and they even express them in different units depending on whether they are referring to coastal waters or zones in the open ocean. As a rule, water masses are considered to be hypoxic when they contain less than 70 micromoles of oxygen per kilogram of water. And if the concentration sinks below 20 micromoles, they are referred to as minimum zones with extremely low oxygen content.

Hypoxic zones usually occur where rivers supply excessive amounts of minerals and nutrients to coastal waters, thus promoting the growth of unicellular and multicellular algae (phytoplankton). This often results in harmful algal blooms. When the algae die, their remains sink to the deeper water layers. There, they are decomposed by microbes that consume more oxygen in the process than can be replaced by freshwater, currents, or wind and waves (mixing with surface waters). At the same time, however, the microbes release large amounts of carbon dioxide, which lowers the pH value of the deep water. This results in even worse living conditions for marine organisms in this zone.

A problem caused on land

Humankind is primarily responsible for the excess nutrient input. The world's human population has almost tripled since 1950. Accordingly, the pressure on farmers to produce enough food has increased. Globally, farmers today use ten times more fertiliser (mainly nitrogen and phosphorus) than they did 50 years ago. A considerable amount of that is washed by rain into the sea. This is often joined by untreated wastewater from cities and municipalities. As a result of this water pollution, the nutrient load in coastal waters has increased so greatly that the number of hypoxic zones doubled during the period from 1960 to 2007. There are now more than 500 worldwide. They can be found almost everywhere: in the Gulf of Mexico and the Baltic Sea, in the East China Sea, along the British coast, and in Australia. In the USA alone there are now 300 areas where the oxygen concentration falls below the critical guideline value for fish of 70 micromoles per kilogram of water.

Many of these are located in shallow coastal areas (less than 100 metres of water depth), particularly where there are relatively weak currents. This allows the water masses to remain in place for a relatively long time. Under these conditions, not only do algae grow very well in the summer, but a very warm and stable surface layer forms, making it difficult for oxygen to penetrate to the deep water. The only things that will break through this stable layer are storms that can stir up and thoroughly mix the coastal waters. In the summer of 2019, for example, Hurricane Barry prevented the formation of an anticipated record-breaking dead zone. But scientists now know that the ventilating effect of a storm does not persist for very long. In most cases the conditions under which the coastal waters were losing oxygen return within one week. And the warmer the air and the sea are, the earlier in the year these conditions are established, and the longer the hypoxic zones prevail. Climate change thus facilitates the formation of these zones.



2.18 > The availability of oxygen determines species diversity and which life forms are viable in a body of water. Coastal researchers calculate the oxygen concentration in milligrams per litre of water and now know at what thresholds higher life forms begin to gradually disappear.

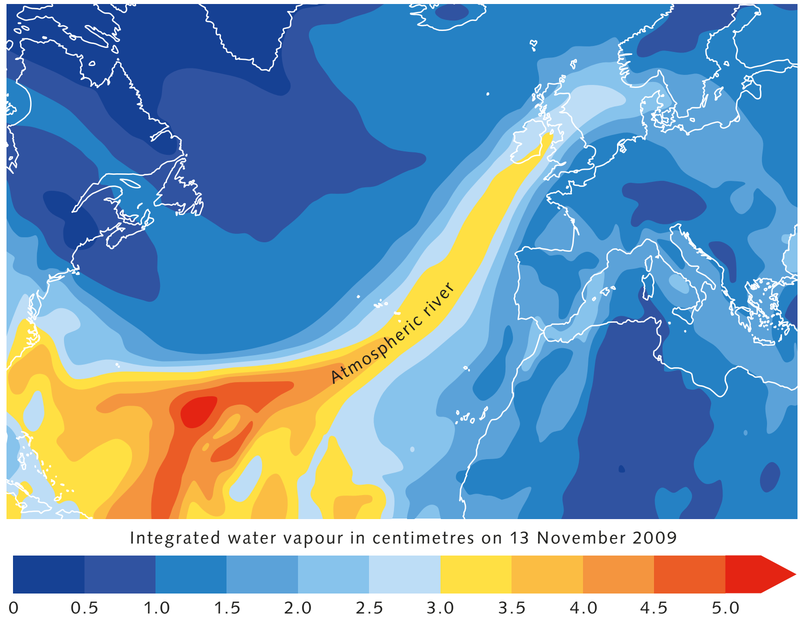
Proportionally small with a large effect

Comparing the oxygen losses in the open ocean related to temperature and circulation with those in coastal waters, the latter are hardly significant in quantitative terms. Their proportion is so small, in fact, that they are practically negligible in the climate-ocean models of the global oxygen budget of the oceans. The consequences of the coastal dead zones for the marine ecosystems and for humans, however, are certainly very serious. Mobile organisms, such as schools of fish, migrate away or change their behaviour, while sessile bottom dwellers grow more slowly or die. Large segments of the entire food web collapse, at least until the end of the summer. Aquatic life as we know it is hardly viable under these conditions. Scientific studies also point to long-term changes. In the affected coastal regions, species diversity and total biomass are declining, and species compositions are changing as well. These developments are particularly detrimental to fisheries.

Many measures are necessary to stop the depletion of oxygen in coastal regions. Most important is a reduction of nutrient input. To achieve this goal, agriculture and livestock farming along waterways must be transformed. Wetlands and mangrove forests, which filter out organic particles before they reach the sea, have to be restored. Only properly treated wastewater should be discharged. This kind of coordinated package of measures has proven to be effective in the coastal areas of north-western Europe, among others. According to the OSPAR Commission, there are now fewer oxygen-poor zones there than there were in the period from 2001 to 2005.

Oxygen content

The oxygen content of the ocean is reported in different units by scientists from different fields of study. Oceanographers and chemists refer to the amount of oxygen in micromoles per kilogram of water, while biologists and coastal researchers give the value in milligrams per litre of water. To convert between the two units the following formula can be applied: 1 milligram of oxygen per litre of water is approximately equal to 30 micromoles of oxygen per kilogram of water.



2.19 > Atmospheric rivers are air currents that carry approximately as much moisture in the form of water vapour as some rivers do as liquid water – thus the terminology. The current shown here caused extreme rainfall in Great Britain in November 2009.

This is also true for a phenomenon known as atmospheric rivers. These are long, usually 400 to 600 kilometre-wide bands of moisture-saturated air, that transport humidity (water vapour) from the tropics into the middle latitudes, over both the Pacific and Atlantic Oceans. Atmospheric rivers are responsible for a large portion of the normal, typical seasonal rainfall on the west coasts of North and South America, as well as in Greenland and on the British Isles. In the US state of California, they bring 25 to 50 per cent of the annual precipitation. Atmospheric rivers, however, can also cause extreme events, especially when their moisture-laden air masses collide with the mountains on the west coast of the USA and are forced to rise. When this happens, heavy rainfall and flooding frequently result. When the air masses of the atmospheric rivers become warmer, they are able to carry greater amounts of moisture. Researchers therefore assume that in the course of climate change the intensity of rainfall they bring will increase along with the risk of flooding.

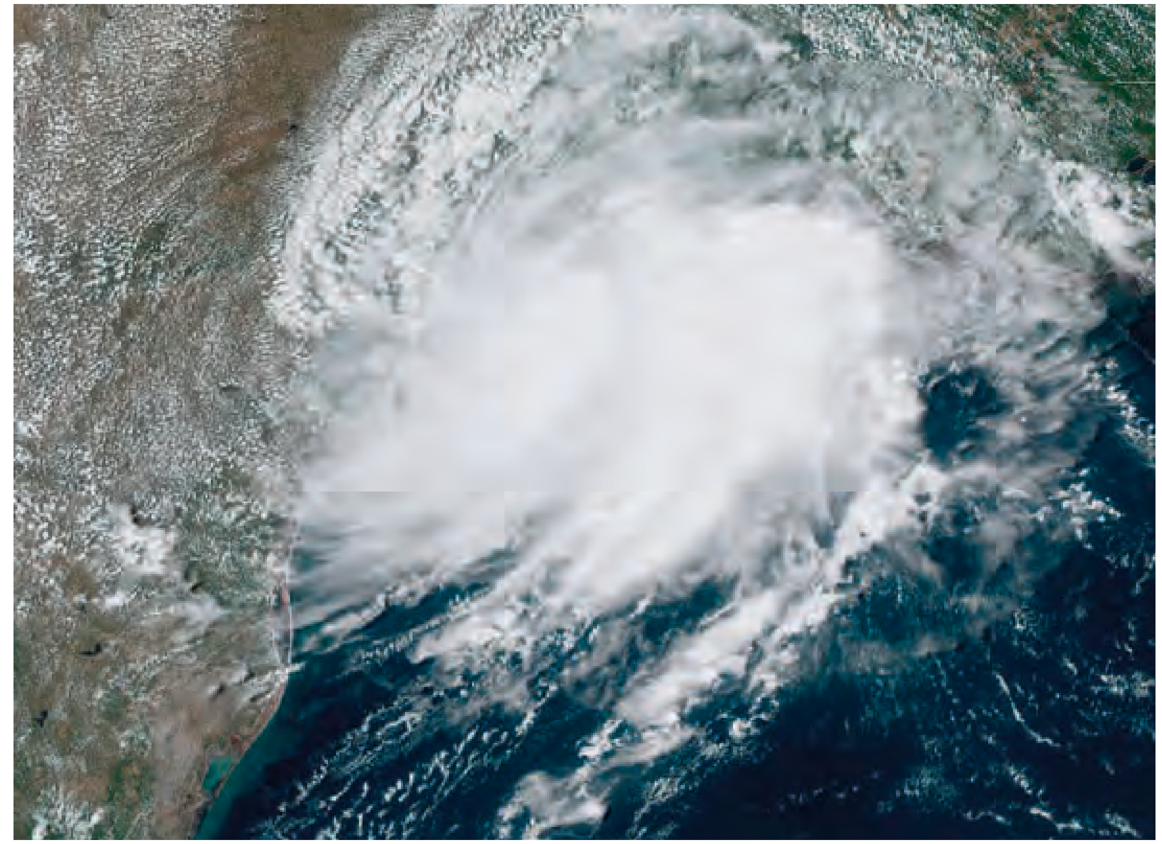
More intensive rainfall is one consequence of ocean warming, but there is also a second consequence. Researchers are now able to confirm that rising water temperatures at the ocean surface are increasing the destructive power of large tropical storms. The physical principle is quite simple: Hurricanes, cyclones and typhoons derive their energy from the heat in the ocean below them. The warmer the water is, the higher the wind speeds that the storm can develop, and the greater its destructive power is when it makes landfall. Climate models have demonstrated this correlation for a long time. But verification of the influence of climate change through direct observation was first possible in 2020.

To achieve this, US scientists analysed satellite images of hurricanes over the past 40 years, and were able to show that as the sea temperature increased, so also did the probability that an approaching hurricane would develop into a major destructive storm of category 3 or higher. The destructive power of major tropical storms is rated according to the Saffir-Simpson hurricane wind scale (SSHWS). This assesses the potential damage of a storm based on its wind speed and assigns it to one of five categories. Under this system, a storm with wind speeds greater than 178 kilometres per hour (category 3) is considered to be a major hurricane.

Heightened evaporation and precipitation also cause changes in the surface layer of the sea, especially with regard to salinity. In regions where more water evaporates in the future than is replenished by rainfall, the surface water will become saltier – for example, in the tropical areas of the Atlantic Ocean and in the Mediterranean Sea. But where the amount of precipitation is greater than evaporation, the surface water will be diluted, and the result will be a long-term decrease in salt content. According to climate projections, the latter case will be most prevalent in the Pacific and Arctic Oceans.

Marine heatwaves

Another kind of extreme event that is now occurring more frequently and is routinely setting new records is the marine heatwave. This is the term specialists use to refer to phases where the water in a certain marine region is unusually warm for at least five consecutive days. Over the past decade, scientists have been documenting such phases in the open ocean as well as in marginal seas and



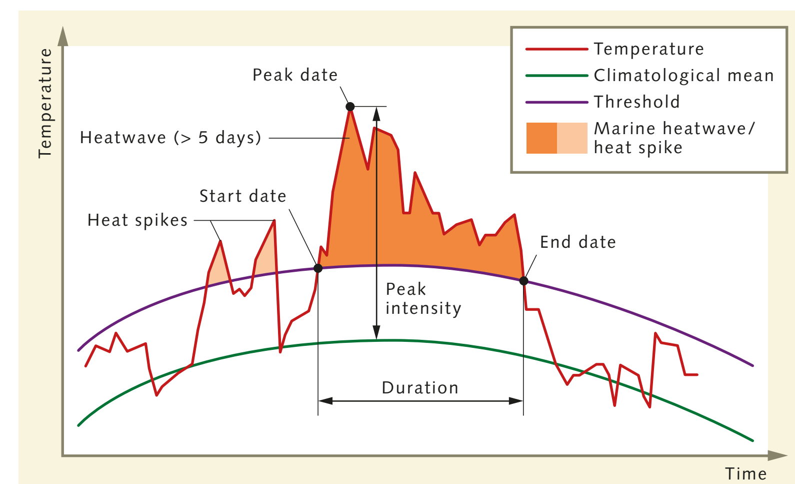
2.20 > The tropical cyclone Imelda made landfall on the Gulf Coast of the US state of Texas on 17 September 2019. Soon afterward, it rained so heavily in parts of Texas that Imelda was ranked at number seven on the list of tropical cyclones with the most abundant precipitation in the USA.

coastal regions. They occur in summer as well as in winter, because the determining factor is not a specific temperature level, but rather how many degrees Celsius warmer the water temperature is at a given location than the average value that would normally be measured there at the same time of year.

Heatwaves often make headlines because they have a long-term impact on the biological communities in the affected marine regions. Notable examples over the past decade include the heatwave along the western coast of Australia in 2011, the Mediterranean heatwaves of 2012 and 2015, and the heatwave in the North Pacific that lasted from 2014 to 2016 and became known worldwide as "the Blob".

The triggers for such warming of water masses can vary greatly. Ocean currents that concentrate warm water at a certain site are often involved. However, marine heatwaves can also form as a result of intense solar radiation and high air temperatures. Under certain conditions winds can cause the water to heat up, but under other conditions air motions could even act even to suppress a heatwave. Moreover, it is now well known

2.21 > Specialists use the term "heatwave" to refer to phases when the water temperature in a marine region is above a certain temperature threshold for at least five consecutive days. The threshold changes with the time of year and is calculated statistically.



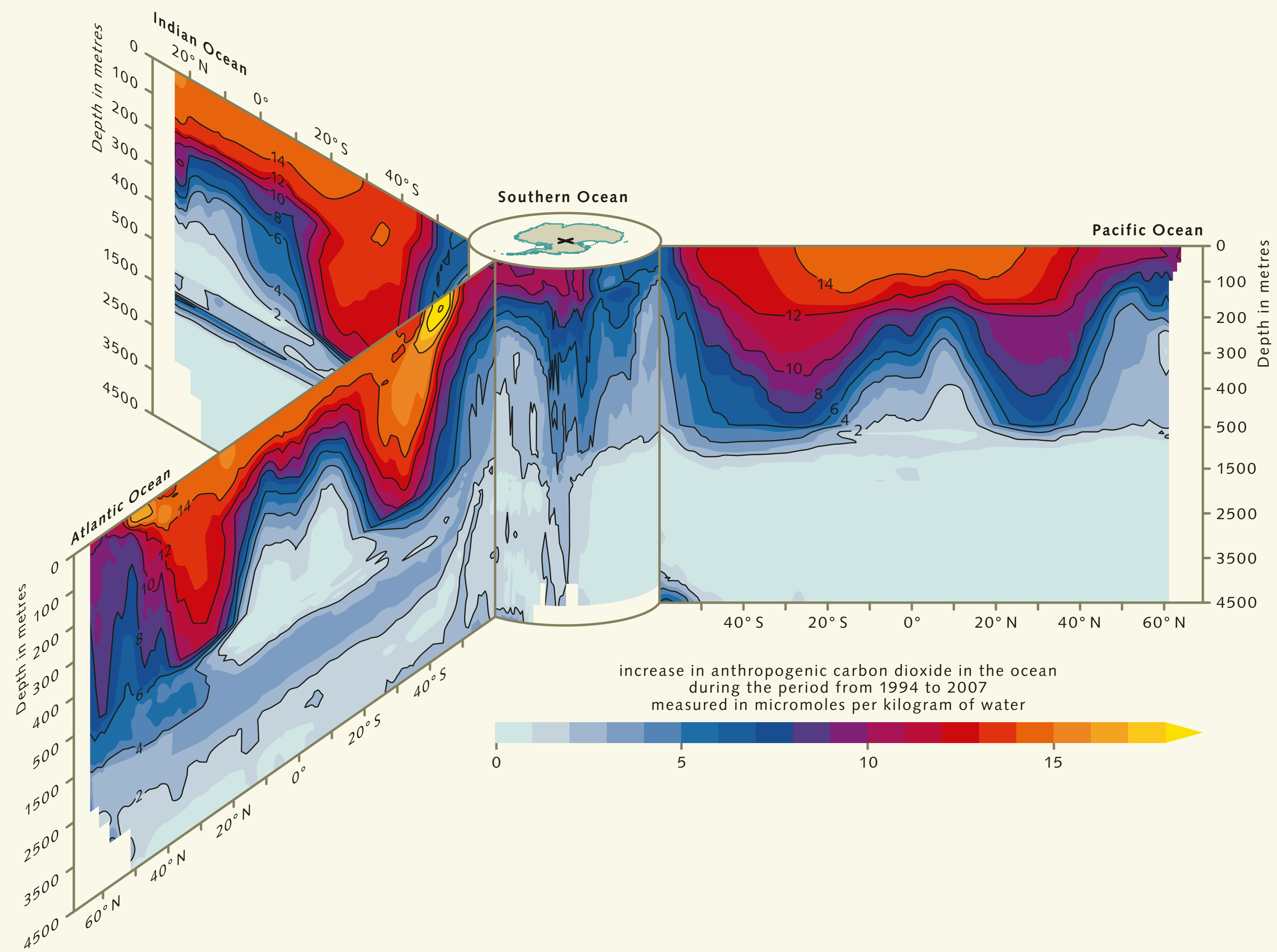
The ocean is acidifying

The ocean not only stores heat, it also removes the greenhouse gas carbon dioxide from the atmosphere. Since the beginning of the industrial era the world's oceans have absorbed 25 per cent of the carbon dioxide emissions produced by humans, with grave consequences for the chemistry of the ocean. When carbon dioxide from the atmosphere is dissolved in seawater, there is a chemical change in the surface water. Its pH value sinks and the water becomes more acidic.

Seawater normally has an average pH value of 8.2 and therefore tends to be slightly basic. This is due to mineral components in the water, particularly calcium carbonates in the form of calcite or aragonite, which at some point were dissolved by weathering from rocks on land and then washed into the sea. But when the ocean absorbs carbon dioxide (from the atmosphere or because marine organisms release it as a product of respiration), it is not simply dissolved in the water like oxygen is. On the contrary, a portion of the carbon dioxide reacts with the water to form carbonic acid. This in turn breaks down into bicarbonates, which are the salts of carbonic acid, and protons (also known as hydrogen ions). The latter drive up the acid concentration of the water, and the ocean becomes more acidic.

The measure for the concentration of hydrogen ions in a solution is called the pH value. This numerical value, however, expresses the concentration as a negative decadic logarithm. This means that the more hydrogen ions there are in a solution, the smaller the pH value is. The mean pH value of the ocean surface has sunk from 8.2 to 8.1 since the year 1860. This seemingly small step reflects an actual increase of acidity concentration on the logarithmic scale of about 26 per cent – a change that the world ocean and its inhabitants have not experienced in millions of years. The acidity signal now extends down to a depth of as much as 2000 metres. If humans continue to emit the same levels of carbon dioxide as they have in the past, the pH value of the oceans can be expected to decrease by an additional 0.3 to 0.4 units by the year 2100, whereby the seawater would become 100 to 150 per cent more acidic. This does not mean that the oceans are actually acidic because even at values of 7.7 they would still be basic by the chemical definition. However, relatively speaking, they would be more acidic than before.

The amount of carbon dioxide that accumulates in seawater depends, among other things, on the water temperature (gases dissolve easier in cold water), factors that reduce the salinity of the water (low-salinity water acidifies more quickly), and the oxygen consumption. For example, many organisms that consume large amounts of oxygen and release correspondingly large amounts of carbon dioxide live in the eutrophic coastal zones. Added to this, when coastal waters become warmer, their biological communities are subjected to three kinds of pressure – by the warming itself, a reduction in oxygen, and acidification. Since only a few species are able to cope with this combined sea change, scientists refer to it as the "deadly trio" with regard to the consequences of climate change for the ocean.



2.22 > During the period from 1994 to 2007, the world ocean absorbed an average of 31 per cent of the carbon dioxide released by human activities and transported it to considerable depths. The different amounts taken up by the large ocean basins are shown in this figure. The black lines indicate a stepwise decrease in CO_2 concentration by two micromoles of carbon dioxide per kilogram of water.

that large climate cycles such as the El Niño phenomenon significantly increase the probability of heatwaves in certain marine regions.

The general warming of the world's oceans in the wake of climate change, however, is much more significant for the future equilibrium. It increases the probability of large heatwaves, which are very harmful, especially for marine organisms with low heat tolerances. These are being more frequently pushed to their temperature limits. This, in turn, strains their adaptive capacity and reduces their prospects of survival. Such species either migrate to other areas or they perish. There are no other options for them.

In the long run, this development drives fundamental changes in the biological communities of the sea, and thus also in the ecosystem functions of the oceans.

No longer a reliable constant

Climate change is altering the world's oceans today in a manner unprecedented in the history of humankind. As a result of global warming, water temperatures are rising continuously along with sea level. These are the two most visible indicators of global warming. At the same time, the ocean is losing oxygen down to ever greater depths, and is becoming increasingly acidic everywhere.

These physical and chemical changes are having a direct impact on a wide range of ocean ecosystem processes, including its function as a reliable weather regulator. Due to the shift of wind-driven ocean currents towards the poles, for example, the heat of the ocean is now transported much further to the north and south than it was earlier, and is altering the weather in those regions.

A trio of stressors – ocean warming, acidification an diminishing oxygen – is also changing the fundamental conditions for life in the ocean. It is reducing the ocean's ability to produce biomass, and is amplifying the harmful effects of direct human intervention to such an extent that the survival of marine biological communities is at risk in many places.

Biodiversity under assault

> Climate-induced changes in the ocean are now affecting marine biological communities at all levels. As a result, many marine creatures are being forced to abandon their traditional territories. Predator-prey relationships are changing and ocean productivity is falling. Moreover, the impacts of climate change are reinforcing each other and weakening the resistance of marine species to other anthropogenic stress factors. There is no longer any question that climate change is one of the driving forces behind the extinction of marine species.

The limits of endurance

The oceans make up the largest and most species-rich habitat on Earth. They are home to an estimated 2.2 million different species, although only a few more than 200,000 have been identified and scientifically described. Most of them have adapted to the living conditions in their native waters over long periods of time. These include the prevailing temperatures, oxygen content, acidity of the water, the natural rhythms at which nutrients or food is available or even abundant, and critical environmental components such as ocean currents, which are important for many species in transporting their spawn or larvae over long distances or distributing them over wide areas. Under these familiar conditions, marine organisms grow best, live longest, and reproduce at rates that guarantee the survival of the populations.

However, these physical and chemical foundations of life in the ocean are currently changing at a pace that has not been seen in the world's oceans for the past 50 to 300 million years. The impacts of climate change can now be observed in all seas and at all depths, and they pose numerous risks to marine ecosystems. Most of the long-term scientific observations of the impacts of climate change on marine biological communities have been carried out in the northern hemisphere. Researchers have been studying climate-induced changes in the North Sea, the Mediterranean Sea, and the ocean regions around Labrador and Newfoundland for several decades. With the notable exception of some Australian observations, there have only been a small number of long-term biological studies from the equatorial regions or the seas of the southern hemisphere. This is why researchers must also rely heavily on numerous laboratory and field experiments, as well as on model simulations and historical species-distribution data in order to obtain a realistic picture of the effects of climate change on marine life.

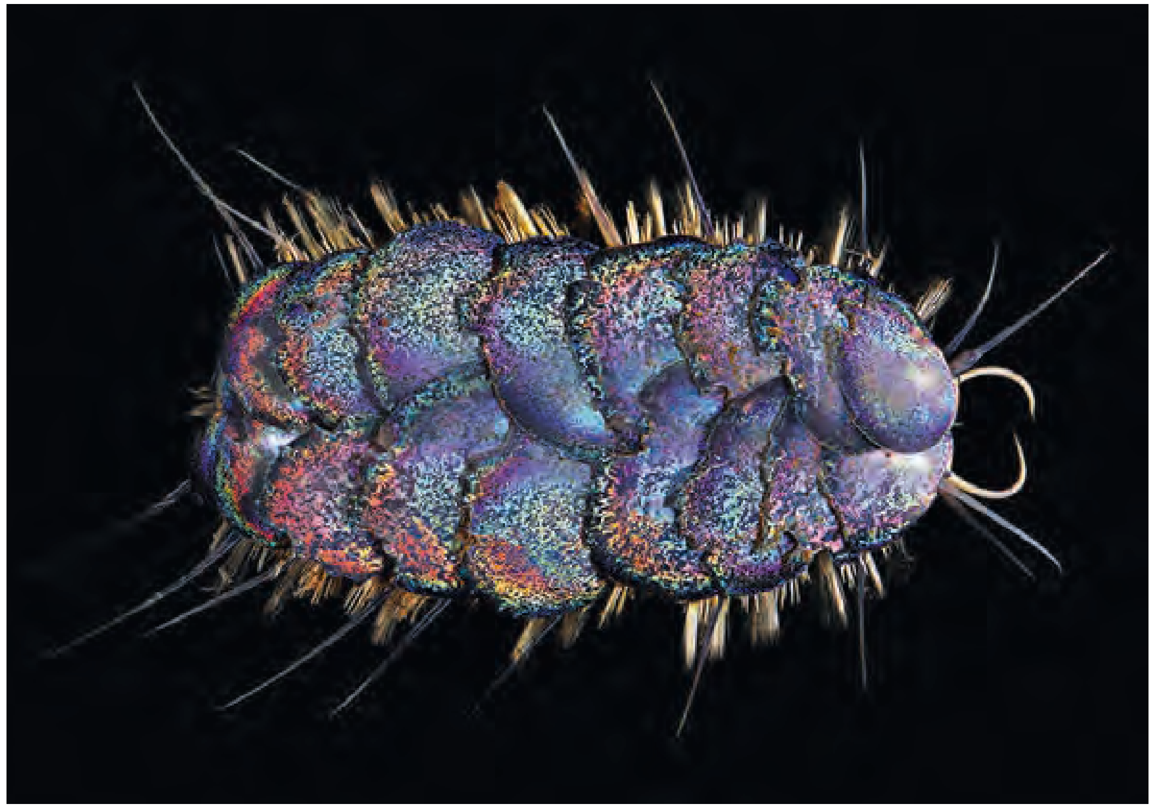
In order to understand how and why marine organisms react to climate change, it is necessary to realize that most marine inhabitants, with the exception of birds and mammals, are cold-blooded animals. These are creatures whose body temperatures are determined by the temperature of their surroundings. As a rule, the temperature requirements of a species thus correspond to the water temperatures that prevail in its native habitat throughout the year, including the total range of seasonal variation. This means that every cold-blooded marine dweller has absolute upper and lower temperature limits at which it can continue to live and grow. Scientists refer to the range between these two limits as the thermal tolerance window, or thermal niche.

This window varies in size depending on the species. Species in temperate latitudes like the North Sea generally have a wider temperature window. This is because of the more strongly pronounced seasonality in these areas. Animals living here must be able to survive through warm summers as well as cold winters. For organisms in the tropics or polar regions, by contrast, the temperature windows are two to four times narrower than those for the North Sea inhabitants. On the other hand, they have had to adapt to generally more extreme living conditions. Species of Antarctic icefish, for example, can live in water as cold as minus 1.8 degrees Celsius. Their blood contains antifreeze proteins. Due to their low metabolism and the abundance of oxygen available in their habitat, they are also able to survive without the red blood pigment haemoglobin. For this reason, their blood is less viscous and they require less energy to pump it through their bodies.

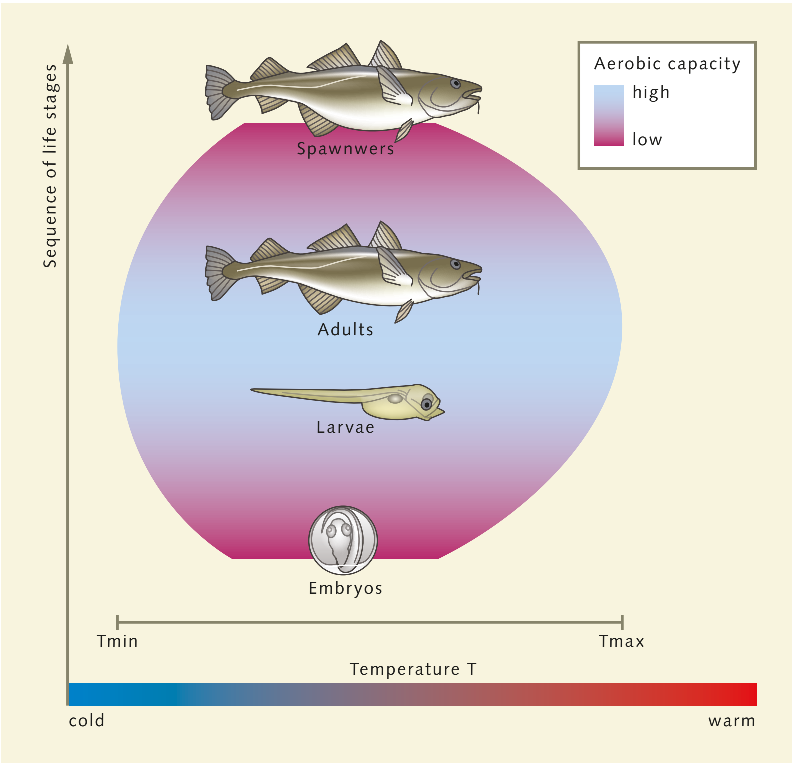
But icefish live at the extreme boundary. If the temperature rises by just a few degrees Celsius, the animals quickly find themselves at their physical limit. At this point they are no longer able to generate sufficient energy to maintain all of their bodily functions. The reason for this is that the energy requirements of the cold-blooded organisms increase exponentially with every degree of warming. There is a corresponding increase in oxygen demand because energy cannot be generated without respiration. For species with a narrow thermal window this increase is especially drastic. In other words, marine organisms can only survive increasing temperatures in their habitat if they are able to supply their bodies with more oxygen. If that is no longer possible, their cardiovascular systems collapse. Scientists therefore also refer to this as the oxygen- and capacity-limited thermal tolerance of living organisms.

To make matters worse, the size of the thermal tolerance window can change over the course of a fish, mussel or starfish's life. In the early life stages, as an embryo in the egg or as a larva, cold-blooded animals are, as a rule, more sensitive to heat than in the later stages of development. This sensitivity is further exacerbated when the animals are exposed to decreasing pH values (acidification) and declining oxygen concentrations at the same time. In this situation, the stress factors often act in concert to amplify the overall effect.

It has recently become known that abnormally warm water temperatures are more dangerous for fish in the embryonic stage and during the mating season. The reason for this difference in thermal tolerance can be explained by the anatomy of fishes. Fish embryos, for example, do not have gills or a cardiovascular system with which to increase their oxygen supply. Furthermore, fish preparing to mate have to produce egg and sperm cells. This increased body mass must also be supplied with oxygen, which is why the cardiovascular systems of animals getting ready to spawn are already under a condition of heightened stress even at lower temperatures.



2.23 > The scaleworm *Peinaleopolynoe orphanae* is one marine species that biologists discovered and described in 2020. The deep-sea dweller from the east Pacific has a carapace of pink to gold-coloured iridescent plates.



2.24 > Every organism has a temperature range within which it can survive. The size of an organism is limited by the ability to supply its body with increasing amounts of oxygen as the temperature rises in order to maintain sufficient energy production. Fish are able to do this much better as adult animals than they can in the larval stage or when spawning.

It therefore follows that fish will suffer particularly from climate change during their reproductive phase, because the water temperature in the spawning area is crucial to their reproductive success. This is true for marine species as well as for the fish in lakes and rivers. A recent study by German marine biologists analysed temperature tolerance data for almost 700 fish species throughout their life stages and compared them with the new climate scenarios **(Shared Socioeconomic Pathways, SSPs)** of the Intergovernmental Panel on Climate Change. The results indicated that if global warming can be limited to the Paris climate target of 1.5 degrees Celsius by the year 2100, only about ten per cent of the fish species studied would be forced to leave their traditional spawning grounds as a result of the water being too warm. But if greenhouse emissions remain at high or very high levels, the warming will be as much as 4.4 degrees Celsius or more. This would force up to 60 per cent of the fish species to leave their traditional spawning grounds.

More rapid species turnover than on land

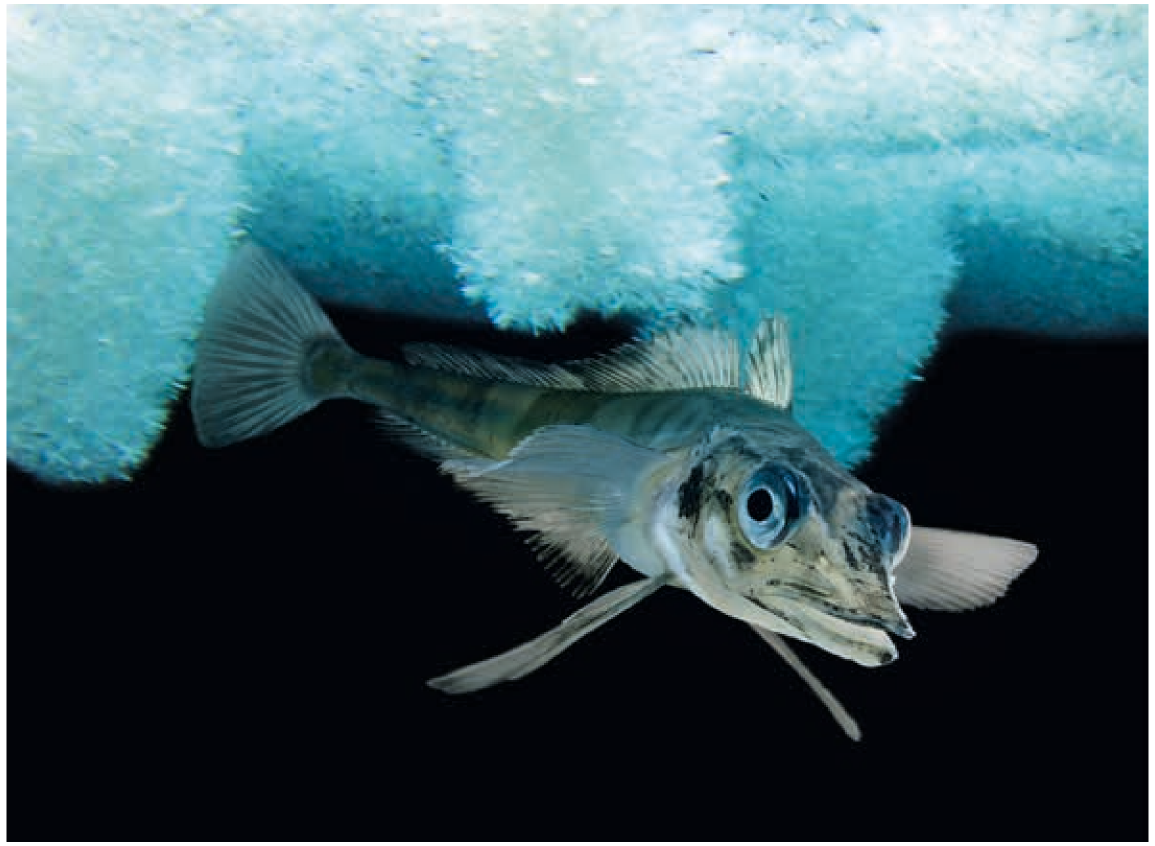
All organisms, like fish, will react to changes in their environment by first attempting to adapt their individual behaviour to the new conditions. Scientists refer to this kind of adaptation as acclimatization. The organisms ramp up respiration and metabolic processes, pump more blood or water and nutrients through their bodies, or eat more if necessary. If they are unable to do this, they must migrate to areas where more familiar environmental conditions prevail. But all of these measures require the organisms to generate additional energy. If they can do that, they have a relatively good chance of survival. If they do not have the necessary reserves, however, the individuals will soon reach their capacity limits and face the risk of death.

As a rule, however, those which are able to acclimatize over the short or moderate term have a chance to reproduce sexually and enable the species to adapt genetically to the new conditions through multiple generations. This essentially means that the organisms produce offspring whose genetic makeup may be modified in such a way that the subsequent generation is better able to cope with the new environmental conditions than their parents' and grandparents' generations. This kind of adaptation is called genetic or evolutionary adaption.

Comparing biological communities on land with those in the sea reveals fundamental differences that are important within the context of climate change. These include:

- The primary producers in the sea (phytoplankton) have much shorter reproduction cycles than the trees or grasses on land. While trees in some cases can live for centuries, the worldwide stocks of plankton are renewed about 45 times every year, which is approximately once every eight days. In theory, this capacity enables plankton to adapt genetically to changing environmental conditions more readily than plants on land are able to.
- The proportion of cold-blooded organisms in the sea is comparatively high, which means that species diversity and distributional patterns in the ocean are determined to a large extent by temperature. On land, by contrast, other factors, such as the amount of precipitation or geographic barriers play a greater role.
- Unlike land animals, the ocean dwellers have virtually no option to retreat into caves or other cool, shady locations during heatwaves. They are completely defenceless against the warm water temperatures, and must therefore take flight sooner.
- Tropical marine species, as a rule, live in regions that are naturally so warm that they are already near the upper tolerance limits of the individual species, so that only a very small increase in temperature is sufficient to exceed their heat threshold.
- Compared to land animals, it is easier for mobile aquatic creatures like fish to follow their preferred temperatures into cooler regions because there are relatively few obstacles, such as undersea mountain chains, deep trenches or strong currents (e.g., the Antarctic Circumpolar Current) to be overcome, and these often do not really present a significant impediment. Many terrestrial creatures or species living in lakes, rivers or ponds, on the other hand, are more likely to encounter geographical barriers, which now increasingly include land areas used by humans, that make it difficult for them to move further or relocate their habitat.

For all of these reasons, heat-driven species shifts in the sea are occurring much faster than on land. For scientists, however, it is not always easy to clearly determine whether the reactions of an individual species or biotic community are exclusively related to climatic changes such as rising water temperatures, acidification or oxygen depletion, or whether anthropogenic stress factors like fishing, resource extraction and marine pollution also play a role. It is an irrefutable fact, however, that marine communities that are already under stress react more



2.25 > Sea ice and near-freezing water temperatures are not at all problematic for the Antarctic blackfin icefish *(Chaenocephalus aceratu)*. It is perfectly adapted to life in the Southern Ocean. Compared to fish in the temperate latitudes, however, its thermal tolerance window is very narrow.

2.26 > Because their prey fish are migrating northward to warmer waters, Arctic seabirds like the ivory gull *(Pagophila eburnea)* now have to fly further out to sea than in the past. This consumes precious energy and causes the offspring to go hungry more often.

sensitively to climate change than those that are not overfished or exposed to high levels of pollution or nutrient overload.

Fleeing from the heat

The most evident response of marine organisms to rising water temperatures is the relocation of their habitats to areas where the animals and plants find their preferred ambient temperatures. The shift can occur either in an active or passive way. It is active when fish, crustaceans and other mobile marine life migrate under their own power to new habitats to escape from adverse environmental conditions. Passive relocation, on the other hand, occurs when the spores, eggs or larvae of a species are carried by changing ocean currents, for example, into an area that was not previously inhabited by that species, but where it is able to recolonize and reproduce because the environmental conditions are suitable. However, researchers also consider it to be a relocation of habitat when a species reproduces and grows only in the cooler part of its traditional distributional area, but dies out in the parts where temperatures are rising. In this situation, the boundaries of its colonies have, of course, also been shifted.

The flight from heat induced by humankind's emissions began more than half a century ago. The habitats of marine organisms have been shifting poleward since the 1950s. Populations that live north of the equator are migrating northward, while those south of the equator are moving southward. Biodiversity in the warm tropics has been declining significantly since that time. Scientists have recognized this trend across all groups of organisms, from single-celled plankton to large fishes. They are even able to reconstruct the rate of this shift over time. So far, it has been occurring at around 51.5 kilometres per decade for mobile species. For organisms that live on the sea floor it is somewhat slower. Their distribution boundaries are moving by an average of 29 kilometres every ten years. Comparing the migration statistics of all groups of organisms on land with those in the ocean, the marine organisms are shifting their habitats about six times faster toward the poles than the organisms on land. However, these numbers should not obscure the fact that all organisms, plant or animal, will react differently to ocean warming, even those that are closely related.

Scientists are observing particularly strong migratory movements from the tropics, where species are fleeing to the north or south in large numbers due to rising water temperatures. As a consequence, researchers are recording an increase in biodiversity in the marginal regions of the tropics where the climate refugees are now competing with endemic species for food and living space. The newcomers often have an advantage, because water temperatures are also rising in the subtropical marine regions. The result is a turnover in the subtropical communities toward a more tropical marine assemblage. Researchers refer to this phenomenon as tropicalization.

In marine regions where geography tends to prevent migration to higher latitudes, for example, in the Mediterranean Sea or the Gulf of Mexico, rising temperatures in the upper layers of the water column are driving the mobile marine inhabitants to greater depths. Because the deep water is generally cooler than the water in the overlying layers, these species usually do not have to migrate very far in order to reach their preferred temperature conditions. But it is uncertain whether these species will be able to find sufficient food in the deeper waters. For algae and other water plants, moreover, the light conditions deteriorate with increasing depth.

A successful flight from warming waters, therefore, does not depend on the individual mobility of a species alone. Rather, there is a combination of climatic and other environmental factors that determine the extent to which marine organisms can change their habitat. These factors include, among others:

- local temperature and oxygen gradients;
- marine currents that transport eggs or larvae to new regions;
- the shape and depth of the sea floor (bathymetry) for those species that spend a part or all of their life on the bottom;
- the availability of nutrients or food, suitable spawning sites, or hard substrates to settle on;

- the presence of new or familiar predators; and
- stressors introduced by humans such as fishing, shipping, resource mining and marine pollution.

Particularly limited retreat options are available to cold-loving species or those dependent on sea ice like the Antarctic icefish, or the polar cod, a key species in the marine Arctic ecosystem. Not only does it have a comparably low thermal tolerance and is therefore rarely found in regions where the water temperature is above three degrees Celsius, but its offspring are also dependent on the Arctic sea ice. The ice offers protection to the young fish and abundant food in the form of ice algae and zooplankton. But the area of summer sea ice on the Arctic Ocean has shrunk by around 40 per cent since the beginning of satellite measurements in 1979. This, for one thing, is reducing the area of the habitat for young polar cod. For another, there is less food available for the young fish, which is why scientists anticipate that their growth will be retarded and that their average body size will decrease.

Heat-driven upheaval of ecosystems

Because individual marine organisms react to rising temperatures in unique ways and at their own speed, a broad restructuring of the biological communities is occurring in many places. Long-established predator-prey relationships are collapsing and processes that have been running smoothly for millennia are no longer in sync. A striking example of this is the ocean's changing spring season, which now occurs much earlier in the year in the high and middle latitudes than it did a few decades ago. This means that algae are blooming earlier every year in response to temperature, by an average of 4.4 days every decade.

However, the erstwhile exploiters of these algal blooms, such as fish, mussels and many other sea creatures, are having a very difficult time in adjusting their reproductive rhythms at this rapid pace. As a result, their offspring may just be ready to start foraging when the algal blooms have already ended.

Seabirds are facing similar problems, as their prey species migrate poleward or produce too few offspring because they missed the algal bloom, putting their populations at risk. The birds have to fly much further out to sea or spend more time on the sea to obtain enough prey. As a result, they are not successful enough in hunting to feed their hungry offspring, and the young animals face starvation.

Due to rising water temperatures, researchers are observing a decline in the reproductive success of northern fulmars, manx shearwaters and kittiwakes, among other bird species in the northeast Atlantic. In the Southern Ocean, by contrast, the breeding success of the wandering and Laysan albatrosses has improved as a result of climate change. The birds are benefitting from the strengthening and the southward shift of the westerly winds over the Southern Ocean, and from the temperature-driven migration of species toward the pole. As long-distance gliders, albatrosses depend upon the wind to reach their fishing grounds. Because the west winds are now stronger and the fishing grounds of the albatross have shifted closer to the continent of Antarctica, the hunting efficiency of the birds has been enhanced, which is a great benefit for their offspring.

Marine reptiles such as turtles and snakes are primarily affected by global warming during their most vulnerable life stage, as embryos in the egg. The ambient temperature of their clutches determines not only the sex of the young, but also their size, their stage of development at the time of hatching, and their general fitness. During the incubation of turtle eggs, if the sand is just one to four degrees Celsius warmer than normal (29 degrees Celsius for a male-female ratio of 50:50), more females will hatch from the eggs and much fewer males, or possibly none, a pattern that will eventually lead to extinction of the species.

A further aspect of carbon dioxide

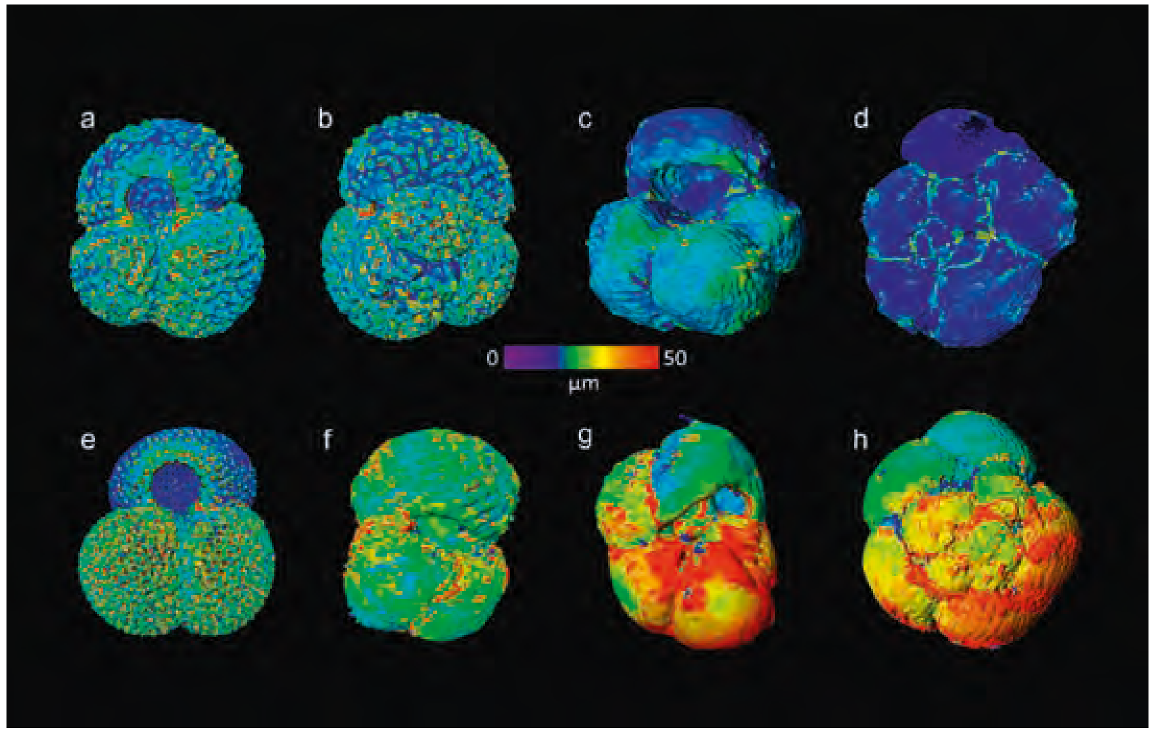
Ocean warming is the most widespread climatic stress factor for biological communities in the oceans today, and it is thus also the major force driving changes in the species distributions in the sea. But there are other responses acting parallel to this that are altering the living conditions in all of the ocean basins. One of these, increasing ocean acidification, has been in the spotlight of modern research over the past two decades, which has helped us to understand the concept that different marine organisms react differently to carbon dioxide-rich water.

Among the organisms that benefit from acidification are the picophytoplankton. These, the smallest of the phytoplankton species, are only 0.2 to two micrometres (thousandths of a millimetre) in size, but in many marine regions they are the most abundant primary producers, in part because they propagate copiously even in waters with low nutrient content. Various field experiments on ocean acidification have now shown that these tiny algae use elevated carbon dioxide levels in seawater as a growth accelerator. They have been found to grow faster and produce more biomass.

On the losing side, however, are many of those marine dwellers, like fish, that must breathe in the water. Carbon dioxide-rich seawater creates elevated carbon dioxide levels in the body fluids of these animals. This impairs the transport of substances through the cell membrane, among other effects. The sensory responses of fish held in carbon dioxide-rich water for research purposes were also altered. Their hearing and vision were impaired and they were less skilful at dodging predators. Cod larvae raised in water very rich in carbon dioxide showed evidence of damage to vital organs such as the liver, kidneys and pancreas. In addition, the mortality rates of the young animals doubled during the critical phase between hatching from the egg and the formation of functioning gills.

In similar experiments, however, herring proved to be much more resistant to the changing pH levels in seawater. One explanation for this might be found in the natural lifestyle of the fish. Herring usually spawn near

2.27 > The sex and general condition of freshly hatched leatherback sea turtles depends on the ambient temperature of the turtles' clutch of eggs. If the sand is one to four degrees Celsius warmer than normal during the incubation period, hardly any males will hatch.



2.28 > One consequence of ocean acidification is that the calcareous shells of foraminifera that lived about 150 years ago (lower row, warmer colours) were as much as 76 per cent thicker than those of the same species today (upper row).

the seabed, where microorganisms constantly decompose sinking biomass, and where carbon dioxide concentrations are therefore naturally higher than at the sea surface. The animals are thus presumably better adapted to a wider range of pH values than fish species like cod that spawn near the surface.

Ocean acidification poses a particular threat to carbonate-secreting organisms such as clams, corals and echinoderms, or planktonic species such as coccoliths (calcareous algae), foraminifera and conchs. All of these need calcium carbonate to build their shells and skeletons. With increasing acidification, however, the concentration of carbonate in the sea decreases, and the concentration in their body fluids decreases unless the organism has a good system of acid-base regulation. For the organisms, this means that when the water is more acidic, they have to exert more effort to form their calcareous shells and skeletons. The long-term results can include decreases in either the shell thickness, the size, weight or efficiency of the marine organisms. With increasing acidification, moreover, it becomes more likely that the carbon dioxide-rich water will corrode mussel shells, snail shells or coral skeletons, damaging or even completely dissolving them.

Research findings by British scientists, who recently compared zooplankton samples from the legendary Challenger expedition (1872 to 1876) with sample material from the Tara Oceans expedition of 2009 to 2016, reveal the extent of pressure on marine organisms due to increasing acidification. They discovered that foraminifera collected in the eastern Pacific more than 150 years ago possessed calcareous shells that were as much as 76 per cent thicker than those retrieved in the past decade from the same ocean region.

But it is not only the tiny marine inhabitants that are affected. In a laboratory study, a joint German-South African research team discovered that even ocean predators like sharks are suffering from the increasing acidity. If the animals remain in waters with a pH value of 7.3 or lower for several weeks (8.2 is the normal ocean value), their small, tooth-shaped skin plates as well as their teeth are affected. Over the long term, this could impair the swimming ability of these predators as well as their hunting yield.

A mean pH value of 7.3 in the ocean is actually not expected to be seen until the year 2300, and then only if the present carbon dioxide emission levels continue unchecked. In upwelling areas, however, like those off the southern and western coasts of South Africa or off the US Pacific coast, researchers are already observing occasional occurrences of these depressed values today. These are mostly cold, nutrient-rich water masses that are also oxygen-deficient and rich in carbon dioxide with a pH value between 7.4 and 7.6, which rise up from greater depths under certain wind and current conditions and end up in the coastal areas. There, because of their high nutrient content, they frequently support large plankton blooms. When the plankton die, microbes break down the plant remains and enrich the already carbon dioxide-rich waters with additional carbon dioxide. Under these conditions the pH value of the water, at least off the coast of South Africa, has even been known to drop to extreme lows of 6.6 for periods of a few days.

Less oxygen, less energy

Most multicellular marine organisms require oxygen to produce the energy necessary to carry out their life processes. Birds and marine mammals like whales or sea lions breathe it in with air from the atmosphere. The others extract oxygen for respiration from the water, which generally contains more oxygen in cold regions than in warm areas. But since the 1950s the amount of dissolved oxygen in sea water has been decreasing in the wake of climate change, both in the open ocean and in coastal waters.

As a result, oxygen minimum zones (OMZs) have now expanded into all the world's oceans. These are generally water layers between the depths of 100 and 1000 metres with oxygen concentrations very far below the hypoxic threshold of around 70 micromoles per kilogram of water. In the Indian and Pacific Oceans these minimum zones have an oxygen content of less than 20 micromoles per kilogram of water. In the Atlantic Ocean the values are commonly below 45 micromoles.

Just how dangerous these kinds of environmental conditions are to life becomes apparent when we consider that many marine organisms have difficulty supplying their bodies with sufficient oxygen even at concentrations of 60 to 120 micromoles per kilogram of water. Large animals in particular like sharks and tuna, with extremely high energy needs, cannot survive in ocean waters where the oxygen concentration is less than 70 micromoles per kilogram of water, so they avoid these areas.

When oxygen, that crucial elixir of life, is only present at such low concentrations, marine life suffers at all levels, from the individual cell processes to the interactions of the total ecosystem. Especially for animals, productive capacity and survival prospects are diminished. For example, oxygen deficiency reduces the reproductive success of many species. Organisms in the oxygen-poor zones are often no longer able to mate and produce offspring, which results in a collapse of the stocks. Animals that are frequently exposed to short phases of oxygen deficiency exhibit a weakened immune system and become less able to defend themselves against disease and parasites. Their growth is also significantly impaired, which is why researchers expect, among other things, that the number of large predators will decline over the long term.

Most mobile ocean dwellers will flee their traditional habitats when the oxygen concentration falls below the threshold value for their species. This reaction may lead the animals to congregate in the marginal zones, where they compete for food and become easier prey for fishermen. The high catch volumes of Peru's fishing fleet can thus be attributed in part to an oxygen minimum zone within the Peru Current at intermediate depths that prevents the huge schools of Peruvian anchovetas *(Engraulis ringens)* from migrating to greater depths. Instead, the fish remain near the surface where they are more easily and efficiently caught.

The expansion of oxygen minimum zones in deeper waters also has a confining effect on mako sharks

(Isurus oxyrinchus), blue marlins *(Makaira nigricans)* and sailfish *(Istiophorus albicans)*. These predators of the open ocean are actually known for their habit of diving down to great depths to pursue fish and squid. In the eastern tropical Pacific, however, these hunting forays do not extend nearly as deep as they do in the western Atlantic. The reason is that the predators run out of oxygen in the deeper waters due to the more pronounced oxygen minimum zone in the eastern Pacific. In the western Atlantic there is sufficient oxygen content at greater depths. Scientists studying the hunting behaviour of blue marlin in the eastern tropical Atlantic found that an expanding oxygen minimum zone in deeper water was forcing the fish to reduce the depth of their dives by around one metre every year. Over the time frame of the study (1960 to 2010), the habitat area of these predators shrank by 15 per cent.

When oxygen-deficient zones form at the sea floor, or if they extend down to this depth from above, the creatures living on the bottom may have to leave their burrows and hiding places and climb to the highest accessible point in the area, in hopes that the shallower water layers contain more oxygen. This response makes them easier prey for predators, but the animals are usually forced to take this risk because the alternative is death by suffocation.

As the habitats for species with high oxygen requirements shrink with the worldwide decline in oxygen concentration in the oceans, organisms with lower oxygen needs are actually benefitting from the hypoxic zones. On the one hand, these are well suited as places of refuge because potential enemies, generally predators with higher oxygen requirements, cannot pursue them there. On the other hand, they offer feeding advantages for some species. The warty comb jellyfish (or sea walnut, *Mnemiopsis leidyi*), for example, is found in the Chesapeake Bay, the largest estuary in the USA, and it can tolerate much lower oxygen concentrations than the fish with which it normally competes for food. If large areas of the Chesapeake Bay now become low-oxygen zones in the summer, the jellyfish can still hunt when their feeding competitors have long since left the area.

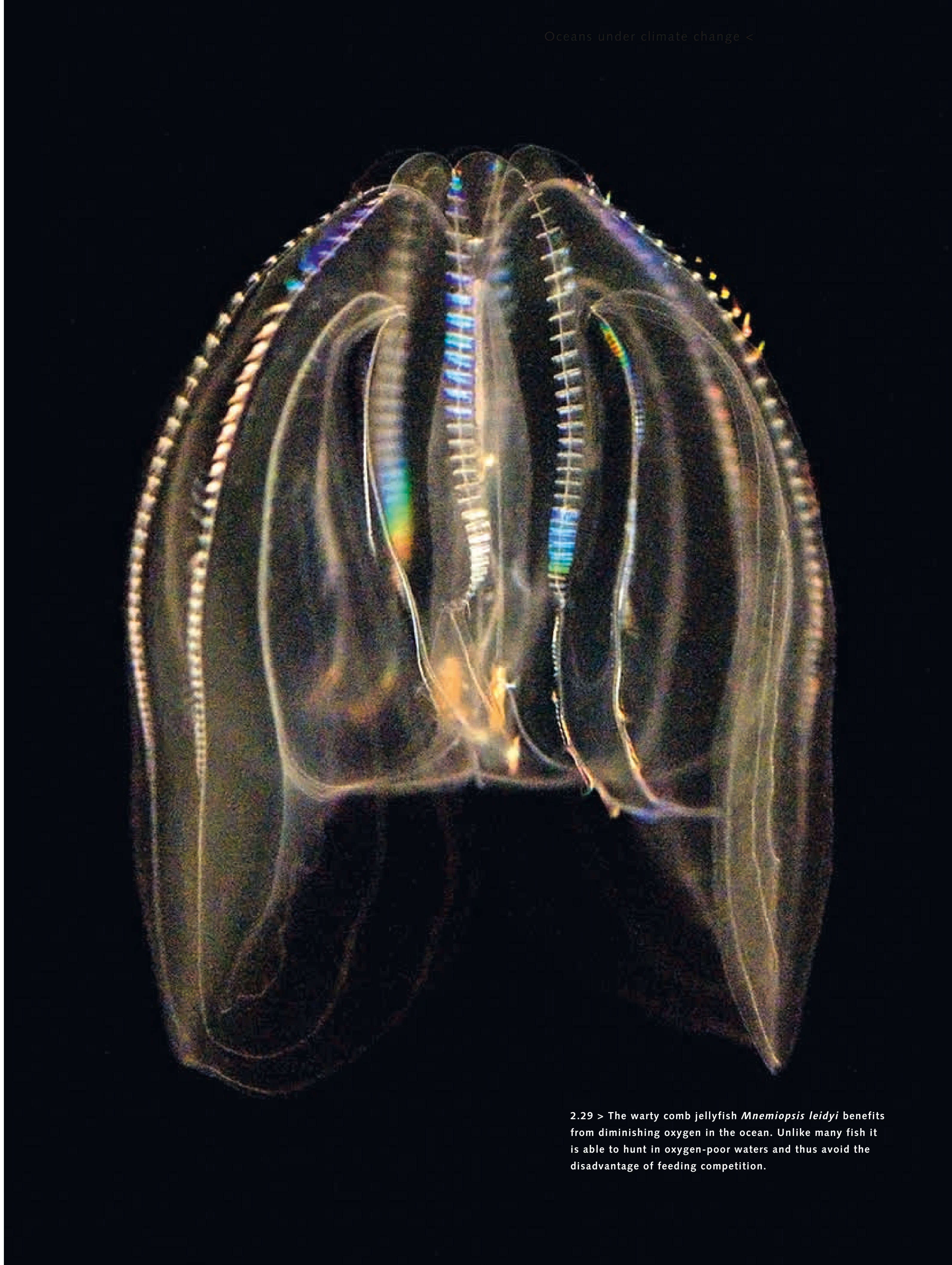
The deadly trio and its ramifications

For now, the consequences of climate change are still considered to be a relatively small factor of environmental stress compared to the more direct impacts of humans on the sea. But some scientists are convinced that climate change will soon become the driving force behind global species extinction.

In the ocean, it especially influences the biological communities where physical and chemical changes are occurring simultaneously, and their interactions are amplifying the impacts of the deadly trio of rising temperatures, increasing acidification and declining oxygen content. Under these conditions, if the species assemblages are affected at the same time by extreme events such as tropical cyclones, marine heatwaves, or flooding with its associated coastal erosion, the extent of damage will increase many times over. In these cases, local mass mortality can no longer be ruled out. There is an increasing danger that the ecosystems will reach a threshold or a tipping point beyond which recovery of the communities is impossible, and the changes will thus become irreversible.

Hurricane Dorian, for example, left a path of destruction in the near-coastal coral reefs of the Bahamas as it ploughed across the northern Caribbean in early September 2019 with maximum wind speeds of 290 kilometres per hour.

After two days of heavy storms, 25 to 30 per cent of the shallow-water coral reef was severely damaged. Winds and waves had overturned coral colonies and the fragile reef structures had been battered by uprooted trees. Sediments stirred up by the storm buried entire segments of the reef under a layer of sand, threatening to suffocate the corals. In addition, the reefs showed signs of bleaching at many sites, which researchers attributed to temperature shock, among other possible causes. Moreover, after the storm many of the fish species crucial to the reef's survival had disappeared. In their initial damage analysis, scientists were not able to determine whether the fish had retrea-ted into deeper waters or if they were injured or killed during the hurricane. It is certain,



2.29 > The warty comb jellyfish *Mnemiopsis leidyi* benefits from diminishing oxygen in the ocean. Unlike many fish it is able to hunt in oxygen-poor waters and thus avoid the disadvantage of feeding competition.

2.30 > Storm consequences: In early September 2019, as Hurricane Dorian raged over the Bahamas, this large coral colony (patch reef) in the Great Abaco Barrier Reef broke apart.

however, that the reef will require several decades to recover from the storm, assuming that climate change allows it to recover at all.

The disastrous interplay between ocean warming, acidification, oxygen loss and extreme events now threatens marine biodiversity in all corners of the world's oceans. Scientists refer to these as the cascading impacts of climate change. If one or more species within a food web reacts to the pressures of climate change, a chain reaction is started that triggers changes at all levels of the ecosystem. Increasingly, completely new species communities or combinations are emerging. It is uncertain to what extent these will be able to contribute to the ecosystem services of the sea.

Another significant change is the decreasing amount of animal biomass in the sea. Model calculations aligned with the **Representative Concentration Pathways (RCPs)** used by the Intergovernmental Panel on Climate Change have estimated that the world ocean will lose around 4.3 per cent of its animal biomass by the year 2100 compared to the period from 1986 to 2005, even if humankind is able to limit global warming to less than two degrees Celsius (RCP2.6).

But if greenhouse gas emissions continue to increase strongly, and the global average temperature rises by more than four degrees Celsius by 2100 compared to pre-industrial times (RCP8.5), the animal biomass in the sea will decrease in response to climate change by about 15 per cent. The losses will be particularly high in the tropical seas and the temperate latitudes.

Furthermore, climate stressors amplify the detrimental effects of direct human interference in marine communities. Diminished fish stocks, for example, react much more sensitively to the effects of climate change than

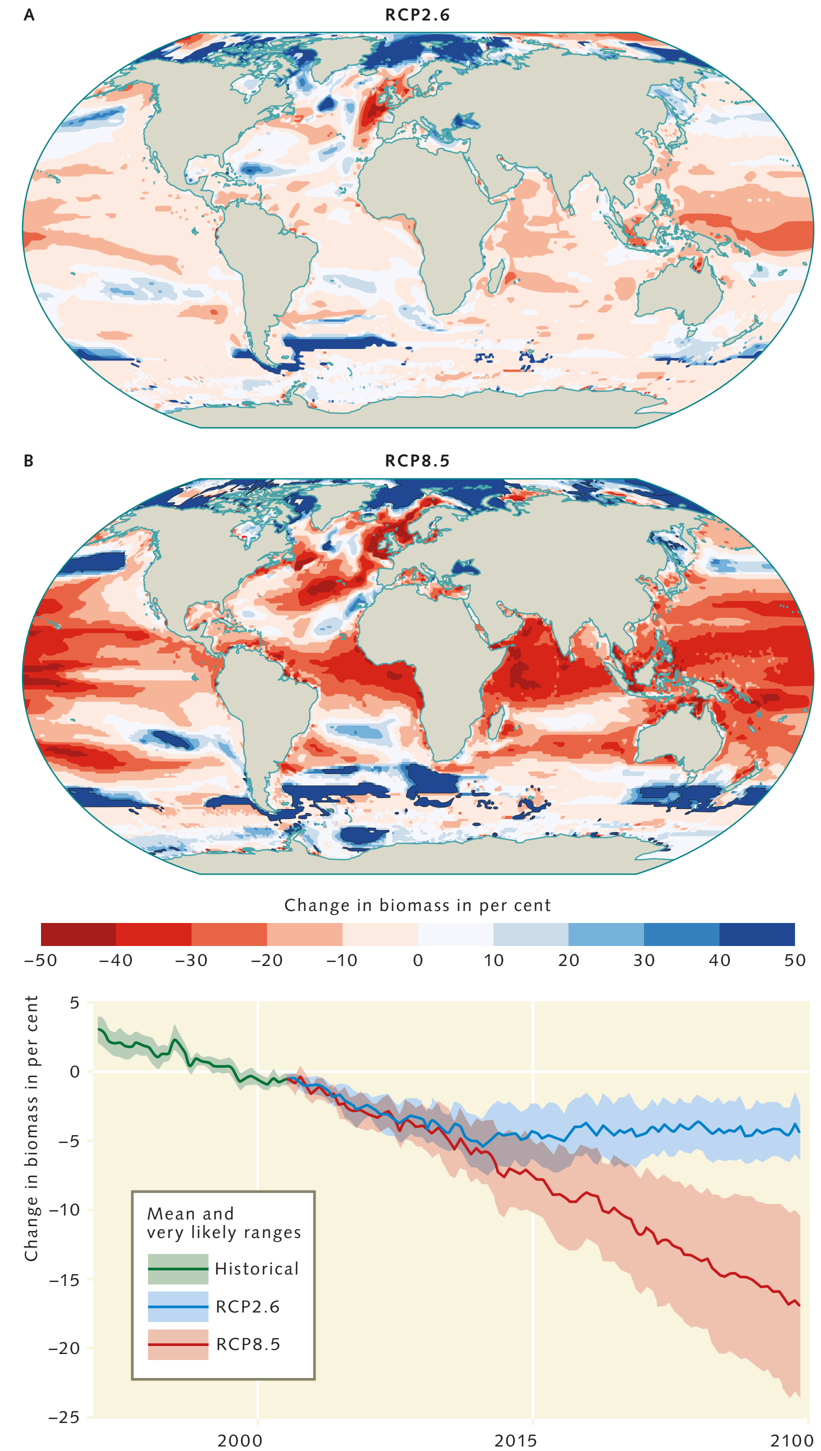
healthy abundant stocks. The same is true for coral reefs that have already been damaged by untreated sewage, or for benthic communities that are disrupted by frequent bottom trawling. When extreme climate events such as heatwaves or abrupt decreases in oxygen content strike these already vulnerable communities, they will have little or no chance of fully recovering from them.

Many coastal biological communities are facing an additional climate problem. Due to rising sea levels, sea turtles, seabirds and many other shore dwellers are losing their traditional nesting places or even their entire habitats.

The prognosis for mangrove forests, one of the hotspots of marine biodiversity, is particularly critical. According to current research, they are able to compensate for a sea-level rise of up to six or seven millimetres per year. They achieve this by storing large amounts of sediment in their dense root systems. In a sense, the forests build their own platforms and climb upward with rising sea levels. But if the regional water level rises faster than the mangroves are able to collect sediment, the trees will drown. New mangroves then can only grow closer to the shore, which means that over longer time periods the forests will migrate landward if there is room available there. Otherwise, they will disappear.

The gravity of the situation is highlighted by the projections of sea-level rise in tropical and subtropical coastal areas. If anthropogenic greenhouse gas emissions maintain their present levels, the rate of rise will increase to six or seven millimetres per year within the next 30 years, thus reaching the critical threshold value for mangrove forests. But if warming can be limited to 1.5 degrees Celsius in accordance with the Paris climate target, many of the coastal and estuarine forests could have a future.

Knowing about these climate-related threshold values for marine biological communities is crucially important, because it allows us to consider key biological knowledge in making decisions about managing the ocean and its resources. With regard to mangroves, for example, it is now well understood that no further measures should be allowed that would prevent the coastal forests from



2.31 > Scientists have found that biomass production in large regions of the ocean will drop by more than 20 per cent if the world warms by more than four degrees Celsius (B) by 2100. If the target of 1.5 degrees is met (A), the losses will be much less.

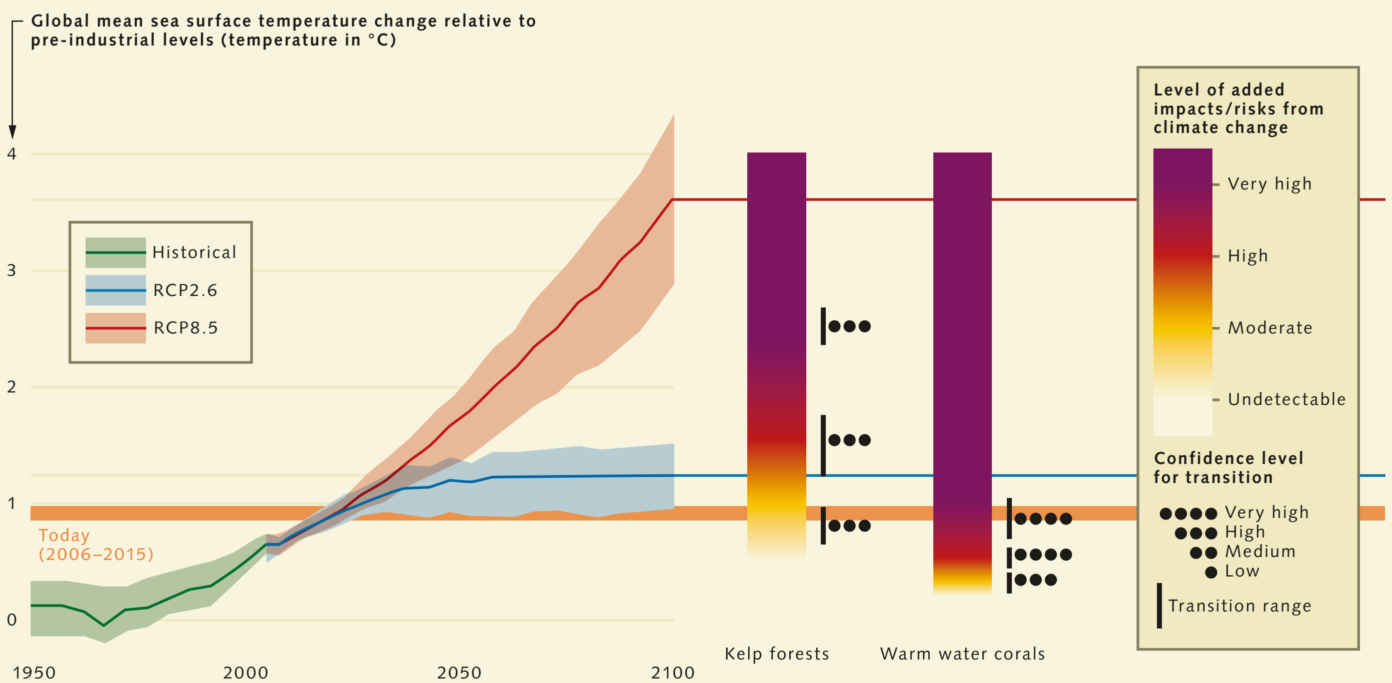
Coral reefs and kelp forests – no chance under extreme temperatures

Over the past 25 years, off the Australian coasts, researchers and recreational divers alike have observed how marine heatwaves are putting enormous pressure on two of the most species-rich, productive and important ecosystems of the oceans. These are the tropical coral reefs and the kelp forests – also called the rainforests of the oceans.

Corals – destructive bleaching

Tropical coral reefs cover less than 0.1 per cent of the global sea floor. Nevertheless, they are the habitat for at least a quarter of all currently known marine species. This diversity is a result of the fact that, as they grow, corals construct enormous calcareous structures containing a myriad of caves, tunnels and niches, in which hundreds of thousands of other marine organisms find food and protection. But humans can also be included among the beneficiaries of the reefs. Worldwide, more than 500 million people in 90 countries benefit in some way from the ecosystem services provided by coral reefs. They fish on the reefs, do recreational diving, make a living from reef tourism, rely on the coral structures to break waves and protect the coasts, or attribute cultural and spiritual qualities to them.

Globally, however, the coral reefs are dying. At least half of them have already been lost due to a variety of regional factors. While they were already being adversely affected by improper fishing practices, eutrophication, water pollution and the clearing of mangrove forests (loss of filtering effect), corals are now suffering severely from the consequences of climate change. Carbon dioxide-rich water inhibits their ability to form skeletons, and threatens to dissolve their carbonate foundations. Because of reduced mixing in the surface waters, as well as the presence of near-coastal hypoxic zones, they lack sufficient oxygen for respiration at many locations.



2.32 > Today, rising water temperatures are already forcing warm-water corals and kelp forests out of their traditional habitats. Australia's Great Barrier Reef, for example, has lost around half of its corals in the past 20 years. If the sea continues to warm, the pressure on these two communities will become so great that they will have scarcely any prospect of survival.

But the greatest damage is being caused by heatwaves, even though tropical corals generally prefer warm water. They thrive in water with temperatures between 23 and 29 degrees Celsius. Some reef-building species can even tolerate temperatures up to 40 degrees Celsius, albeit only for short periods. If the animals are exposed to temperatures warmer than 29 degrees Celsius for an extended period of time (in the Red Sea the threshold value is higher), they suffer from heat stress and cast out their lodgers. These are symbiotic algae called zooxanthellae, which live within the tissues of the coral polyps, produce sugar through the process of photosynthesis, and supply a considerable amount of it to their hosts. Without the algae, the corals lose their most important source of food. They become susceptible to disease and, along with the algae, they also lose their colour, which is why this reaction to heat stress is also known as coral bleaching.

When a coral becomes bleached it does not die immediately. If the water cools down again within a relatively short time the algae can return and the colony might recover. But if the heatwave continues for a longer period, the corals will starve. Researchers are observing these deaths more and more frequently around the world as the number and intensity of marine heatwaves increases. In the summer of 2019/20, the Great Barrier Reef off the east coast of Australia was hit by a long-lasting heatwave, the third one within five years. It resulted in coral bleaching that, for the first time, extended across all three regions of the reef system and impacted more colonies than ever before. Australian coral experts agree that climate change has now arrived in the cooler, southern part of the reef. And because heatwaves are occurring more frequently around the world, corals now have less time to recover from heat stress and recolonize the dead regions. The best-known coral reef in the world is therefore one of the many tropical coral reefs worldwide that will continue to shrink as long as the greenhouse gas concentrations in the atmosphere are not reduced and water temperatures are not stabilized.

Kelp forests – retreating toward the poles

Like coral reefs, kelp forests also form three-dimensional structures in the sea in which countless other species find protection and a home. The dense underwater forests of brown large algae prefer cooler waters, however, and therefore grow predominantly in temperate and subpolar marine regions. They are found on about a quarter of all the world's coasts, where they perform essential functions. During their growth, kelp forests extract large amounts of carbon dioxide from the sea. They buffer the shore areas against high waves, serve as spawning grounds for countless fish species, and play an important role in nutrient recycling in the sea. Their wellbeing depends on many factors, including sunlight, availability of nutrients, and the abundance of algae-feeding organisms (especially sea cucumbers and fish). For the most part, however, their distribution is determined by water temperature, which is why the world's kelp forests in both the northern and southern hemispheres have been undergoing significant changes for decades.

On the coast of Japan, for example, the brown algae have been gradually retreating northward since the 1980s. This is because the Kuroshio Current is becoming warmer. At temperatures between 18 and 20 degrees Celsius, algae-feeding fish like the Japanese parrot fish *Calotomus japonicus* are especially active and eat kelp faster than the rate of new algal growth.

Similarly, a heatwave off the west coast of Australia in the summer of 2010/11 was intense enough to destroy 43 per cent of an original area of almost 1000 square kilometres of kelp forest. As a result, the northern boundary of its distributional area was pushed southward by around 100 kilometres. With its retreat, the former habitats of the giant algae are being colonized by tropical and subtropical marine species, including many grazing organisms that are preventing recovery of the kelp forests today by eating practically every sprout of the giant algae that appears.

This total regime change has serious consequences for the coastal ecosystems and everyone who benefits from them. Western Australia's fishing and tourism industries, for example, depend heavily on the existence of kelp forests. If these continue to shift southward, there will be more serious negative consequences than just the millions in economic damages.

Many endemic species that can only live in the kelp forests will also die out locally. Where the kelp forests disappear, biodiversity declines, along with the amount of carbon fixed by the plants and the overall amount of animal and plant biomass, a trend that cannot be halted as long as ocean temperatures continue to rise.

collecting sufficient sediment material. Currently, however, this is happening in numerous river channels and estuaries, for example with the construction of dams or the dredging of gravel and sand. Wells drilled for groundwater, oil or natural gas in coastal areas are equally harmful. Their extraction leads to subsidence of the coastal lands and thus amplifies the effect of sea-level rise. The lands of the Mekong Delta in Vietnam, for example, are sinking today by six to 20 millimetres per year as a result of human intervention. Under these conditions, the outlook for mangroves is extremely dire.

Less bounty from the sea

Climate change is altering the distribution and productivity of marine organisms on a global scale, and thus adversely affecting the important ecosystem services of the ocean. Where coral reefs, kelp and mangrove forests are dying out, for example, waves are rolling up onto the shores unchecked and accelerating their erosion. Tourists who once came in droves to marvel at the biodiversity of these habitats are now losing interest, and culturally or spiritually inspiring sites are losing their magic.

The decline of marine biodiversity is particularly noticeable in the reduction of biomass in the ocean that is available to humans. The primary victims, therefore, are commercial fishing and aquaculture businesses as well as the many small-scale fishermen who fish for their own consumption. They are all being increasingly faced with the following challenges in the wake of climate change:

- decreasing nutrient concentrations in the surface waters of the low and middle latitudes due to enhanced stratification, which lowers primary production in these regions. This results in decreasing food supplies for fish, mussels, crabs and other seafood;
- a shift in fishery productivity toward the poles with a corresponding decline in fish stocks in the lower latitudes;
- decreasing reproductive success of numerous fish species;
- the loss of important fish spawning sites, particularly coral reefs, kelp and mangrove forests;
- decreasing individual body size in various species;
- due to temperature changes, a greater susceptibility to disease and parasites for species raised in aquaculture; and
- increasing frequency of harmful algal blooms and oxygen-poor zones in coastal regions where aquaculture is carried out.

A shift in the distributional areas of many species due to climate change also presents difficulties for effective fishery management in fixed sectors, as well as for the protection of rare species in designated marine protected areas. For example, if large schools of fish leave their traditional habitats due to rising water temperatures or diminishing oxygen concentrations, they may cross a boundary into adjacent fishing sectors. This would result in a decrease in stocks in the former sector and an increase in the new sector. The monitoring of this kind of boundary-crossing population changes and incorporating them into the fishery management plans of the various sectors in a timely manner currently poses enormous challenges for scientists and fishery managers. Mastering these will only be possible when the observation systems are improved and all of those involved are able to cooperate across sector boundaries.

The situation is similar for marine protected areas. In the future, these areas will only achieve their conservation purpose if their boundaries migrate together with the species in need of protection, or if the protected areas are interconnected. Here, as elsewhere, climate change is forcing human societies to develop new solutions, to constantly re-evaluate decisions, and to adapt those where necessary.

Minimizing the impacts of climate change on the oceans must become a top priority in policy-making. Humankind still has some time left, but we must act without delay if we are to preserve the oceans and their unique biological communities.

Conclusion

Ocean barometer

The world’s attention is currently focussed on the temperature trend in the global ocean. As long as it continues to rise, global warming will progress unimpeded. This knowledge is based on the fact that the ocean is the most effective heat-storage component in the Earth’s climate system. Since the 1970s, the oceans have absorbed more than 90 per cent of the heat energy trapped by anthropogenic greenhouse gas emissions and stored it at increasingly greater depths. The oceans have thus helped to significantly slow the rise in global surface temperatures, and to delay drastic changes in the Earth’s climate system. In the future, the ocean will also act as a gauge and monitoring service. Until water temperatures stop rising, or possibly even begin to drop, humankind will not be able to speak of any true progress in the struggle against climate change.

The warming of the seas and oceans is producing numerous dramatic changes. The water masses are expanding, causing sea level to rise and threatening millions of residents, especially in tropical coastal areas. At the same time, the ocean is losing oxygen, the elixir of life, because warmer water cannot store as much gas as cold water. Ocean currents are losing strength and wind-driven mixing is weakening because of the stronger stratification related to temperature differences. Extreme events like marine heatwaves are occurring more frequently. Furthermore, the chemistry of the ocean is changing. Since the onset of industrialization, the oceans have absorbed around a quarter of the anthropogenic carbon dioxide emissions. As a result, the pH value of the ocean has fallen and seawater has become more acidic, causing living conditions to deteriorate, especially for marine organisms with calcareous shells and skeletons.

The fatal aspect of the effects of climate change on the ocean is that they not only act to amplify their effects through feedback mechanisms, they also weaken the resistance of biological communities to other human interventions such as fishing, resource mining and pollution.

In response to climate stress, most animal and plant species are abandoning their traditional habitats and pursuing their necessary environmental conditions. This means that they either move poleward or they migrate down into deeper and colder water layers, if that option is available.

The major losers in this species migration driven by climate change are the cold-loving animal and plant species, because they have no other place to retreat to; organisms with calcareous shells or skeletons that are dissolved by acidification; sessile organisms like corals, whose dispersal mechanisms are too slow for them to escape the heat; and highly active predatory fish that cannot obtain the high levels of oxygen they need for respiration in the oxygen-poor water layers.

These few impressive examples suffice to illustrate that climate change is already changing the species structure in the oceans on a large scale. Not only is biodiversity declining, but total biomass production is decreasing as well. Marine ecosystems are losing their ability to perform the many ecosystem services utilised by humans. And with regard to the diversity of marine life, climate change is becoming the most powerful driver of species extinction, and in this respect represents an enormous challenge for sustainable ocean management.

It is crucial that, beginning immediately, the short- and long-term consequences of ocean warming, acidification and oxygen depletion are taken into account in every decision related to the use of the oceans.

3 Food from the sea

> For a long time, the ocean was seen as an inexhaustible storehouse of food. But the days of plentiful supply are long past. Through overfishing, coastal development and climate change, humankind has already deprived many marine species of their vital necessities. New strategies for sustainable fisheries and aquaculture management chart a course towards improvement but are rarely implemented in actual practice.

Issues with fisheries

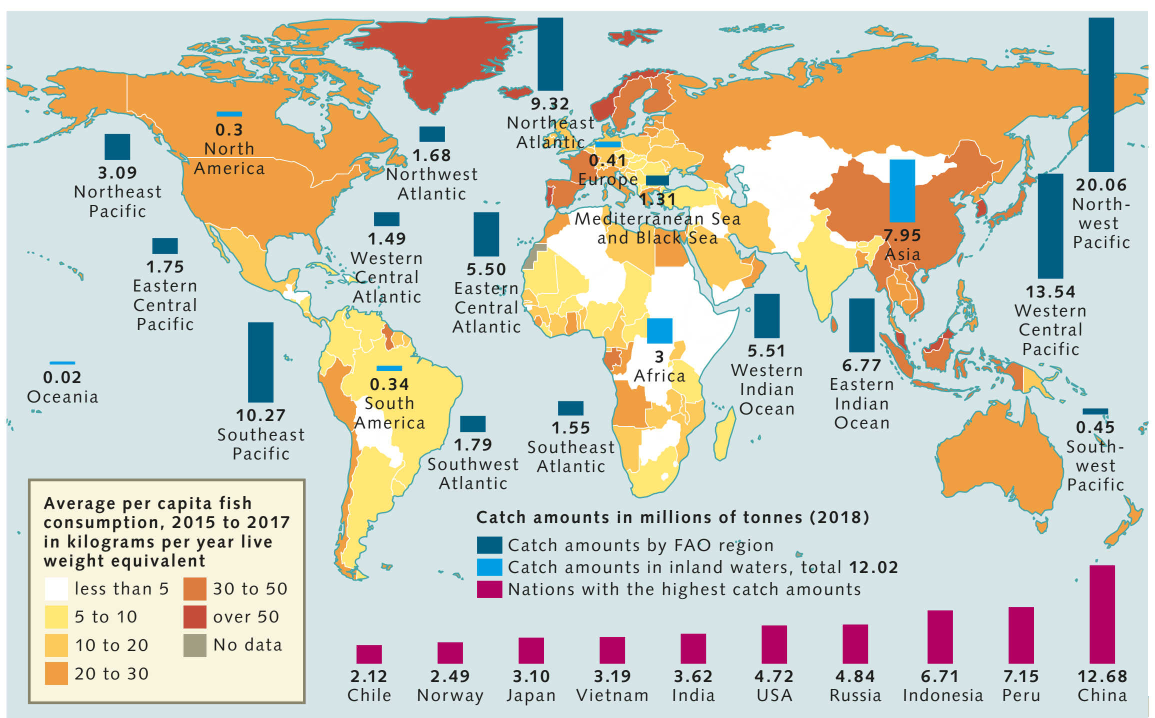
> Anchovies, tuna and similar fish are among the most heavily traded of all food products and are being caught in record numbers. Yet the number of overfished stocks is also rising because fishing quotas are too high and illegal fishing is being practised in many places. New regulations and technologies hold potential to deter offenders. However, for the world's fish stocks to recover fully and still be able to provide us with sufficient food in the future, the political will to implement conservation strategies comprehensively is vital.

A growing appetite for fish

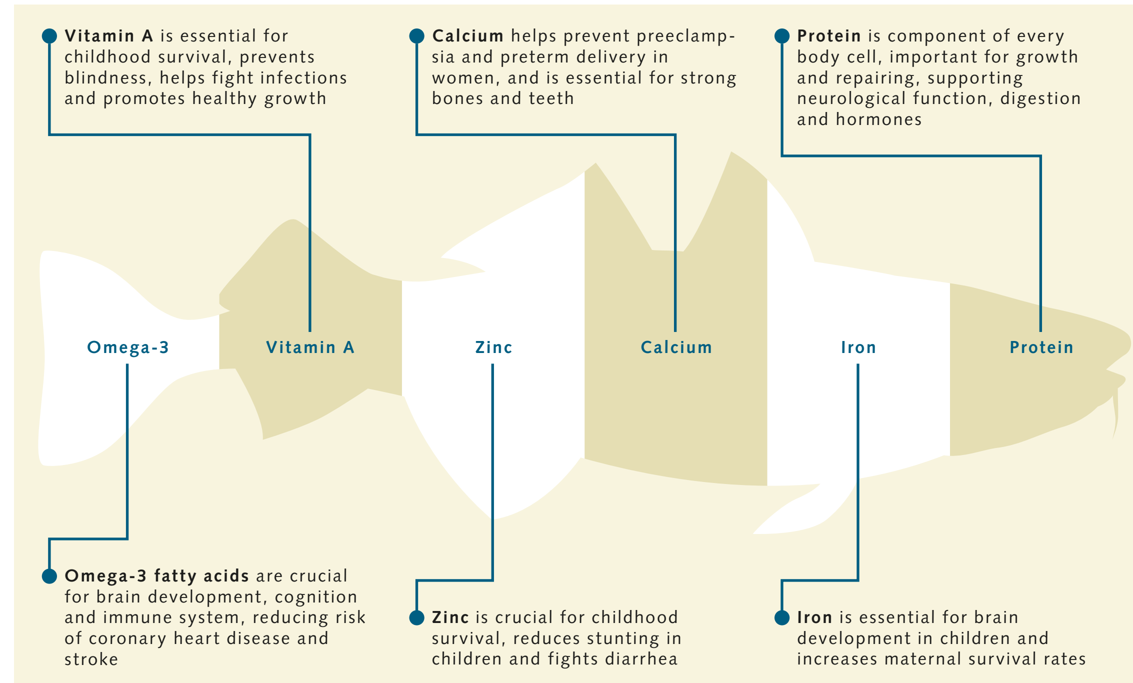
Fish consumption
The term "fish consumption", as used by the FAO, encompasses all fish species as well as molluscs, crustaceans and other aquatic organisms that are farmed or caught for human consumption.

Not only do people enjoy eating fish, clams, crustaceans and other seafood – per capita consumption is rising steadily. In recent decades the global demand for aquatic foods has grown so rapidly that today twice as much fishery produce is produced for human consumption as 40 years ago. The global population grew over the same period from 5.6 to 7.6 billion people; this can only explain a part of market expansion. The main reason appears to be a mounting appetite for fish. While it has been calculated that the average citizen of the world ate around 13.4 kilograms of fish each year during the period from 1986 to 1995, the most recent fisheries report of the FAO (Food and Agriculture Organization of the United Nations), from the year 2018, gives a per capita consumption of 20.5 kilograms per year. This report includes fishery products from the ocean as well as those from lakes, rivers and ponds.

Worldwide, fish and seafood account for 17 per cent of the total amount of animal protein consumed by humans. A detailed study of who eats fishery products indicates that more than 3.3 billion people obtain at least one-fifth of their animal protein requirements through aquatic foods. In countries like Bangladesh, Cambodia, Gambia and Indonesia, this share approaches as much as 50 per cent, which means that fish products play a paramount



3.1 > Fish and seafood are caught and consumed around the world, but in very different quantities. In South East Asia, Western Europe, Scandinavia and Greenland people consume considerably more fish than in northern Africa, in eastern South America, or in the Near East.

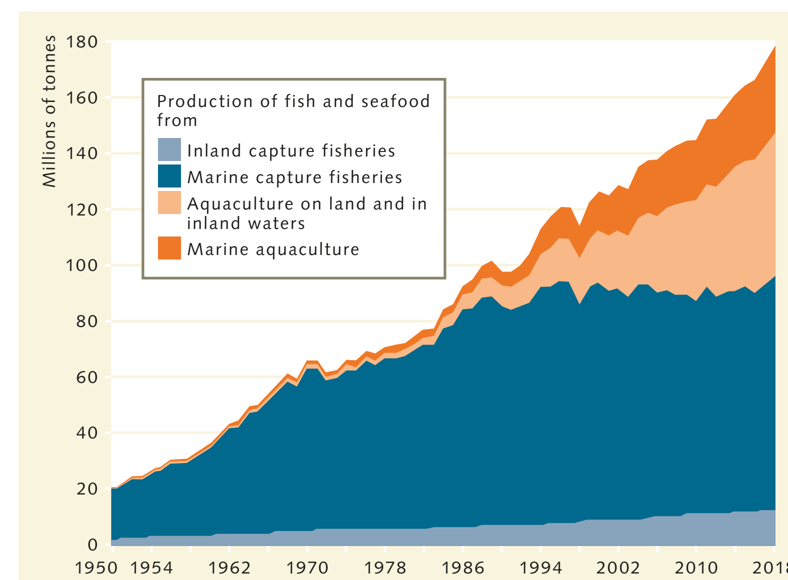


3.2 > Fish are an important source of protein. They also contain many vitamins and nutrients, as well as polyunsaturated Omega-3 fatty acids, which are the crucial building blocks of cell membranes. A less well-known fact is that heavy metals, dioxins, marine biotoxins like ciguatoxin, and antibiotics may also accumulate in fish meat.

role in the food supply of the populations there. Germany ranks near the middle of this range. While every citizen of Indonesia eats more than ten grams of fish protein each day, Germans, according to the FAO statistics, average four to six grams per day. The annual per capita consumption in Germany is between ten and 20 kilograms of fish (live weight).

The increasing worldwide fish consumption can be attributed to a number of factors. For one, more fish and seafood are being produced. For another, demographic changes and improvements in freezing and delivery chains have contributed to the more frequent appearance of fish on the plates of people in industrial countries, but also in developing countries where urbanization is advancing. Statistics indicate that in areas where people are moving from the country to the cities, and are beginning to earn higher incomes for extended periods of time, they also purchase more fish and seafood or order more of these foods at street stands and restaurants. Moreover, in many places fish is cheaper than meat and is considered to be an especially healthy option because of its vitamins, essential polyunsaturated fatty acids (Omega-3 fatty acids) and low cholesterol content. According to the FAO, developing countries imported around 49 per cent of the globally traded fishery produce in 2018. This means that the import share of these countries has more than doubled over the past four decades.

3.3 > The amounts of fish caught, as well as the fish and seafood produced in aquaculture, have been rising worldwide for decades.



3.4 > Fisheries and aquaculture provide a livelihood for more than ten per cent of the world's population. Most of the small-scale fishers live in Asia. This woman is selling her catch at a market in Vietnam.

The increasing consumption rates are made possible by more intense fishing activity in open waters, and by the rising production of food fish and other organisms by aquaculture methods. While global fish and seafood production was around 140 million tonnes in 2006 according to the FAO, by the year 2018 it had risen to around 179 million tonnes. Around 46 per cent of that (82 million tonnes) came from aquaculture and the remaining 96.4 million tonnes were caught wild by fishermen and -women.

Marine fisheries still make up the largest proportion of wild catches today. In 2018 they accounted for around 84.4 million tonnes. This is equal to a share of 88 per cent and is only two million tonnes less than the previous peak value from the year 1996. The seven most important marine fishing nations, in order, are China, Peru, Indonesia, Russia, the USA, India and Vietnam. Together they are responsible for more than half of all the catches in the oceans.

After constant growth in the numbers of fish caught each year, which lasted into the 1990s, the production levels for marine fisheries levelled off, and have now remained relatively stable since 2005. The official total amount over the past 15 years has generally been in the range of 78 to 81 million tonnes annually. A notable peak in 2018 can primarily be attributed to the activities of Chilean and Peruvian anchovy fishers. In that year they caught significantly more Peruvian anchoveta *(Engraulis ringens)* with their nets than in the preceding three years.

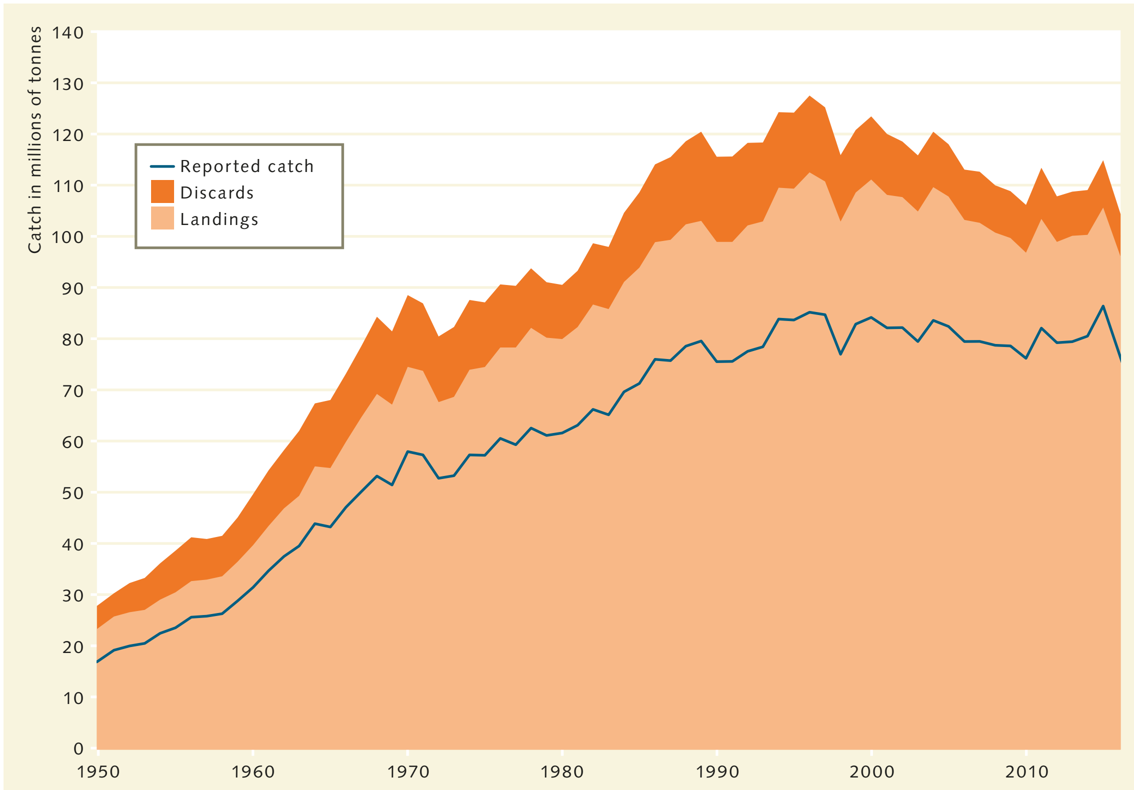
The FAO now records fishery data for more than 1700 marine fish species. But it is difficult to say to what extent their figures truly reflect the actual catches. In its report, the FAO itself points out that it mainly works with official catch data submitted by the individual countries. If there is important data missing from these catch reports or if nations refuse to cooperate with the FAO, as is the case with Brazil, the organization attempts to fill the gaps by estimating the amount of the missing catches. To do this, it draws on other official sources, such as statistics from the Regional Fishery Bodies (RFBs) and from regional fisheries management organizations (RFMOs).

Alliances for collective fishery management

Regional Fishery Bodies (RFBs) are advisory bodies established among countries with mutual fishing interests in a particular area. The objectives and tasks of such intergovernmental fishery bodies can be very diverse, with interests relating to either inland or marine fisheries, or to promoting the development of domestic fisheries. Some RFBs adopt legally binding conservation and management measures for all members and in this manner may regulate fishing within a limited geographic area outside their respective Exclusive Economic Zones (EEZs). Because these decisions have a legally binding character under international law for all members, the individual fishery bodies are also referred to as regional fisheries management organizations (RFMOs). These include, for example, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the General Fisheries Commission for the Mediterranean (GFCM) and the North-East Atlantic Fisheries Commission (NEAFC).

International cooperative research initiatives like the Sea Around Us project try to combine official catch data from the FAO with estimates of bycatch, as well as with illegal or unreported landings. As might be expected, there is a great deal of uncertainty in their scope. At any rate, their method results in higher estimates of the totals of fish caught worldwide. For example, in 2016 according to Sea Around Us, some 104 million tonnes of ocean fish and other marine animals were caught. For the same year, however, the FAO reported catches of only 78.3 million tonnes of marine fish species. The difference of 25.7 million tonnes reflects illegal or unreported catches. 8.1 million tonnes of these, about 7.8 per cent of the total catch, were thrown overboard as bycatch. According to these figures, approximately every fourth fish that is caught is not accounted for in the FAO statistics.

Critics also argue that the FAO's figures on the trends in wild catches and aquaculture production fail to address two important aspects. First are the amounts of wild sardines, herring, sprats and other schooling fish that are caught and processed into animal feed such as fishmeal and fish oil, and are thus not used for direct human consumption. These account for an estimated 25 per cent of all marine catches. The second is that in reporting the

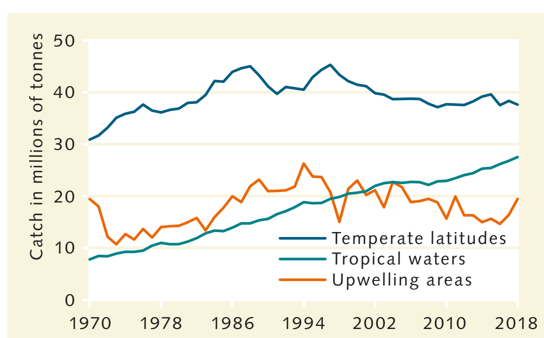


3.5 > For its statistics, the Sea Around Us research project combines officially reported catches with estimates of illegal fishing excursions and also includes bycatch that is discarded directly into the sea again. Their calculated total amount of fish caught is therefore significantly higher than that reported by the FAO.

aquaculture portion, the weights they use for shellfish include the shells. In farmed animals like oysters, however, the shells make up as much as 80 per cent of the total weight but they are not ultimately eaten. For this reason, according to the critics, the total production by the aquaculture industry is not equivalent to the amount of food produced. That amount should be accordingly smaller.

Mostly anchovies and pollock in the nets

If the FAO total catch figures from 2017 to 2018 are broken down into individual fish species, the Peruvian anchoveta *(Engraulis ringens)* clearly stands out over the rest. More than seven million tonnes of this schooling fish, which can be up to 20 centimetres in length, were caught off the west coast of South America in 2018. It is thus unquestionably at the top of the list of the world's most heavily fished species. Pacific pollock *(Theragra chalcogramma)*, which is known as Alaska pollock on the German market, comes in second place with a total of 3.4 million tonnes. Third place, at 3.2 million tonnes, goes to the skipjack tuna *(Katsuwonus pelamis)*, the most heavily fished of all tuna species. It lives mostly in the tropical and subtropical seas, but is also occasionally caught in the North Sea.



3.6 > Most fish are caught in the temperate latitudes. But fishing in the tropics is growing steadily.

3.7 > The Japanese flying squid *Todarodes pacificus* lives in the northern Pacific and is one of the most heavily fished of all cephalopods. Catch numbers have been declining in recent years, perhaps because population numbers have plunged by more than 70 per cent.

Tuna and similar species are being more intensively fished every year. This trend continued in 2018, reaching a new peak of 7.9 million total tonnes. The rise can be attributed to greater numbers of fishing excursions in the western and central Pacific. While around 2.6 million tonnes of the skipjack, yellowfin *(Thunnus albacares)* and other tuna species were caught annually in the mid-2000s, this value is now up to 3.5 million tonnes. The amounts of cephalopods caught reached a similar level. The most abundantly fished species of these were the Humboldt squid *(Dosidicus gigas)*, the Argentine shortfin squid *(Illex argentinus)* and the Japanese flying squid *(Todarodes pacificus)*.

In recent years, fishing has increased significantly in the tropical regions of the Indian and Pacific Oceans. But the largest catches are still being made in the middle latitudes with their temperate climate. In 2018, around 37.7 million tonnes of marine species were caught here.

Much too heavily fished

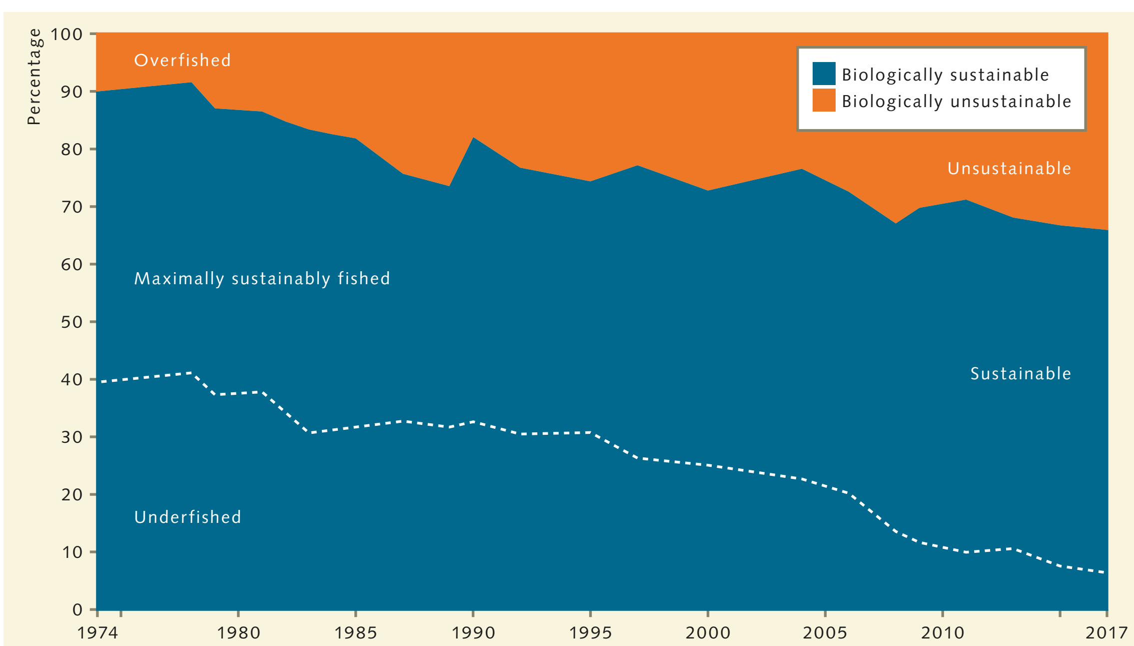
When catch numbers increase steadily or are sustained at high levels, the question of the damage that fishing is inflicting on the ocean's biological communities will eventually have to be addressed. A definitive answer to this question is not possible, however, because we do not know enough about the status of most fish stocks. This is due to a paucity of scientific data. It is not known how large these stocks were originally or how much they have been depleted due to fishing, which is why there are no management or protection concepts for these marine fish species and stocks. Nevertheless, unmonitored species are being fished so extensively that the catches make up about half of all the global marine fish landings.

The other half, however, are from scientifically monitored fish populations. These are generally species that constitute large populations, are fished on an industrial scale, and are native to waters where industrialized nations have primary oversight. Scientific evaluation of the stocks and monitoring of fisheries requires money as well as effective fishery authorities, which is why there is a notable lack of reliable information on the state of the stocks and the scale of fisheries in developing countries.

But even when these data are available, it can still be difficult to determine the productivity of a fish population and the maximum numbers of fish that can be taken under the existing environmental conditions without causing long-term damage to the stocks. There is a very wide range of opinions, even among fishery biologists. A fish stock is generally considered to be healthy when it contains a sufficient number of animals for a maximum sustainable yield (MSY) of fish to be removed without causing a long-term impact to the size of the population. Under this concept, enough individuals always remain in the water for their offspring to replace the stocks sufficiently for the MSY of fish to be taken again the following season. The FAO refers to this situation as a stock that is fished at the maximum sustainable level. However, this wording commonly leads to misunderstandings. People often equate the size of sustainably fished stocks with the size of natural, unfished populations. Actually, the former is usually 30 to 50 per cent smaller than the latter. Only populations that are not fished at all can reach their natural stock size.

A stock is considered to be overfished if the remaining population is too small to completely recover and produce consistently high fishing yields over the long term. This condition is becoming more and more common around the world, as the number of stocks known to be exploited beyond their resilience limits has been increasing for decades. There are thus ever fewer fish in the sea. According to FAO figures, one in ten scientifically assessed stocks (ten per cent) was considered to be overfished in 1974, but by 2017 that number had increased to 3.4 in ten (34.2 per cent). In other words, the proportion has more than tripled in four decades. In 2017, only 6.2 per cent of all known fish stocks were considered to be lightly fished or underfished. The remaining 59.6 per cent, according to the FAO, were fished at a sustainable level. That means that the number of fish removed was not more than the number that could be naturally replenished.

Even more grave are the findings of a recent study by Canadian and German fishery biologists of the population



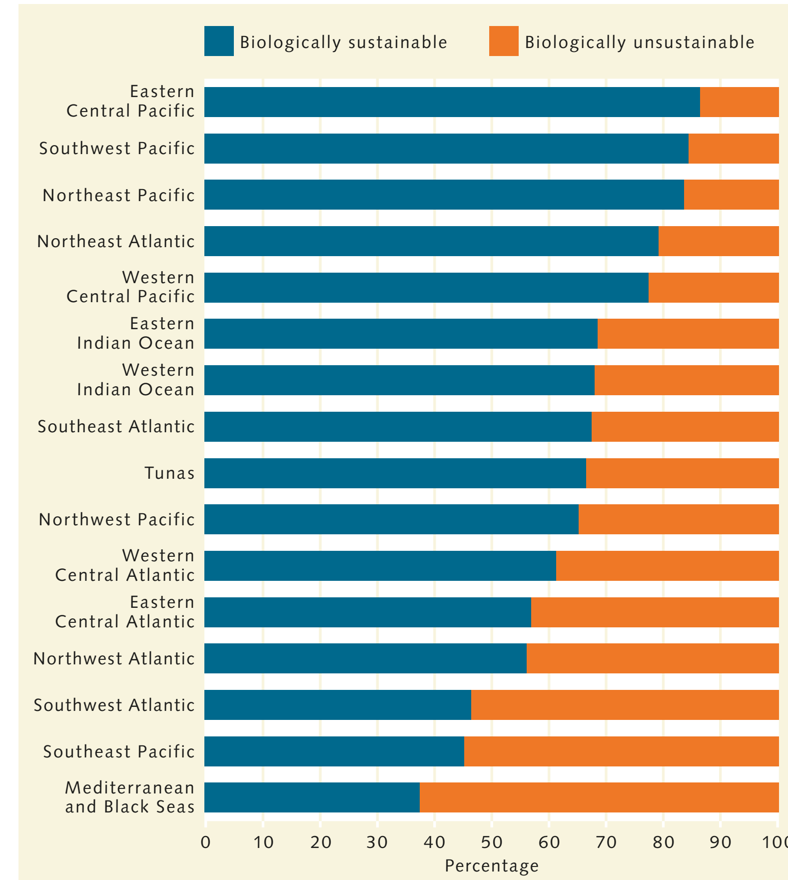
3.8 > A clear downward trend: According to the FAO, 34.2 per cent of all scientifically monitored fish stocks were overfished by the year 2017. 6.2 per cent were underfished and 59.6 per cent were fished at the maximum possible sustainable levels.

development trends of 1300 marine organisms over the past 60 years, including invertebrates, using the combined catch data from Sea Around Us. By their assessment, 82 per cent of the populations surveyed are now below the levels necessary to produce maximum sustainable yields. This means that more animals are being removed than can be replaced. In the long run, therefore, according to the researchers the fishers will bring home smaller and smaller catches, even when they fish more intensively and for longer periods of time.

Marine conservationists and many scientists are therefore calling for rejection of the popular single-species management strategy, moving instead towards maximizing sustainable fisheries yields. The large number of overfished stocks shows that the old approach is no longer sustainable, and that it ignores the role of fish in the food webs of the seas. By fishing to the very limits of sustainability, critics argue, humans also leave no buffer or margin for species to react to changing environmental conditions. For example, if the reproduction rate of a species declines because the waters in its spawning areas become warmer due to climate change, the catch limits for maximum sustainable yield can change very rapidly. Intelligent fisheries management, on the other hand, as practised to some extent in the European Union and particularly in the USA, aims at somewhat lower yields. This reduces the risk of unintentional overfishing and makes the populations less susceptible to environmental changes.

In the European Union, for example, fisheries managers do not look only at the stock size of the species. Instead, they work in a more process-oriented manner and pose the question of how high the fishing mortality of a stock can be and still achieve and maintain its MSY size over the long term (FMSY). According to scientific opinion, therefore, the recommended catch quotas, as a rule, should be smaller than the theoretical maximum. From this point of view, the only thing that would conserve resources more effectively would be to stop fishing completely.

The reality, however, is that in many places a fish stock being designated as overfished does not stop fishers from continuing to target that species. In the Mediterranean and Black Seas, for example, the FAO now classifies 62.5 per cent of the actively fished stocks as overfished. Ceaseless fishing pressure throughout recent decades has led to the eradication of at least 17 popular fish species in the Turkish sectors of the two Seas, including the Atlantic bluefin tuna *(Thunnus thynnus)*, the swordfish *(Xiphias gladius)* and the Atlantic mackerel *(Scomber scombrus)*. Their disappearance has set off chain reactions in the affected ecosystems. For example, mackerel predators like the porbeagle *(Lamna nasus)* have not been sighted in the Turkish coastal waters in decades. The same is true for white sharks *(Carcharadon carcharias)*, which, until the 1980s, had been known to follow migrating schools of tuna as far as to the Sea of Marmara. Today these great



Tuna stocks are singled out as they are largely migratory and straddling across statistical areas.

3.9 > The FAO comparison shows that the Mediterranean and Black Seas are among the most intensively fished marine regions in the world.

predators are considered to be extinct in this part of the Mediterranean.

Conflict of interest at the cost of the sea

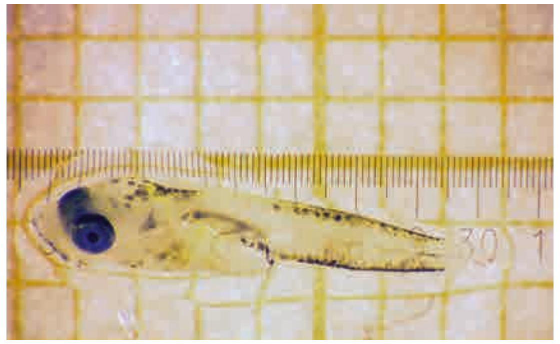
Overfishing of the seas is not a new phenomenon. Fishermen had recorded sharply declining catch numbers as early as the 1970s, for example, when the herring stocks in the northeast Atlantic collapsed in response to very heavy fishing pressure. Also at that time, the stocks of Peruvian anchoveta shrunk dramatically and the cod fishery in the waters of Newfoundland collapsed. Concerns about domestic fish stocks prompted some coastal states to establish an Exclusive Economic Zone (EEZ) 200 nautical miles wide, where fishing by foreigners was prohibited from that time on. This approach was subsequently adopted in the United Nations Convention on the Law of the Sea (UNCLOS), which entered into force in 1994.

With the Exclusive Economic Zone at their doorsteps, the industrial nations, at least, began to keep track of catch statistics and to scientifically monitor the condition of stocks. In the mid-1990s, increasing numbers of research papers and media articles began to appear reporting that the catches of many key species had collapsed dramatically due to overfishing. And in June 2003 a globally acknowledged report by the Pew Oceans Commission on the health of the oceans described overfishing as a serious threat for the first time.

Alarmed by the prospect of collapsing stocks, many countries, particularly the industrialized nations, began to regulate fishing in their Exclusive Economic Zones. They were successful in some areas. But countries of the European Union, among others, still lack strong political will to give top priority to marine conservation and to follow scientific recommendations on fishing restrictions. The main reason is that they have not been able to satisfactorily answer the question of how people whose livelihood has depended on the catching of wild fish will earn a living in the future.

Fish and fishery products are now among the most abundantly traded foodstuffs in the world. In 2018, the total first-sale value of all fishery products produced by capture fisheries and aquaculture came to USD 401 billion. At that time, fisheries and aquaculture together represented the livelihood of around ten per cent of the world's population. In the year 2018, according to the figures of the FAO, around 39 million people worldwide worked directly in the fishing industry (including inland fisheries), while 20.5 million people were employed globally in aquaculture farming. Compared to the reporting year of 2015, both sectors had shown moderate growth.

85 per cent of all fishers and aquaculture farmers live and work in Asia. By no means does the typical fisherman or -woman work on a large trawler. FAO statistics indicate that around nine out of ten of the workers are from developing countries, where they earn their livings in small-scale fishing or aquaculture facilities. In Europe, as well as in North and South America, on the other hand, the number of people working in the fisheries industry has been declining in recent years. In 2015 there were 338,000 Europeans working in fisheries, but just three years later this figure had fallen to only 272,000. By



3.10 > By the year 2020, so few herring and cod remained in the western Baltic Sea that these two fish species could no longer produce enough eggs for their entire spawning area. Climate change, aided by the comb jellyfish, finished them off, and the search for juvenile fish by researchers and fishers was in vain (l.: herring larva, r.: cod larva).

3.11 > An Indonesian aquafarmer wades through his fully stocked shrimp-breeding pond. This Asian country, after China, is the second-largest aquaculture producer in the world, with annual growth rates of up to 12.9 per cent.

Pros and cons of different fishery management approaches			
Approach	**Description**	**Pros**	**Cons (or challenges)**
Total allowable catch (TAC)	Sets a limit on the amount of total harvest permitted	Can cap harvest at a sustainable level	May incentivise the race to fish, high-grading (discarding of low-valued fish) and misreporting; may be difficult to enforce, particularly in artisanal fisheries
Individual quota (IQ)	Assigns a property right to portions of a quota	Can cap harvest at a sustainable level; may promote economic efficiency (particularly if rights are tradeable); incentivises management for long-term sustainability	Privatisation of public resource; may be difficult to assign rights; consolidation of IQs by individuals or firms
Territorial use rights for fishing (TURFs)	Area-based management in which specific users have rights to access one or more fish resources	Incentivises management for long-term sustainability	Additional management measures may be needed to cap extraction at sustainable levels; determining the appropriate size of TURFs may be complicated
Community-based co-management	Local people are allowed to participate in decision-making and enforcement	May facilitate monitoring and enforcement	More likely to function well for high-valued stocks; too many stakeholders may hinder effective management
Permits	Restrict the number of users who are able to access the resource	May reduce fishing pressure; may improve enforcement	Additional management measures may be needed to control quantity of harvest
Gear restrictions	Rules regarding the number, types and designs of gear permitted in a fishery	May protect spawning females, juveniles, largest fish or protected species and assure that fish get to reproduce before being caught (e.g. mesh-size requirements); may protect habitats (e.g. ban on dynamite fishing); may minimise bycatch; useful for data-limited fisheries	Additional management measures may be needed to control quantity of harvest; can be difficult and costly to enforce; do not necessarily promote economic wellbeing
Size limits (commonly related of to gear restrictions)	Designed to protect a particular stage, age or size targeted species	May protect larger, potentially more productive fish, or young fish until they reach reproductive age	Additional management measures may be needed to control quantity of harvest; do not necessarily promote economic wellbeing; spawning size may increase or decrease

Pros and cons of different fishery management approaches			
Approach	**Description**	**Pros**	**Cons (or challenges)**
Seasonal closures (in all or at particular fishing sites)	Temporary closures, often set to protect sensitive portions of the life cycle	May protect juveniles, spawning fish or the whole stock; easy to implement	Additional management measures may be needed to control quantity of harvest; may cause excess capacity
Buybacks	Purchasing fishing gear, vessels, quota or permits to reduce excess capacity and/or improve profitability in the sector	May decrease incentives to overharvest; may reduce fishing pressure; may aid in protecting sensitive species	Potential for capacity to rebuild or gains in efficiency to counteract buyback programme; competing fleet may increase
Ban discards	Aimed at eliminating or minimising fish caught and discarded at sea (i.e. all harvest must be landed)	May reduce fishing pressure per quantity landed; may incentivise direct or indirect consumption of less desirable fish; results in better extraction information, which may improve assessments	Additional management measures may be needed to control quantity of harvest; difficult to enforce; requirement to land choke species could prematurely close target fisheries
Harvest control rules designed to maintain stocks at productive levels	Performance is evaluated using reference points (RPs) that describe desirable states (target RPs) and threshold states to avoid (limit RPs)	Provide fishery managers with (ideally) scientifically and economically justified targets	Reference points can be hard to estimate and enforce in real time, and may also change over time
Ecosystem-based management	Management that recognises the dynamic nature of ecosystems, and human nature interactions and effects of interactions throughout the system	Can address broader objectives than the more common focus on managing individual species in isolation	Interactions are complex and can be difficult to clearly identify; basic information is not always available; ecosystem may change to an alternative state
Marine protected areas (MPAs) and refugia	Areas in which extractive activities are limited or prohibited	May result in fishery benefits through larval export and spillover (i.e. movement of juveniles or adults from the MPA to the adjacent fishable area); may increase food provision where fisheries have been overfished; MPA effects will be strongest for Fully Protected MPAs, which prohibit extractive or destructive activities and minimise all impacts (also referred to as marine reserves)	Benefits from larval export and spillover are often uncertain; may increase cost of fishing; may promote overfishing at the boundaries of the MPA; difficult to finance; may generate social conflicts; often not easy to set in the proper area due to conflicting interests
Regional management organisations	Organisations that coordinate management for fish stocks that exist in multiple political boundaries	May result in improved management for transboundary, straddling stocks or stocks that will shift spatially in the future	Domestic political issues may impede thorough regional enforcement of straddling stocks; international conflicts may arise

comparison, around 30.8 million people in Asia earned their livings in fisheries in 2018.

To date, more than 95 per cent of all fish landings take place within the Exclusive Economic Zones. This means that fisheries management is primarily the responsibility of the individual nations. These use various instruments and strategies to manage their stocks.

Experience over the past three decades has shown that overfishing can be reduced and stocks be conserved through systematic regulation. Nevertheless, not every measure tried was effective in achieving the desired ecological improvements. Some of the regulations left too many options for circumvention by the fishers, while others worked for species with high reproduction rates but failed for species with fewer offspring. Still other guidelines can be implemented on a local scale – for example, in remote, small fishing communities – but are not suitable for industrial-scale fisheries.

The secret plundering of the seas

Leaving unwanted and discarded bycatch out of the calculation, about every fifth or sixth ocean fish that is bought or prepared around the world is caught illegally. This falls under the official designation of illegal, unreported and unregulated (IUU) fishing.

"Illegal fishing" is considered to be all fishing activities that violate applicable national and international regulations or the rules of the responsible regional fisheries management organizations.

The category of "unreported fishing" includes fishing excursions whose catches are not reported to any official authorities, trips on which false information about species fished, fishing area, or amount of bycatch is provided, or those on which other required information is withheld, for example, relating to the transfer of catches to reefer ships. Strictly speaking, subsistence fishing (fishing for personal consumption) as well as catches by small-scale fishers are also part of the unreported fisheries in many countries. But in these cases, presumably, no one would accuse the fishers involved of criminal activity.

"Unregulated fishing" refers to fishing activities for which there are still no national or international control bodies, but which nevertheless violate international laws or globally applicable principles and conventions for the conservation of biodiversity. This includes, for example, fishing by ships that are not registered anywhere and are therefore stateless, or fishing in particular RFMO waters although the flag state of the vessel is not a member of that RFMO.

The temptation to carry out IUU fishing is great. One reason for this is that high-value food fish such as tuna bring a high price. Another is that fish and seafood are traded on a global market. According to the FAO, around 38 per cent of all fishery products in 2018 (wild-caught and aquaculture) were for export. The value of these goods was USD 164.1 billion. Experts estimated the sale value of illegal catches at USD 10 to 23 billion. But the ecological, economic and societal damages that are incurred due to illegal fishery are thought to be much higher.

In many cases, experts are now referring to this problem in terms of transnational organized crime, the scope of which not only threatens marine ecosystems in a dramatic way but is also creating a security problem. Large-scale illegal fishing operations by foreign fleets in the coastal waters of African countries, for example, are depleting or destroying the local fish stocks and endangering the food security of the coastal populations. Livelihoods are being stolen from the small fishers, and this can encourage criminal activities, including piracy. Added to this, the countries are losing millions in tax income. Furthermore, illegal fishing operations are undermining local, regional and international conservation efforts. If the extent of IUU fishing in a marine region is not known, and the lack of information results in incorrect estimates of its stock and catch numbers, there is very little chance of success in protecting the stocks.

Furthermore, illegal fishing is often connected to human rights abuses and slavery, especially in South East Asia. According to the International Labour Organization (ILO), numerous victims have reported extortion, psychological and sexual abuse, fatal accidents caused by the lack of safety measures on board fishing vessels, and extremely hard and dangerous work for starvation wages.

Experts recommend a range of measures to stop systemic IUU fishery. These are based on the concept that large-scale illegal fishery should no longer be seen as a management problem, but as a type of organized crime, and should be prosecuted as such. Everyone involved must be informed of the fact that other criminal activities are often linked to illegal fishing, including corruption, falsification of documents and human trafficking. To stop the plundering of the oceans, coastal states must strengthen and rigorously enforce their fishery laws. It is the duty of the international community to not only support the nations concerned in monitoring their coastal waters, but also to establish clear rules, functions and responsibilities in the fight against illegal fishing at the international level.

At the same time, mechanisms must be implemented that help to make information about ships, their owners, routes and fishery licenses more easily available. The lack of information about active participants and other responsible parties is still one of the greatest obstacles in the fight against illegal fishing. In addition, regional networks and partnerships between governments, agencies and environmental organizations need to be expanded, and cooperation among the states strengthened in the area of maritime security. It is also essential to expose and prosecute the financial transactions and money laundering processes associated with illegal fishing.

There are two relatively new and important tools being used in the struggle against large-scale fishery crimes. One is modern satellite and positioning technology, and the other is the international Agreement on Port State Measures (PSMA) to prevent, deter and eliminate illegal, unreported and unregulated fishing. This pact entered into force in 2016 and had been ratified by 66 states by February 2020. It empowers coastal states to block entry of ships under foreign flags to their harbours

3.12 > The endangered totoaba from the eastern Pacific Ocean is mainly caught by Chinese deep-sea fishers. It is targeted because on Asia's markets a single swim bladder of this coastal fish will bring a price of USD 1400 to 4000 for its alleged healing properties.

3.13 > A team of US American and Ghanaian coastguard officers inspect a ship in the Gulf of Guinea that is suspected of illegal fishing. Seafood is the most important source of animal protein for the people of Ghana. But the coastal waters of this African country have been overfished for decades.

when there is reason to believe that they are involved in illegal fishing activities and have such catches on board.

It is important to note that illegally caught fish generally enter the market through one of two pathways. In one case, the trawlers transfer their catches onto a freezer or factory ship while still at sea, where the fish are then immediately processed and may be mixed with products from legal catches. It is then practically impossible for inspectors, intermediaries or customers to trace the provenance of the individual fish filets, which is why the transfer of catches on the open sea is prohibited by some regional fisheries management organizations. Nevertheless, this practice is carried out in many places, and is the reason why transshipment is seen as one of the biggest loopholes for illegal fisheries. The second way to get them into the market is to transfer large amounts of the illegally caught fish into deep-freeze containers, then reload these onto a container ship in a nearby harbour and send them out into the world from there. The advantage here is that freezer containers are less frequently inspected in the harbours compared to other transported goods. In addition, less specific information about the container's contents is required. In a 2016 report on illegal fishing in West African waters, investigators concluded that 84 per cent of all official and unofficial catches in West African waters were transferred to freezer containers and left the region through a handful of ports heading to other countries such as Spain.

The PSMA regulates, among other things, the information and documents a harbour authority should demand when a (reefer) vessel requests permission to enter the port. It also prescribes on-board inspections and a thorough exchange of information between all responsible parties. In addition to the national authorities of the coastal state concerned, these include the government of the state under whose flag the vessel in question is sailing, the responsible regional fisheries management organizations and international institutions such as the FAO. Experts believe that if it is correctly implemented the PSMA could help to bring an end to systematic, large-scale illegal fishery, because it would prevent the landing and further transport of illegal catches.

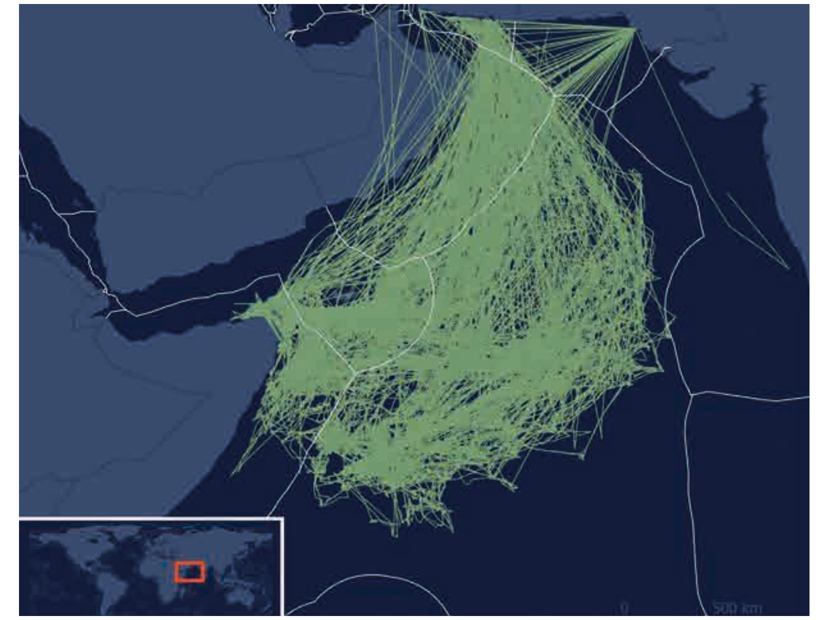
A new web portal showing the locations of large reefer and factory ships (Carrier Vessel Portal), which went online in the summer of 2020, will also bring greater transparency. On the portal, which is operated by the environmental group Global Fishing Watch and combines positioning and satellite data, registered users can, for example, analyse the routes of industry ships, or find out which ports they regularly enter. The vessel names can then be checked against the positive and negative lists that are now published by several regional fisheries authorities.

It is the view of the FAO that the flag states need to assume a greater role in the efforts against illegal fishing. With its *FAO Voluntary Guidelines for Flag State Performance*, it calls on all nations to respect international law, to ensure observance of national and international fishery regulations, to fulfil their inspection obligations, to prosecute illegal activities by their own fishing fleets and to share relevant information and cooperate more closely with national and international institutions. In this way, fishers who have been proven guilty of criminal activities could be prevented, for example, from cancelling their ship's prior registration in order to register with a less restrictive country. This technique of avoiding the law is known as "flag hopping". The FAO has no means of forcing flag states to honour the guidelines, however, because their implementation is still voluntary. The same is true for FAO guidelines on the documentation of fish catches, which are meant to allow the states, fishery organizations and other stakeholders to establish transparent supply chains, making it possible at any time to verify whether fish products of any kind are from legal catches.

Pursuing criminals with satellites and positioning data

Proving the illegal activities of fishers has largely been unsuccessful so far due to the vastness of the oceans and the shortage of funds for personnel and equipment in many places. These surveillance gaps can now be closed with the help of modern satellite and positioning technology, as a report published in June 2020 by two environmental organizations specializing in fishery issues shows. They analysed radio and satellite data from the Arabian Sea (northwest part of the Indian Ocean) and discovered that during the fishing season of 2019/2020 alone more than 110 Iranian fishing vessels entered and illegally cast their nets in the territorial waters of Somalia and Yemen. Fishers from India, Pakistan and Sri Lanka did the same, although in much smaller numbers.

Evidence of illegal fishing in Somalian waters has been available for some time. The true magnitude of the crimes, however, only became known after scientists began to deliberately search for clues. Their work was facilitated by the fact that more and more ships around the world are being fitted with an Automatic Identification System (AIS). The system was first developed as an aid to prevent ship collisions and is now required equipment on all larger ships (gross tonnage of 300 or more). Position coordinates are transmitted every few seconds along with the course and speed, and every three minutes the basic ship information is sent out, so that other nearby ships have access to up-to-date information and can adjust their course as necessary.



3.14 > The green lines on this map show the routes of 175 Iranian ships that fished in the Arabian Sea between 1 January 2019 and 14 April 2020. More than 110 of them illegally entered the territorial waters of Somalia and Yemen.

Although the data transfer system was originally designed only for direct contact between ships, today the AIS signals are also received by radio towers and satellites and recorded by data centres. In this way, observers of fishery activities around the world can trace the routes of large fishing vessels (over 24 metres long) in real time, and are thus much better able to estimate the total number of ships in operation. Fishing vessels less than 24 metres long generally do not have an AIS on board. According to the FAO, around 60,000 fishing vessels were located and identified in 2017 using AIS data. At the time only 20,000 of those were listed in publicly available registers.

However, monitoring of the fishing fleets using AIS can only work if the systems remain switched on. For example, in recent years it has been shown repeatedly that Chinese fishers have deliberately turned off the positioning systems of their ships in order to conceal their locations. In 2019, this ploy was used by as many as 800 ships to fish illegally off the coast of North Korea for Japanese flying squid *(Todarodes pacificus)*. Global Fishing Watch only managed to detect the fleet because the bright lights of the ships were visible on satellite images. For squid fishing, the ships hang bars with as many as 700 light bulbs over the water to attract the animals to the sea surface. Since 2003, the stocks of this very popular squid have declined by 70 per cent. Now, knowing the intensity with which China has been pursuing this species year in and year out, the reason for the plummeting stocks has been revealed.

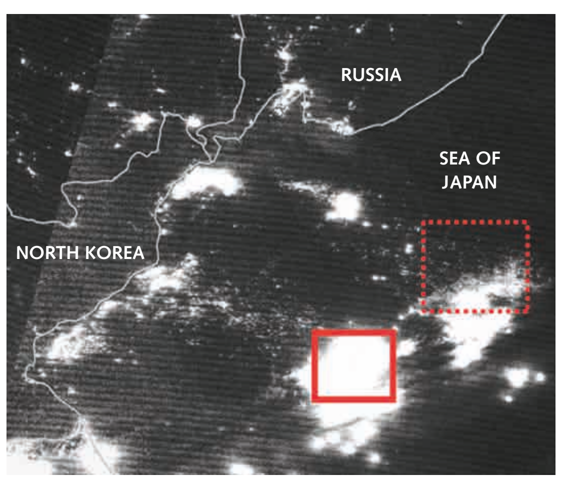
Because of these kinds of offences, an absence of transparency, neglect of its obligations as a flag state, and a number of other failures in the fight against illegal fishery, China is considered to be the world's worst-performing coastal state, followed by Taiwan, Cambodia, Russia and Vietnam. The best records are achieved by Belgium, Latvia, Estonia, Finland and Poland, all of which are European countries.

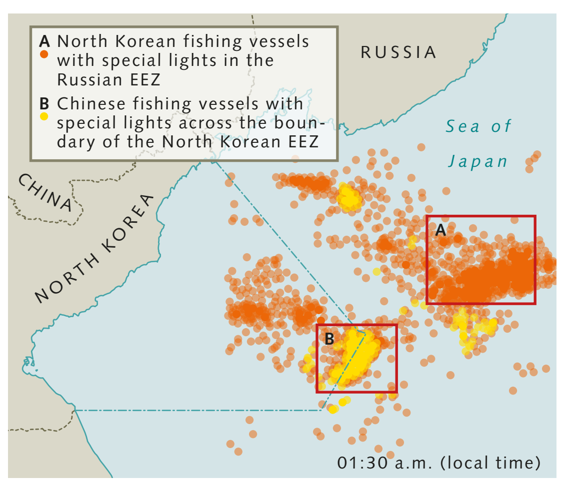
A look at the total ecosystem

Despite the negative headlines regularly received by China's fishing fleet, there is hopeful news on other fronts. For example, the FAO is seeing increasing evidence that where fish stocks are carefully monitored, and catch quotas adhered to, previously overfished populations are often capable of recovering. The Atlantic menhaden *(Brevoortia tyrannus)* of the herring family, also known as bunker, is one of these encouraging examples.

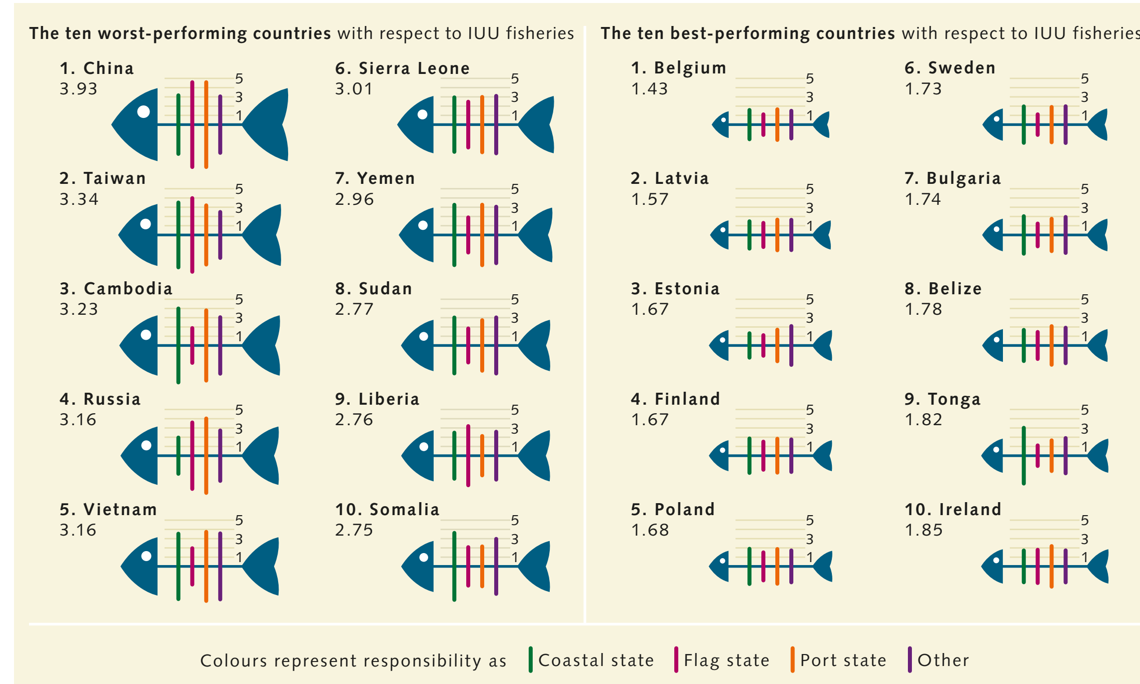
This schooling fish is known to be a key link in the food web along the Atlantic coast of North America. It is a source of food for all of the large predators. Humpback whales, dolphins and seabirds prey on it, as do some highly valued and desirable food fish such as tuna, striped bass *(Morone saxatilis)* and bluefish *(Pomatomus saltatrix)*. In addition, menhaden are fished on a large scale to be processed as fishmeal that is used as feed in agriculture or aquaculture. The species is also used as a bait fish and in the production of fish oil.

No other fish has been caught in greater numbers along the east coast of North America in a single year than this species. Until ten years ago this fishery was carried out almost completely unrestrained, which resulted in drastically reduced stocks. In order to stop the plunging trend, fisheries authorities introduced catch quotas in 2012, strictly enforced their compliance, and had the stocks monitored through an ambitious scientific support programme. Since then, the schools of herring have been growing again, which has led to a noticeable improvement in the ecosystem along the east coast of the USA that also benefits the people there. Humpback whales now regularly follow the schools of herring into New York Harbor, which is a great boost to the tourism industry because both locals and visitors want to see these marine mammals close up. And in the US state of Maine there is again sufficient bait fish for the lobster fishery.





3.15 > Bright lighting visible on satellite imagery taken on 25 September 2019 reveals the Chinese squid-fishing fleet off the coast of North Korea. Meanwhile, North Korean fishers are moving into Russian waters. Because they use fewer luring lights than the Chinese, their ships appear less brightly on the images.



3.16 > Based on 40 indicators, fisheries experts have compiled an index for all of the world's 152 coastal states that indicates the extent to which each country experiences and combats illegal and unreported fishing. The higher the index and the longer the individual fish bones are depicted in the figure, the worse the country's performance is in its response to illegal fishing.

In August 2020, the fishery authorities took a further step. Under pressure from scientists, ornithologists, fishers and environmentalists, they unanimously decided that fishing quotas should no longer consider only the size that herring stocks need to be in order to renew themselves (single-species management), but instead should be based on a multi-species management approach that also takes into account the needs of marine predators, especially the striped bass. Under the new policy, fishers are limited to catching a volume of herring that will leave the striped bass enough food to reproduce at a level for their stocks to recover. The predator fish in this case serves as the ecological reference point.

The basic idea behind this concept is to take into account the health, productivity and resilience of the entire ecosystem when determining catch quotas, including the needs of all the marine organisms that depend on a particular fish species. Scientists refer to this principle as the ecosystem approach. Unlike fisheries management concepts of the past, this approach does not focus on a single species, sector or problem. Instead, officials are encouraged to consider the many dependencies and interactions within marine communities, and to examine the ways in which human intervention is altering them. Fisheries management using the ecosystem approach is characterized by:

- a focus on conservation of the ecosystem, its structures, functions and processes;
- consideration of the relationships between desirable target species such as herring and those species that are of less or very little interest;
- recognition that the health of the seas also depends on processes on the land and in the air, and that the land, ocean and atmosphere represent a closely knit system;
- incorporation into its design of the ecological as well as social, institutional and economic perspectives, and the extent to which these influence each other;
- appreciation not only of the consequences of fisheries for the respective ecosystems, but also the consequences of all human activities, thus including climate change.

The FAO had developed recommendations for implementing this approach as early as 2003. Since then, most of the industrial countries involved in fishing as well as the majority of regional fisheries management organizations have adopted it and adapted their regional and national regulations accordingly.

But, in the opinion of many fisheries experts, there is still a lot of room for improvement with regard to its implementation. There is a need not only for political will, but also for more scientific data on all aspects of fisheries. The USA is leading the way so far, and is investing a great deal of time and money in the monitoring of their fish stocks. Experience has also proven that successful fisheries management brings all of the relevant and affected interest groups into the decision-making process. The local coastal communities must have a say, as well as business representatives, scientists, government leaders, environmentalists and representatives of other sectors that are influenced by fisheries. The success that can be achieved through this kind of cooperation at all levels is clearly illustrated by the recovery of the large schools of the Atlantic menhaden.

Deep-sea fishery
"Deep-sea fishery" generally refers to fishery on the high seas where water depths are from 200 to 2000 metres. The most common method of fishing here is with trawl nets.

More protection for the high seas

Effective protection measures by individual nations are largely limited to the coastal waters within their own Exclusive Economic Zones (EEZs). International waters, officially referred to as the high seas, begin at the outer boundaries of the EEZs. Basically, anyone is permitted to fish in this area. In recent decades a relatively small number of states have increasingly begun to take advantage of this right. This may be because of overfishing in their own coastal waters, because the demand and thus the selling price for fish have gone up, a result of technical innovations that have made high-seas fishing more practicable, or due to government subsidies of these fishing activities that have made them more profitable. The ten leading high-seas fishing nations are China, Taiwan, Japan, Indonesia, Spain, South Korea, the USA, Russia, Portugal and Vanuatu.

However, only since the introduction of automatic ship information and monitoring systems has it been possible to identify the marine areas in which the fleets are casting their nets. In a global analysis of high-seas fisheries in 2016, scientists were able to track the routes of at least 3620 fishing vessels, 35 tankers and 154 reefer vessels. Far more than three-quarters of them came from China, Taiwan, Japan, Spain and South Korea. The fishing operations covered an area of 132 million square kilometres and thus involved around half of the total area of the high seas. Ships outfitted for catching squid operated intensively near the boundaries of the territorial waters of Peru, Argentina and Japan. Deep-sea fishing, on the other hand, concentrated on the regions around Georges Bank in the northwest Atlantic, areas of the northeast Atlantic, and to a smaller degree in the central and western Pacific. The monitored ships spent an average of 141 days at sea before sailing back into a port.

It is difficult to quantify the amount of damage being inflicted by the increasing fishing pressure in international waters. One reason for this is that there are no reliable stock and reproduction statistics for many species, especially for exclusively deep-sea species. Another is that it is not clear how many fish the deep-sea fleets actually catch in many areas. In 2018, according to the estimates of Sea Around Us, three per cent of the global catches came from deep-sea areas.

To help curtail overfishing in various international waters and avoid resource conflicts, many nations have now established regional fisheries management organisations (RFMOs). These institutions develop collective rules and regulations for fisheries in their respective areas and are responsible for their implementation. The FAO therefore grants them a deciding role in the protection and management of natural stocks, primarily because it is the responsibility of the RFMOs to decide whether or not to adopt the voluntary FAO guidelines or recommendations for action in the particular RFMO area. Whether the individual RFMOs actually fulfil the roles of stock guardian and protector prescribed to them cannot be determined with certainty. Although reviews and surveys of the organizations are now regularly carried out and the results published, a current evaluation procedure for all RFMOs based on scientific standards does not exist.

3.17 > Fishers in the Vietnamese province of Phú Yên cast a net around a school of anchovies. This coastal region is known for its anchovy fishery. The countless millions of the schooling fish that they catch are mostly processed into fish sauce.

When experts from Pew Charitable Trusts reviewed the work of three regional fisheries management organizations in 2019, they came to the conclusion that, among other things, all three bodies

- had implemented too few of the international guidelines, especially those that were aimed at putting an end to overfishing and at the recovery of stocks,
- required too much time to introduce new, modern management strategies and
- failed in the task of building a consensus among their member states on key issues of fisheries management.

Critics of industrial deep-sea fishing therefore doubt that stocks on the high seas can be effectively protected as long as economic and, in part, strategic interests are of uppermost importance, and as long as some states subsidize their deep-sea fleets with more than USD 13 billion per year. Subsidies are defined as direct or indirect financial contributions, mostly from government institutions, that result in lower fishing costs, more catches or a higher profit margin. These include, among others:

- contributions for the construction of new ships or the repair of vessels already in operation,
- government financing for the construction of new fishing harbours or technical improvements to existing facilities,
- tax relief for fishing businesses,
- fishery development programmes and
- fuel-price reductions.

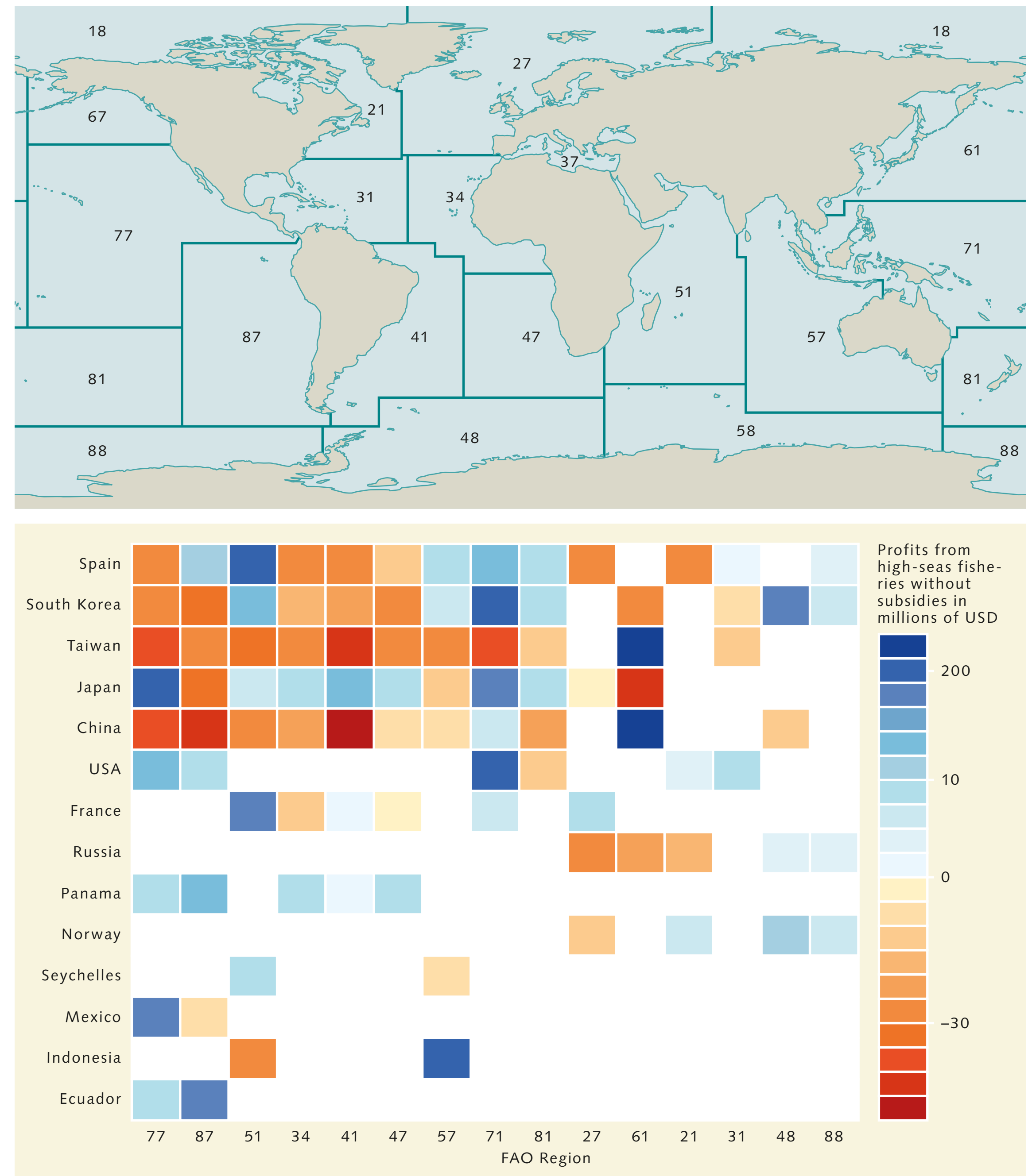
Unless subsidies are tied to strict guidelines, they usually result in fishers fishing for longer periods of time, more intensively, and further from their home port. Subsidies for fisheries around the world (coastal and deep-sea) are estimated to total between USD 14 and 35 billion. This would mean that more than one-third of the costs of fisheries (35 per cent) is financed by taxpayers.

In 2016, for example, an analysis of global deep-sea fishing revealed that without government financial support, fishing in more than half of the high-seas areas being targeted would not have been economically feasible. This means that without subsidies many concerted activities that create excessive fishing pressure would not even be happening. This is especially true for trawler fishing in the deep sea and for a large proportion of the squid capture in international waters. Still the governments pay, albeit in differing measure. The deep-sea fisheries of Japan are most heavily subsidized, followed by Spain, China, South Korea and the USA. Amazingly, for all five of these countries, the total contributions by far exceed the total income from deep-sea fisheries. The only really profitable targets on the high seas, according to calculations by scientists, are the high-priced predators such as sharks and tuna.

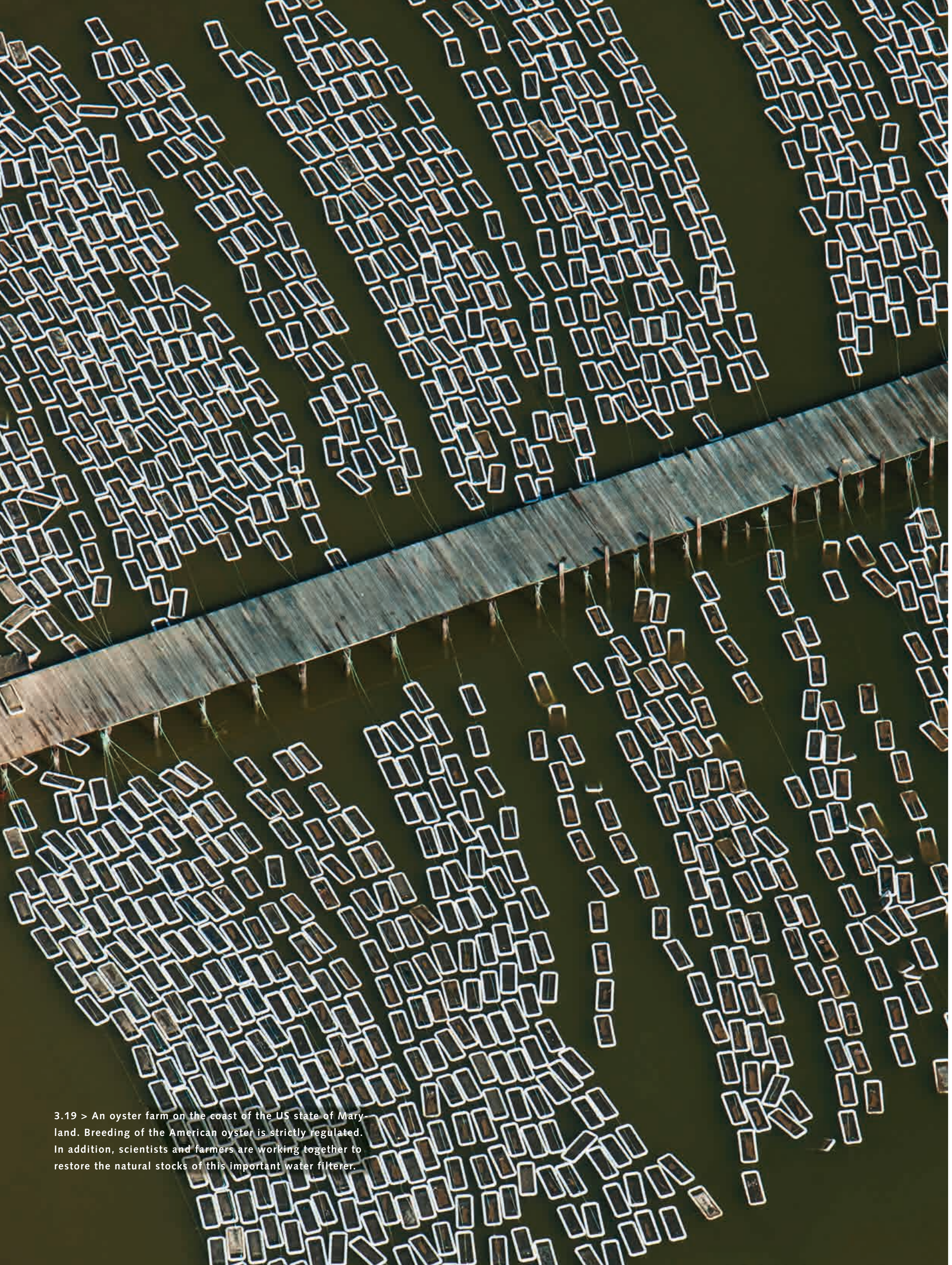
If scientific calculations show that fishing on the high seas is not profitable, why do countries continue to do it? The researchers believe that the businesses actually do make a profit in the end, for example, by catching and selling more fish than they report to the authorities. In addition, costs can be reduced by transferring the catches to reefer ships while still at sea, which prolongs the period of time that the fishing vessel can continuously remain at sea. Another possibility is that the ship's crew is either poorly paid, or not paid at all.

Countries like China and Russia also use deep-sea fishing to pursue foreign policy interests. This is exemplified by the fishing operations of these two nations in Antarctic waters. Claiming the rights to resources in the Southern Ocean and showing a presence there is more important than the question of whether the fishing is economically profitable. And finally, it is probably also worthwhile to fish sporadically in regions that have not been fished or only sparsely fished in the past.

Here again, a negative example is provided by Chinese fishers, who cast their nets and lines on a massive scale near the boundaries of the marine protected area of the Galapagos Islands during tuna season. In the summer of 2020, 243 Chinese vessels cruised through the ecologically sensitive region, more than in any year previously. Beside vessels suspected of illegal fishing, the fleet also included reefer ships for transferring the catches on the high seas. The native Ecuadorian fishers could only watch



3.18 > Deep-sea fishing would be an unprofitable business in many parts of the world if the fishery nations did not subsidize their fleets with an estimated USD 4.2 billion per year (value for the year 2014). This sum is around twice as much as the profits that the deep-sea fisheries would generate without government aid. The profitability of fisheries on the high seas depends on the individual states, the region of operations, the targeted species and the distance from ports. As the figure illustrates, primarily the South Korean, Taiwanese, Chinese and Russian fisheries would suffer significant losses without government support.



3.19 > An oyster farm on the coast of the US state of Maryland. Breeding of the American oyster is strictly regulated. In addition, scientists and farmers are working together to restore the natural stocks of this important water filterer.

helplessly as the biosphere was plundered. They themselves have fishing inspectors on their ships who monitor the catches and ensure that rare species are protected. The Chinese fleet, however, operates outside of the international public eye.

In 2017, when the Ecuadorian coast guard stopped a Chinese reefer ship inside the marine protected area and opened its container, the soldiers discovered around 6000 deep-frozen sharks, including endangered species such as hammerheads and whale sharks. Cases like these highlight the need for clear political commitment from all parties involved and effective implementation of and compliance with all directives and agreements. Without these, the promises of protection for the ecosystems of the high seas will be no more than empty words.

Is abstinence the only solution?

Critics of industrial fisheries are therefore appealing for a global shift in consumer attitudes. Marine conservation organizations argue that every thoughtless seafood meal contributes to a sell-out of the oceans. Like meat, wild-caught marine fish should be viewed as an exceptional delicacy in industrialized nations such as Germany, and only occasionally served. And when it is, it should come from sustainable, regional coastal fisheries. Fish that are transported around the world before being consumed, according to their rationale, do little to contribute to a sustainable way of life.

For the populations in poorer countries and on Pacific islands, on the other hand, fish is a necessary dietary staple. Because there are few inexpensive alternatives, these people are very dependent on fish as a source of protein. For the world's oceans to provide sufficient food in the future for the Earth's growing population, fish resources must be fairly distributed. A crucial aspect of this will have to be less fish and seafood consumption for those who can afford and have access to alternatives. Furthermore, according to the FAO, 35 per cent of the production of fisheries is still going to waste either because refrigeration-chain and hygiene regulations are not observed, buyers are not found for some products, or the buyers do not eat their purchases. The waste percentage is particularly high in North America and Oceania, where around half of the fish caught are ultimately not consumed.

Other voices advocate for designating at least 30 per cent of all marine space as protected areas, and for prohibiting direct human intervention of any kind in these regions, in order to offer a refuge for marine biological communities. There is a long list of convincing arguments for such measures. In marine protected areas there is a very good chance of recovery for previously heavily fished stocks. Biodiversity is generally high or even increases after protection status is declared. Moreover, many species reproduce more successfully because sexually mature animals are not caught, or spawning sites on the seafloor are not destroyed by bottom trawling. Marine protected areas, sometimes referred to as kindergartens or seed banks, also contribute to the recolonization of adjacent marine regions and the more rapid recovery of endemic stocks there.

Furthermore, the biological communities in marine protected areas exhibit a greater resistance to the impacts of climate change, which is why many environmentalists and scientists see this strategy as the best solution.

The fish trade, in turn, relies on products from certified, sustainable fisheries – for example, those that meet the criteria and have been certified by the Marine Stewardship Council (MSC). In the past 20 years the MSC has awarded its blue sustainability seal to around 300 fisheries. It is the only internationally recognized certificate for sustainable wild-fish capture, although many individual countries also have their own national certification and inspection procedures for sustainable fishery products. In Germany, for example, these include Naturland Wildfisch, Followfish and Dolphin Safe.

Catches from MSC-certified fisheries, or those that are under MSC review, now make up 15 per cent of the official worldwide landings. The growing number of certified fisheries highlights the customers' and retailers' wish for sustainably produced products, and promises success in convincing the fisheries to improve their fishing operations and to have these efforts confirmed by a label.

Many of the certified fisheries were forced to make adjustments on behalf of marine conservation before they

3.20 > The snow crab is one of the most important target species of Japan's fisheries. Scientists therefore monitor its stocks by means of annual research catches and related stock modelling.

were able receive the label. For the most part, the changes were aimed at reducing direct consequential damages to the marine habitat by the fishery. Independent evaluations by experts have shown that MSC-certified fish stocks not only exhibit a larger biomass, but that the stocks also grew after certification.

However, experts advise caution in interpreting this positive trend as evidence of an overall improvement in worldwide fishery practices. An MSC certification is not an all-purpose, end-all weapon in the fight against overfishing. For one thing, the effort and costs required by the process are so great that smaller fisheries are often unable to afford them. For another, environmentalists feel that the MSC regulations actually do not go far enough. Until recently, for example, certified fisheries were permitted to employ sustainable techniques on the same fishing trip with more traditional, destructive fishing techniques, such as bottom trawls, without losing their certification. Environmentalists have also accused the MSC of ignoring evidence that the certified companies are involved in the shark-fin trade or, in violation of MSC regulations, that they surround schools of dolphins in order to capture the tuna hunted by the marine mammals. Such operations generally result in the death of a large number of dolphins.

In order to prevent these practices in the future, a consortium of environmental organizations has submitted a list of 16 core demands to the MSC, with the hope that these will be considered in the current revisions of the MSC regulations. These include, among others, the need to ensure that

- the overall ecological footprint of the fishery activities of a certified company is assessed, including the non-certified portions;
- the fishers are no longer permitted to employ non-certified fishing techniques, for example, those that would lead to unnecessary bycatch;
- all fish species caught, including those in the bycatch, are subject to sustainability criteria and overfishing is prohibited;
- MSC-certified operators are no longer permitted to employ bottom trawls in marine regions with highly sensitive biological communities.

It remains to be seen whether the MSC will consider these recommendations.

In coastal regions where fishing is only practised by artisanal fishermen and -women, involving the local stakeholders in management decisions and giving them the responsibility for implementation and monitoring of the mutually agreed rules has paid off in many places. This stewardship or co-management process relies on the fishers to manage the resources in a sustainable way, because they have the exclusive right of use and thus a strong personal interest in protecting the marine ecosystem.

But such community-based, cooperative management approaches only function effectively where the number of participating stakeholders is small, where there is a high degree of collective unity, where all participants pursue the same interests and where the individual rights of use may not be sold to outside investors. Yet even if these conditions are met there is still a need for state oversight. Any policy solutions must also be tailored to the local conditions. Experience has shown that attempts to apply the same management strategies everywhere are likely to fail.

In its fisheries report published in 2020, the FAO emphasised that, in view of the increasing number of overfished stocks, the goal of putting an end to overfishing in the oceans by 2020 has not been met. The international community is therefore called upon to:

- show a stronger political will, especially at the national level;
- invest in improvements in fisheries management;
- promote the transfer of technology and knowledge, especially with regard to science-based fisheries management;
- limit fishing activities to levels that do not endanger the reproduction of fish stocks;
- influence the purchasing behaviour of consumers through information campaigns or effective marketing; and
- develop global fishery and marine monitoring systems, and make all of the data available to the public in a timely and transparent way.

According to the FAO, developments in recent decades have proven that fishing pressure has been most successfully reduced in marine regions where regulations have been implemented and compliance monitored. In Argentina, Chile and Peru, for example, the proportion of overfished stocks sank from 75 per cent in the year 2000 to 45 per cent in 2011. Today, in the USA, there are only half as many overfished stocks as there were in the year 1997.

Other examples of success have been realized in the waters of Iceland and Norway, by the crab-diver fishery of Chile, which has become limited to artisanal fishers, in the waters of the coral triangle, and in the waters of Japan where the formerly overfished populations of the snow crab *(Chionoecetes opilio)* have recovered.

But in areas without a functioning fisheries management plan, according to the FAO, the situation for fish stocks is dire. Around three times more fish are caught in these areas than in intensively monitored regions of the sea. In addition, the stocks are often only half as large, and are generally in very poor condition. For this reason, the degree of success that sustainable fisheries management is now bringing for a number of countries has not been sufficient to halt the general worldwide decline of marine fish stocks. It is thus essential to learn globally from one another, share knowledge of successful and effective fisheries management strategies, select approaches that take local conditions into account, and implement them in close cooperation with the local populations.

3.21 > With bottom-trawl fishing in the deep sea it is hard to predict which species will end up in the net. Here is a small selection of animals that were brought up in survey catches by New Zealand scientists at 1200 metres depth.

Aquaculture – a growth sector

> Almost half of all fishery products consumed worldwide now come from aquaculture, whereby only one in three fish or crustaceans grew up in the sea. The remainder was farmed in freshwater aquaculture facilities. Experts nonetheless predict a bright future for food production at sea, provided that it will be possible to implement sustainability strategies and reduce the environmental footprint of pond and cage aquaculture. There are many ideas as to how this could be achieved.

Food from ponds and cages

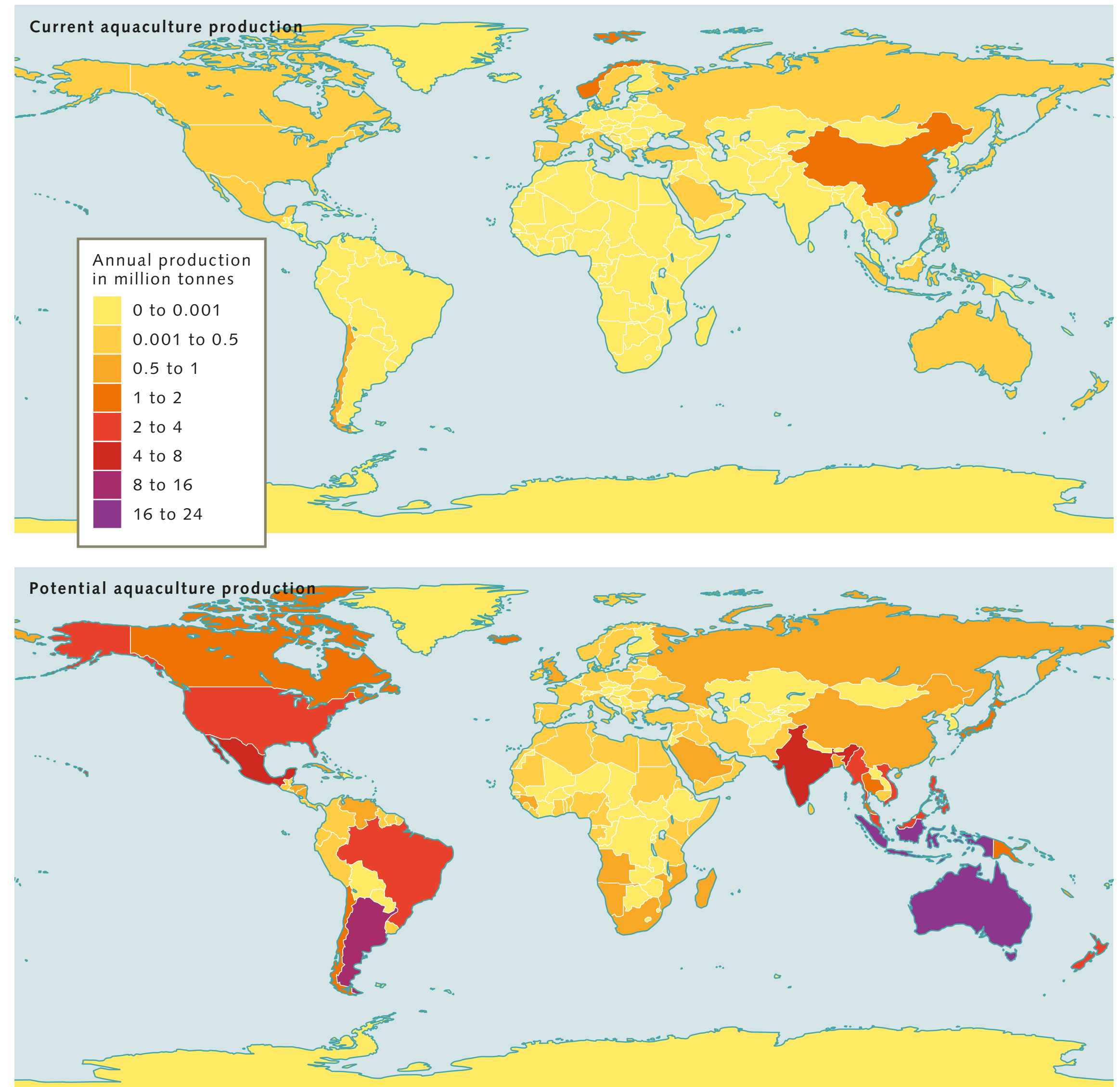
The importance of aquaculture has increased massively over the past 20 years. In 2000, just a quarter of all fishery products came from aquaculture facilities; today it is almost half. This makes aquaculture the fastest growing food production sector. In 2018, according to the FAO, 114.5 million tonnes of fish, seaweed and seafood with a market value of USD 263.6 billion were produced in aquaculture systems around the world – more than ever before. Aquatic animals accounted for 82.1 million tonnes; seaweed production totalled 32.4 million tonnes.

Roughly two thirds of the fish, crabs, mussels and other aquatic organisms farmed worldwide came from lakes, ponds or land-based freshwater aquaculture facilities. Coastal and marine aquaculture, which includes saltwater ponds along the coast and cages in coastal waters, produced a total of 30.8 million tonnes of animals in 2018. The majority of these were mussels (56.2 per cent; 17.3 million tonnes). The total amount of finfish farmed at sea was 7.3 million tonnes, while crustacean production totalled 5.7 million tonnes.

Increases of this magnitude have raised hopes worldwide that fish farming and seafood cultivation in aquaculture systems could be a solution to the problem of ensuring a continued supply of sufficient quantities of animal protein to a growing world population – and at a significantly lower resource use and lower greenhouse gas emissions than terrestrial livestock farming. Unlike pigs, cattle or goats, fish do not use energy to generate body heat. Instead, a large part of the calories ingested through feed is channelled directly into growth, which is why it is possible to produce significantly more fish meat than beef, pork or goat meat with the same feed input.

According to optimistic calculations, less than 0.015 per cent of the oceans' surface area could produce as much fish in aquaculture as the currently landed wild catch. If, for the moment, we disregard areas of conservation concern such as coral reefs as well as possible social, environmental and economic concerns, fish farming would theoretically be feasible on more than 11.4 million square kilometres of ocean; mussels could be grown on more than 1.5 million square kilometres, biologists specializing in aquaculture argue. If all this area were actually used, it would be possible to produce an estimated 15 billion tonnes of fish per year – almost 100 times more than the amount of fish and seafood people currently consume annually.

Other scientists, however, are sceptical of both the rates of increase and the growth potential of aquaculture. In their view, the increases to date in the FAO aquaculture statistics come mainly from domestic fish farming in China, whose figures are considered highly questionable and represent provincial planning targets rather than actual production. If the statistics were adjusted, they argue, it would be evident that marine aquaculture had reached its zenith and freshwater aquaculture was hardly growing at all. In order to be able to use fish and seafood sustainably as a source of protein for many people in the future, the primary goal should rather be to manage marine fisheries in a long-term sustainable manner. Instead, however, so these scientists note, misinformed politicians are focusing on aquaculture expansion, which in certain areas is actually detrimental to food security. For example, wild-caught edible fish such as anchovy, sprat, herring or mackerel are largely not consumed directly, but are processed into fish feed for salmon and other predatory farmed fish. The mass of wild-caught fish input is greater by far than the mass of fish output sold for human consumption, the critics say.



3.22 > Aquaculture fish farming is a business with growth potential, as this comparison shows. If all the world's coastal countries utilized one per cent of their suitable coastal waters for sustainable fish farming, production volumes would multiply in most countries, with the exception of China and Norway, both of which already produce more farmed fish at sea, which indicates either intensive aquaculture methods or a greater utilized ocean area.

Proponents of aquaculture counter that criticism of adverse aquaculture practices is justified and important. It should not however result in positive projects being discredited and policy-makers becoming overly cautious of new aquaculture approaches. In overfished regions such as the Baltic Sea, sustainable aquaculture could help to improve the situation of both fishers and wild stocks in the long term.

But it is also a fact that less than a third of the farmed fish and aquatic invertebrates are now raised without supplementary feed. This means that their share has dropped significantly over the past 20 years, although the total mass of animals reared without supplementary feed has increased to 25 million tonnes. At the turn of the millennium, 43.9 per cent of all farmed aquatic animals were raised without supplementary feed. Their share has now dropped to 30.5 per cent, the majority of which are mussels, which filter feed from seawater or brackish water.

3.23 > Seaweed farmers in the Solomon Islands bring freshly harvested macroalgae ashore. The cultivation of plants in the sea is hard physical work and for many coastal inhabitants it is their only source of income.

The farming of fish, mussels and crustaceans in marine aquaculture facilities or coastal saltwater ponds is now practised around the globe. The three largest marine fish producers are China, Norway and Indonesia. Together, they produced more finfish (3.8 million tonnes) in 2018 than the entire rest of the world (3.6 million tonnes). Marine crab and crustacean farming is dominated by China, Indonesia and Vietnam. Marine shellfish farming however is almost exclusively in Chinese hands. The People's Republic produced approximately 14.4 million tonnes of marine shellfish in 2018, almost seven times more than the rest of the world combined.

The future belongs to macroalgae

China is also the leading producer of macroalgae and seaweeds, the global harvest of which has almost tripled in the past 20 years. Seaweed farming is thus the fastest growing aquaculture sector. In 2000, 10.6 million tonnes of macroalgae and seaweed were harvested. By the reporting year 2018, seaweed farmers, mainly based in East and South East Asia, were already producing as much as 32.4 million tonnes. More than 85 per cent of this production originated in China and Indonesia alone.

Two of the seaweed farmers' best-sellers are the tropical seaweed species *Kappaphycus alvarezii* and *Eucheuma spp.*, from which carrageenan is extracted, a thermally stable gelling and thickening agent used in the food and cosmetics industries, for example in the production of vegetarian bread spreads. In the European Union, it is authorized as a food additive and thickener under the food additive number E 407. Other farmed aquatic macroalgae, such as the Japanese brown algae *Laminaria japonica* or the kelp species wakame *(Undaria pinnatifida)*, are sold directly as food and served in Asian cuisine, for example as an ingredient in soups. Production residues or low-quality algae are usually not disposed of, but used as a feed in mussel farming, among other things – an important step on the way to closed nutrient cycles and greater sustainability.

Since macroalgae and seaweeds are very rich in nutrients and do not require fertilizers or feeds that could pollute coastal waters, their cultivation is considered an environmentally friendly method of food production. For this reason, producers in other regions of the world are now also showing interest in seaweed farming. However, in order to reduce the food sector's ecological footprint, large-scale algae production would have to undergo a massive level of expansion. Scientists have calculated such a scenario: If humanity were to pursue the goal of producing only one per cent of all food from algae, 147 times more algae would have to be grown for human consumption than is currently the case.

Similar or even greater quantities would be needed if macroalgae were put to additional uses. For example, there are discussions as to the conditions required for the production of bioethanol and biomethane from red and brown algae. Both products could potentially replace fossil resources. Moreover, some of the algae contain Omega-3 fatty acids and could therefore be used as fishmeal or fish oil substitutes in aquaculture facilities. Studies in ruminant livestock husbandry have shown that macroalgae fed to cattle reduce their methane emissions. And when applied to the land as fertilizer, they increase the soil's nutrient levels.

Even more frequently, however, algae cultivation is now being discussed with regard to the creation of natural long-term sinks for large quantities of atmospheric carbon dioxide. The world's naturally occurring macroalgae forests (also called kelp forests) sequester about 1.5 billion tonnes of carbon per year through photosynthesis. Just over one tenth of this, an estimated 173 million tonnes, is stored locally in the sea floor or transported to the deep sea and thus removed from the Earth's carbon cycle. In this way, the kelp forests make an important contribution to reducing the carbon dioxide concentration in ocean waters and in the atmosphere.

The climate mitigation potential of the algae farmed in aquaculture systems so far is rather low in comparison. For example, if all the farmed macroalgae harvested in 2014 (total quantity: 27.3 million tonnes) had not been processed but instead disposed of in the deep sea, only 0.68 million tonnes of carbon would have been removed from the system, i.e. only 0.4 per cent of the natural kelp forests' carbon sequestration service. On the other hand, a study by US scientists found that 48 million square kilometres of the ocean is suitable for the industrial cultivation of macroalgae. This corresponds to about five times the area of the USA. According to the researchers, using these waters fully for seaweed cultivation would probably fail due to the effort and costs involved. At a regional level, however, the cultivation of macroalgae can make perfect sense as a means of carbon sequestration and storage, especially since the macroalgae also contribute to lowering the water's pH value and increasing its oxygen content during their growth, as long as the algae do not die off and become decomposed by microorganisms.

However, in the long term more intensive seaweed farming alone will not be enough to stop global warming. While the world's kelp forests remove roughly 173 million tonnes of carbon from the Earth's climate system every year, humans added around ten billion tonnes by burning coal, oil and gas in 2019 alone. The kelp forests would need around 60 years to absorb and store this much CO_2. Nevertheless, it is important to make better use of the

3.24 > Giant kelp *(Macrocystis pyrifera)* forms dense kelp forests off the Pacific coast of North America. The brown algae grow to a length of up to 45 metres, making it the world's largest bottom-anchored marine organism.

enormous potential of seaweed cultivation. Appropriately planned and implemented, large-scale seaweed cultivation could help protect the climate, improve food security, open up new sustainable sources of raw materials and improve conditions for marine organisms.

The dark side of aquaculture

Fishmeal and fish oil
Fishmeal is a protein-containing, flour-like product that is produced by drying and then finely grinding whole fish or fish offal. In contrast, for the production of fish oil, cooked fish is pressed and the emerging liquid is separated into different components.

The expansion and intensification of aquaculture in coastal waters poses a number of threats to marine ecosystems, especially when it comes to animal-based aquaculture. In South East Asia, for example, around 100,000 hectares of valuable mangrove forests were cleared between 2000 and 2012. Almost one third of the forest had to give way to the creation of coastal shrimp aquaculture ponds. In Indonesia, the proportion of mangroves cleared for aquaculture was almost 50 per cent. In the same regions, many stretches of coastline had already been transformed in the 1990s with a view to the expansion of shrimp farming, which brings in foreign currency. As a result, wild-caught tropical shrimp declined, and local coastal fishermen landed less fish because the mangrove forests – the natural nursery grounds for juvenile shrimp and fish – were gone.

Furthermore, the significant area lost to coastal aquaculture is only one problem of many. The feed used in such facilities still partly consists of fishmeal and fish oil. For its production, small schooling fish such as the Peruvian anchoveta *(Engraulis ringens)* or the Atlantic herring *(Clupea harengus)* are overfished worldwide. According to the FAO, approximately 18 million tonnes of fish caught were processed into animal feed in 2018. This quantity is far lower than the peak of more than 30 million tonnes used in 1994, but also well above the low of 2014 (14 million tonnes). Critics of this practice have calculated that currently roughly 25 per cent of the schooling fish caught are processed into fishmeal or fish oil. In this way, fish that in many parts of the world are consumed especially by the poorer population are transformed into fishery products such as salmon fillets, which ultimately only the better-off in society can afford, say the critics. In their view, farmed salmon, seabass, etc. can only contribute to solving the global food problem if substitutes for fishmeal and fish oil are cheaper and used more extensively by farmers.

Excess feed in marine aquaculture installations not only pollutes fjords and coastal waters but downright over-fertilizes them. In many places this can lead to increased algal growth and also to the development of oxygen-deficient zones. For a long time, fish and shrimp farmers around the world also made unregulated use of antibiotics in order to contain diseases in the much too dense animal populations. In the shrimp ponds of South East Asia, among other regions, this resulted in the development of pathogens resistant to antimicrobials and ultimately led to several waves of severe outbreaks that destroyed large parts of the Asian shrimp production, especially stocks of the high-yielding giant tiger prawn *(Penaeus monodon)*, also known as black tiger shrimp.

Much research has been done to curb the disease outbreaks. Instead of the giant tiger prawn, whiteleg shrimp *(Litopenaeus vannamei)* now predominate in South East Asian breeding ponds. Moreover, attempts to breed disease-resistant shrimp were successful, so that the use of medication has been greatly reduced. Many Norwegian salmon cages are now also home to a significant number of lumpfish. The small, greenish iridescent fish are used as cleaner fish because they prey on a parasite of salmon that occurs naturally in Norway's fjords – known as salmon louse *(Lepeophtheirus salmonis)*. This copepod attaches itself to the skin of the farmed fish and causes wounds that can be fatal to the salmon. But the lumpfish eat the parasites before they can do any great damage, thus eliminating the need for medication or expensive pest control. This benefits not only the salmon and the fish farm operators, but also the environment.

However, the only way to prevent "faunal mixing" as a result of improper aquaculture management would appear to be targeted bans on fish farming. For example, in December 2019, after a fire in an aquaculture installation off the coast of Vancouver Island, thousands of Atlantic salmon escaped into the surrounding sea, which is home to wild Pacific salmon. Marine conservationists and environmentalists now fear that the former caged animals may transmit diseases, viruses and parasites to the native

3.25 > For a long time, the giant tiger prawn *(Penaeus monodon)*, also known as black tiger shrimp, was the most widely cultured prawn species in the world. It has now dropped to fourth place. Nonetheless, a total of 750,000 tonnes of this species was produced in 2018.

Pacific salmon, with which these wild stocks cannot cope. And there is also the risk that the two species will mate and produce offspring. Researchers speak of "genetic pollution" in such cases.

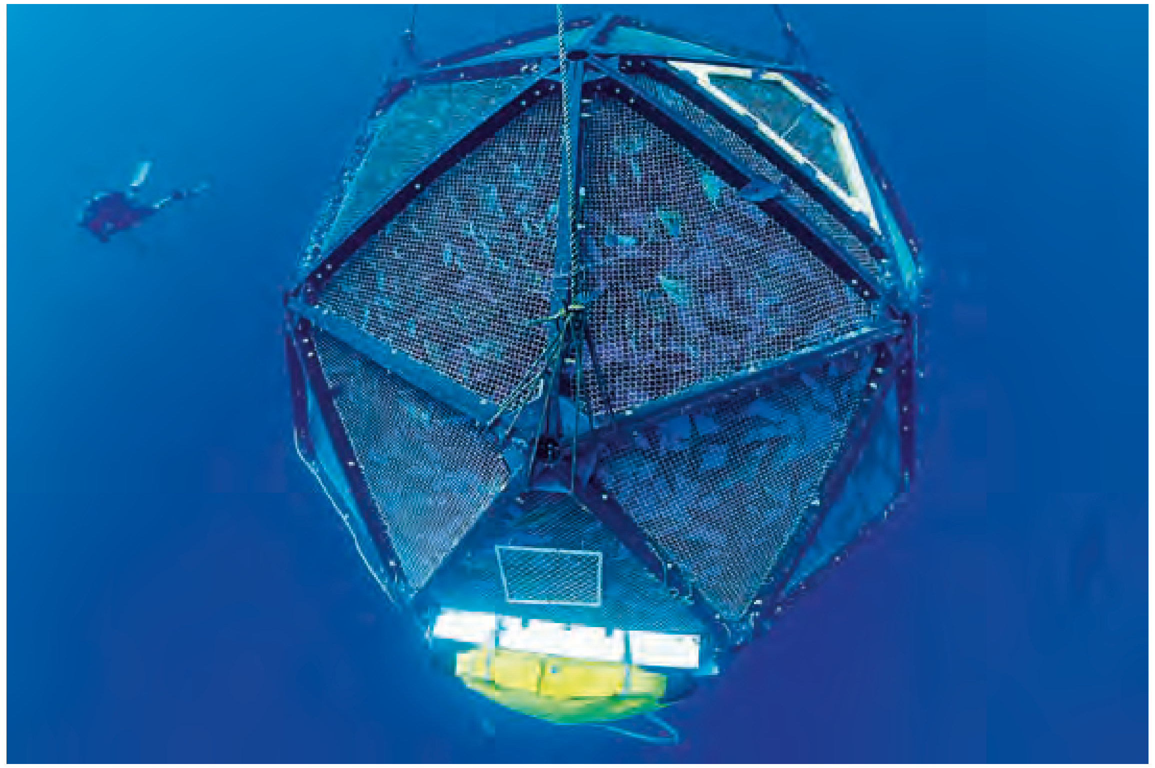
Parasites introduced through aquaculture may multiply abruptly under certain circumstances and, in the worst case, impact food webs and entire ecosystems in the facilities' wider vicinity. In polluted coastal waters there is also an increased risk of new pathogens emerging that may also be dangerous to humans, for example pathogens that cause diarrheal diseases. This risk is elevated especially in the coastal regions of India, Bangladesh and Myanmar. Despite the high population density, these regions are also home to intensive aquaculture facilities and the annually recurring monsoon rains ensure regular flooding, in the course of which pathogens can spread quickly and come into contact with people.

If one considers against this background the call for the growing global demand for fishery products to be met primarily by means of an expansion of aquaculture, it is obvious that new, efficient and, above all, resource-conserving strategies for food production at sea are needed. Hope is offered by approaches that focus on the entire ecosystem, both in aquaculture and in fisheries.

Progress and innovation in aquaculture

The severe ecological consequences of intensive marine and coastal aquaculture (especially when it comes to fed production systems) have prompted science and industry to search for new, more environmentally friendly methods and technologies. Notable progress has been made in several areas, such as in species selection, feed composition and the development of integrated circular systems.

More than 600 species of fish, crustaceans and mussels are currently farmed in aquaculture systems around the world. A notable positive development is the fact that increasingly native species are farmed in the respective regions. In Europe, for example, these are sea bass



3.26 > Free-floating or anchored fish cages with remote-controlled feeding units, as tested here off the coast of Hawaii, could offer the opportunity to shift fish farming out to the open sea and reduce aquaculture's ecological footprint in coastal waters.

List of current most popular alternative ingredients to replace fishmeal/fish oil

Category	Pros	Cons	Solutions and opportunities
Terrestrial plant-based ingredients, including crop by-products (e.g. rapeseed, wheat flour, soybean meal)	Easily accessible and can be produced in large quantities; economically competitive	Presence of anti-nutritional factors; low digestibility; poor palatability; imbalanced amino acid profile; do not contain nutritional benefits of omega-3 fatty acids	Apply more advanced processing technology or enzymatic treatment to enhance nutritional quality; add attractants or palatants; can be modified via advanced genetics techniques to have long-chain fatty acids
Terrestrial animal by-products (e.g. poultry meal, feather meal, blood meal)	Readily available; economically competitive; free from anti-nutritional compounds	Nutritional quality largely depends on processing technology; high in saturated fats and less healthy fatty acids; must be blended with polyunsaturated fats; use limited by regulations related to perceived disease risk; do not contain nutritional benefits of Omega-3 fatty acids	More advanced processing technology; supplementation of essential amino acids; increase awareness and improve consumer perception
Seafood and aquaculture processing waste (e.g. fish head or bones)	Potential availability is substantial due to the large amount of processing waste (30 to 70% of fish volume)	Nutritional limitations; need for infrastructure; costly to transport; risk of contaminants	More advanced processing technology
Microbial ingredients (e.g. bacteria, microalgae and yeast)	Compatible nutritional profile; some (but not all) have significantly lower greenhouse gas emission intensities than land-based alternatives	Limited nutrient bioavailability due to rigid cell walls; high production cost	More advanced processing technology; scale to bring down the cost
Under- and unexploited fishery resources (e.g. zooplankton, krill and mesopelagic species)	Large biomass potential; not used for direct human consumption	Exploitation could have significant ecosystem impacts; difficult to assess stock size and dynamics; technological innovations needed for increased exploitation and exploration	Improve stock assessments to increase understanding of stock composition and exploitation potential; ecommend precautionary approach
Genetically modified (GM) plant ingredients	Disease/pest resistance; higher nutritional quality; longer shelf life; free from anti-nutritional factors; cost competitive	Regulatory limitation; mixed positive and negative effects on nutrient balance and growth; negative consumer or producer attitudes	Get adopted by legislation; enhance consumer awareness; further study to understand anti-nutritional aspects of GM ingredients and possible expression of transgenic DNA in fish
Insects (e.g. black soldier flies, silkworm, termites)	Rich protein content; favourable lipid profiles; readily produced	Presence of indigestible chitin in exo-skeleton; bioaccumulation of pesticides; low amount of polyunsaturated fatty acids in terrestrial insects; need to scale	Technological improvements to enhance mass production; improve understanding of the effect of insect meal on fish health; increase awareness and improve consumer perception

(Dicentrarchus labrax), gilt-head bream *(Sparus aurata)* and turbot *(Scophthalmus maximus).* All three species are being produced in increasing quantities. In the tropics, the same is true for species such as barramundi *(Lates calcarifer)* and groupers (Serranidae) as well as for *Rachycentron canadum* – a spiny relative of the mackerel – known as cobia, black kingfish or black bonito. Both cobia and groupers like warm water. Both species grow quickly and are very well suited for aquaculture production. Moreover, their meat quality is very good, so producers are hoping for high production volumes and good sales prospects.

Intensive aquaculture research and rising world market prices for fishmeal and fish oil have resulted in a significant reduction in the proportion at which these components have been added to aquaculture feeds over the past two decades. In the past, feed for predatory fish such as salmon or sea bass consisted mainly of animal products. Nowadays grains, oilseed crops or legumes substitute these animal products to such a degree that the proportion of fishmeal in feeds for trout and salmon, for example, has fallen to ten per cent or less. This proportion could be further reduced if it were possible to cost-effectively produce microalgae in such large quantities that they could replace fish oil. Similar to fish oil, microalgae contain omega-3 fatty acids, which are indispensable for fish health and are one of the reasons why fish is so nutritious for humans.

When asked how freshwater consumption can be reduced in circular land-based systems, aquaculture researchers have taken their cues from aquariums for ornamental fish and developed purification systems that filter out and convert the excreta of the fish. In this way, it is possible to produce one kilogram of fish with less than 100 litres of fresh water. For comparison: in conventional pond or flow-through processes, 2000 to 200,000 litres of water were needed up to now to produce the same quantity of fish. Scientists have also developed water treatment systems and management instructions that can reduce the adverse impacts on the water used in these widely employed conventional systems.

The model of a closed nutrient cycle was the inspiration for the development of new Integrated Multi-Trophic Aquaculture (IMTA) systems, in which selected species from different levels of the food web are kept in such a way that the excreta of one species serve as fertilizer or feed for the next species and are used as effectively as possible by the latter. An example would be a facility where fish are kept alongside mussels, macroalgae and crustaceans. Feed is only used at the start of the chain, in the form of fish food. The fish faeces are then filtered out of the water by the mussels and algae which utilize them as a source of nutrients. Meanwhile, the crustaceans on the sea floor consume what is left over from the production of fish and mussels and sinks to the bottom.

The advantages of such systems are obvious: While surplus nutrients are prevented from entering coastal seas as a result of the facilities' operation, the operators' economic risk is also reduced as the parallel production of different species within a single system reduces the production costs per species. Moreover, the producers can market a wider range of products which makes them more resilient to short-term fluctuations in demand and prices. Taking into account the customers' increasing awareness of sustainably produced foods, it is likely that fishery products from integrated aquaculture facilities will be purchased more often than products from less sustainable production and that the operation of such facilities will enjoy greater acceptance by the local population.

Researchers are still conducting experiments on the most beneficial combinations of species for specific regions. However, in the tropical regions it is becoming apparent that integrated aquaculture systems could be an elegant solution for the urgently needed production increases in marine aquaculture. While most of the research in this regard is being undertaken in South East Asia, intensive work is also ongoing in Canada, Chile, Israel and South Africa.

Regionally adapted solutions

A switch from conventional aquaculture to integrated systems will not suffice everywhere. Especially where natural coastal ecosystems have suffered enormously from intensive use in the past, the dismantling of existing aquaculture installations will also have to be considered if damaged coastal areas are to be revitalized. The example of the Chinese coastal metropolis of Xiamen shows just how comprehensive such a restoration endeavour needs to be. Until 2002, the entire coastal waters of this port city with its 5.1 million inhabitants were devoted to aquaculture. For more than two decades, muck from the ponds and the residues of the intensive use of feed in fish cage installations polluted the bay on which the city is located. In the period of 1984 to 1996, this pollution contributed to major fish kills which occurred roughly twice a year. The mangrove forest died off almost completely and populations of seabirds and river dolphins experienced dramatic declines.

The city then initiated a new four-stage marine and coastal management plan to turn the situation around. The aquaculture installations were completely dismantled, the local mangrove forest was replanted, wetlands were renaturalized, wastewater treatment plants were built and walls and embankments hampering water exchange were demolished, to name just a few of the measures as part of the comprehensive programme. According to scientists the results are impressive: Water quality in the bay has improved so much that there are renewed prospects for herons, river dolphins and many other species.

However, the radical dismantling of aquaculture installations is a feasible solution only in exceptional cases. The complete decommissioning of facilities is contraindicated by the growing global demand for fishery products. If we want to continue to meet this demand in the future, the FAO believes that this will only be possible if even more animal and plant products are produced in aquaculture systems. Moreover, in many coastal regions and areas, marine food production is the only source of income for the local population. The closure of aquaculture facilities would deprive many people of their livelihoods, especially in the tropics.

Highly divergent approaches to the future of aquaculture are being discussed in the scientific community. Some experts recommend a focus on class, not mass. They favour the operation of individual integrated facilities distributed over a large area so that their ecological footprint is as small as possible. But these facilities should then produce high-quality products and market them at an appropriate price.

Other scientists advocate an expansion of global aquaculture, premised on avoiding both environmental damage and conflicts with indigenous populations. Their suggestions include the following:

- define and enforce environmental standards;
- plan the location of new aquaculture installations on the basis of scientific information and in consultation with other local marine user groups;
- introduce certificates or label schemes for sustainable aquaculture production and make supply chains transparent;
- intensify the farming of non-fed species;
- in the case of fed species, further optimize feed ration formulation and feed use;
- find alternatives to marine mass fish farming in net cages – for example, by creating synergies through the conversion of such systems to integrated systems with farmed fish, cleaner fish, algae and mussels;
- reduce susceptibility to disease through breeding and genetic modification;
- shift production to the open sea to reduce the burden on coastal waters;
- stake efforts on ecosystem-based husbandry systems, in coastal areas as well as in the open sea.

Each of these ideas has its benefits. However, for every pro there is also a con when it comes to implementation. It is often argued that many of the proposed measures are too expensive and thus uneconomical for operators of aquaculture facilities. To the disappointment of aquaculture researchers, there have hardly been any field trials that yielded strong figures to refute this argumentation. Calculations of the economic viability of sustainable aquaculture approaches are mostly based on computer modelling.

Pros and cons of different mariculture pathways and approaches

Pathways or approach	Description	Pros	Cons
Environmental standards and regulations	Standards (e.g. water quality) set and monitored by governing agency	May help reduce incidents of disease transfer, nutrient and chemical pollution and habitat loss	Expensive; prohibitive if unstructured or poorly defined
Seafood traceability	Tracing a seafood product through the entire supply chain	Enhances food safety; improves operational efficiency and market access; helps eliminate illegal activities; helps mitigate fraud and counterfeiting	Expensive; proprietary information conflicts; involves federal and state or provincial policies
Marine spatial planning	Coordinated spatial planning that considers scientific and economic information and other resource users; could build on land-use policy and market-based approaches on land	Prioritises mariculture placement based on the available information; may help reduce conflict with other user groups; can be used to place farms in ways that minimise disease transfer and interactions with wild species	Expensive; may be time-consuming; needs to adapt as environmental conditions and social preferences change
Sustainable sourcing for alternative feeds	FM/FO replaced by terrestrial crops, rendered terrestrial animal products, fish processing waste and other novel products	Reduces fed mariculture's dependence on capture fisheries for expansion	Current barriers to widespread adoption (e.g. high costs); may affect the health of fed species and/or health benefits for consumers
Selective breeding	Breeding organisms with desirable traits in order to produce offspring with improved traits	May improve feed efficiency; may improve disease resistance, reducing antibiotic use (which reduces risk of antibiotic-resistant disease strains)	Escaped mariculture species may interact with wild populations, which can lead to hybrids with reduced fitness
Genetic modification	Gene transfer to improve certain traits	May improve feed efficiency; may improve disease resistance, reducing antibiotic use (which reduces risk of antibiotic resistant disease strains)	Escaped mariculture species may in-teract with wild populations, leading to hybrids with reduced fitness
Unfed mariculture	Farming lower-trophic-level species such as bivalves and aquatic plants	Improves water quality in the surrounding environment through filtering; does not require direct feed	Insufficient demand for low-trophic level production may preclude large expansion; dense cultivation of plants can block flows, creating environmental challenges; low edible conversion requiring more production per pound; more sensitive to climate change; diverts nutrients from surrounding environment
Integrated multi-trophic mariculture	Farming of different trophic levels to reduce nutrient concentrations	In some cases, reduces nutrient and chemical pollution	Can be technologically challenging to implement; expensive

Pros and cons of different mariculture pathways and approaches

Pathways or approach	Description	Pros	Cons
Offshore mariculture	Mariculture located in conditions similar to those of the open ocean	Less constrained by water or land availability for farming sites; may decrease nutrient and chemical pollution given the appropriate design and location (e.g. distance, depth and current); improves growth and condition (lower parasites and disease) of species; increases production without additional impact	Higher production costs; potential for interactions with wild fisheries; efforts to protect farmed animals can result in the harming or killing of large predators (e.g. sharks, seals)
Intensification	Concentrated and monoculture production systems	Can result in high yield per unit area	Increased risks of pollution, disease outbreak and the introduction of invasive species; may be less resilient; should be designed based on carrying capacity and should adopt ecosystem-based management
Selectivity in feeding	Feeding FM/FO at particular times in the life cycle and feeding in ways that do not put excess feed into the environment	Helps reduce nutrient pollution; may help reduce dependency on FM/FO	Can be expensive (e.g. requires technology to automate in offshore systems)
Selectivity in disease treatment	Using antibiotics only when necessary; development of vaccines	Reduces risk of antibiotic-resistant disease strains	Expensive compared to alternative approaches associated with environmental risks
Certification/ labelling/ ranking	Use market-based incentives to award and promote sustainable practices	Can incentivise greater adoption of sustainable mariculture systems and improve public awareness of sustainably farmed seafood	Certification process can be expen-sive and thus pose challenges for small operations; labelling can be confusing for consumers

But the fact is that if aquaculture is to be practised in harmony with nature, there cannot be just one blanket approach. Instead, it is essential that the methods used are adapted to local and regional conditions. It is upon policy-makers to define and introduce the laws and regulations that will resolve the often unclear issues of ownership and liability, provide attractive incentives for the sustainable operation of facilities (such as tax benefits, subsidies, etc.) and prescribe methods and threshold values for the effective environmental monitoring of aquaculture operations.

Scientists argue that in countries where there are no clear rights, regulations and responsibilities, operators of aquaculture facilities have no reason to invest in sustainable technologies and feed research. If aquaculture were to be expanded in such contexts, it could reasonably be expected that water quality would rapidly decline, that the marine environment would be severely damaged and that the health risk for coastal residents would increase. The decision as to whether and how to expand aquaculture is therefore not an easy one. Costs and benefits would need to be weighed carefully.

Certification marks for responsible aquaculture

A variety of certification marks allow customers who wish to buy fish and seafood from responsible or sustainable aquaculture systems to recognize such products. Based on the sustainability label of the Marine Stewardship Council (MSC) for wild-caught seafood, there is also a quality label for socially and ecologically sustainable aquaculture – that of the Aquaculture Stewardship Council (ASC). The ASC has developed aquaculture standards for 17 species groups whose market value is high and the production of which has far-reaching impacts on the environment. These farmed species include marine animals such as abalone, venus clam, common mussel, oyster and scallop, as well as salmon, sea bass, gilt-head bream, stone bass and cobia. Since November 2017, there has also been a joint ASC-MSC standard for seaweed cultivation. In the course of the ASC certification process, plant operators are motivated to:

- use fewer pesticides, chemicals and antibiotics;
- reduce water pollution;
- feed more efficiently and thereby prevent eutrophication of facilities and coastal waters;
- implement technical upgrades to their facilities to prevent farmed fish from escaping;
- treat all employees fairly and in accordance with appropriate social standards;
- interact in a positive way with the local communities in the facilities' surroundings.

In addition, participating aquaculture companies must ensure that their supply chains are designed in such a way that they exclude any possibility of erroneous substitution or admixture of certified and non-certified fish and that each product can be reliably traced back from the point of sale to the aquaculture facility from which it originates. By the end of 2019, the ASC had certified more than 1100 aquaculture facilities in 42 countries. Together, they produced almost two million tonnes of fish and seafood. Compared to 2014, the number of participating farms had increased by 450 per cent and the amount of fishery products produced according to ASC standards had increased by 181 per cent. The environmental requirements imposed by the ASC are also having an effect: certified shrimp farms in Vietnam, for example, were able to halve their adverse environmental impact through improved waste management. ASC salmon farms reduced their reliance on fishmeal from wild catches by three per cent. The certification guidelines for aquaculture facilities that bear the German Naturland label for certified organic aquaculture are stricter than the ASC standards. Operators undertake, among other things, to:

- adhere to species-appropriate husbandry conditions and low stocking densities;
- use certified organic feed, the fishmeal and fish oil content of which originates from residues from the processing of culinary fish and not from industrial fisheries specifically exploited for feed production;
- refrain from the use of genetic engineering, chemical additives, growth promoters and hormones;
- comply with strict regulations on the use of medication (e.g. the use of antibiotics is prohibited in shrimp farming);
- provide high social standards for their employees.

Operators of shrimp farms are under a further obligation to reforest former mangrove areas. With requirements such as these, Naturland also sets itself apart from the minimum requirements set out in the EU Regulation on organic aquaculture animal and seaweed production. This legislation came into force on 1 July 2020 and for the first time lays down rules for organic fish and seafood production throughout Europe.

While environmental organizations such as Greenpeace welcome the Regulation in principle, they also describe the rules as the lowest common denominator. Important criteria are not sufficiently strict in their view, with most stocking rates, for example, being set too high and hazardous chemicals having been approved for use. Critics note that the EU Regulation thus falls far short of the standards that the Naturland association, for example, has been setting for more than a decade.

Conclusion

A food source at its limit

The world cannot be fed without fish – all experts agree on that. More than 3.3 billion people get at least one fifth of their animal protein from aquatic foods. The importance of marine fish is even greater for coastal populations in developing nations and for the inhabitants of small island states. For many of them, fish is often the only affordable source of animal protein. Most other people are also consuming more and more fish and seafood. Since 1995, global per capita fish consumption has increased from 13.4 kilograms to 20.5 kilograms per year.

This increase has been made possible by more intensive fishing, especially in lakes, and an expansion of domestic and marine aquaculture. Nevertheless, marine capture fisheries still account for the largest proportion of wild catches, as international catch figures have remained at a very high level for about 15 years. It is difficult to quantify the damage caused by this intensive marine fishing because half of the fish caught come from stocks that are not subject to any kind of scientific monitoring. According to FAO (Food and Agriculture Organization of the United Nations) data, more than one third of the scientifically assessed stocks are now considered overfished. Other studies assume an even higher figure, as the FAO statistics do not, for example, take sufficient account of illegal, unreported and uncontrolled fishing.

New technologies such as satellite monitoring, automatic vessel identification systems and data portals on fishing and reefer vessels now allow inspectors to detect illegal fishing activities to a greater extent. Greatly encouraging is also the fact that in areas where stocks have been managed in a sustainable and science-based manner and fishing activities have been closely monitored, once overfished fish populations have been able to recover. In contrast, the situation is dire wherever there are no controls or where fisheries management is far removed from scientific advice; this is true even in some parts of the European Union.

Neither scientists nor politicians agree among themselves as to the role marine aquaculture can play in feeding the growing global population in the future. Some experts point to the theoretical possibility of enormous increases in production; others are much less optimistic in their outlook.

In the past, the construction and operation of aquaculture facilities have resulted in large-scale environmental degradation. Science and industry are therefore devoting a great deal of effort to the development of more sustainable production standards, technologies and facility designs. Their implementation or utilization should conserve natural resources, minimise the use of medication and chemicals, and reduce the overall impact on the ocean. To date, the integrated or ecosystem-based approaches with closed nutrient cycles offer the best prospects in this regard.

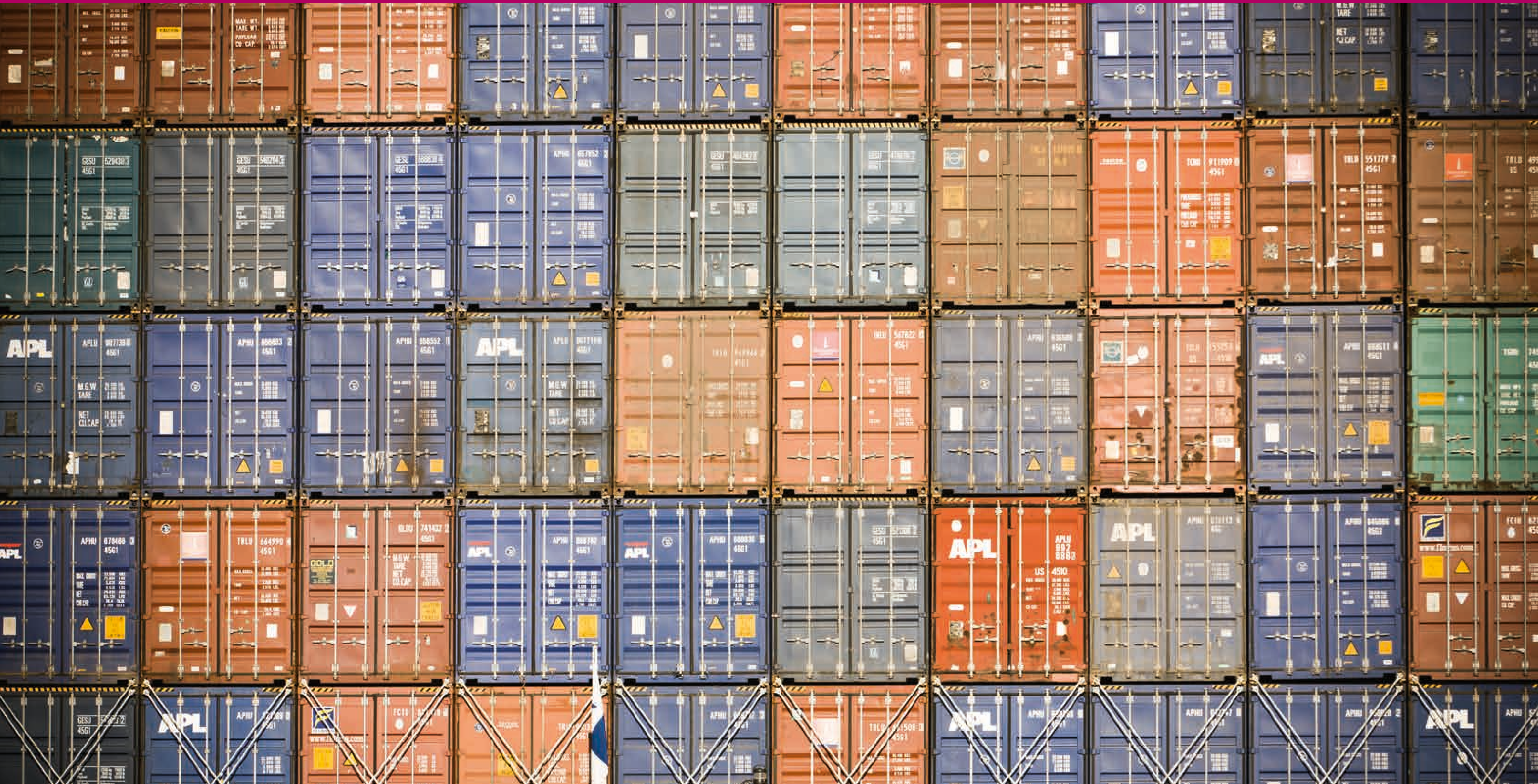
Great hopes rest on the cultivation of macroalgae, the fastest expanding aquaculture sector. Intensive research is also being conducted on substitutes that will allow for the reduction of the proportion of fishmeal and fish oil in feeds.

However, in order for sustainable business strategies to prevail in the long term, stricter regulations and controls are needed in the aquaculture sector. Quality labels such as the ASC logo can be supportive in this respect.

But there are also ever louder calls for the consumption of fish and seafood to be reduced, given that as a result of the increasing consumption of fish worldwide, the sea as a food source has long since reached its limits.

4 Transport over the seas

> In recent decades shipping has become the backbone of international trade. More and more goods are being transported from one continent to another by ship. But this growth also has a downside. Exhaust emissions from ships pollute the air and accelerate climate change, while noise, sewage, garbage and invasive species put pressure on marine ecosystems. New, environmentally sound solutions are needed as quickly as possible.



Shipping at a turning point

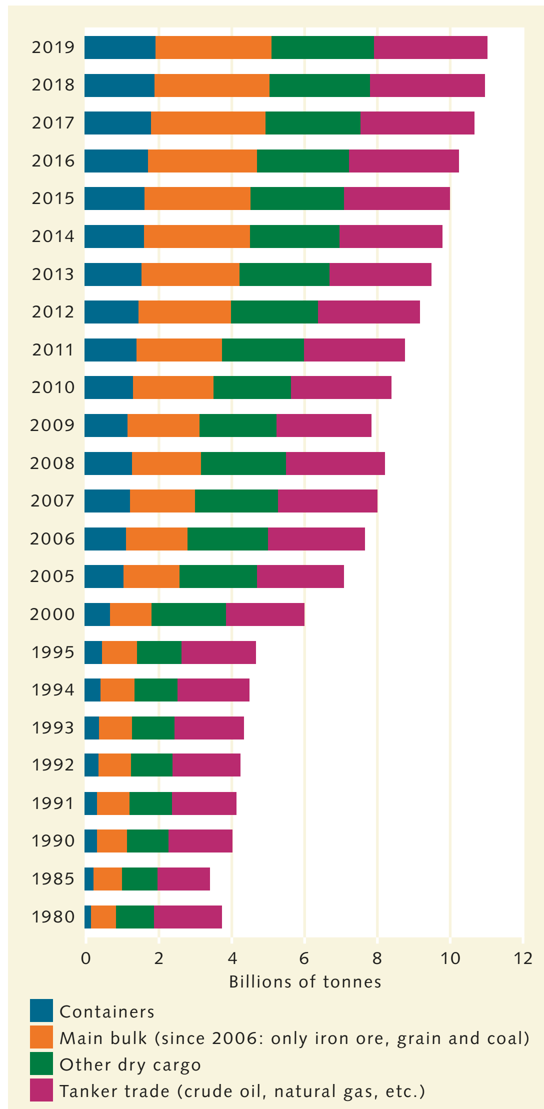
> The international merchant shipping fleet now numbers almost 100,000 vessels conveying bulk resources and other goods around the globe. Competition is fierce and environmental concerns scarcely featured in the past. However, it has become clear in the meantime that the sector must reduce its carbon footprint and improve its environmental performance. This calls for new propulsion systems, strict and globally applicable environmental standards and major financial input to upgrade a partially ageing fleet.

The backbone of global trade

Without shipping across the seas and oceans there would be no fresh bananas or mangoes for purchase in European stores, nor would there be any products made from raw materials such as petroleum, iron ore or phosphorite. These are, for the most part, produced, farmed or mined on other continents, and ultimately transported to Europe by bulk carriers, container ships or tankers for sale or further processing. Over 80 per cent of all goods and raw materials traded worldwide are carried to their destinations by ships. Transport by ship is especially important for developing countries, where transportation over land or by air is impractical because of inadequate roads and airports. In these regions, ships are often the only means of moving large quantities of goods from place to place over rivers, lakes and coastal waters.

The motivation for transport over the seas is always the same, and it can be expressed in very simple terms: Ships transport goods and products from a region where they are relatively inexpensive to produce to places where they can be sold at a much higher price. In terms of the total value of goods traded worldwide, shipping is estimated to account for only around 60 to 70 per cent. This is because relatively high-priced goods and products are often sent as air freight, especially when they are expected to reach the recipient as fast as possible.

For statistical purposes, ship transport can be divided into three different categories. The first includes the transport of crude oil, natural gas and petroleum products such as diesel, kerosene, propane gas, bitumen and asphalt in tankers. The second category comprises bulk cargoes, especially iron ore, grain and coal, which are transported in bulk carriers. The third category encompasses all container goods traded worldwide, as well as special non-liquid goods including piece goods, automobiles and animals.



4.1 > The quantity of goods transported by ship has been increasing for years. More than two thirds of all freight consists of bulk goods, other dry cargo and container goods. The remainder is tanker cargo.

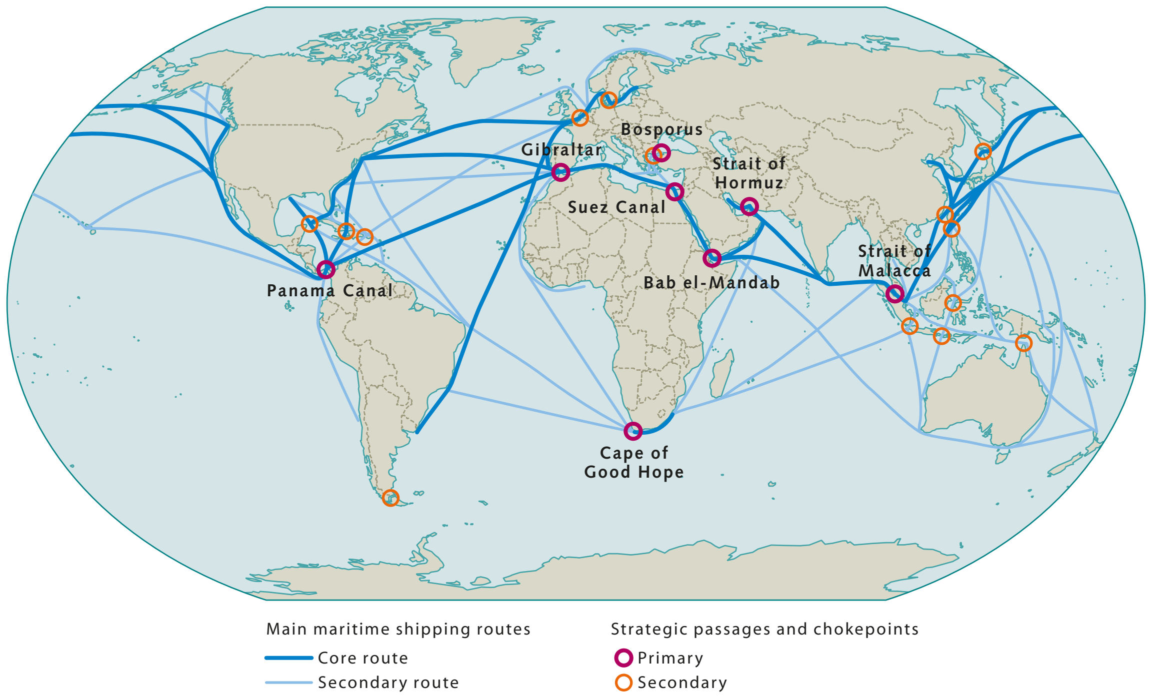
Significant differences can be seen between the freight statistics from the year 1970 and those of today. For one, the total quantity of goods transported by ship has more than quadrupled within this period of 50 years. It increased from 2.6 billion tonnes in 1970 to around eleven billion tonnes in 2019. For another, the overall proportion of oil and natural gas transport has decreased considerably. While these made up 55 per cent of all transported goods and products in 1970, they were only around 28 per cent in 2019, whereby the total amount of petroleum has not decreased at all. On the contrary, more than twice as much oil was shipped in 2019 than in 1970. But transport in the third category described above has increased even more. In terms of value, 60 per cent of the goods traded are now shipped in containers. This large proportion is due to the fact that goods loaded into containers such as entertainment systems, computers, clothing, sporting goods and foodstuffs, are generally far more expensive per tonne than bulk goods such as oil, iron ore or coal.

The direction of the flow of goods has also changed. Until about two decades ago the same transport and trade patterns were being followed as in colonial times, by which the so-called developing nations exported large quantities of resources and raw materials by ship and imported relatively smaller amounts of consumer goods. But the trends have been changing since the beginning of the new millennium. Many of these countries now also import raw materials and actively participate in the trade of intermediate and end products as both buyers and sellers. This means that goods and products not only leave these lands, but they are also imported on a large scale. According to the United Nations Conference on Trade and Development (UNCTAD), the significant increases in these shipping trends can be mainly attributed to increased trade among developing nations.

This development has been enhanced by the globalization of production processes and the increasing division of labour, in the course of which companies have transferred many of the individual steps of product manufacturing to different countries and continents. It is primarily ships that have the task of transporting the various intermediate products from one location to another where they then undergo further processing. According to UNCTAD, more than half of the products made by companies with their headquarters in industrialized countries are now produced and sold abroad. At the same time, these companies import raw materials and intermediate products from other countries in similar quantities. These two developments have created a situation where many markets have become strongly international and have thus also resulted in the establishment of many corresponding dependencies. For instance, when the 400-metre-long giant container ship *Ever Given* became wedged in the Suez Canal in March 2021, clogging this bottleneck of global trade for six days, the disruptions to freight transport worldwide were severe. Hundreds of freighters were caught in the backlog, closely time-phased supply chains tore and the economic impacts were felt for long.

The high degree of globalization of economies worldwide also explains why political tensions among large industrial powers can have direct effects on international merchant shipping. The trade dispute between China and the USA in 2019, for example, not only slowed the growth

4.2 > The mega-freighter *HMM Hamburg* is 400 metres long and can carry 23,964 containers. This capacity makes the ship, which sails a regular route between Europe and East Asia, one of the largest container ships in the world.



4.3 > Most shipping travels along established routes that connect the industrial centres with each other. Specialists distinguish between core routes and secondary routes, and are also familiar with the shipping lanes where caution is advised due to the high volume of ship traffic.

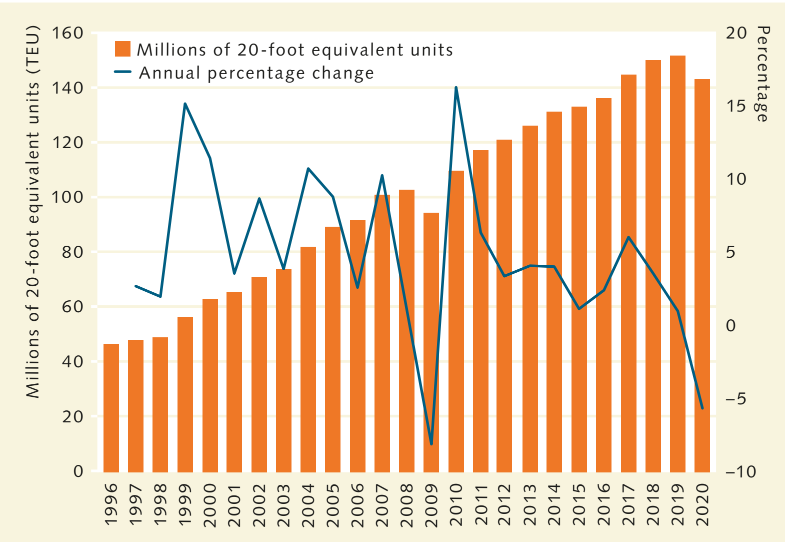
of the entire industry, it also caused many US producers to look for alternative markets and to redirect their flow of goods. As an example, raw materials and goods that had been exported to China prior to the beginning of the dispute subsequently began to go primarily to South East Asia.

The rise of the containers

Increasing globalization of production and markets since the 1970s has presented an enormous challenge for marine shipping. For example, to save on storage costs, producers began to order their goods and commodities in smaller batches and to expect delivery at a specified time ("just in time"). In order to meet these demands, the shipping companies could no longer treat the goods as bulk cargo, but were forced to load them in smaller units that could be quickly loaded onto trains or trucks at the destination ports and sent on from there to their final destinations. Thus began the rise of container shipping, which continues to grow today. This development is reflected, among other things, by the growing size of the individual container ships. While the first generation of ships (built in the early 1970s) had a load capacity of 600 to 900 containers, the newest generation of container ships can now transport 24,000 containers to destinations around the world.

The giant container ships are mainly used on the regular routes between Europe and Asia, or those across the Atlantic and Pacific. This is because competition between shipping companies is greatest on the major international shipping routes, and the pressure on prices there is particularly high. The more containers a ship can transport in this situation, the lower the prices a shipping company can offer and thus remain more competitive. Based on this logic, a large number of container ships have been built in recent years, and the overall prices for ship transport have continued to fall accordingly. The lower prices, in turn, have increased the motivation for merchants to order their goods for delivery on short notice rather than pay extended storage fees. For this reason, international production and delivery chains are now so dependent on container-ship transportation that the UNCTAD experts employ the trends in this transport branch as a direct indicator of overall economic development.

4.4 > A liquid-gas tanker docked at the Port of Malta. Because the global trade of liquified natural gas is steadily increasing (11.9 per cent growth in 2019), the number of these special ships is also mounting.



4.5 > The increasing container transport in numbers. The moderate decline in 2020 is due, among other things, to the global economic consequences of the corona pandemic.

The stakeholders in bulk freight transport have also embraced the motto, “the bigger, the cheaper”. Until about 20 years ago, most of the bulk carriers used could typically load around 200,000 tonnes of cargo. Then, in 2011, the first ship of the Valemax, or Chinamax Class was put into service, with a length of more than 350 metres and a carrying capacity of 400,000 tonnes. It transports iron ore from Brazil to China and other Asian ports. Worldwide there are now 61 of these ships in use, which is a significant factor in the 25 per cent decrease in transport prices for iron ore on the Brazil–China route.

The merchant fleet in numbers

However, the ships are not only getting larger, their numbers are also growing. In early 2020, UNCTAD experts reported a total of 98,140 cargo, container, tanker, ferry and passenger ships operating worldwide. Their total freight volume was 2.06 billion tonnes. Bulk carriers, which continue to be the largest business segment, accounted for 43 per cent of this. Oil tankers, with a freight-volume share of 29 per cent, made up the second largest division. This means that the available freight volume of the merchant fleet has more than doubled within the two decades since 2000, when the freight volume was 800 million tonnes.

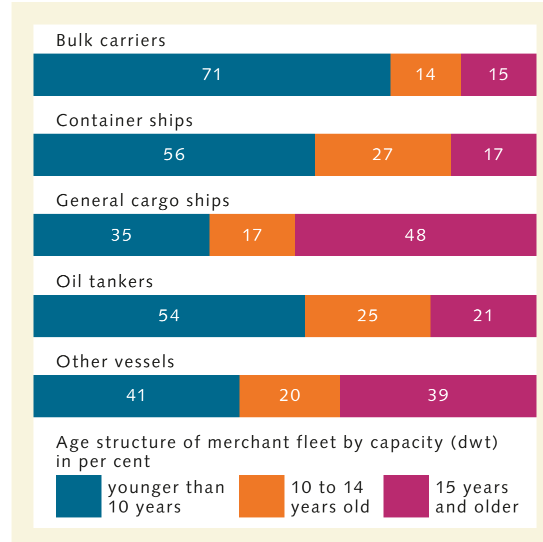
Outflagging
Outflagging is when a ship is not registered in the home state of the shipping company, but in another country, yet the ownership of the ship does not change. The reasons often involve cost savings as well as the ability to hire foreign personnel.

The quantity of goods transported, however, has not increased by an equivalent amount. This has resulted in an excess in total capacity, causing freight prices to go down and the profits of shipping companies to shrink, especially in the container sector. This trend, which has been ongoing for years, has led to the buyout of smaller container shipping companies, and to larger companies entering into alliances with their market competitors. Three large groups now control more than 80 per cent of the global container business. It is important to note here that the shipping companies are no longer concerned only with the transportation of goods from one port to another. In order to profitably fill the large container ships in particular, the companies attempt to take control of the transport chain as early as possible, before the goods even arrive at the port of departure, and to retain control for as long as possible, ideally until their delivery directly to the recipient.

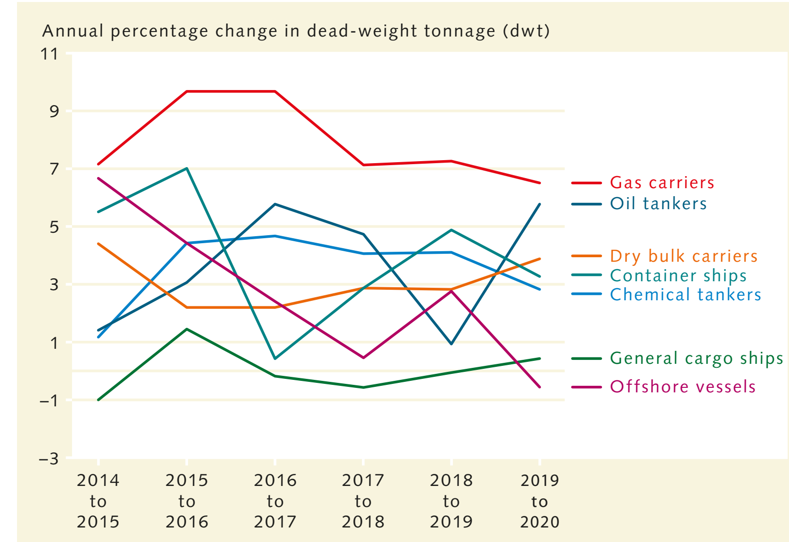
As a result, the shipping companies have evolved into multimodal logistics enterprises. They not only organize the ship transport; in many places they also operate the container port terminals. They also undertake the subsequent transport of the containers to inland locations and operate container depots there as well. This trend is especially significant for countries and regions that are not on the large trade routes. The trade infrastructures in these places are not as well developed, and this often means they have to pay higher freight costs than countries along the established routes.

The huge investments in large container ships and bulk cargo freighters by shipping companies are also reflected in the age structure of the international merchant fleet. The average age of a ship at the beginning of 2020 was around 21.3 years. Sorting by age categories, however, revealed that the bulk carriers, container ships and oil tankers were mostly only ten years old or younger. The fleet of general cargo ships and ships of other types (ferries, etc.), on the other hand, were far from modernized. In 2019 these kinds of ships were generally more than ten years old.

In recent years, as a result of investments by Asian shipping companies, China, Singapore and Hong Kong have risen into the ranks of the top five ship-owning



4.6 > In recent years shipping companies have concentrated new construction investment on bulk carriers and container ships. There are therefore many newer ships of these types.



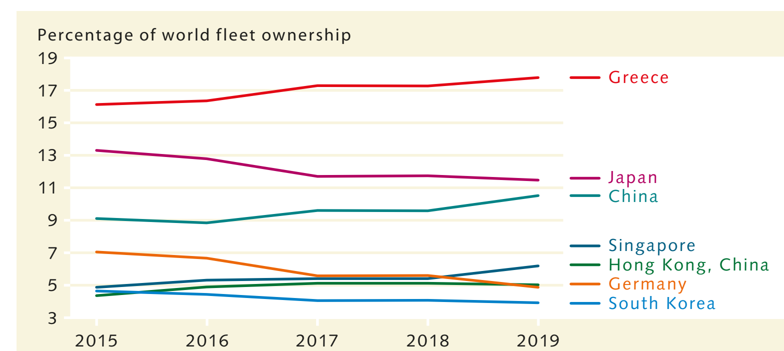
4.7 > The situation in the commercial market dictates which types of ships are needed. The growth from 2019 to 2020 was primarily seen in the fleet of gas and oil tankers.

nations. Together with Greece (first place) and Japan (second place), the owners from these countries possess so many ships that they transport more than half of the worldwide available freight volume.

But the great majority of ships in the merchant fleet (70 per cent of the freight capacity) are registered under foreign flags, because of the many financial and regulatory advantages associated with this practice. Open registries, for example, have made it easier in the past for shipping companies to hire foreign crews and save on taxes. Today, however, ship owners make the decision to register under foreign flags for other reasons. For example, if a ship is registered in a country with a good reputation worldwide, the inspections in port take less time and the shipping company saves money each time. However, the question of modern security precautions (cyber security) and certified processes is also becoming increasingly important. Both of these are needed to guarantee the smooth operation of the shipments as well as long-term acceptance by the customers. The ship owners therefore always select a registry or flag whose services best fit their own business profile and are ultimately the least expensive. Ships today that still sail under their own national flags generally do it because they belong to state-owned companies or institutions, they receive state subsidies, or they provide transport services in another country that has limited the access to its domestic market by providers from certain nations.

The leading flag states are Panama, Liberia and the Marshall Islands, followed by Hong Kong (China) and Singapore. These and the many other flag states are increasingly obligated to effectively enforce applicable shipping regulations as well as to uphold safety, environmental, labour and social standards.

Whether the flag states and ship registries are fulfilling this role is being monitored in Europe’s ports, for



4.8 > Almost 40 per cent of all merchant ships belong to people or companies based in Greece, Japan or China. The shares of all other nations lie in the single-digit range.

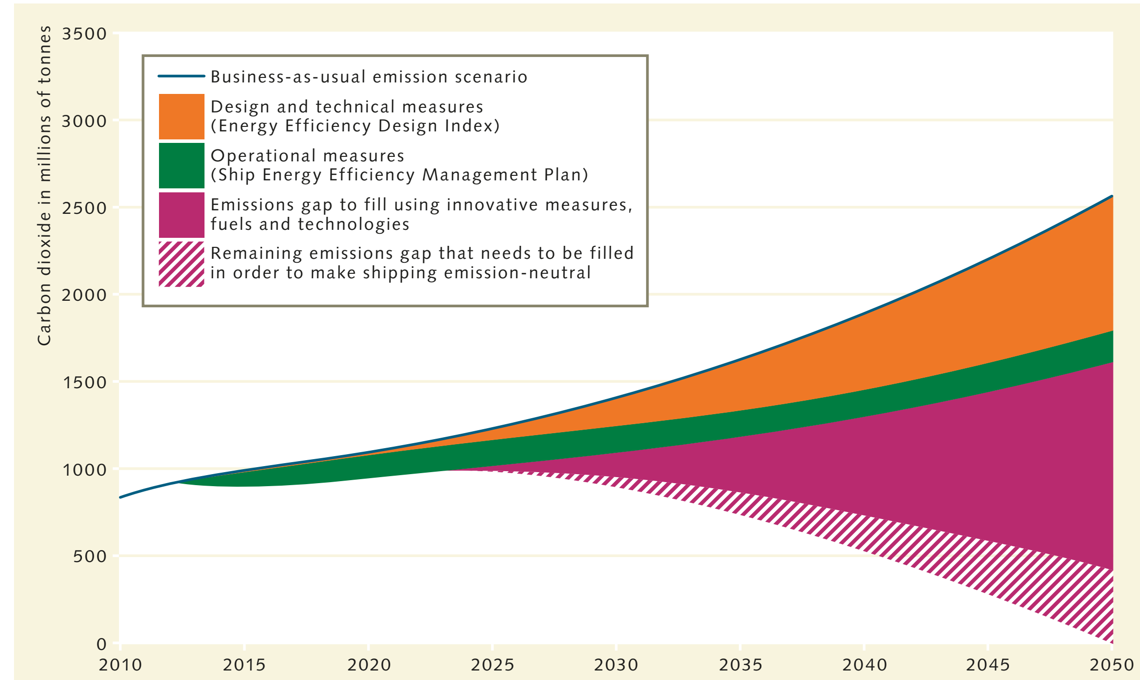
example, through ship inspections according to the community standards set down in the Paris Memorandum of Understanding on Port State Control (Paris MoU). This has now been ratified by 27 European states.

Every member state reports the results of its ship inspections to the Committee of the Paris MoU, which publishes an annually updated rating list for flag states and ship registries. Participants with comparatively few violations earn a position in the "white" category on this list. States and registries in the "grey" category have only moderately fulfilled their supervisory obligations, and assignment to the "black" category indicates serious shortcomings.

In 2019, member states of the Paris MoU carried out almost 18,000 ship inspections. More than half of these revealed substantive issues. Ships were detained in port 526 times, and prevented from continuing their voyage under the existing conditions. Ships were barred from entering ports 27 times. The reasons included sailing despite being detained, failure to have repairs carried out, or being detained as a result of inspections three times within three years. In its current rating list, the committee has 41 flag states in the "white" category, 16 in the "grey" category, and 13 on the "black" list. The high-risk nations include the Comoros, Albania and Togo, followed by Moldova, Tanzania and Ukraine.

Although flag states are increasingly called upon to enforce regulations and rules, with regard to the actual shipments themselves, it is becoming less and less important where the participants come from. Merchant shipping is a thoroughly internationalized area of business. The operation of a ship can involve people and machines from more than a dozen countries. For example, when a ship that was built in Korea and belongs to Greek owners is chartered by a Danish shipping company, it may then hire a Filipino crew through an agent on Cyprus. Meanwhile, the same vessel could be registered in Panama, insured in the United Kingdom and transporting goods manufactured in Germany on a scheduled route from a port in the Netherlands to Argentina, with terminals in the two ports operated by companies based in Hong Kong and Dubai. The software and IT services necessary for terminal operation, in turn, may be provided by a company in India. This globalization is only able to function because critical aspects of merchant shipping such as container size, information and data systems, as well as quality and safety requirements are standardized worldwide, and the same standards apply in many places.

4.9 > Soot, sulphur oxides, particulate matter: Ships have been poisoning the air for decades. The seagoing vessels using heavy fuel oil as a fuel were especially problematic. Since January 2020, however, a new regulation is in effect that requires fuels to be lower in sulphur.



4.10 > To cut the carbon dioxide emissions of merchant shipping in half by 2050, the International Maritime Organization is relying on a number of technical innovations. By their calculations, simply operating the ships in an energy-efficient and fuel-saving way is not enough by far.

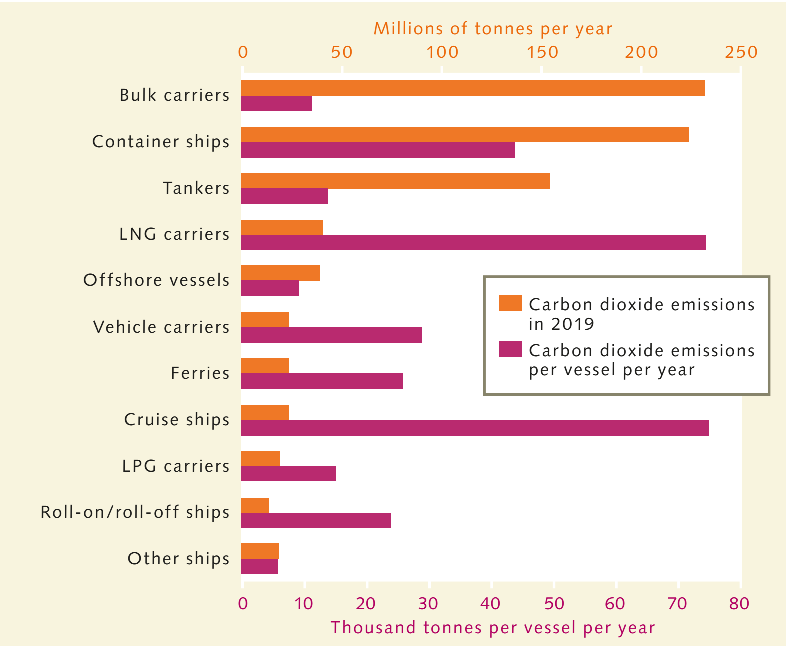
Pathways to emission-free shipping

Today, the most energy-efficient means for transporting goods and commodities internationally is still by ship over the ocean. However, engine-powered shipping has been generating increasingly more greenhouse gases over the past ten years, as diesel engines have been used almost exclusively. For these, the ocean vessels consume either heavy fuel oil or marine diesel oil as fuel. According to the International Energy Agency (IEA), the following fuels were used in international shipping in 2019: heavy fuel oil, amounting to 180 million tonnes of oil equivalent; distillate fuels, such as marine diesel, amounting to 45 million tonnes of oil equivalent; and natural gas, mainly in the form of liquefied natural gas, amounting to 0.1 million tonnes of oil equivalent.

When these fuels are combusted they produce substantial quantities of greenhouse gas emissions. According to the International Maritime Organization (IMO), international shipping (combined fisheries and merchant shipping in both national and international waters) generated greenhouse gas emissions amounting to 1076 million tonnes of carbon dioxide equivalent (CO_2e) in 2018, an increase by 9.6 per cent compared to 2012, when the value was 977 million tonnes. This means that shipping now contributes 2.89 per cent of the total amount of global greenhouse gases released by humankind. If growth in the shipping sector continues through the middle of the century at its present rate, experts predict a further increase of ship-generated carbon dioxide emissions by 50 to 250 per cent.

This trend would surely result in a failure to limit global warming to less than two degrees Celsius by 2100,

Carbon dioxide equivalent (CO_2e)
CO_2 equivalent (CO_2e) is a unit of measure used for amounts of greenhouse gas emissions that, besides carbon dioxide, also includes other greenhouse gases like methane and nitrous oxide. Their impact on environmental warming of the Earth's atmosphere is thus recalculated to an equivalent amount of carbon dioxide (CO_2), so that the warming effect of a mixture of greenhouse gases can be expressed by a single number.



4.11 > The UNCTAD experts keep accurate records of how much carbon dioxide is emitted by which types of ships and fleets. Their tally for the year 2019 shows that bulk carriers had the highest total fleet emissions because there is such a large number of them. Cruise ships were at the top of the individual ship rating.

the goal prescribed by the Paris Climate Agreement of 2015. Shipping, like all other key sectors, will therefore have to drastically reduce its greenhouse gas emissions. Initial plans are already being made toward this end. In April 2018 the IMO resolved to reduce the amount of all greenhouse gas emissions by 2050 to half of the amount released in 2008. This includes a reduction in the amount of carbon dioxide emissions by 70 per cent by this date. The long-term goal, however, is to completely eliminate emissions.

The shift to emission-free shipping will require a radical transformation within the sector. Experts from the International Energy Agency and UNCTAD have concluded that operational measures to reduce emissions by shipping, such as slower cruising or improved utilization of capacity on ships, will be far from sufficient to effectively reduce the greenhouse gas emissions. Instead, alternative forms of propulsion, as well as new fuels whose combustion releases minor amounts or no greenhouse gases at all will have to be developed.

But time is pressing. In the view of the Getting to Zero Coalition, a private-sector initiative, ships with emission-free propulsion will have to be deployed at the latest by 2030 in order for the goal of emission-free shipping to be achieved over the long run. But it is precisely on this point that the sector now finds itself in a dilemma that the operators themselves refer to as a system blockade. The problem is summarized as follows:

International maritime shipping is a capital-intensive sector of industry involving large investments, such as for the construction of new ships, that can only pay off over many years. For this reason, investors have a strong interest in keeping a ship in operation for as long as possible. Competition is great and the profit margins are comparatively small. Furthermore, the wellbeing of the entire sector depends on the global availability of sufficient fuel.

The development of alternative fuels, however, has not yet advanced sufficiently to alleviate uncertainty among potential investors. Moreover, it is anticipated that the possible alternative fuels will initially be more expensive than petroleum-based fuels. This expectation, in turn, raises questions about the competitive potential of ships with new technologies assuming that market conditions do not change. To address this problem it may be conceivable, for example, to promote the changeover to new fuels with lower or zero emissions by imposing an international CO_2 tax.

Many stakeholders within the shipping industry itself would approve of such a step if it could be applied across the board and equally for all competing parties. Most of them have long been aware that marine fuels have been traded far too cheaply, and that the industry has not yet contributed in any way for the long-term damage caused by ship emissions. Experts with the International Monetary Fund are likewise in favour of a carbon tax. According to their calculations, a tax of USD 75 for every tonne of carbon dioxide released could reduce the emissions caused by shipping by 25 per cent by 2040 and generate an income of USD 150 billion, which could then be invested for research and development.

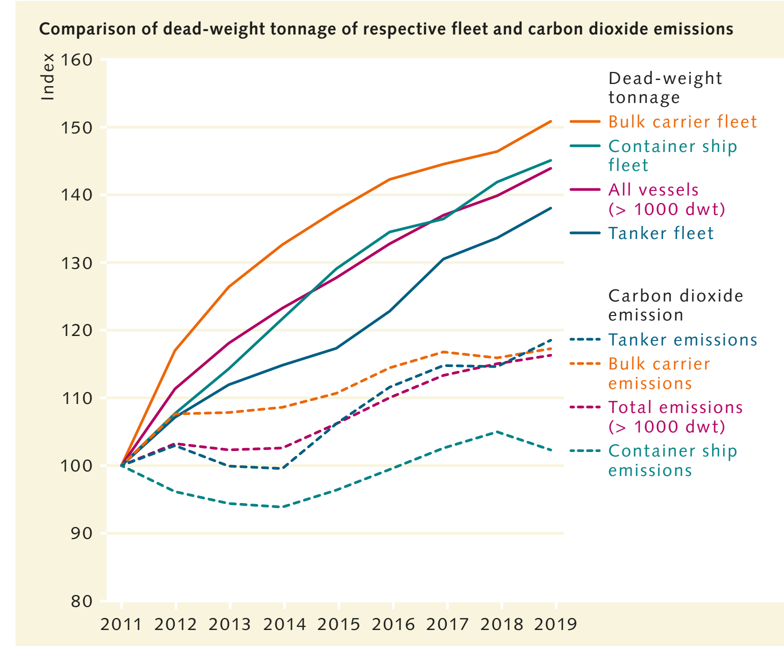
This approach is also supported by the International Chamber of Shipping (ICS) and other industry organizations. They suggest a joint IMO funding programme for research and development of emission-free propulsion systems and fuels. It would be financed by ship charterers, who would pay a set fee for each tonne of fuel they purchase. This would generate about USD five billion, money that is urgently needed for research.

The key idea behind this approach is: The higher the charges on carbon dioxide emissions and the cheaper the new technologies become, the more likely ship owners will be to replace their conventional fleets with ships with low-emission propulsion systems. The IMO has been collecting data on the fuel consumption of the international merchant fleet since January 2019. Ships with a gross tonnage of 5000 and greater (standard size specification for ships) must report once a year the amount of fuel they have consumed broken down by voyages. The purpose for collecting this information is to improve estimates of energy consumption and the volume of emissions in shipping.

However, in order to achieve decarbonization, what is needed most of all is money. According to a study by the Global Maritime Forum, the shipping industry will have to invest around USD 1.0 to 1.4 trillion during the period from 2030 to 2050 in order to cut the emissions in half by 2050. USD 1.4 to 1.9 trillion would be required for a complete decarbonization of the industry. Just for comparison, in the year 2018 alone governments and the private sector invested USD 1.85 trillion in the energy sector. This shows that such sums are not totally inconceivable.

However, a significant obstacle to increasing investments in the shipping industry has been the fact that it is not the investor or ship owner who would benefit from the technical innovations, but the companies that charter the ships for transport. As a general principle in international shipping, the charterer pays for the fuel and, where applicable, also for the tax on greenhouse gas emissions. So, although the ship owners would have to pay for the conversion, others would reap its benefits.

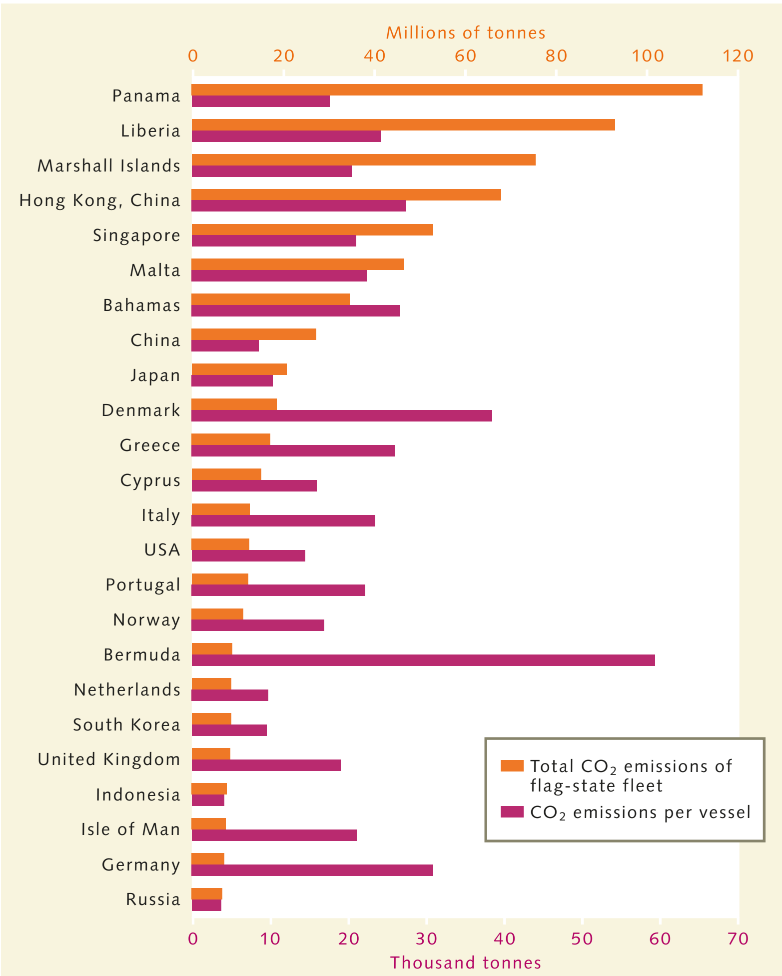
Ship owners and investors, moreover, have a strong interest in keeping their vessels in service for as long as possible in order to achieve the maximum profits. The specialists at UNCTAD have therefore made a relevant calculation. If ships remain in operation for as long in the future as they have in the past, almost 30 per cent of the present-day fleet of offshore supply ships will probably still be in service in 2051. More than 20 per cent of all ferries and



passenger ships, and significantly more than ten per cent of all freighters would still be operating. The UNCTAD authors conclude that low-emission technology must therefore come onto the market as soon as possible so that as few of the new-construction ships as possible are fitted with conventional motors. A report by a large producer of ship fuels makes the point even more vividly. It refers to 2030 as “tomorrow”, and to 2050 as merely the life of a ship away.

Because of this situation of complex interests and the steadily rising urgency for reduced emissions, specialists in the transport industry are demanding clear guidelines from politicians and shipping organizations. What is needed is a globally binding set of rules and a secure, level playing field where green technologies should not be reserved only for the most economically successful companies. Instead, there must be international investment incentives that compensate for initial competitive disadvantages (alternative fuels are more expensive than marine diesel oil or heavy fuel oils). For example, tax relief might be considered for investments in sustainable ship technology. In a survey to find possible solutions conducted in the summer of 2020, leading stakeholders in

4.12 > Since 2011 the load capacity of the merchant fleet has grown at a significantly greater rate than its total emissions. This means that transporting goods with a fully loaded mega-freighter produces a smaller amount of greenhouse gases than the same quantity of goods sent with two ships.



4.13 > The greenhouse gas emissions of a ship are assigned to the carbon footprint of its flag state. Although the total emissions of ships registered in Germany make up a relatively small quantity, the amount calculated per ship is relatively high. That is because they are mostly container ships.

international merchant shipping identified the following five high-priority action areas:

1. Increase demand for low-emission ship transport

The demand for low-emission shipping must be stepped up in order to provide more security for investors and shipping companies. Charter companies and customers must agree to long-term contracts and make ecological delivery commitments. State-owned companies and large corporations with ambitious emission goals could help to get this started.

2. Uniform rules and deadlines

To guarantee equality in competition and opportunity, the shipping industry needs uniform global rules and deadlines for the implementation of emission-reducing measures. Towards this purpose, it is also important to coordinate the new guidelines of the International Maritime Organization (IMO), expected to be released in 2023, with leading national and regional shipping authorities.

3. Cross-sectoral research and development

For the development of low-emission ship technology, the industry has to think beyond its own sector boundaries and engage in cooperative research projects with other parties that are working on similar problems outside the shipping industry. These partners could be from the energy or automobile industries, for example. In addition, much more capital and expertise will be needed in order to advance the technology, and at the same time provide the necessary infrastructures for its production and operation.

4. Expansion of pilot projects

Significant progress can be achieved by testing green pilot projects under normal competitive conditions on selected transport routes, and including all stakeholders such as customers, charter companies, shipping companies, ship owners and port agents. Container ships sailing on shorter scheduled lines would be particularly suited to such practical tests.

5. Coordinated voluntary commitment by the entire shipping industry

In order to increase the effectiveness of the existing climate initiatives, the goals and measures of the various efforts must be unified and strengthened. A jointly created steering committee could take on this challenge with the primary task of transforming ideas into action and freeing the industry from its present developmental stagnation.

What will power the ships of tomorrow?

One of the hurdles along the path to low-emission shipping is the lack of progress thus far in developing emis-

Main international regulatory policies covering air pollution and greenhouse gas emissions in maritime shipping

Name	Geographic coverage	Year introduced	Description	Regulatory actor
IMO Initial Strategy	Global	Adopted in 2018	Reduce absolute greenhouse gas emissions from shipping at least 50 % by 2050 relative to 2008; reduce CO_2 emissions per transport work at least by 40 % by 2030, pursue efforts towards 70 % by 2050	IMO
Data collection system (DCS) for fuel oil consumption	Global	2019	All ships over 5000 tonnes engaged in international voyage must collect consumption and other data for each type of fuel oil consumed. Flag states must collect and aggregate the data and submit to the IMO	IMO
Submission of CO_2 emissions reports (MRV)	Ships calling at EU ports	2018	Companies must submit a CO_2 emissions report for all voyages in the European Union for all vessels under their responsibility	European Commission
EU Emissions Trading System (ETS)	Ships calling at EU ports	2022 (expected)	Proposal to include shipping in the ETS as part of the Green Deal	European Commission
Energy Efficiency Design Index (EEDI)	Global	Enforced in 2013	Requires minimum energy efficiency per tonne-km for new large vessels and mandates improvement steps depending on vessel type: 10 % in 2015, 20 % in 2020 and 30 % in 2030 compared with average performance of vessels built in 2000 to 2010	IMO
Ship Energy Efficiency Management Plan (SEEMP)	Global	Adopted in 2016	Monitors ship efficiency performance, mandates collection and submission of relevant data and establishes mechanisms to improve efficiency of existing ship operations	IMO
Global sulphur cap	Global	January 2020	Limits the sulphur content of maritime fuel used on board vessels trading outside of sulphur ECAs to a maximum of 0.5 %. Ships without exhaust gas scrubbers are not permitted to carry fuel for use with a sulphur content exceeding 0.5 %	IMO
Emission Control Areas (ECAs)	Baltic Sea, North Sea, Caribbean Sea and North American Sea	Enforced respectively in 2005, 2006, 2012 and 2014	To operate in these areas, ship engines must comply with stricter standards for SO_X and NO_X than in global waters. In particular, there is a limit of 0.1 % sulphur for fuel used by ships operating in SO_X ECAs and NO_X TIER III standards apply to ships operating in NO_X ECAs	IMO

Notes: IMO = International Maritime Organization; MRV = monitoring, reporting and verification; EU = European Union; SO_X = sulphur oxides; NO_X = nitrogen oxides

4.14 > Over the past two decades the IMO and the EU Commission have undertaken a number of steps to reduce the emissions of merchant shipping. Their most important initiatives are listed here.

sion-free fuels and propulsion systems. For transportation through inland waters or for short distances in coastal waters, battery-driven electric motors are a viable option. There are presently around 250 ships with electric or hybrid propulsion in operation worldwide or now being built. Norway, for example, plans to have about 80 electric-powered ferries in regular operation by 2022. But electric propulsion systems are also being installed on tugboats as well as on aquaculture and fishing vessels. The first cruise-line companies have announced that they will equip new ships with large battery systems to make hybrid propulsion possible. Furthermore, electric current from onshore sources will become more readily available to serve cruise ships and other vessels during port layovers. This measure alone would reduce up to eleven per cent of the greenhouse gas emissions caused by international shipping.

But for maritime shipping, which accounts for 85 per cent of the greenhouse gas emissions in shipping, and which is greatly dependent on fuels with a high energy density, there is as yet no alternative fuel known that could conceivably cut emissions in half by 2050. For the transition, shipping firms like the French company CMA CGM are turning to liquefied natural gas (LNG). This is natural gas that is cooled down to minus 161 degrees Celsius. At this temperature it changes to a liquid and shrinks to one-six-hundredth of its original volume, so that 600 litres of natural gas become one litre of liquid gas. In this state, a significant amount of space can be saved in its transportation and storage. It is transformed to the gaseous phase again to be burned in the ship's motor. But first, undesirable components like carbon dioxide, nitrogen and water are removed, leaving a composition of almost 100 per cent methane. This cleaning step is one of the reasons that ships fuelled by LNG, such as CMA CGM's giant freighter *Jacques Saadé*, emit up to 20 per cent less carbon dioxide, 99 per cent less particulates, and 85 per cent less nitrogene dioxide than comparable freighters powered by heavy fuel oil. The change to LNG thus significantly reduces the emission of pollutants.

4.15 > No more black clouds of soot: The container ship *Jacques Saadé*, operated by the French shipping company CMA CGM, is powered by liquified gas and is presently the largest freighter with this kind of alternative propulsion system.

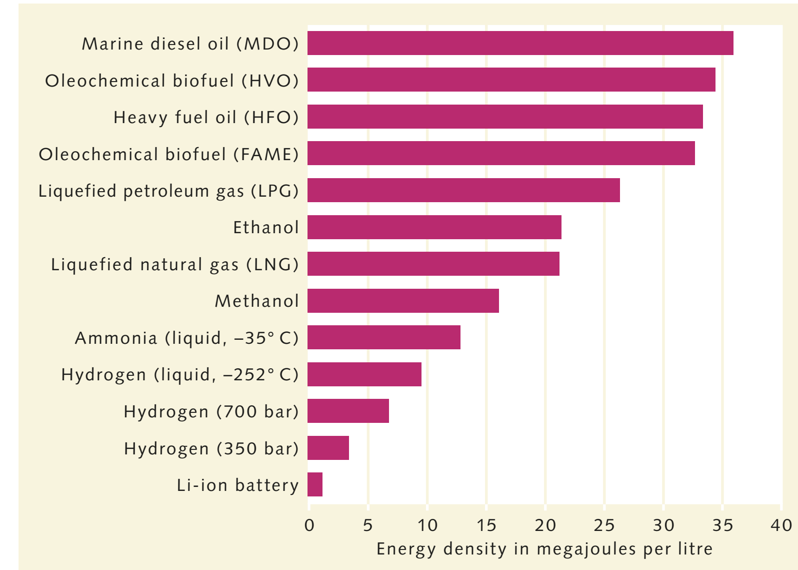
The emission reductions, however, fall far short of what is necessary to achieve the IMO target or the goals of the Paris Agreement. LNG is thus largely considered to be only an interim technology, although even this view is now being disputed. Conservationists and climate activists argue that although the burning of natural gas releases less carbon dioxide than burning heavy fuel oil, such large quantities of the greenhouse gas methane escape during the production, storage and transport of LNG that the overall global warming impact of using LNG is at least equal to if not greater than burning oil for propulsion. Experts are therefore calling for improved greenhouse gas determinations for all marine fuels, including biofuels, that will take into account emissions during production as well as those from combustion.

Ship designers worldwide are currently testing several potential new fuels, including hydrogen, ammonia, methanol and biofuels. But with all of the alternatives they are still being deterred by the economic limitations. The new fuels are still more expensive than heavy fuel oil. In addition, they are less efficient, which means that larger quantities are necessary, in turn making their storage more expensive and subject to strict safety regulations. Moreover, many ports currently lack the infrastructure needed to provide sufficient quantities of alternative fuels.

What is required, therefore, are new energy-efficient propulsion systems combined with tank facilities large enough to store the necessary amounts of fuel. The international merchant fleet presently requires an annual energy supply on the order of 3.3 petawatt hours. This would be enough to supply the greater New York City area with electricity and heat for more than 60 years. According to calculations by the International Energy Agency (IEA), more than 80 per cent of the fuel required by merchant shipping could be provided by sustainably produced biodiesel, ammonia and hydrogen by 2070. However, this progress assumes that around 13 per cent of the hydrogen produced worldwide will be used in shipping by that time, as well as a continued increase in the energy efficiency of transportation. Specialists at the Global Maritime Forum, on the other hand, speculate that sustainably produced ammonia will be the primary fuel for ships in the future because it is more economical to produce and store than hydrogen.

Initial tests for improving the energy efficiency of ship propulsion are already underway. In August 2018, for example, the Mærsk shipping company installed two Flettner rotors on their tanker *Mærsk Pelican* for trial purposes. These are large cylinders installed vertically on the ship's deck like sailing masts. When the wind flows past these turning cylinders, a power of up to three megawatts is generated that propels the ship at right angles to the wind. In the first year they were used, the rotors helped the tanker to save 8.2 per cent in fuel and 1400 tonnes in carbon dioxide emissions. These savings are far short of the IMO target, but the company has decided to keep the rotors and continue to let the wind augment the propulsion of the tanker.

There are already propulsion systems working in submarines that most experts hope will become the future for merchant shipping. The underwater vehicles use fuel-cell technology and are powered by hydrogen stored in metal hydride storage systems. In commercial shipping, fuel cells have been tested as a source for on-board energy and have proven to be more efficient than comparable diesel units. However, the fuel cells have not been



4.16 > High-energy-density fuels are required to power ships' motors. This chart illustrates that low-emission alternatives like hydrogen have less than half the power of marine diesel oil.

4.17 > All emission reductions are important. For this reason, a number of operational measures as well as various kinds of new or advanced technology are being considered in the shipping industry. This summary shows the energy savings and resulting fuel savings associated with each of these.

Energy efficiency solution		Energy and greenhouse gas emission savings
Design and technology options		
Design modifications and structural optimisation	Increase in ship carrying capacity	10 % (for larger ships) to 25 % (for smaller ships)
	Increasing the length/beam ratio	3 % to 5 %
	Higher strength steel, material substitution	0 % to 1 %
Reduction of drag/skin friction	Hull surface texturing	2.5 % to 7.5 %
	Air lubrication	0 % to 13 %
	Wake equalising and flow separation reduction	1 % to 3 %
Increasing propulsion efficiency	Pre-swirl devices	2 % to 6 %
	Post-swirl devices	2 % to 6 %
	High-efficiency propellers	3 % to 10 %
Renewable energy integration	Sails	Up to 30 % in best cases, where applicable
	Flettner rotors	8 % on average, and up to 20 % in best case, broader applicability than sails
	Solar electricity	0 % to 1 %
Machinery improvements (main and auxiliary engines)	Main engine performance measurement and control	1 % to 2 %
	Waste heat recovery	5 % to 11 % (requires large engine power)
	Engine hybridisation and optimisation of engine size, power and loads (includes de-rating)	0 % (steady engine load) to 24 % (dynamic load)
Operational improvements		
Speed reduction		27 % hourly fuel consumption reduction at 10 % reduction in speed
Weather routing		2 % to 5 %
Trim/draft optimisation		1 % to 2 %
Hull and propeller condition management and maintenance		3 % to 12 %
Ship system management – includes reducing on-board energy use, fuel consumption measurement and reporting		Enabler of energy saving technology developments
Overall energy efficiency management – includes the application of the IMO Ship Energy Efficiency Management Plan (SEEMP)		Enabler of energy saving technology developments

powered by hydrogen but by other fuels like methanol, natural gas or diesel fuels. These fuels are more accessible and are often easier to store.

The use of hydrogen-powered fuel cells for ship propulsion, on the other hand, is still in the early test stages, with applications so far limited to smaller passenger ships, ferries or sport boats. Fuel cells big enough to power large merchant ships do not yet exist. One reason for this may be that the associated propulsion technology as well as the hydrogen fuel itself are still significantly more expensive than a diesel motor powered by heavy fuel oil.

Seaports and climate change

The severe impacts of climate change are already being felt by the international shipping industry, especially in ports, the hubs of international transport chains, whose exposed locations in low-lying coastal areas or estuaries make them particularly vulnerable. When ports are forced to interrupt their operations due to extreme weather events, the transportation of goods comes to a complete standstill – with radical consequences. In August of 2005 in the USA, as a consequence of Hurricane Katrina, three ports through which 45 per cent of all agricultural products were normally imported and exported had to be closed, causing a nationwide increase in food prices of three per cent. Reports indicate that Hurricane Harvey had a similar impact on fuel prices in 2017.

A survey by the magazine *The Economist* revealed that more than half of the goods traded globally pass through ports that are exposed to high risk due to climate change, whereby the ports situated in estuaries or river courses are often subjected to different climate impacts than those directly on the coasts. Scientists, however, see an increasing risk of damage for all 136 mega-port cities in the world. The most severe impacts of climate change on ports include the following:

Flooding as a result of rising sea level and increasing frequency of storm surge events

The consequences of rising water levels are not limited to the suspension of loading operations for the duration of the flooding, but also include long-term damage to loading facilities, containers, warehouses and railways in the entire port area. According to a study in 2018, a one-metre rise in sea level by 2100 will likely result in the flooding of more than 60 per cent of all European seaports, with extremely high waters of up to three metres above mean sea level included in the calculation. Many seaports in Greece, Great Britain and Denmark could face the danger of flooding as early as 2080.

Heavy rainfall resulting in high water levels or flash floods

Extreme rainfall can lead to rising water levels and flash floods, as well as flooding and erosion of riverbanks. Not only are important streets, bridges and rail connections in the ports damaged, but also the port facilities themselves. Poor visibility, wet soils and strong currents in river ports also increase the danger of accidents when ships are loading and unloading. Another problem is sediment displacement, which can alter the shape of river beds and affect shipping traffic.

Rising temperatures, heatwaves and severe drought

Not only do rising air temperatures and heatwaves endanger the health of passengers, ship crews and port personnel, extreme heat also affects railways, streets and other paved surfaces, which are abundant in the ports. Moreover, the water levels of rivers decline during extended periods of drought, which makes it difficult to operate port facilities located on rivers. In the Arctic region, warming is thawing the permafrost and causing harbour structures to lose their foundational stability. At the same time, the riverbanks and sea coasts are eroding, which is strongly affecting port operations in many areas.

Extreme winds and waves

Storms and high waves have catastrophic impacts. They exacerbate coastal erosion, wash over or undercut port facilities, and cause damage to cranes, vehicles and other exposed equipment. Furthermore, loading operations are interrupted during heavy storms, increasing the costs and financial losses for the port operators. Ports in the paths of

Metal hydride storage
Hydrogen can be stored by bringing it into contact with certain metal alloys. These react with the hydrogen to a metal hydride, which binds the hydrogen chemically in its metal lattice. To release the hydrogen, only heat needs to be applied. In this manner more than ten times as much hydrogen can be stored than in a pure pressurized tank.

The Port of Rotterdam – flooding as a calculated risk

The Port of Rotterdam in the Netherlands, Europe's largest commercial port, has been pursuing an ambitious programme to adapt to the consequences of climate change since 2008. It focuses on flood protection, which the port operator is addressing in close cooperation with the city administration, the Dutch government, and companies located in the port area.

4.18 > The arc-shaped gates of the Maeslant Barrier close when the Rotterdam metropolitan area is threatened by a storm surge. It protects the city and the port from high water levels.

Based on calculations that assume a rise in sea level of 35 to 85 centimetres during the period from 1990 to 2100, the project partners studied the flood risk for all sectors of the port and established a detailed plan of measures. For example, electric power lines threatened by flooding were waterproofed or elevated, and buildings at risk were augmented with flood-protection technology. Furthermore, there is now a Disaster Management Plan that assures that in the case of flooding all work can be stopped according to an orderly procedure and then be resumed as soon as possible. For all new structures, the risk of regularly occurring flooding in the future must be taken into account from the outset, and appropriate protective measures included in their design.

Port authorities have also set a target for reducing greenhouse gas emissions by port and industrial operations by 95 per cent by 2050. After all, the emissions by businesses in the port area account for one-fifth of the total emissions of the Netherlands. Methods to achieve this ambitious goal include:

- electrification of many processes, which can then be powered by current from renewable sources;
- capture and subsequent processing or storage of carbon dioxide produced during the refining of fossil resources;
- use of biomass fuels in industrial processes where fossil resources were previously used;
- extensive use of alternative, low-emission fuels such as green hydrogen;
- establishment of a circular economy.

Through the digitalization of many information streams, the approximately 30,000 ships that call at the Port of Rotterdam each year can be processed more efficiently. This includes the timely sending of accurate arrival times to the ships.

Scientific studies in the Port of Rotterdam have shown that if all of the container ships arriving in 2018 had known twelve hours in advance when they were expected in the port (known as "just in time arrivals"), the ships' commanders could have reduced the speed of their ships accordingly, allowing reductions in fuel use and emission levels of four per cent.

Another field trial in December 2020 found savings of as much as eight or nine per cent when the captains received precise instructions up to 24 hours before port entry, and were able to adjust their ship's speed accordingly.

tropical storms are particularly hard-hit. In 2017, for example, Hurricanes Irma and Maria caused combined damages of USD 252 million in the ports, airports and streets of the British Virgin Islands alone. For one week, Hurricane Sandy paralysed operations in one of the largest container ports in the USA, resulting in economic damages and subsequent costs of up to USD 50 billion.

The protective and adaptive measures that port operators can take depends on the hazard level. Extreme events like storms or intense heat require different solutions than climate threats that progress gradually, such as the deterioration of Arctic permafrost coasts or permanent flooding due to sea-level rise.

Extreme events require protective measures that immediately reduce the risk. But as a rule, these are very expensive, particularly because the infrastructures in many ports are comparatively old and were not designed to cope with the present and imminent climate conditions.

Gradual processes, on the other hand, require long-term strategies that are in part dependent on political action. In many cases, in fact, the basic question has to be considered of whether the port has any future at all in the face of rising sea level. The possible courses of action are protection, raising, or moving, and each of these has its particular disadvantages. The construction of large protective walls leads to further coastal erosion, destroys near-coastal reefs and other habitats, and is also very expensive. Physically raising port terminals only makes sense when all of the other port facilities can also be raised with them. Efficient operation would otherwise be impossible. The decision to relocate a seaport, on the other hand, depends on the availability of an alternative site, with harbour approaches deep enough for the giant container ships and sufficient space to adapt to the continuing rise in water levels. The costs and environmental consequences of the new construction would likewise have to be assessed.

Ports as geopolitical outposts

Without a doubt, ports have a key function in the intermeshed flow of global commodities. Whoever controls them not only controls the import and export of goods in particular regions, thereby influencing their markets and economic development. Ports can also play a strategic role, for example, when they serve as ports of call and supply points for foreign naval forces. Until the 1980s, the world's ports were mostly in public hands. Their operations were organized either by the individual municipalities or directly by the state. With the introduction of container shipping, however, criticism of the public administrations became more and more frequent. The work of the ports was alleged to be inefficient, and they were accused of reacting much too slowly to the current needs of the transport industry. The World Bank recommended that coastal states and port cities privatize their ports by awarding concessions to operating companies that had sufficient expertise and capital to modernize the facilities and port operations at a pace matching the changes in the shipping industry itself and the growth of the global flow of goods.

Many stakeholders followed this advice and placed control of their ports or individual loading terminals into the hands of operating companies. Smaller companies like this had existed previously, but the privatization of many ports around the world allowed many of them to rise to the status of global players. These included the A. P. Møller-Mærsk group of companies, which includes not only the large terminal operator APM Terminals, but also Mærsk, the world's largest shipping company. A. P. Møller-Mærsk now operates container terminals around the world, enabling it to dovetail its shipping and terminal businesses in a highly cost-efficient manner.

The modernization of ports is showing results. Container ships in scheduled traffic now spend less than 24 hours in a port. In the most modern ports, the loading and unloading of container ships can be completed in as little as 14 to 15 hours. The ships are thus able to quickly continue their journeys, saving time and money. However, the privatization of terminals and ports also has its darker aspects. For example, western security experts criticize the fact that China, through its investments in European, African and South East Asian trading ports, is gaining control over these locations, and is establishing outposts where it had no influence previously. The People's Repu-

4.19 > Since the China Ocean Shipping Company (COSCO) took charge of the Port of Piraeus, more container ships loaded with goods from Asia have been calling at the Greek Mediterranean port.

blic denies such geopolitical ambitions. On the other hand, it has been expanding its influence for years.

The China Ocean Shipping Company (COSCO), although actually a large shipping company, is now the largest terminal operator in the world with regard to the total number of containers loaded. The company is active in 61 port terminals around the world and controls, among others, the Greek Mediterranean port of Piraeus, where, according to reports, COSCO has invested USD five billion in expansion and infrastructure. Container turnover in Piraeus has grown by more than 700 per cent since the takeover by COSCO, mainly because giant Chinese container ships that enter the Mediterranean via the Suez Canal are unloaded here and the goods are then distributed throughout the Mediterranean by smaller ships. This strategy is known as transhipment. COSCO is also investing in railway lines that can transport goods from Greece to the Balkans and Eastern Europe. This distribution directly from Piraeus saves time and is less expensive than having the giant container ships travel all the way to Rotterdam or Hamburg and then sending the goods from there to their ultimate destinations. Specialists therefore believe that Piraeus will soon become the busiest port in the Mediterranean region.

Another large Chinese port operator is China Merchants Group. By its own account, the Hong Kong based, state-owned company operates 41 ports in 25 countries and regions, including the port in Colombo, the capital of Sri Lanka and one of the busiest and most profitable container ports in the world. China Merchants Group also manages operations in the Port of Djibouti, one of the main supply ports for US and other international naval forces deployed to fight piracy in the Horn of Africa. This situation is a thorn in the side for many western security experts.

Direct collateral effects of shipping

While the greenhouse gas emissions from international shipping alter the sea in indirect ways by driving global warming, the transport of goods across the oceans

Retreating sea ice in the Arctic allows more frequent open passage

Climate change is transforming shipping, particularly in the Arctic region where the marked retreat of sea ice is opening up new shipping lanes. This is true for both the Russian marginal seas and the waters of Alaska. In places where the sea ice is receding, fishing boats are able to venture into previously unexploited fishing grounds. Drilling ships or platforms can exploit natural gas and oil deposits that were inaccessible before. Cruise-line companies can offer cruises toward the North Pole, and shipping companies and merchant enterprises may save considerable time and expense by shipping their goods and merchandise via the shorter Arctic sea routes from northern Europe to north-east Asia.

Shipping traffic in the Arctic region is still somewhat regionally focused, and a large proportion of the voyages are made in the summer and autumn, when the coastal waters are ice-free and the risk of accidents is smaller. But Russia in particular has been making a strong effort to develop the Northeast Passage through its Arctic coastal waters, which includes the Northern Sea Route, and thus make it more attractive for trans-Arctic voyages. New icebreakers are to keep the shipping routes open in the winter as well. The construction of ports and connected rail networks is expected to facilitate the transport of raw materials from the Russian Arctic. As a result, shipping traffic on the Northern Sea Route has already expanded immensely.

In 2017, around 10.7 million tonnes of freight were transported by ship through Russian coastal waters. In 2018 it increased to 20.18 million tonnes, and in 2019 to around 31.5 million tonnes. However, for complete trans-Arctic voyages from Europe to Asia, or vice versa, the savings have been relatively minor so far because of the high additional costs associated with sailing through Arctic waters, such as ice-worthy ships and specially trained crews. Furthermore, some of the Russian marginal seas are so shallow that only smaller ships can travel through the ice-free passages, which drives up the costs per tonne of freight.

Shipping experts therefore believe that shipping and trading companies will not invest in regular trans-Arctic service through the Northern Sea Route until profit-making transport is guaranteed. Models indicate that this will not be possible even for smaller freight ships until 2035, and for larger ships probably not before 2051. Until then the transport of goods from Europe to Northeast Asia will continue to traverse the much longer southern sea route, from the Mediterranean through the Suez Canal and the Indian Ocean.

4.20 > Shipping traffic through the Northeast Passage has mainly been limited to regional transport so far, including the transportation of liquid gas from the Arctic to Europe or East Asia. But the further and earlier in the year the sea ice recedes, the more attractive it becomes as an alternative to the Suez Canal route. In January of 2021, for the first time, three LNG tankers made the passage in winter without the help of an icebreaker. Further voyages of this kind will follow.

Cruise tourism – amusement at the expense of the environment, people and the sea

In the 1960s and 1970s, as more and more transatlantic travellers began opting for planes instead of ships, the passenger-ship industry had to find a new business concept to attract people back to their ships. US-ship owners looked to their fellow countrymen's appetites for gambling and leisure. These were the formula for success in Las Vegas. Why wouldn't ships be able to function as a combination hotel, bar and casino? The idea paid off beyond all expectation. Blackjack, poker and duty-free shopping attracted people to the sea in droves, and since the 1990s, cruise tourism has become the foundation for the fastest-growing travel sector worldwide. According to the Cruise Lines International Association (CLIA), international participation in cruise tourism increased during the period from 1990 to 2018 from 3.8 million to 28.5 million passengers, half of them from North America and one-quarter each from Europe and the rest of the world. The growth continued until the outbreak of the corona pandemic in 2020, when the number of passengers fell to around seven million.

Up to that time, according to the German Environment Agency, there were over 500 cruise ships in operation worldwide, the largest of which could carry more than 6000 passengers and 2200 crew members. These floating cities are still operating today, primarily in the Caribbean and the Mediterranean Seas. But the traffic on secondary routes in Asia, Europe and the polar regions had also increased significantly by 2020, so that experts now speak of a global branch of industry. In 2018, the cruise-ship branch employed 1.18 million people and generated a total aggregate value of USD 150 billion.

The largest share of cruise-line income is reaped by three corporate groups: the Norwegian Cruise Line Holdings, the Royal Caribbean Group, and the Carnival Corporation & plc. Together they control 77 per cent of the market. The tourism profit chain has been perfected by these three companies to such an extent that the coastal resort locations the ships visit hardly profit from mass tourism any more. The passengers only spend a short time on land. For the most part they eat, drink, shop and relax on board, even though, in most cases, the cities they call on, or nations in the case of island states, have financed the expansions of ports and supply facilities that made it possible for the ships to dock there in the first place.

Only the cities that serve as departure and destination ports still profit to a meaningful extent from the ship passengers, but even here the ship companies have taken over the cruise terminals as well as taxi and bus lines that bring the tourists to the ship at the beginning of the trip and back to the train station or airport at the end. In the Caribbean, ship companies have even bought entire islands so that they can offer shore excursions while taking in 100 per cent of the resulting profits.

The destination cities and, above all, the environment pay a heavy price for the expansion of the cruise-ship industry. The most severe consequences include:

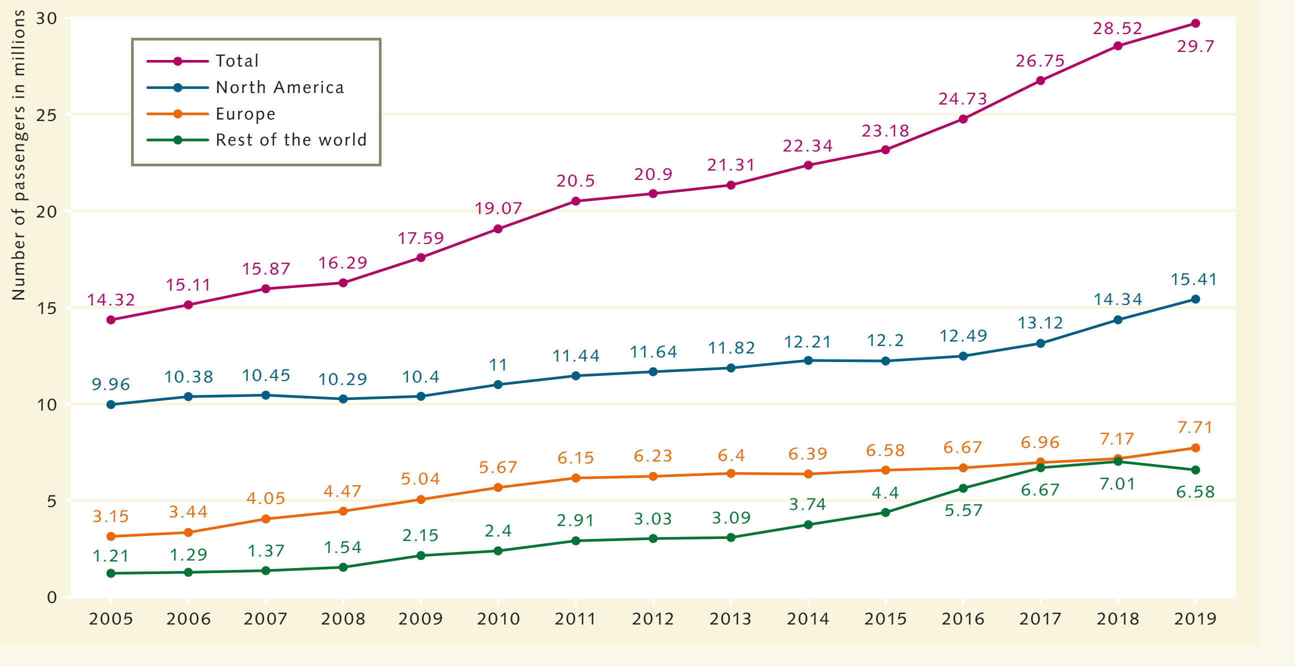
- **Massive waste arisings:** An average of 4400 kilograms of garbage is produced each day on the large cruise ships. This is often offloaded in the transit ports and overburdens local landfills or incineration plants. Reports that ships dispose of the waste on the high seas are also not uncommon.
- **Large quantities of wastewater:** Insufficiently treated wastewater carries nutrients as well as pathogens such as enterobacteria and viruses into the sea, with diverse and complex impacts upon marine biological communities.
- **Major exhaust emissions:** By the burning of fossil fuels, cruise ships release large amounts of gases, particulate matter and other pollutants. In many places, the motors continue to run in the ports in order to supply the ship with electricity, and the port cities have suffered severely from the pollution, especially with regard to air quality. For example, in 2017, before the new IMO fuel regulations came into effect, cruise ships of the Carnival Corporation emitted ten times more sulphur oxides in European waters alone than the more than 260 million passenger cars that travel on European roads.
- **Large volumes of ballast water:** The ballast water of cruise ships also contains wastewater, oil and oil-bearing substances, as well as bacteria and organisms from other regions of the world. When this water is released into the sea there are many largely unpredictable consequences for local ecosystems.
- **Enormous noise and light pollution:** Cruise ships are brightly lit at night and, except for the brief intermediate stops for shore excursions, are constantly underway. The resulting immense light and noise levels are especially stressful for marine organisms and seabirds.

Several years ago, the United States Environmental Protection Agency estimated that every day on board a cruise ship with more than 3000 beds, around 80,000 litres of wastewater, one tonne of garbage, more than 640,000 litres of greywater, around 24,200 litres of oil-polluted bilge water, more than eleven kilograms of batteries, fluorescent lights and medical waste, as well as four plastic water bottles per passenger are produced. With this in mind, and considering that about 70 per cent of the ports visited by cruise ships lie in regions with especially high marine species diversity, the potential damage from improper disposal of this garbage and effluent is very evident.

The industry is reacting to the environmental protection requirements of the IMO and to criticism from scientists and environmentalists with technical innovations. Lower-emission fuels (especially LNG), exhaust filters, wastewater treatment and waste incineration systems, the elimination of disposable tableware, and a shore power supply during port stops are supposed to improve the environmental balance of mass tourism at sea. However, experts seriously doubt that this type of business can truly be carried out sustainably. After all, the ships are bringing countless thousands of people to places that are often no longer able to cope with such a large influx of visitors. This is not only true for small Caribbean islands, but also for large tourist cities like Venice, Barcelona and Palma de Mallorca. And if a destination loses its appeal, perhaps because the coral reefs have died or the island is covered with tourist garbage, the caravan of cruise ships moves on to find a new, as yet untarnished dream destination.

Working conditions on the ships are also often criticized. Most of the employees have only short-term contracts and many work for low wages. When ships were immobilized around the world because of the corona pandemic, many of the workers were not allowed to travel back to their home countries. They were trapped on the ships without pay and with no bargaining power.

The extent to which this industry will be able to recover from the loss of passengers due to the corona pandemic remains to be seen. Some market specialists are predicting a possible end to the golden era, while others see a good chance of a renaissance. The question of whether mass tourism at sea continues to have a future ultimately depends on millions of customers who want to pursue their dream of a sea voyage, while giving little or no thought to the social, ecological and economic footprint that cruise tourism leaves behind.



4.21 > Until the outbreak of the corona pandemic, the cruise-line branch was reporting new passenger records every year. Around half of the holidaymakers came from North America, a quarter from Europe and another quarter from the rest of the world.

4.22 > When the world's largest cruise ship, *Harmony of the Seas*, was being built, thought was also given to fun in the pool. With a length of 66 metres each, the two red tubes are the longest water slides on a ship.

also has very direct impacts. The most important of these include:

- noise pollution from the propeller and motor, and other sounds caused by the ships;
- pollution of the marine environment by exhaust and the illegal dumping of wastewater and garbage;
- the introduction of alien species in the ballast water or attached to the ship's hull;
- pollution of the sea by poisonous anti-fouling coating;
- collisions with large marine mammals.

Noise in the sea

The sea is not a naturally quiet habitat, especially not in those regions where wind, tides or currents move the water masses and where vibrant life is found. Whales sing and click, more than 800 fish species are known to drum, grunt or bark, seahorses gnash with their skull bones, and snapping shrimp snap with their large claws. These sounds are produced to communicate with other members of their species: to warn the others of danger, to find the perfect partner for mating, for navigation, or to hunt prey. Sending out acoustic signals and being able to hear them are thus important survival traits for many marine organisms, from the very smallest zooplankton to the largest of marine mammals.

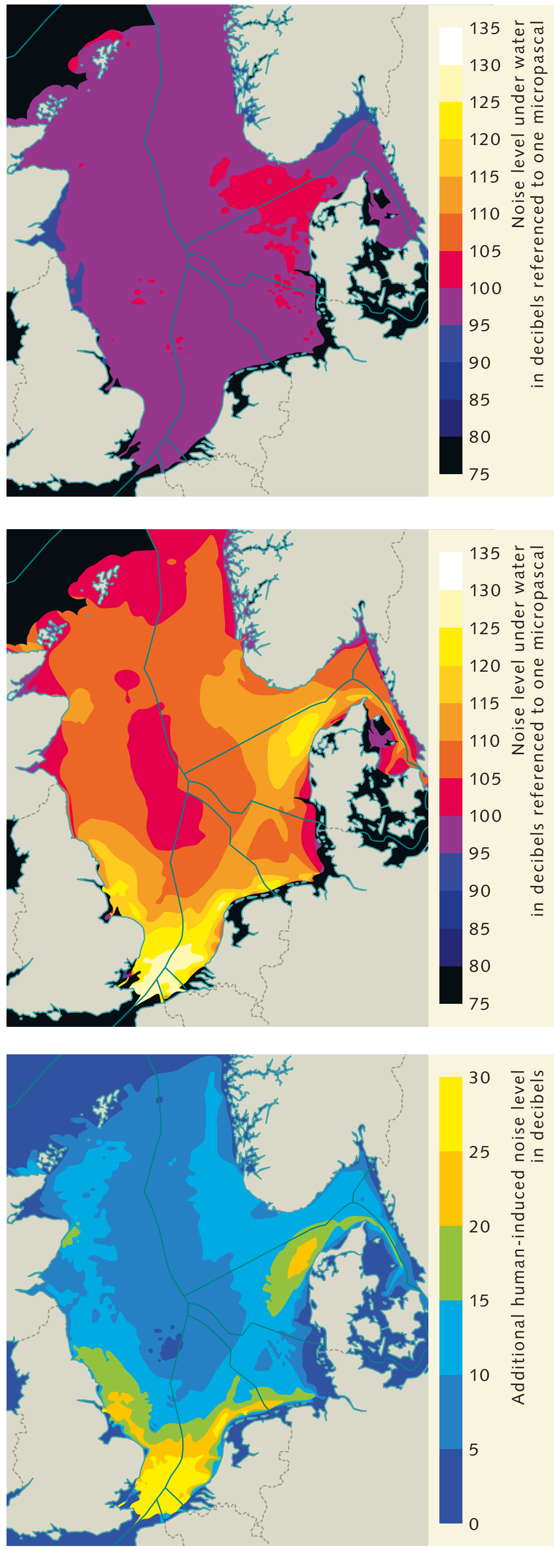
Communication through sound functions in the light-washed surface waters as well as in the darker depths or in cloudy waters. In normal circumstances it is extremely efficient because sound waves propagate five times faster through water than in the air, and lose almost no energy in the process. This means that sounds in the deep seas can travel thousands of kilometres in some cases, a property that baleen whales, among others, take advantage of. Their songs can be heard over distances of hundreds of kilometres. Smaller marine inhabitants like the North Sea painted goby *(Pomatoschistus pictus)*, on the other hand, produce comparatively subdued sounds when they want to communicate with a potential mating candidate. In this case, the fish closely approach one another and communicate over a short distance of about two body lengths.

But successful communication with sounds is becoming increasingly difficult for most marine animals because more and more noises generated by humans are being added to the natural background of sounds in the sea. Researchers distinguish two categories of anthropogenic sound. The first comprises noises that occur unintentionally or as a by-product of human activity. These include the sounds of motors and propellers made by all motor-driven boats and ships, but also noise caused by the beam trawls and nets deployed in trawler fishing. It also includes loud construction sounds on bridges, drilling platforms, harbour and wind-power installations, as well as explosions during naval exercises.

The second category includes sounds that are produced intentionally because humans use them to make underwater measurements. Fishers use echosounders to hunt for schools of fish. Geologists and geophysicists use seismic airguns to study the stratigraphy of the sea floor, and the oil industry uses these same tools to explore for undiscovered deposits beneath the sea.

In extreme cases these activities may produce noises so loud that the sound waves can cause physical harm to marine animals, such as loss of hearing or even death, for example, when an airgun is discharged to search for oil or natural gas. Pile driving for bridges and wind turbines produces intensities that rupture the swim bladders of fish in the close vicinity. Zooplankton die in such large numbers that scientists now use their mortality rates as a benchmark for accompanying studies.

Researchers generally distinguish between impulsive and continuous sound. The former has a short duration, but for marine organisms it is completely unpredictable. For this reason, the animals cannot adapt their behaviour. With continuous sound, on the other hand, adaptation is theoretically possible. This type of sound may be produced, for example, during the extraction of raw materials, but it occurs most commonly in marine areas with heavy ship traffic or near ports. Noise measurements in the North Sea by European researchers have shown that the regular ship traffic in the English Channel and beyond increases the natural sound level, which is caused predominately by wind in the southern North Sea, from 100 decibels to 130



4.23 > By its very nature the North Sea is a loud region. Winds and waves produce a natural underwater noise level of up to 100 decibels, as shown in the top map. Due to human activity, especially shipping, the noise level is increased by as much as 30 decibels (middle and bottom map). It is particularly loud along the shipping lanes in the English Channel and at the entrance to the Baltic Sea.

decibels. This may not seem like a lot at first but, because of the logarithmic nature of the decibel scale, a volume increase of only three decibels is equivalent to twice the intensity. Just for comparison, the intensity of a normal conversation between two people has a decibel level of 65, while screaming produces a level of around 80 decibels. Although the difference is only 15 decibels, the intensity level of screaming is 30 times that of the normal conversation. Applied to the increased noise level in the North Sea, this means that it is about 1000 times louder for marine life with ship traffic than without.

For various reasons related to measurement techniques, however, a conversion factor is necessary for comparing the loudness of noises above to those beneath the water surface. As a general rule, the volume measured above the water surface plus a constant of 61.5 decibels gives the corresponding volume under the water. This means that a sound with a volume of 70 decibels above the water is exactly as loud as a sound with 131.5 decibels underwater. As a result, from a human perspective, the background noise of ship traffic in the English Channel (130 to 135 decibels) can be compared to the noise level in a large, open-plan office (about 75 decibels).

But for the inhabitants of the sea, the increased noise level represents an enormous barrier to communication and a severe stress factor, comparable to the situation of two humans standing on opposite sides of a heavily travelled highway trying to share information crucial to their survival. The comprehension of long complex sentences is not possible under these conditions. Instead, they can only shout out catchwords to each other, gesticulate wildly or abandon the conversation entirely.

Marine animals react in ways very similar to this. Grey whales and minke whales call louder when ship noise can be heard. Painted gobies abandon one of their two mating calls and pay more attention to their partner's courtship movements, while seals and beluga whales dive to try to escape the noise. As a result of these and other behavioural reactions, some animals may eat less, which has a direct impact on their health and growth rates. Others may notice enemies too late, make the wrong choice of mate, produce fewer offspring or avoid certain marine areas altogether.

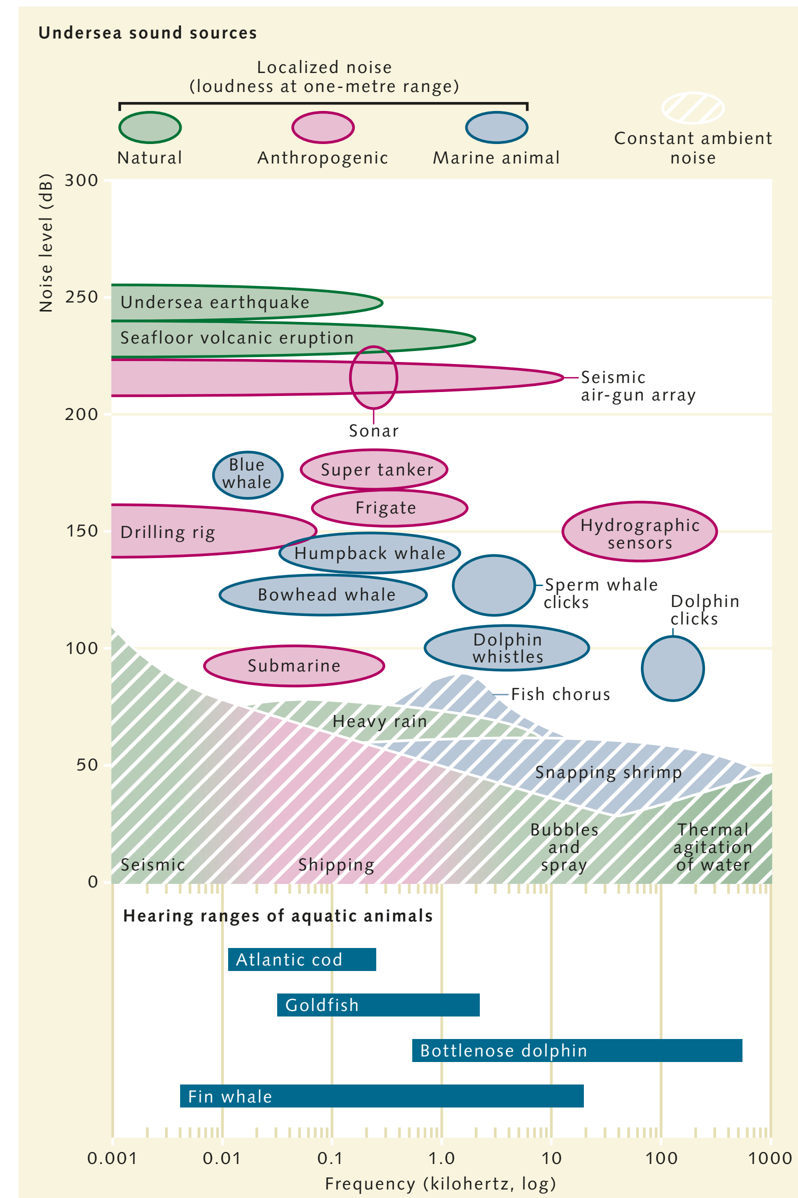
Ship noise therefore disturbs not only in the short term, it also causes long-term harm within the marine environment.

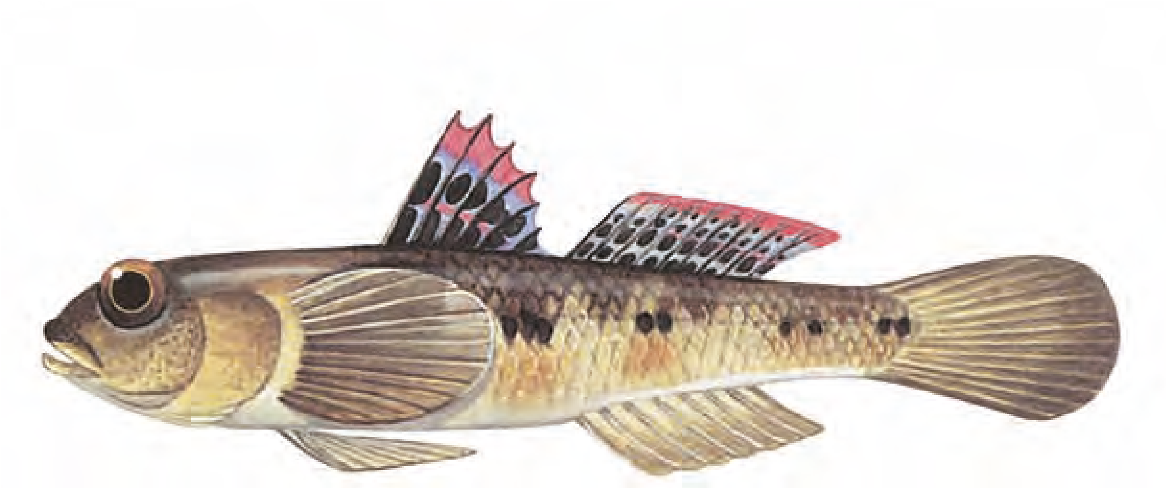
In order to stop this trend, the IMO adopted guidelines in 2014 to reduce underwater noise from ships. These address the following sources of noise:

- **Shape of the propellers:** The propellers are the greatest source of noise from a ship, because the churning of the water produces a lot of small bubbles that then collapse noisily. The number of bubbles can be reduced by better propeller design.
- **Suspension of the engines and other machine parts:** The transfer of engine noise and associated vibrations to the ship's hull and thus to the water can be mitigated, for example, by installing shock absorbers in the engine and gearbox mounts and by installing damping panels. The IMO also recommends vibration-damping suspension systems and mounts for other components such as pumps, pipes and air conditioners.
- **Design of the ship's hull:** The loudness of a ship is also influenced in part by the shape of its hull, because under certain conditions air bubbles can also form on the hull. But with the help of special software these flaws in hull shape can be detected and eliminated during the planning and design phase. It is also important that the design and position of the ship's propeller are carefully coordinated with the shape of the hull.
- **Cruising speed:** Extensive experimental trials have indicated that the cruising speed of a ship has a considerable influence on the noise level. The studies show that noise pollution is reduced by 40 per cent when the speed of the ship is reduced by only ten per cent. A slowdown programme in the Port of Vancouver has shown that the hunting success of the indigenous killer whales is improved by as much as 22 per cent when ferries, recreational boats, freighters and fishing boats limit their speed to eleven knots instead of 17.
- **Ship maintenance:** The hull and the drive propellers of a ship need to be cleaned regularly to remove any irregularities on the surface. Rough surfaces slow the ship down, and cause it to require more energy for propulsion. This results in more noise on the ship and in its marine environment.

In the European Union, the Marine Strategy Framework Directive of 2008 applies. This stipulates that, by 2020 at the latest, underwater noise must be limited to a level that does not harm the marine environment. However, achieve-

4.24 > Underwater noise created by humans extends over the entire range of frequencies at which marine animals communicate, and it is often so loud that it has a permanent impact on their lives.





4.25 > The painted goby likes it quiet. A laboratory experiment has shown that even low levels of additional noise are sufficient to disturb the mating ritual of these fish. The researchers are concerned that noise pollution produced by humans in the sea is having negative consequences for the fish.

ment of this target is still far from being realized. For example, although the year 2020 has already long passed, the responsible German authorities are still working on an approach by which the current state of noise in the sea can even be assessed. There is obviously still much to be done.

Ship exhaust and garbage

Port cities are among the places with the worst air quality. This is mainly because of the enormous amounts of sulphur oxides, soot particles, nitrogen oxides, aromatic hydrocarbons, heavy metals and other pollutants that are released by the combustion of heavy fuel oil and marine diesel oil. Sulphur oxides (SO_X), for example, are harmful to humans and the environment. Not only do they cause respiratory problems and lung cancer, they are also a leading cause of acid rain, which has negative consequences for forests, crops, and aquatic organisms. They are also contributing to accelerated acidification of the oceans.

The heavy oil formerly used as fuel in marine shipping contained particularly high levels of sulphur. Up to 3.5 per cent was allowed, which is equal to 3500 times the amount of sulphur content permitted in European road traffic. Since 1 January 2020, however, a stricter regulation has been in force according to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Convention). This states that ships outside of designated Emission Control Areas (ECAs) are only allowed to use fuel with a maximum sulphur content of 0.5 per cent. If the fuel used exceeds this value, the ship has to be fitted with an effective exhaust filter system (scrubber) and have it turned on. In the North and Baltic Seas, as well as in EU ports, the limit has been 0.1 per cent sulphur content since 2012. Compliance with these rules is monitored by MARPOL member states and their designated authorities. In their roles both as flag states and as port nations, these have the authority and the responsibility to inspect ships and enforce the MARPOL regulations.

The MARPOL Convention also regulates the handling of waste that is produced on board ships. Accordingly, with certain exceptions (food waste, non-hazardous cargo residues, cleaning agents and additives as well as animal carcasses), no waste may be disposed from ships into the sea. Since January 2013, this rule has been in force worldwide. In the Baltic and North Seas, the applicable regulations are even stricter because, like Australia's Great Barrier Reef, these two seas have the status of particularly sensitive sea areas. Such areas are worthy of enhanced protective regulations based on their unique animal and plant communities, due to certain social, economic or cultural characteristics, or because of their importance for science. In these areas, for example, the disposal of any animal cadavers generated during a voyage is not allowed. Discharging food waste into the sea that is not pulverized is also prohibited.

According to MARPOL, ships with a net tonnage of 400 or greater, or those with at least 15 persons on board, are required to keep a Garbage Record Book. It must document every discharge of garbage, regardless whether it is carried out at sea or in a port, including details of the time, precise ship's position, and the kind and amount disposed.

Ballast water
Merchant ships carrying little or no cargo take on ballast water to ensure sufficient draught and to improve stability. Before they can be loaded again with goods, they have to discharge the ballast water. In this way, organisms in the water are introduced into new habitats.

During ship inspections, the accuracy of these records is an obligatory part of the relevant check.

In spite of the clear provisions of the MARPOL Convention, significant amounts of garbage and other refuse are still dumped into the sea. The primary reasons for this include the illegal disposal of garbage at sea by ships, poor waste management practices on board, and the absence of appropriate receptacles for ships' garbage and sewage in the ports. Some crews also dump their garbage at sea in order to avoid paying the disposal charges in the ports, which can sometimes be quite high. Calls are therefore increasing for port operators around the world to stop charging for garbage disposal as an additional cost, but to include it as a fixed component of the basic port-use fee for all ships, regardless of whether or not each individual ship disposes of its garbage or wastewater properly in the port. In this way there would no longer be a reason for the illegal dumping of garbage. There is, however, a downside to this procedure. If the garbage fee is no longer calculated according to the total amount arising, there is no longer a pressing financial motivation to generate less garbage on board.

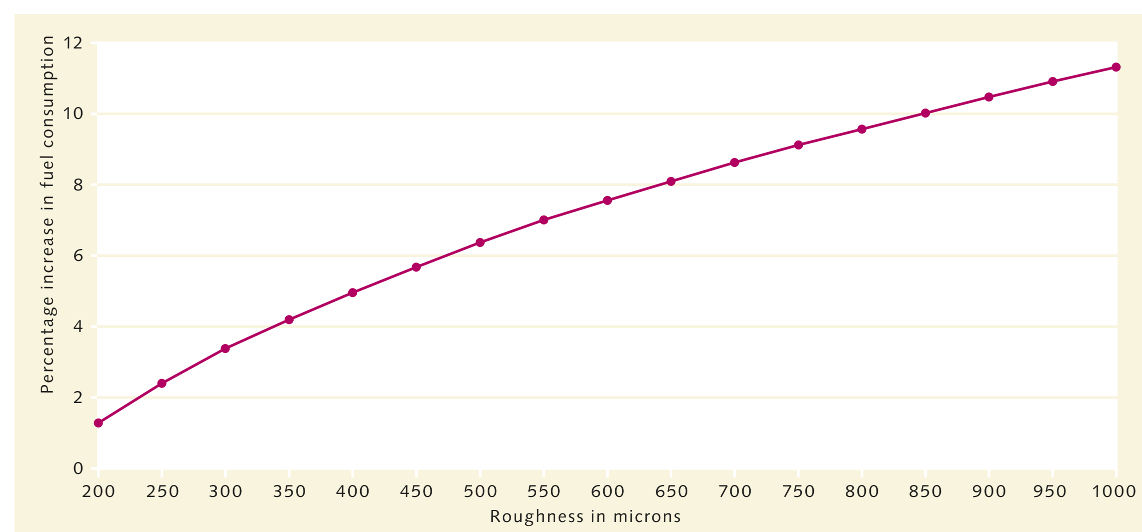
The IMO also recognizes a great deal of room for improvement in this area, and is now working with the Food and Agriculture Organization (FAO) on a new plan of action that aims to reduce the ship-generated input of plastic refuse into the oceans. Because sewage is also often dumped in the open sea, which contributes to eutrophication of the oceans, institutions such as the German Federal Maritime and Hydrographic Agency (BSH) and the Helsinki Commission (HELCOM) for the protection of the Baltic marine environment are compiling best-practice approaches and technical solutions that can be applied to improve sewage disposal.

Alien species in tow

Shipping traffic is one of the major causes for the spread of exotic or non-native marine organisms in the world. The immigrants travel from one marine region to another either in the ships' ballast water or attached to the hull or other exposed underwater surface. Although it was previously believed that most of the immigration was related to the discharge of ballast water, it is now known that as much as 69 per cent of all introduced species are due to growth on the ships' hulls.

Biofouling is the term that specialists use to refer to the unwanted attachment of microorganisms, algae and marine animals to ships' hulls, offshore drilling rigs or aquaculture installations. Arriving at the next port of call, or the one after, the invasive organisms fall from the outer hull of the ship, or they produce offspring that are released into the water column. If the environmental conditions in

Exhaust scrubber
Purifying ship exhausts by means of scrubber systems is not a sustainable approach, for this gives rise to liquid effluents polluted with contaminants and heavy metals that the ships generally discharge directly into the sea. In 2020 some 4300 ships worldwide operated exhaust scrubbers. They generated at least ten billion tonnes of effluent per year.



4.26 > As algae and other organisms grow on a ship's hull, its surface becomes rougher. This causes more friction between the hull and water, which means that more fuel is required to propel the ship through the water.

4.27 > A thin biofilm of tiny algae and microorganisms is enough to double the roughness of a ship's hull. If mussels attach themselves to the hull, the roughness is ten times as great.

Range of representative coating and fouling conditions	
Description of condition	Average coating roughness in microns
Hydraulically smooth surface	0
Typical as applied anti-fouling coating	150
Deteriorated coating or light slime	300
Heavy slime	600
Small calcareous fouling or weed	1000
Medium calcareous fouling	3000
Heavy calcareous fouling	10,000

the new location are favourable when this happens there is often nothing to prevent the new settlement, especially when there are no natural enemies or pathogens in the new area, and there are sufficient numbers of the introduced organisms to reproduce rapidly.

The introduction of non-native species can have very diverse impacts on the local marine environment. Sometimes the newcomers blend into the existing local communities without a problem, but in other cases they can completely disrupt them, become a nuisance, and cause fundamental changes in habitats and food webs – often with catastrophic consequences for the local marine economy and the coastal populations.

As an initial step to mitigate the spread of such invasive species by shipping, the IMO member states have adopted an International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention). This came into effect in September 2017 and requires, for example, that crews follow a ballast-water management plan tailored to their ship type, and maintain logs of every action taken. Over the long term, most ships will also have to be equipped with a water treatment system for the ballast water. As a clear guideline, whenever possible, ships should only discharge ballast water in marine areas that are at least 200 nautical miles from the nearest coast and in waters deeper than 200 metres.

However, this does nothing to eliminate the danger of the spread of alien species by fouling. To address this problem, a much broader and multi-sectoral approach is necessary. The forms of biofouling, according to experts, are extremely diverse, and the consequences and possibilities for combating it are too complex to allow for a simple solution. Furthermore, with the escalating use of the oceans by humans, the number of man-made surfaces to which organisms are able to attach is increasing, with a corresponding danger of displacement of the organisms. There are not only more ships, recreational boats, drilling rigs and aquaculture installations, but also drifting plastic garbage, fishing nets and much more.

The IMO has therefore issued guidelines for dealing with fouling, and in 2018 initiated a major research programme in cooperation with the United Nations Environment Programme and scientific partners. It is called GloFouling (the "Glo" stands for global) and it aims to develop tools and best-practice solutions in the fight against biofouling, and to identify ways of sharing information among scientists, officials and industry, and of implementing packages of measures from the national to local levels. The initiators also hope that the successful reduction of biofouling on ships' propellers and hulls will lead to improved energy efficiency and thus to significant reductions in fuel consumption and emissions by marine traffic. Studies suggest that the cleaning of propellers and hulls as well as the use of anti-fouling paints would result in energy savings of up to ten per cent.

But the latter method has had harmful environmental impacts in the past. Effective anti-fouling paints developed in the 1960s contained tributyltin (TBT) and other highly poisonous organotin compounds. This is one of the most poisonous chemicals to ever be purposely introduced to the environment by humans. Mussels, barnacles and algae that come into contact with TBT ship coating are killed. However, for a long time it was not recognized that the poison was leaching out of the anti-fouling coating, especially during harbour and shipyard work, and accumulating in the river and marine sediments as well as in the food webs. It thus became a threat not only for the bottom fauna in rivers and seas, but over time also for fish, marine mammals and ultimately humans.

For this reason, the use of tributyltin and other organotin compounds in anti-fouling paints has been prohibited since the IMO International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS Convention) came into effect in 2008. The development and testing of efficient but environmentally sound anti-fouling strategies and systems is a topic of current research. Until these can be developed, the ships' hulls and propellers must be cleaned every six to seven months, either by divers and robots in open waters or during layovers in the shipyards.

On collision course

Collisions with ships and other seagoing vessels are presently one of the greatest dangers for whales. For species like the North Atlantic right whale *(Eubalaena glacialis)*, whose migration route along the east coast of the US intersects with heavily travelled shipping lanes, it is an issue of basic survival. There are now only around 400 of these baleen whales left in the world. With every animal that is killed the total extinction of this species becomes more likely. According to the International Whaling Commission (IWC), humpback whales in the Arabian Sea, fin and sperm whales in the Mediterranean Sea, blue whales off Chile and Sri Lanka, Bryde's whales in the Gulf of Mexico, as well as the grey whales off the west coast of North America and whale populations around the Canary Islands are seriously endangered.

The collisions of whales with large ships such as tankers, cruise ships or cargo ships usually go unnoticed by humans, however, which makes quantification of the problem extremely difficult. However, the animals suffer severe external and internal injuries that often lead to death. The incidents can usually only be documented when carcasses wash up onto the shore and investigations are carried out to determine the cause of death. The cases

4.28 > Cleaning robots such as the *HullSkater*, developed in Scandinavia, will remove fouling and grime from ships' hulls with little effort in the future. Its use will eliminate the need for divers.

most frequently documented are collisions between large whales and all types of vessels. However, smaller species such as killer whales or dolphins are just as endangered as the grey, blue or humpback whales.

In order to reduce the risk of collisions with ships, the IWC has suggested the following measures over the past 20 years, some of which have already been implemented:

- creation of an international database on collisions between ships and whales;
- development of high-tech warning systems, such as heat detection systems to identify whale blows, buoys that can automatically detect whales, and microphone systems that locate whales and report their presence in real time to an information system;
- identification of high-risk areas where special precautions need to be taken for the protection of whales. These include, for example, the waters around the Canary Islands and off the east coast of the USA, as well as in the Gerlache Strait of the Antarctic Peninsula (cruise-ship tourism);
- identification of particular whale populations whose stocks are at risk of collision with ships;
- development of guidelines to help shipping mitigate the risk of collisions.

These guidelines recommend steering clear of areas with large numbers of whales, or planning the itinerary with reasonable foresight so that collisions can be avoided. In the Gulf of Maine, for example, an area highly frequented by large whales, shifting the shipping lane to the Port of Boston by just a few kilometres to the north would suffice to reduce the risk of collisions with the rare right whale by 58 per cent, and with other baleen whales by 81 per cent. If ships can not steer around the high-density whale territories, they may be directed to reduce their speed to less than ten knots in critical areas. At lower speeds the danger of collision is greatly reduced. Special observers on the ship's bridge as well as information and warning systems like Whale Alert, used off the east coast of the US, can help to verify the presence of the animals in time to avoid a strike.

4.29 > The danger of ships colliding with marine mammals has been a problem since people first went to sea. This drawing, made in 1886, appeared in the US magazine *Scientific American*, and illustrates the collision of the Dutch steam ship *Waesland* with a whale.

Conclusion

A key industry under pressure

In recent decades, international merchant shipping has been geared towards continuous growth. Larger, faster, always more. This has been the motto of the industry that transports between 80 and 90 per cent of all goods traded worldwide, making it the backbone of our global consumer society. For a long time, the climate and environmental impacts of this development were simply accepted. The industry's key role and the steadily growing importance of shipping for global production and supply chains made this possible.

But with the signing of the Paris Climate Agreement and increasing global awareness of the environmental and climate impacts of the transportation industry, maritime shipping now stands at a crossroads. Its highest regulatory body, the International Maritime Organization (IMO), has set a target to cut the greenhouse gas emissions of the merchant fleet in half by 2050, as compared to the emissions in 2008. Carbon dioxide emissions in particular are to be reduced by 70 per cent.

Operational adjustments such as reduced cruising speed and regular hull cleaning have a tangible fuel-saving effect, but these alone are not sufficient to achieve the emissions goal. A radical transformation of the entire industry is necessary. What is needed initially is major investment in the development of new propulsion systems and alternative fuels to replace the hitherto prevalent heavy fuel oil and marine diesel oil. Ammonia and hydrogen currently appear to be the most promising alternative fuels, but practical solutions for their use in maritime shipping are still lacking.

The next step is to equip the fleet with the new technological systems or to replace it from scratch, a process that will also cost a lot of money.

Globally uniform regulations, a supranational tax on greenhouse gas emissions, and strict controls by the flag and port states are vital in order to substantially boost research and development activities and provide investors with the planning security they so vitally need.

At the same time, coastal nations are facing the challenge of protecting their ports from the consequences of advancing climate change. In view of the rising water levels and the increasing frequency of extreme weather events in the future, the highest priority attaches to protective measures designed to mitigate the impacts of storm, flooding and extreme heat events.

Intensive efforts are also being made to combat the growing problems caused by coastal erosion. Some leading international ports like Rotterdam are developing their own climate goals and strategies to drastically reduce the high greenhouse gas emissions of all their port operations and all associated industries.

In addition, the direct environmental impacts of shipping, such as pollution by exhaust fumes, solid waste, liquid effluent and noise, and the issue of invasive species are gaining more attention. Some of these issues have already been recognized for decades and are being progressively addressed through international regulation. Scientists are just beginning to discover others, however. Noise pollution by shipping traffic, for example, has much broader consequences for the marine environment than was previously known.

The danger of collisions with large marine mammals is also comparatively new on the agenda. A number of studies suggest that anticipatory planning of routes in combination with slower speeds in areas of high animal density will be the most successful strategies.

5 Energy and resources from the ocean

> Today, industry and business are interested in a wide range of resources found in the ocean, including sand, crude oil and natural gas, while preparations are under way for the industrial exploitation of vast ore deposits in the deep sea. At the same time, governments and corporations are expanding the production of green electricity from the sea. Both of these developments will result in even more large-scale human interventions in the ocean environment.

Deep-sea mining – plans are taking shape

> The presence of valuable resources such as nickel, copper, cobalt and rare-earth metals in the ocean has been known for more than 140 years. So far, mining them was technologically scarcely possible and was unprofitable. However, climate action is causing demand for these metals and minerals to surge. The question arises whether they will continue to be mined only on land or can soon be extracted from the sea as well. Initial production tests have been carried out in the deep sea, but the environmental impacts have not yet been studied sufficiently.

Fundamental to technological progress

Mobile phones, internet and streaming TV have become as firmly embedded in our daily lives as electric vehicles, wind turbines and storage systems for the photovoltaic electricity generated in our homes. The increasing digitalization and electrification of our lives, however, has its price. To produce the necessary technology and expand the networks, large quantities of metals will be required, especially those of the rare earth group. Tungsten makes telephones vibrate, gallium and indium are necessary for light-emitting diode technology in lamps, semiconductors depend on silicon metal and hydrogen fuel cells require platinum-group metals.

Beside these, other mineral raw materials such as copper, nickel, cobalt, lithium and tellurium also have to be extracted from the earth using costly mining processes. As a rule, these activities are highly destructive to the environment, and in some countries the mining of raw materials also leads to corruption, war and the displacement of local inhabitants, and can have severe consequences for indigenous populations, especially when the mining is carried out in an unregulated or illegal manner.

These consequences loom even larger when we consider the fact that the demand for these metals and minerals can only increase with the various transformations in energy and transportation systems that result from our responses to climate change. Just two examples: It is now estimated that the European Union will require up to 18 times more lithium and five times more cobalt for the production of electric vehicles and energy storage in 2030 than was needed in 2020. According to the European Commission, the demand for rare-earth metals contained in the permanent magnets used for electric cars, digital technology and wind generators could increase tenfold by 2050. How to meet this mounting demand?

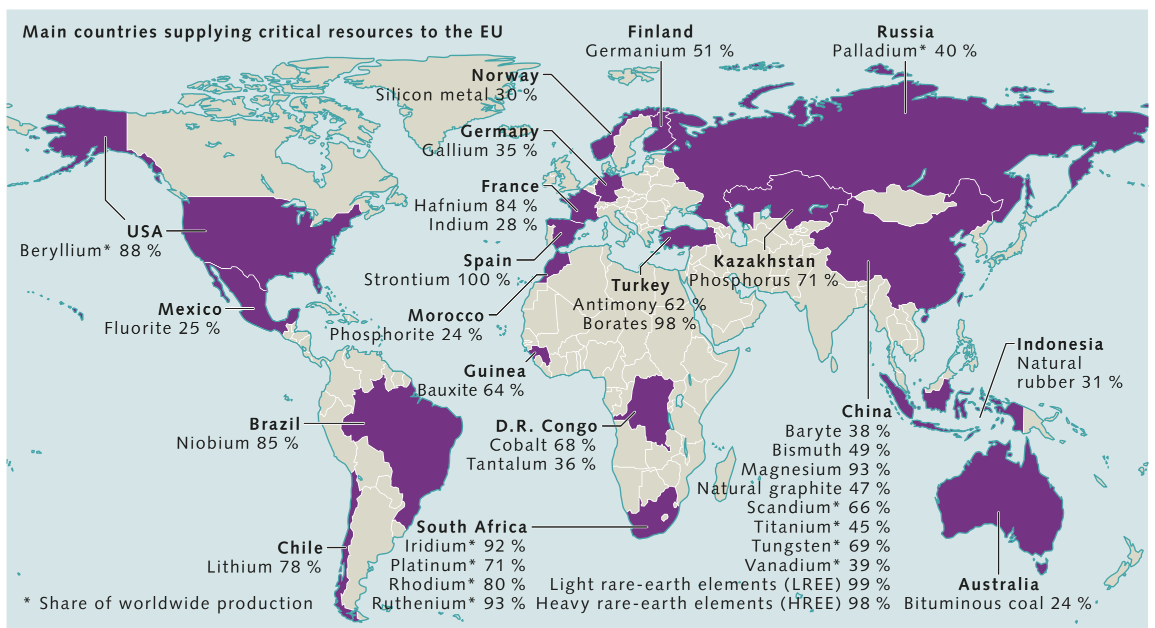
To date, there are only two areas on Earth where people have not yet engaged in commercial mining. One of these encompasses the entire Antarctic region, including all waters and land masses south of 60 degrees south latitude.

The Protocol on Environmental Protection to the Antarctic Treaty prohibits both the mining of mineral resources and the extraction of energy resources in this region. The latter include fossil materials such as coal, oil and natural gas. The second area as yet untouched by commercial mining is the bed of the deep sea. This can be defined as the bottom of the world's oceans at water depths greater than 200 metres.

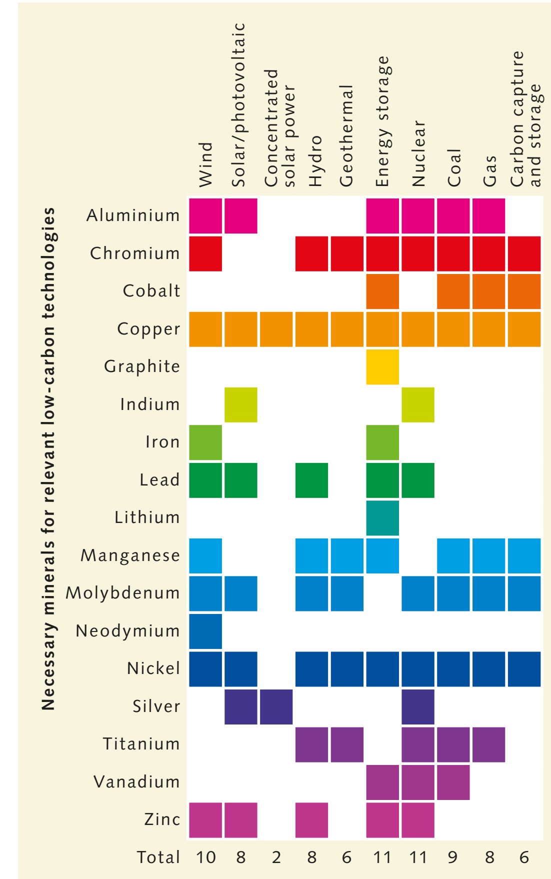
But the rising global demand for mineral resources is increasingly drawing the attention of the mining industry towards the oceans. There are a number of metals present in commercially promising quantities in the deep sea, including those of the rare earth group. Geologists distinguish three different kinds of potentially minable deep-sea ore deposits, each of which, unlike the deposits on land, contains a large variety of different metals. These three groups are manganese nodules, cobalt-rich ferromanganese crusts, and massive sulphides.

Manganese nodules

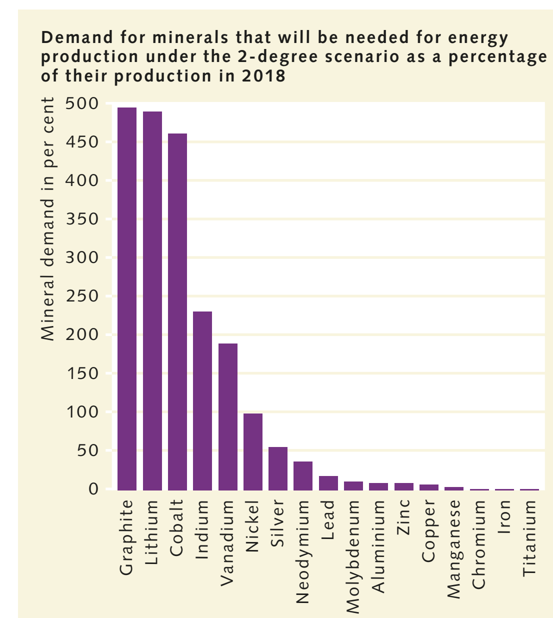
Manganese nodules are mineral bodies that are black-to-brown in colour, generally round with a diameter of one to 15 centimetres, and usually structured like an onion peel. They form primarily on the deep ocean floors covered by sediments (particle deposits) at water depths of 3500 to 6500 metres. Oxygen-rich deep water is necessary for their formation as well as a grain or nucleus, around which multiple layers of iron and manganese oxides are deposited over millions of years, along with minor and trace metals such as nickel, cobalt, copper, titanium, molybdenum and lithium.



5.1 > The European Union has to import many of the critical raw materials needed in Europe and relies on delivery of these from a few specific countries. There is an especially great dependency, for example, on China (99 per cent of all light rare-earth metals) and Turkey (98 per cent of the required borates).



5.2 > The global energy transition can only succeed if sufficient mineral raw materials are available. As many as eleven different metals are needed in the construction of wind turbines, photovoltaic systems and energy storage units.



5.3 > If mankind wants to limit global warming to two degrees Celsius by the year 2100, it will have to completely restructure its energy sector. According to the World Bank, the demand for products in the field of energy technology will increase significantly by 2050, especially for graphite, lithium, cobalt and indium.

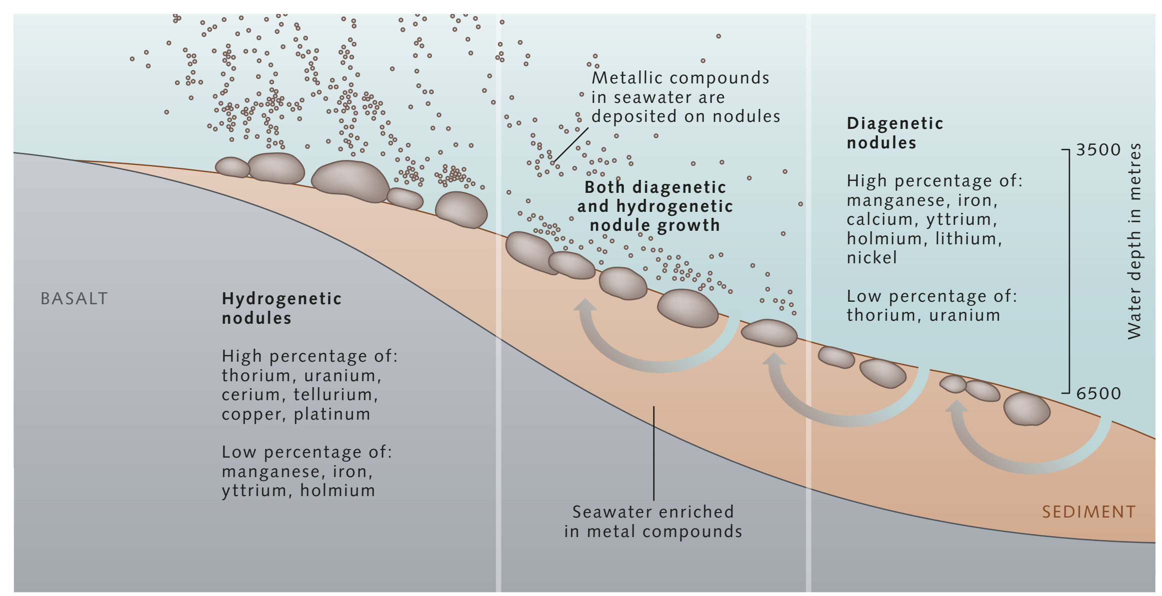
5.4 > Manganese nodules grow over time spans of millions of years by the precipitation of metals dissolved in the seawater or pore waters, forming in concentric layers around a nucleus. This gives them their spherical shape and onion-skin-like structure.

The nucleus is usually a piece of hard sediment or a nodule fragment, but may occasionally also be a fragment of basalt or other rock, or a piece of broken clam shell. Scientists have also found nodules that formed around a shark's tooth or the tiny inner-ear bones of a whale. The metals, on the other hand, are natural components dissolved in the seawater and the pore waters within the sediments, and are deposited onto the manganese nodules through diagenetic and hydrogenetic processes.

Diagenetic accretion occurs when metal oxides precipitate from the pore waters that circulate through the upper sediment layers of the seabed. Among other elements, these pore waters contain dissolved manganese, which diffuses upwards and trickles out of the sea floor due to differences in concentration. On contact with the oxygen-rich ocean water it is oxidized and manganese oxides precipitate. These accumulate in concentric spheres around the nucleus. Other metals dissolved in the pore waters, including copper and nickel, are also captured with the manganese oxide. These originate primarily from the microbial breakdown of organic material in the sea floor. They may also be released, however, through the dissolution of calcareous or silicate shells of dead plankton in the sediments. As a rule, manganese nodules extract more than 80 per cent of their metals from the pore waters. This constant supply of material allows them to grow, albeit no more than a few centimetres over a time period of a million years.

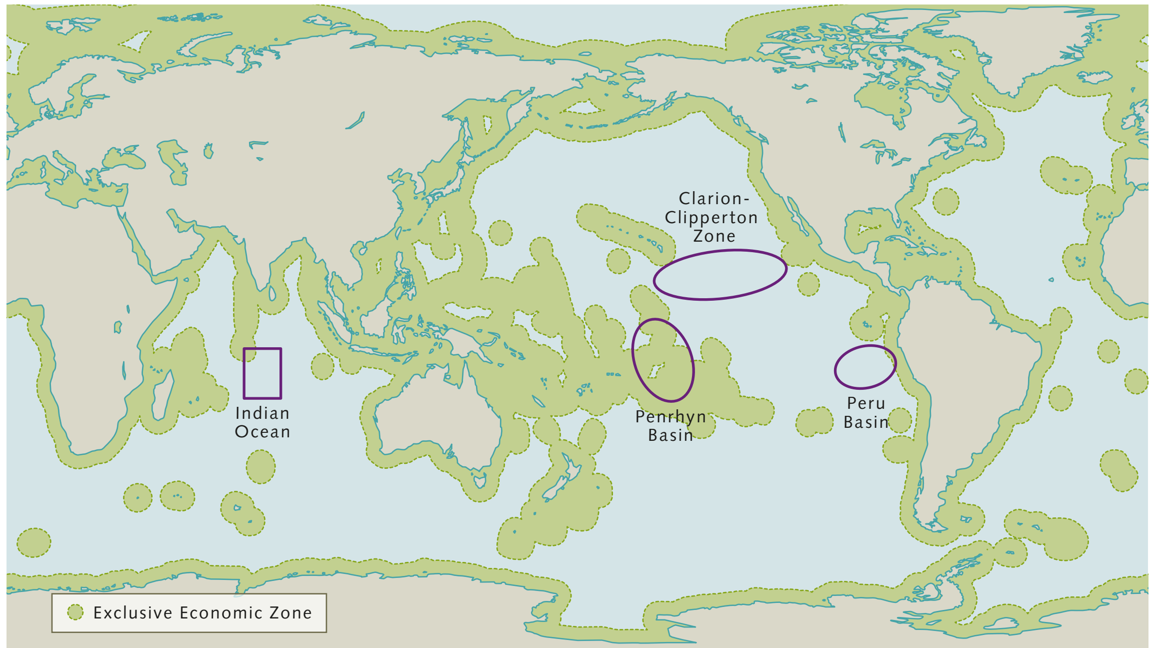
Hydrogenetic processes also contribute to the growth of most manganese nodules. These involve the precipitation of colloids (minute particles from one nanometre to one micrometre in size) of hydrated manganese and iron oxides directly from the seawater. Manganese nodules that are formed exclusively, or mostly, through hydrogenetic processes are found on the slopes or peaks of seamounts. Their composition is determined by the water chemistry and by biogeochemical processes between the seawater and the particles it contains. Nodules formed by hydrogenetic processes grow extremely slowly. Their diameter increases by only a few millimetres per million years. However, they accrete more cobalt and rare earth metals than the nodules of predominately diagenetic origin.

Manganese nodules are typically found lying detached on the sea floor, with usually between one-third and two-thirds of the nodule embedded in the sediment. In some areas there are only a few nodules per square metre of seabed, while other areas can have as many as 1000. The largest and economically most attractive occurrences are found in the manganese nodule belt of the Clarion-Clipperton Zone (CCZ). This is situated in the



5.5 > Manganese nodules grow in one way through the precipitation of metal oxides from the pore waters in marine sediments (diagenetic accumulation), and in another by the precipitation of manganese and iron oxides directly from the seawater (hydrogenetic accumulation). These two processes can occur simultaneously.

5.6 > The commercially most interesting occurrences of manganese nodules are found in the Clarion-Clipperton Zone of the North Pacific, the Peru Basin, the western Pacific Penrhyn Basin and the central Indian Ocean.



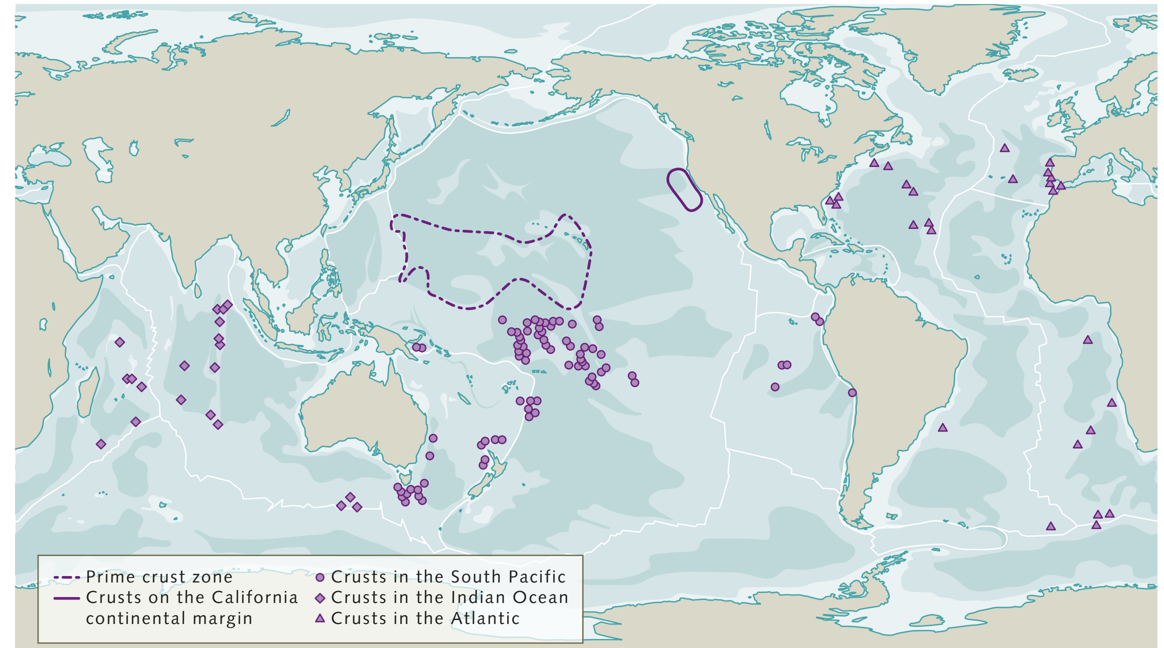
near-equatorial region of the North Pacific between Hawaii and Mexico. Other significant manganese nodule deposits are found in the Peru Basin (southeast Pacific), the Penrhyn Basin (western Pacific) and in the central Indian Ocean.

The manganese nodule belt of the Clarion-Clipperton Zone in the Pacific, with an area of around five million square kilometres (circa 5000 kilometres long and 1000 kilometres wide), is larger than the European Union. About three-fourths of this deep-sea area is characterized by a flat sea floor. Seamounts rise up throughout the remaining areas, some with heights of up to 1000 metres. On the deep-sea plains there are some areas where almost all of the nodules are large, ranging from four to 15 centimetres in diameter, and others where almost all the nodules are smaller than four centimetres. Smaller nodules cover around 85 per cent of the deep-sea plains in the Clarion-Clipperton Zone. Areas with larger nodules comprise about twelve per cent, and nodules are absent in the remaining three per cent of the areas. In areas especially rich in nodules, the clumps of ore are so dense that they commonly have a wet weight between 15 and 30 kilograms per square metre of seabed area. It is estimated that the Clarion-Clipperton Zone contains nodule deposits with a total wet weight of 25 to 40 billion tonnes.

These have attracted particular commercial interest because of their high contents of manganese (30 weight per cent), nickel (1.4 weight per cent), copper (1.1 weight per cent) and cobalt (0.2 weight per cent). These four metals are necessary, among other things, in the production of communication technology and electric cars and for steel refinement. Along with nickel and manganese, cobalt, which until now has primarily been mined in the Democratic Republic of the Congo, is also a particularly indispensable component of modern lithium batteries. Compared to all of the known deposits on land, the manganese nodules in the Clarion-Clipperton Zone alone contain around 3.4 to five times more cobalt, 1.8 to three times more nickel and 1.2 times more manganese. Moreover, the nodules also contain comparatively high proportions of titanium, molybdenum and lithium.

Cobalt-rich ferromanganese crusts

Cobalt-rich ferromanganese crusts are hard coatings of iron and manganese oxides that form on the slopes of



5.7 > Ferromanganese crusts are mainly found in marine regions with the oldest oceanic crust, where the ore deposits have had the most time to grow. This is the case in the western Pacific, for example.

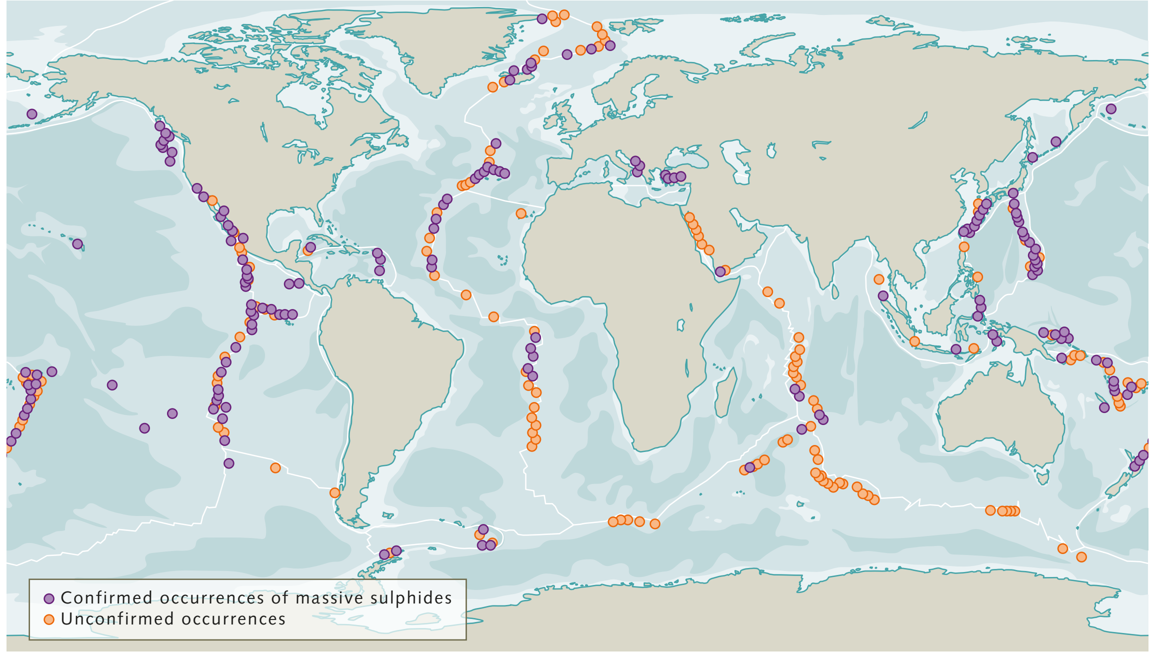
seamounts and, like hydrogenetic manganese nodules, obtain most of their metals from the surrounding seawater. Unlike in the flat deep-sea plains, no sediments are deposited on the slopes of the seamounts. Ocean currents wash away sinking particles rather quickly, so the ferromanganese crusts are only able to grow extremely slowly – about one to five millimetres per million years.

Various metals that are crucial for the production of modern energy supply, computer and communication systems are concentrated in the crusts. These include cobalt, titanium, molybdenum, zirconium, tellurium, bismuth, niobium, tungsten, rare earths and platinum. The rare metalloid tellurium, for example, is used both for cadmium-telluride alloys in thin-film photovoltaics and for bismuth-telluride alloys in computer chips.

Around two-thirds of the occurrences of cobalt-rich ferromanganese crusts that are considered significant for deep-sea mining are located in the Pacific Ocean, while 23 per cent are in the Atlantic and about eleven per cent in the Indian Ocean. Deposits in water depths from 800 to 2500 metres are considered to be commercially promising. The known crusts are generally three to six centimetres thick, in exceptional cases sometimes up to 26 centimetres, so experts calculate that they contain 60 to 120 kilograms of ore per square metre of slope surface. The total global quantity of cobalt-rich ferromanganese crusts is estimated at 40 billion tonnes, whereby only half of these could be profitably mined given the present state of knowledge. To date, however, much fewer than one-tenth of the known occurrences have been studied in detail.

Massive sulphides

Sea-floor massive sulphides are metal-sulphur compounds (metal sulphides) that form at hydrothermal vents on the sea floor, in water depths of 1600 to 4000 metres. These hydrothermal deposits are associated with volcanic structures and therefore occur primarily at tectonically weak points in the Earth's crust, for example, at mid-ocean ridges, at island arcs and in back-arc spreading zones. They form as a result of the circulation of seawater through the uppermost three kilometres of the oceanic crust. The seawater is heated by deep-lying heat sources (magma chambers) and transformed into a hot, acidic and highly concentrated solution that can dissolve metals from the volcanic rocks.



5.8 > Massive sulphides form at hydrothermal seeps, which only occur at tectonically weak points in the Earth's crust, for example at mid-ocean ridges, in back-arc spreading zones and at island arcs. As yet, however, only the occurrences at hydrothermal seeps that have cooled down are considered to be minable.

The hot hydrothermal solution eventually rises and seeps out of the sea floor at specific sites. When it comes into contact with the cold, oxygen-rich seawater, the dissolved metals are precipitated in the form of metal sulphides. These include, for example, pyrite, chalcopyrite and sphalerite.

As a result of the focused, upward flow of the hydrothermal solution at the hot seeps, spectacular chimney-like structures called "black smokers" are formed. These can reach heights of 20 or 30 metres, or even more. At some point, however, the chimneys become unstable and fall apart. Another chimney then begins to form and grows to a certain height until it also collapses. This continuous successive process results in the formation of metal sulphide mounds on the sea floor, which are subsequently further altered and consolidated by internal chemical reactions through the mixing of the hydrothermal solutions with penetrating seawater. These ore deposits can be several hundred metres in diameter and several tens of metres thick. In addition, the hydrothermal solutions can also precipitate their load of metals beneath the sea floor. This forms a zone of mineralization called a stockwork.

The sea-floor massive sulphides are the present-day counterparts to the fossil volcanic massive sulphide deposits on land. The latter are important sources of copper, zinc, lead, silver and gold. These same metals are found in the massive sulphide deposits on the sea floor. However, the current deposits in the sea contain additional minor and trace metals that are important for modern high-tech applications. These include cobalt, antimony, indium, selenium, tellurium, gallium, germanium, bismuth and molybdenum.

More than 630 active hydrothermal seeps with proven metal sulphide accumulation are now known to scientists. But hydrothermal fields always contain a combination of active and inactive areas. In this case, inactive means that no hydrothermal solutions are presently seeping out of the sea floor. For two reasons, only the inactive areas can be considered for possible mining of the massive sulphides. For one, it is assumed that there is less danger of the destruction of rare deep-sea ecosystems here than at active seeps. For another, in the active areas the high temperatures of several hundred degrees Celsius and strongly acidic solutions would probably damage the mining equipment in a very short time.

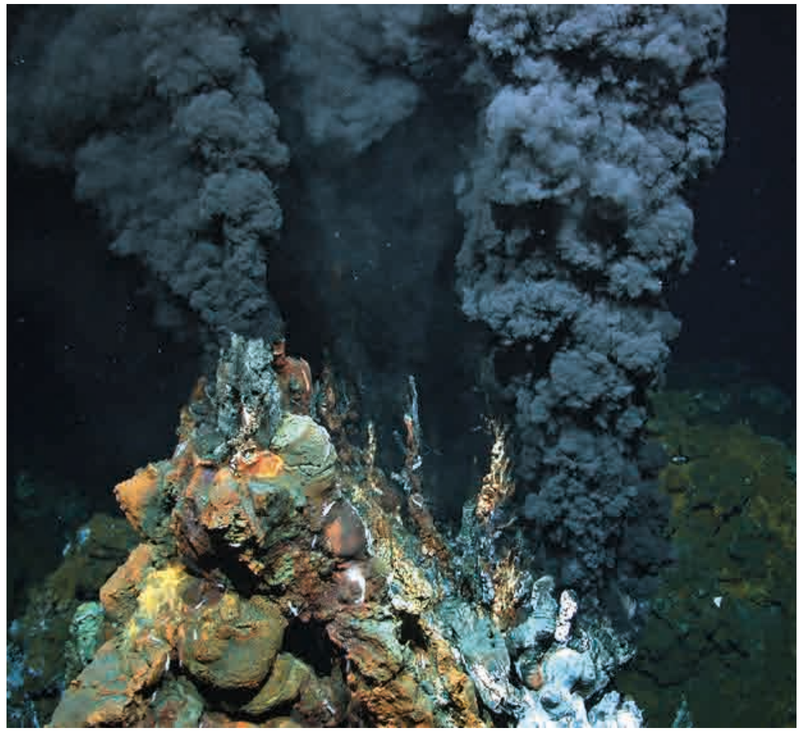
As yet, only a few completely inactive massive sulphide deposits are known. This is because inactive deposits are much more difficult to find than the active seeps. The latter can be located comparatively easily on the basis of their chemical signature and the particles that the escaping hydrothermal solutions produce in the surrounding seawater.

Guardian of the heritage of mankind

Around 81 per cent of all known manganese nodule fields, 46 per cent of the ferromanganese crusts and 58 per cent of massive sulphides are located in international waters, and therefore do not fall under the jurisdiction of any individual nations. Rather they belong to the common heritage of mankind, as Article 136 of the United Nations Convention on the Law of the Sea defines the sea floor outside of the Exclusive Economic Zone.

This heritage, which encompasses about 42 per cent of the Earth's surface, is managed by the International Seabed Authority (ISA), which has its headquarters in Kingston, Jamaica. It regulates and oversees all activities related to the commercial use of the international seabed and its subsurface. Furthermore, it is the obligation of the ISA to ensure the balance of interests between industrialized and developing countries as established in the Law of the Sea. Because no deep-sea mining is being carried out at an industrial scale as yet, its main tasks at present are to issue and oversee contracts for exploration of deep-sea deposits, to draft regulations for future mining, and constantly update the adopted statutory foundations. To date, 167 nations and the European Union have joined the ISA.

Applications for an exploration contract can be submitted by either states or private companies. As a prerequisite, however, the applicant has to pay a fee of USD 500,000 and the home state of the company, known as the "Sponsoring State", must support the application. In addition, the state must have adopted and implemented its own marine mining legislation, which it can use to verify compliance with the licensing obligations as well as the company's financial and technical capabilities at any time.



5.9 > Metal sulphides are precipitated where high-temperature hydrothermal solutions rise out of the sea floor and mix with cold, oxygen-rich seawater. They are deposited and, over time, form spectacular chimney-like structures called black smokers.

National regulations on marine mining may not be more permissive than the international regulations in this regard. The Sponsoring State is accountable for the activities of the contract partner it supports. In Germany, the State Authority for Mining, Energy and Geology (LBEG), headquartered in Hannover, is responsible for overseeing exploration activities.

Through its Federal Institute for Geosciences and Natural Resources (BGR), Germany itself holds exploration contracts for two areas in international waters. The first of these has been valid since 2006 for the exploration of manganese nodule deposits. The area involved consists of two tracts, both of which are located in the Clarion-Clipperton Zone in the Pacific Ocean. One tract lies in the central area of the manganese nodule belt, and the other is an area of about 60,000 square kilometres in the eastern part of the zone. Regarding the latter, around 20 per cent of the area may be considered minable for manganese nodules because only there is the seabed flat enough and the nodules present at a sufficient density to make mining worthwhile.

The second German exploration contract area encompasses a 10,000 square kilometre deep-sea region of the Central Indian Ridge and the Southeast Indian Ridge in the southwestern Indian Ocean, where abundant occurrences of sulphides are presumed to be present. Geologists of the BGR, together with deep-sea experts from other German research institutes, have been regularly carrying out expeditions to the contract area since 2015 in order to determine the extent of the deposits there as well as to study species diversity and evaluate the impacts of possible mining activity. In the German contract area they have now discovered twelve sulphide deposits with 30 active and 34 inactive sites (e.g., sulphide mounds with numerous chimneys). Based on chemical and physical investigations in the water column, evidence has been found for twelve additional deposits.

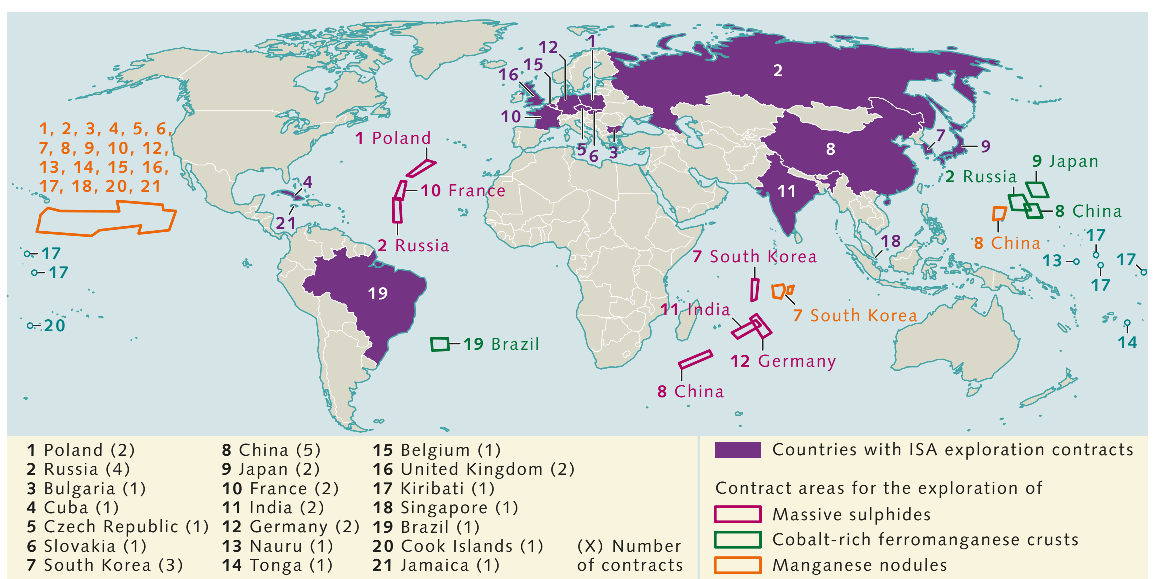
Plans are progressing

Since the year 2002 the International Seabed Authority has issued 31 contracts for exploration rights for mineral resources on the sea floor. There are 19 contracts for the exploration of manganese nodules with areas of around 75,000 square kilometres each, an area larger than the German state of Bavaria, five contracts for the exploration of ferromanganese crusts with areas of 3000 square kilometres each, and seven contracts for the exploration of massive sulphides in areas of 10,000 square kilometres each. With all of the contracted areas together, the ISA has so far authorized a sea-floor area of around 1.5 million square kilometres for the exploration of resources, an area as large as France, Spain and Germany combined.

Each contract has a duration of 15 years and includes the option for multiple extensions of five years each time if the contracted party has been unable to complete the exploration work for reasons beyond its control (for example, due to a pandemic), or if the global economic situation precluded the mining of raw materials in the deep sea. Holders of an exploration licence also have preferential rights to subsequent mining and are allowed to test their technology for raw-material production in the deep sea. For this, however, they are required to have an environmental impact statement approved and recognized by the ISA Legal and Technical Commission.

Deep-sea mining technology

MANGANESE NODULES: To date there has been no mining of manganese nodules. But over the past ten years at least five different companies and government institu-



5.10 > Since 2002 the International Seabed Authority has issued 31 contracts for exploration of the sea floor for mineral resources. These comprise 19 contracts for the exploration of manganese nodules, five for ferromanganese crusts and seven for massive sulphides.

5.11 > *Patania II*, a caterpillar-like collector of manganese nodules made by the Belgian company DEME-GSR, is twelve metres long, 4.5 metres high, four metres wide and weighs 25 tonnes. The prototype was tested successfully in the spring of 2021 in the Clarion-Clipperton Zone at a water depth of 4500 metres.

tions have contributed to its technological advancement by testing initial prototypes for future mining tools, albeit at reduced size and weight scales. The Korean research institute KIOST, for example, has designed a collector for manganese nodules as well as a conveyor system for transporting the nodules to the sea surface, and has already tested both of these in water depths of 1200 and 1400 metres.

A water depth of 4400 metres was achieved in 2017 with the basic chassis assembly of the manganese nodule collector *Patania I*, which was developed and successfully tested by the Belgian company DEME-GSR. The company has an exploration contract for the Clarion-Clipperton Zone. In September 2018 it publicly presented for the first time the *Patania II* collector, which had been upgraded with a manganese nodule collection system. An early deep-sea deployment of this prototype in the contract area (also at a water depth of 4400 metres) in 2019 failed due to technical problems with the cable connecting it to the ship. A second test in the spring of 2021, however, was successful, and was closely monitored by European researchers in order to gain information about the impacts of nodule mining on the marine environment and to evaluate the observation systems.

Both the Belgian and South Korean manganese nodule collectors are caterpillar-like vehicles in design, and both employ a hydraulic collection system to pick up the loose nodules lying on the sea floor. The Indian contract holder MoES, on the other hand, is adopting a mechanical concept for collecting the nodules, and is developing a mobile system with barbed shapes to rake up the nodules. After they are picked up, the nodules are cleaned, crushed and transferred to a vertical conveyor system. Depending on the design used, the nodules are then transported to a delivery platform at the water surface via a pneumatic process or by the use of a slurry. There they are dewatered and loaded onto bulk carriers for transport to shore.

COBALT-RICH FERROMANGANESE CRUSTS: For mining ferromanganese crusts, the China Merchants Industry Holdings (CMI) has developed a prototype that was successfully tested at a water depth of 1300 metres in the South China Sea. The machine not only proved its ability to move along the sea floor, but also to cut and crush ferromanganese crusts. Dislodging ferromanganese crusts from the subsurface of the sea floor is a technical challenge, because the crusts often replicate the form of the underlying bedrock surface. For example, if there are

5.12 > The now bankrupt Canadian company Nautilus Minerals developed three remote-controlled underwater vehicles for mining a massive sulphide deposit in the Bismarck Sea off Papua New Guinea: a shaper (auxiliary cutter, right), a bulk cutter (centre) and a collector (left).

boulders, rounded blocks and slabs of rock, or the flow structures of ancient lava beneath the crusts, the crusts will precisely follow those structures. As a result, mining machines could easily become stuck on very uneven grounds. The Chinese vehicle, however, appears to move in steps that compensate for the unevenness. For cutting and crushing the crusts, engineers rely on designs that employ either a high-pressure water jet or rotating roller bits like those used in mining coal.

MASSIVE SULPHIDES: The mining of massive sulphides will probably prove to be equally difficult, but initial progress is being made here as well. The now bankrupt Canadian company Nautilus Minerals, for example, developed a process for mining a massive sulphide deposit at a depth of 1600 metres in the Bismarck Sea off Papua New Guinea using three remote-controlled underwater vehicles, and even had the machines built. The fleet consists of a shaper to level the seabed, a bulk cutter (the main mining vehicle) and a collector.

However, experts doubt that all three of these vehicles can be deployed feasibly at one time. The area of the targeted ore deposit, with a diameter of a few hundred metres, is relatively small. Moreover, the deposit is cone-shaped. This means that its area decreases in size with increasing depth, which would severely limit the mobility of the mining machines. The specialists see a further obstacle in the presence of hard volcanic rocks in the vicinity of the massive sulphides, which would have to be removed. Nautilus Minerals wanted to use a roller-bit technology for this, but experts believe that this procedure would be very difficult. Nevertheless, the Japan Oil, Gas and Metals National Corporation (JOGMEC) is pursuing a similar approach. In 2017 the company carried out an initial successful mining test for sulphides in the Okinawa Trough in Japanese territorial waters. Plans for undersea mining in the Okinawa Trough foresee an annual production of 1.3 million tonnes of ore following additional multi-year development and testing phases.

A consortium of German companies comprising Harren & Partner, Combi Lift and Bauer is counting on a single piece of equipment to mine massive sulphides. Their designers are developing a vertical mining system that works on the same principle as diaphragm wall cutters, like those used for rectangular foundations in underground construction, but also in pipeline, harbour and canal construction. The vertical cutter consists of a steel frame with counter-rotating cutting-wheel drums on the underside. This kind of design has already been used successfully in the sea to mine diamonds at a water depth of 165 metres.

With this method, the need for removal of the associated volcanic rocks in projected sulphide mining could be largely avoided and more focus given to production of the ore. The technology would make it possible to cut several dozen metres deep into the massive sulphides at selected locations, thus leaving a very small footprint of only a few square metres at each site on the sea floor. Specialists would therefore expect a much smaller environmental impact. For example, there would be a minimal amount of drill cuttings or tailings released onto the sea floor. It would allow a more focussed mining of the ore on the sea floor without causing a significant suspension plume. Moreover, the installation of a vertical conveyor pipe would be eliminated, and with it the environmentally risky transport from the deep water to the surface. However, the earliest possible test-scale trials of a prototype of this device are planned for 2026 at a water depth of 2400 metres in the German contract area in the Indian Ocean.

Technical development not yet complete

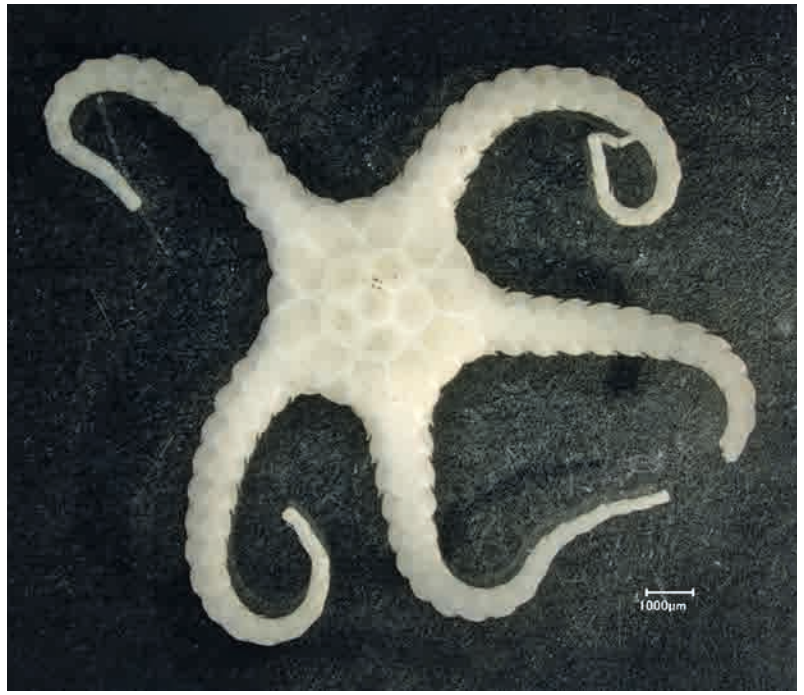
In theory, all of these technical mining concepts may sound comparatively straightforward and achievable, but in practice the technology has to overcome a myriad of challenges over the long term. These include, among other things, water pressures of 400 to 600 bars and ambient temperatures near the freezing point at the deep-sea floor, as well as corrosive salt water. In addition, the cutters, nodule collectors and conveyor systems would have to operate for long periods of time without maintenance because bringing them to the sea surface for repairs would involve considerable expense.

All of the test operations so far have been carried out with prototypes at a reduced scale. For production at an industrial scale, mining machines four to five times as large will have to be built and tested. Methods for the metallurgical processing of manganese nodules and crusts are also still in the early stages of development. For the first time in the world, a concept for the complete smelting and utilization of manganese nodules has been developed by scientists from Germany’s Federal Institute for Geosciences and Natural Resources and RWTH Aachen University, and has already been tested successfully on an expanded laboratory scale. The project partners are presently working to convert the process to an industrial scale. The initial objective is to demonstrate the feasibility of virtually residue-free metallurgical processing and, secondly, they want to find out what a smelting plant would have to look like, and how expensive it would ultimately be to actually extract all the materials contained in the manganese nodules and process them into marketable intermediate products.

Present estimates suggest that the costs of preparation and processing of the nodules would probably make up about one-half to two-thirds of the total investment and operating costs of a deep-sea mining project. The investment costs would amount to around USD 1.5 billion, a sum that is on the order of that required for the development of land-based deposits. The operating costs are estimated at USD 160 to 400 million per year, which means that deep-sea mining is probably not economical today with the current world market prices for metals. The increasing demand for raw materials, however, should cause a long-term rise in prices. Due to these financial aspects and the technological uncertainties set out above, experts believe that it will take at least another five, but more likely ten years before marine mineral resources can be mined on a large scale for the first time. How realistic this assumption is remains to be seen.

Progress or dirty business?

The increasing technological feasibility of marine mining has rekindled the dispute over the desirability and sustainability of extracting ore deposits from the sea. Proponents argue that the resource requirements of humankind are increasing enormously as a result of the transition from fossil fuels to renewable energy (electricity storage, e-mobility). If states do not satisfy this demand, it will put their economic development and the prosperity of their populations at risk. In order to meet the demand for raw materials, the existing mining facilities on land would



5.13 > The brittle star *Amphiophiura bullata* is one of several new deep-sea species that researchers have discovered in the Clarion-Clipperton Zone in recent years. Genetic analyses have revealed that some of the previously unknown brittle stars belong to new ancestral lineages that have evolved in the deep sea over more than 70 million years.

have to be expanded or new mines opened. Either of these options would have immense environmental impacts. Supporters of deep-sea mining therefore point out that:

- For deep-sea mining it would not be necessary for forests to be cleared, groundwater levels to be lowered, or people to be resettled or displaced. Furthermore, there would be no need for costly infrastructures such as roads, power lines, buildings and dewatering systems;
- No large tailings piles would be generated because the ore deposits are directly accessible, and there would be no need to remove tonnes of overburden material;
- With deep-sea mining no pollutants or heavy metals would be released, a problem that often leads to severe environmental damage in the mining of ores on land;
- Deposits in the deep sea, such as manganese nodules, often contain three or more metals in economically viable quantities, so that a number of materials can retrieved from a single site. On land, different deposits have to be excavated for each individual metal;
- The mining of raw materials in the sea can only be carried out by machines. Compared to mining on land, there would thus be significantly less risk for mine workers. Child labour, which is especially common in developing countries, would not occur;
- Mining the marine deposits would help to diversify the currently increasingly concentrated sources of supply on the international commodity markets. For many metals, a large proportion of production comes from a single country, some from politically unstable or undemocratic states that use their market power for political leverage. Resources from the deep sea would mitigate dependency on these nations, because their extraction from international waters is subject to international law and thus to control by the international community.

Opponents of deep-sea mining are not at all convinced by these arguments. Firstly, they are concerned about the environmental impacts of extracting raw materials from the sea. Secondly, they criticize the role and the regulations of the International Seabed Authority and remain unconvinced that the income from the sale of humanity's mutual heritage would benefit people in the poorest developing countries.

Impacts on the marine environment

After 30 years of research, a lot has been learned about the possible consequences of deep-sea mining for species diversity and biological assemblages on the seabed, although researchers still do not completely understand the functioning of deep-sea ecosystems and their role in the many services provided by the sea. There are a plethora of mobile and sessile organisms living on and beneath the sea floor, including in those areas rich in manganese nodules. They range in size from nematodes, which are only a few tenths of a millimetre long and make up the largest share of species diversity, to sea cucumbers and metres-long fish. Sponges and deep-sea corals grow on the nodules and provide a source of food and protection for many other animals.

5.14 > The marine snail *Chrysomallon squamiferum* is the first deep-sea species to be added to the red list of endangered animal species because of impending mining operations. The snail lives at three hydrothermal vents east of Madagascar. Two of these are located in areas for which exploration contracts have already been issued.

5.15 > Octopuses are one of the many deep-sea inhabitants that are directly dependent on manganese nodules. They attach their eggs to sponges that grow on the manganese nodules.

Who lives where on the sea floor depends on the particular conditions at a given location. In the German contract area of the Clarion-Clipperton Zone, for example, the sedimentological and geochemical conditions on the seabed can change within a distance of less than 1000 metres. In addition, the expansive deep-sea plain is punctuated by seamounts and ridges. The associated biotic communities are adapted to the local conditions.

The diversity of life in the deep sea is much greater than was previously believed. In recent years, scientists have been able to identify and describe numerous species from the Clarion-Clipperton Zone. In addition, through the use of molecular genetic investigation techniques, they have also succeeded in obtaining an initial impression of the diversity of deep-sea organisms. This is so huge that it is often compared with the species diversity of rainforests. However, the population density of most of the individual species on the sea floor is low, which is why only an estimated ten per cent of the smallest organisms (meiofauna, benthic organisms from 0.32 to 1.0 millimetres in size) and 30 per cent of the mid-sized animals (macrofauna, body size from two to 20 millimetres) have been scientifically described so far.

On the other hand, the conditions that deep-sea inhabitants have adapted to, which are very inhospitable from a human point of view, are well known. Food is only sporadically available, the water pressure is immense, and temperatures are low. It is also pitch dark 24 hours a day. Most organisms feed on the few particles that sink down from the upper layers of the sea. The consequences of the paucity, and especially of the short-term availability of food following the sinking of plankton blooms at the surface, are that the animals grow slowly on the sea floor, reproduce very late in life, and under some circumstances have extremely long cycles of brooding.

In the period from 2007 to 2011, for example, US American scientists observed a female deep-sea octopus of the species *Graneledone boreopacifica* off the coast of California whose offspring hatched from the eggs after it had guarded its clutch for four and a half years. Soon thereafter, German deep-sea researchers were able to verify that deep-sea octopuses in the Peru Basin laid their eggs directly on manganese nodules. The animals had attached their eggs to sponges growing on the manganese nodules at a water depth of about 4000 metres.

In the eastern part of the Clarion-Clipperton Zone, other researchers have determined that around one of every two deep-sea inhabitants larger than two centimetres (megafauna) is dependent on manganese nodules because these present virtually the only firm substrate onto which sponges, corals and other sessile organisms can attach. If the nodules were to be removed by giant mining machines, there would no longer be a substrate for recolonization unless restoration measures were carried out to replace the nodules with other solid objects. European researchers are presently carrying out a series of experiments to test the feasibility of these kinds of measures.

Larger organisms are comparatively rare in the Clarion-Clipperton Zone. Researchers calculate just 0.5 animals per square metre of seabed area. The smallest animals, which live mainly within the sediment (microfauna, smaller than 0.3 millimetres), are much more abundant. With an average density of around 300,000 organisms per square metre, they represent the greatest proportion of animals by far. During mining, however, not only the nodules themselves would be removed, but also the upper ten centimetres of the seabed, along with all of the organisms living on it or in it. How long it would subsequently take for nature to recover from this massive intervention is poorly understood.

Using so-called disturbance and recolonization experiments, scientists have been able to show that interventions in deep-sea life result in long-lasting, but extremely variable changes in the abundance and species composition of animals. In 1989, in order to simulate manganese nodule mining, scientists ploughed up the deep-sea floor across an area of a few square kilometres in the Peru Basin with a harrow. They returned 26 years later to investigate the life in and on the ploughed seabed. They found that the traces of ploughing were still very visible. Surprisingly, the biogeochemical conditions in the sea floor had been altered to such an extent that even the microorganisms able to live there were still severely impacted and, according to predictions, would need at least another 50 years to even approach a state of full recovery.

An overview study from the Clarion-Clipperton Zone also concluded that, following an intervention, some of the species living in the sediment will return to the area relatively soon, meaning within a few months to years, and that their numbers even exceed the original abundance, while other species require decades to recover. Experts therefore contend that the resettlement of disturbed areas can take many generations. The composition of the biotic community on and in the seabed remains altered for decades after the event, although research results from one kind of area cannot be extrapolated – neither to other deep-sea regions nor to other types of marine mineral deposits (sulphides, crusts).

In addition to the stripping of the top layer of the seabed, however, experts expect to see other kinds of environmental impacts from the mining methods that have been developed for manganese nodules. For one, there would be disturbances caused by the noise, the vibrations and the bright lights of the giant excavation machines. For another, as a result of the collection of manganese nodules and the processes for cleaning and transporting the ore, clouds of sediment or turbidity can be expected to form, mainly near the sea floor but also higher in the water column. Researchers expect that the hydraulic nodule collectors now being built will stir up 500 to 1000 tonnes of sediment from the sea floor per hour. This amount of material will be extremely problematic when it settles back onto the surface. Under natural conditions, sedimentation rates in the deep sea are only a few millimetres per 1000 years. But the agitation from nodule mining would cause a drastic increase in this rate.

From experiments and computer calculations it has been determined that 90 to 95 per cent of the sediment churned up by the mining machines would be redeposited quickly within a radius of up to ten kilometres. However, the newly formed sediment surface has a completely different structure and composition than the original sea floor, and thus no longer resembles the former natural habitat. The remaining particles are carried away by ocean currents and deposited outside of the mining area. Experts believe that industrial mining of the manganese nodules will lead to significantly higher sedimentation rates as far away as 20 or 30 kilometres.

The impacts that these turbulence clouds and sediment deposits will have on the biotic communities of the deep sea probably vary from species to species, and have not yet been thoroughly researched. Initial investigations indicate that microorganisms in the sediment can tolerate up to about one additional centimetre of cover by resuspended sediment. If this sediment layer is thicker, very few animals will survive. Sessile animals like sponges and corals, which live on the sea floor close to the mining area and filter the otherwise very clear bottom water to obtain food, will be covered by the masses of sinking sediment particles and have very low chances of survival. But octopuses, fish and the larvae of many other deep-sea species could also suffer under the clouds of sediment. In addition, scientists cannot rule out the possibility that the turbidity clouds caused by deep-sea mining could be detrimental to fisheries.

Basically, then, the bottom line for science is this: Because no deep-sea mining has yet been carried out at an industrial scale, and there is a lack of relevant accompanying studies, no dependable conclusions can be drawn regarding the true intensity and duration of the disruptive intervention, nor about its long-term consequences for the biotic communities of the deep sea. Therefore, the only option for regulatory bodies such as the International Seabed Authority is to introduce regulations at the outset that limit the consequences as far as possible. Minimizing large-scale consequences will require the development of low-impact equipment and careful and adaptive territorial planning for mining areas. The current level of knowledge, however, is not sufficient to allow effective protective measures to be taken. Many areas of the deep sea can be considered as still undiscovered. Furthermore, no one can say with certainty exactly what role the deepest layers of the ocean play in the many mass cycles of the sea, and thus ultimately for the Earth's climate processes.

The International Seabed Authority addresses this lack of knowledge by requiring compliance with the **precautionary principle** and the highest environmental standards, and by establishing regional environmental management plans. For the protection of species diversity in the Clarion-Clipperton Zone, it has also created nine protected areas on the sea floor of 160,000 square kilometres each, which constitute around 30 per cent of the total area. However, it has not yet been scientifically proven that their size, location and species diversity would be sufficient for the recolonization of potentially disturbed mining areas. For this reason, the Legal and Technical Commission of the ISA is now discussing whether an additional three or four protected areas should be established that encompass habitats previously not considered. In addition, international negotiations are being held to determine where appropriate protected zones should be established for all other areas of the high seas that are rich in resources, and what obligations these would carry for the contract holders. The primary goal is to create binding regulations for careful and adaptive territorial planning for deep-sea mining, and provide effective environmental protection measures on a regional level.

Criticism of the International Seabed Authority

Environmentalists, however, doubt that the International Seabed Authority can justly fulfil its diverse roles as contractor, mining facilitator, fee collector and top-level inspection and environmental protection body. The ISA bodies, but particularly its key organ, the Legal and Technical Commission, which is responsible for legal and science-technology questions, are very insufficiently funded and too understaffed in the field of environmental expertise to be able to properly carry out their tasks. Moreover, there are fundamental conflicts of interest within the agency resulting from the various requirements. For example, how can an agency be expected to effectively protect the environment when at the same time it is evaluated based on the extent to which it enables deep-sea mining?

The environmental organization Greenpeace accuses the ISA of issuing exploration contracts to various companies that are acting on behalf of only a few corporations from industrialized countries. The subsequent deep-sea mining in international waters would thus preferentially benefit these companies. The burden of the many risks associated with mining, on the other hand, would be carried mainly by the developing countries. For one reason, this is because they act as the Sponsoring States for private mining companies and, for another, because large ore deposits lie within their national waters. Although the ISA cannot make decisions about the mining of these, conceivable damages such as the collapse of ecosystems or the impacts on fisheries would mainly affect the coastal populations of these countries.

Other experts dispute Greenpeace, saying that there are currently no private investors in massive sulphides and ferromanganese crusts, and that about half of the manganese nodules are also state-held contracts involving both industrialized and developing countries. Companies that want to carry out mining in international waters also have to be insured against environmental damage and pay into an environmental compensation fund. With respect to the criticism of the ISA, it should be noted that the Authority itself calls upon all member states to send additional specialists to strengthen the Commission's environmental expertise.

These experts also praise the international cooperation within the ISA and the progress that the Seabed Authority has made in recent years. In July 2000 the legal foundations for prospecting and exploration of manganese nodules were adopted. This was followed in May 2010 by the regulations for massive sulphides and in July 2012 by those for ferromanganese crusts. Since July 2016 the ISA member states have been negotiating mining regulations that will become a component of the Mining Code, an overarching set of regulations for the exploration and industrial mining of mineral resources, which, in the view of many observers, offers the rare opportunity to establish science-based environmental protection measures prior to the actual mining activities.

The Mining Code regulates the formal aspects of proposal submission, protection of the environment through environmental impact statements, including environmental management and monitoring, as well as public involvement, occupational safety, monitoring of mining activities by inspectors, and the shutdown plans. In addition, the regulations shall spell out what fees and compensation payments the mining companies must pay to the ISA when they extract raw materials from international waters and privately profit from the common heritage of mankind. Directly related to this is the question of how the potential income could be fairly distributed to all countries. The Convention on the Law of the Sea contains an important clause that says raw material mining in the sea may not be detrimental to production on land. If one or more nations do incur a disadvantage due to deep-sea mining, perhaps because it causes a decline in raw-material prices or their ore deposits are no longer exploitable and the state loses income in the form of taxes, then according to the Law of the Sea they must be compensated by the ISA. How and by whom has also not yet been completely clarified.

Circular economy plus X – the better alternative

Only the future will tell whether industrial deep-sea mining will someday become a reality. Environmentalists demand a general ban and comprehensive protection of the deep-sea environment. The arguments of businesses and governments, on the other hand, are based on the rising demand for raw materials and the need to secure the supply of these and the jobs that depend on their respective industries.

Added to all of this, there is also the fear that individual resource-rich nations will gain excessive market power and use it to exert political leverage. One conceivable solution to this dilemma entails a combination of different strategies, based on the premise that the global economic system and consumer behaviour could be fundamentally altered and no longer based exclusively on growth and consumption.

To start with, this would require adoption of a sustainable circular economy. Among other things, this presupposes that:

- there are sufficient metals within the circular economy to meet demand;
- products undergo further development so that as little mineral resources as possible are used in their production;
- goods and products have high durability and a long lifetime;

In high demand – sand and gravel from the sea

While deep-sea mining remains a prospect for an uncertain future, many countries have been extracting sand and gravel from the sea for decades. These two loose aggregates are now among the most sought-after raw materials in the world. They are important not only for the production of concrete, glass, and electronic devices like computers, but also as fill sand at construction sites and in harbours, for coastal protection through beach replenishment, and for land reclamation. From 1960 to 2017, for example, the coastal city-state of Singapore was expanded by more than 130 square kilometres by means of sand filling, and an additional 56 square kilometres are planned by the year 2030. Over the past 20 years, the city-state has imported around 517 million tonnes of sand and gravel for this purpose, making it the world's largest importer of sand.

"Sand" is a collective term for mineral raw materials with a diameter from 0.063 to two millimetres, regardless of the minerals that the individual grains are composed of. Gravel is coarser and can contain material with grain sizes up to 63 millimetres. Most sand originates as the product of natural erosion of rocks on land. But an important portion is also contributed by glaciers, whose ice masses slice along mountain slopes like a planer, and by streams and rivers, which, almost unnoticed, eat into the landscape and wash away large quantities of sand. It usually takes tens of thousands of years before a boulder is reduced to the size of sand and is deposited on the banks of a river or in the sea. But sand is also generated directly in the sea. Parrotfish, for example, eat corals and eventually excrete the indigestible remains of the coral skeleton as sand. An adult may produce as much as 90 kilograms of coral sand each year in this way. Added to this are the many snail and clam shells that are ground up by currents, waves and wind.

All of the sand generated in these ways, however, is insufficient by far to cover the sand demands of humankind. In the year 2014, experts at the United Nations Environment Programme (UNEP) estimated that between 32 and 50 billion tonnes of sand and gravel are processed worldwide every year. If this level of consumption continues, which is probable considering the growing world population and increasing urbanization, the natural resources on land, in rivers, and in the sea will be exhausted in less than 30 years. The prices for these two raw materials are already rising considerably, currently at a rate of five to ten per cent annually in Germany.

The quantity of sand and gravel being removed from the world's oceans is difficult to estimate because the data are not recorded in a central location, and sand deposits in many rivers and coastal areas are excavated illegally. In many places, experts actually refer to a sand mafia. The business is growing because of the enormous increase in demand for the material, especially in economically emerging regions such as China, India and Africa, where there is a great deal of new construction. For example, cement is necessary for the production of concrete. Six to seven tonnes of sand and gravel have to be added to one tonne of cement, which is mixed with water and aggregates to produce concrete. As a result of the global construction boom, the amount of concrete produced every year is enough to build a wall around the Earth at the equator that is 27 metres high and 27 metres thick. Calculating the amount of sand and gravel needed for this, the enormous magnitude of raw-material consumption becomes obvious.

For large construction projects, even desert nations like the United Arab Emirates have to import sand or recover it from the sea, as their local dune or desert sand is not suitable for the production of concrete. This is because the sand grains in the desert have been too thoroughly rounded. Their surface is too smooth and their size too uniform for the cement and other components to effectively adhere to them. The sand grains from rivers or the sea, by contrast, are more angular and have a rougher surface. This is perfect for use as construction sand.

In Great Britain, around every fifth tonne of sand or gravel currently processed as concrete in England and Wales comes from the coastal waters of the island nation. Nevertheless, in 2018 the country held only second place on the list of Europe's largest marine sand producers. According to the International Council for the Exploration of the Sea (ICES), which provides scientific advice for the North Atlantic, the Netherlands topped the list with a production quantity of around 24.6 million cubic metres. Depending on the grain size, this is equivalent to a total weight of 30 to 40 million tonnes. Around half of this was used for land reclamation on the North Sea coast and on the Dutch islands. This is needed to replace the volumes of sand that are washed away every year by the autumn and winter storms on the North Sea. In 2018 in Europe, a total of around 54.13 million cubic metres of sand and gravel were removed from the sea.

Marine sand and gravel are generally only used when there are no appropriate deposits on land. The mining of sand and gravel in the sea is generally more expensive than on land, which is why, from a global perspective, deposits on land or in rivers are usually preferred. The impacts on the affected environments are enormous. River beds are deepened, which increases the current speed, causing bank areas to be washed away and bridge pilings to be undercut. When coastal sandbanks are removed, the land areas behind them lose their most effective wave barriers. As a consequence, flooding, coastal erosion and storm damage increase. Through uncontrolled sand extraction from the sea, Indonesia has already lost 24 islands.

Biological studies have also proven that sand production is very detrimental to life on the sea floor. In the North Atlantic alone, more than 48 fish species are dependent on sandy bottom conditions for their spawning areas, including some popular food fishes such as herring. Although the impacts are relatively local, the damage can be very severe when the mined sand or gravel area is the only one around and dependent species lose their only possible habitat. Production contracts should therefore not be issued until a thorough assessment has been carried out. Areas that have been intensively used for sand extraction require an average of five to ten years before they are completely recolonized. Depending on the local environmental conditions (sea swell and sediment motion) and the water depths that are excavated, however, the recovery phase can also take decades.

If dredging is carried out for a short period of time or only once, the original conditions may return within two to four years in an ideal situation. In this case, the biotic communities that are more accustomed to fast currents or strong tides will recover fastest. Species that live in quieter water conditions will generally require longer. If especially deep holes are created by the extraction of sand, and finer material is subsequently deposited there, it may even result in the development of completely new biotic communities.

For these reasons, scientists recommend clear guidelines for the mining of sand and gravel in the sea. These include moratoriums on production in regions and at times when important fish species are spawning, regular shifting of the areas of extraction so that the bottom communities have a greater chance of recovering, and maintaining refuges. These lie between the areas of extraction and can serve as retreats for the impacted bottom dwellers.

In addition, for the mining of marine sands a compromise must be found between minimization of the area exploited and duration of the recovery phase. When sand is extracted from a single location, creating a deep hole, less total area is impacted, but a longer time is required for the hole to fill naturally and recolonization to occur. If the area of mining is expanded, and only the upper layer of the seabed is scraped off, a larger area is affected but the recovery time is shorter, at least in shallow water depths. In deeper water the seabed requires longer to recover from any kind of disturbance because the water masses do not transport and redeposit as much sediment as they do in shallow-water areas.

5.16 > Off the Dutch island of Ameland a suction dredger extracts sand from the bottom of the North Sea to be used in widening the island's beach.

5.17 > These pictures show two of the coral atolls in the South China Sea that China has transformed into islands using sand replenishment. Both the Fiery Cross Reef (above) and the Subi Reef have served as military stations since 2017. The atolls have been largely destroyed as habitats for corals and associated reef dwellers.

- all end-of-life devices and the materials they contain are recycled and reused.

Circular systems not only preserve the environment, they also have economic advantages. Through the recycling of metallic waste and scrap, the amounts of raw materials extracted by mining would be reduced and a great deal of energy saved in production. The mountains of waste would stop growing. Furthermore, many metals can be recovered with no loss in quality.

Worldwide today, recovery rates for materials such as iron, zinc, copper, gold and silver already reach 50 to 90 per cent. With many other metals there is great potential to improve recovery rates. However, it is also a fact that electronic products and their resulting scrap continue to become more complex, which makes the recycling of individual materials more difficult and in some cases no longer economical. Furthermore, a circular economy can only function if the amount of materials recovered is sufficient to cover worldwide demand.

Experts believe, however, that, in view of rapid population growth and increasing technological transformation around the world, the need will remain for metallic raw materials to be extracted from natural deposits in the future. On the other hand, the supply situation could be improved by a more thorough development of deposits.

Given this background, a few years ago the European Commission contracted scientists to determine the amounts of valuable minerals and metals that might still be present in the tailings of former mines or strip mines, and how they could be extracted in future.

Their results indicated that the probability of finding raw materials such as chromium, niobium or vanadium in the tailings piles is great, particularly because land-based mining in the past has always concentrated on the production of only one or two resources. However, it must be considered that some effort would be required to recover the metals and minerals that were previously not recognized as important. Methods by which various materials are all extracted at the same time are the most sensible, even though these kinds of processes are generally very energy-intensive.

Other researchers are searching for ways to directly extract dissolved metals from sea water. For example, there is an estimated 180 billion tonnes of lithium stored in the ocean. But the actual concentration of this metal in sea water is only 0.2 parts per million. In order to extract this very minor amount, scientists employ specially coated electrodes, which they repeatedly subject to an electric current. As a reaction to the electric current, the lithium ions migrate out of the water into the electrode. This method works in an experimental setting, but it is still far from being applicable on an industrial scale.

For this reason, in 2017, a number of German scientists posed the question of whether it would be conceivable to search for ore deposits in the subsurface of the shallow, near-coastal shelves before undertaking deep-sea mining, which is technically more complex and fraught with serious consequences. The seabed of the continental shelf is merely an extension of the continent, which could mean that metal or mineral deposits occurring on land near the coasts also extend out onto the sea floor. These near-coastal resources could probably be extracted comparatively easily, and with significantly less risk, than the ore deposits in the deep sea.

For example, geologists have predicted the presence of large gold deposits off the west coast of Africa, nickel deposits in the Arctic Ocean and lead-zinc deposits in the Gulf of Mexico and Mediterranean Sea. In many of these regions resource extraction would not be a new concept. In several shelf seas, oil and natural gas have been produced for more than 70 years. In other coastal areas, sand and gravel are being extracted, albeit with serious consequences for the sensitive coastal marine ecosystems.

This means that as long as demand continues to rise and truly sustainable alternatives are lacking, the extraction of mineral resources will always be a matter of balancing interests, posing the question of how the benefits compare to the somewhat unforeseeable consequences to the environment and people. The international community is now, for the first time, faced with the decision of whether industrial mining should actually take place in the international deep sea.

Freshwater reserves in the seabed

In the past, it was only in arid regions that freshwater was viewed as a precious asset. Now, however, the lakes, rivers, springs and wells in many of the Earth's coastal regions are also drying up. The reasons for this are many and varied. In some places it is raining less as a result of climate change. In others the precipitation is no longer regularly spaced through time, but occurs episodically as heavy rain events. During these extreme precipitation events most of the water runs off the surface because the soil cannot absorb it fast enough. At the same time, human demands upon freshwater resources are increasing because more people are moving to the coastal regions or taking their vacations there, while farmers are watering larger areas. In some places, the inland surface waters and groundwater reservoirs are being senselessly polluted, for example through over-fertilization or the excessive application of pesticides. In response to the increasingly frequent and severe water shortages, researchers have long been searching for new freshwater reservoirs. Their explorations have become strongly concentrated on areas beneath the sea. It has been known for a number of years that untapped groundwater reserves exist below the sea floor near the coasts, and that this is presumably the case on all the continents. Most of the offshore reservoirs of this kind discovered so far are on the east coast of the USA, the northwest coast of Europe and the west coast of Australia. It is estimated that all of the known reservoirs beneath the sea together store around one million cubic kilometres of freshwater. This amount would theoretically be enough to fill the Black Sea twice or, to give a more practical example, to supply the population of Germany with drinking water for more than 192,000 years.

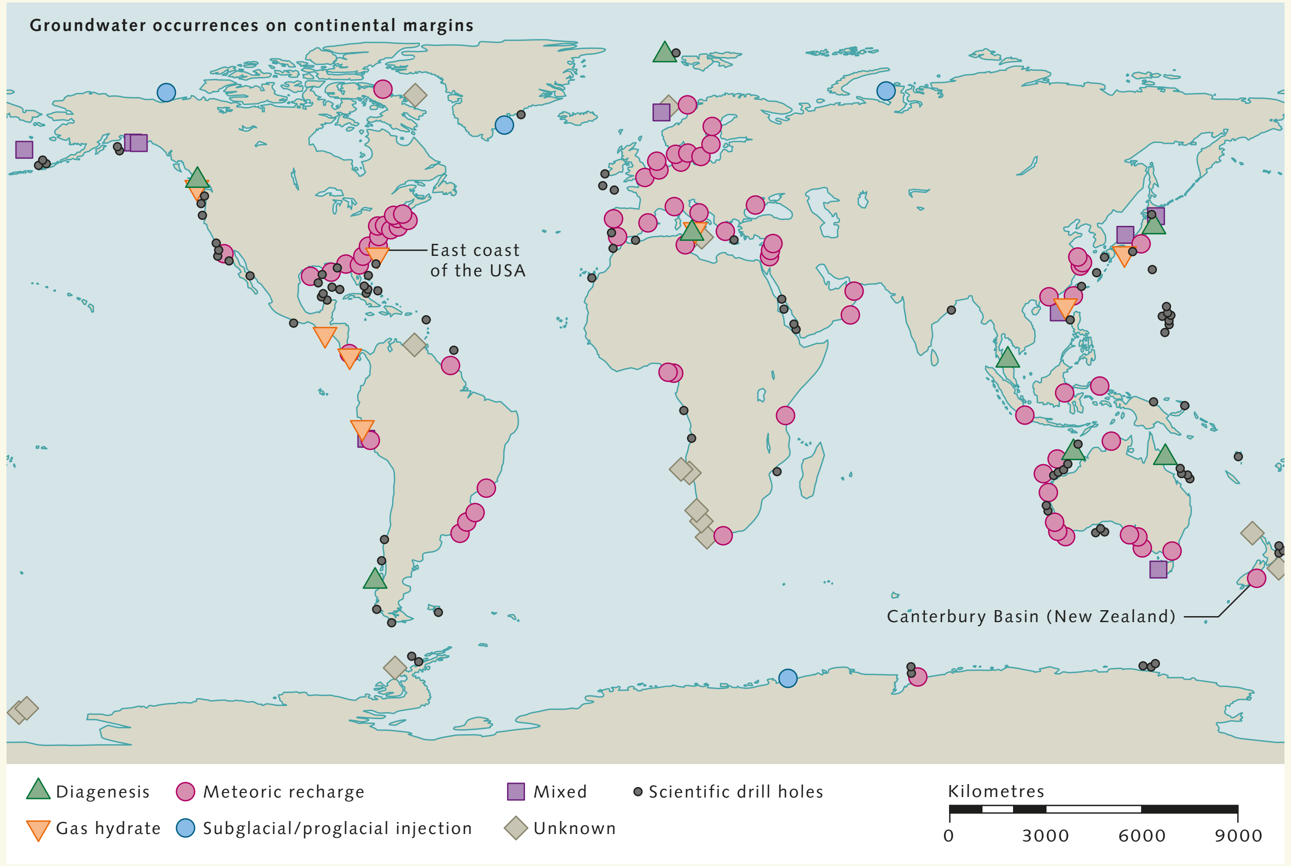
Occurrences of groundwater below the sea can originate in different ways. Experts currently distinguish between five fundamentally different formation processes. Some reservoirs are formed by the natural breakdown of gas hydrates in the sea floor, during which low-salinity water is released. In other places, water accumulates in the subsurface as a result of physical and chemical processes during the induration of sediments. Geologists refer to this kind of rock formation process as diagenesis. Occurrences in coastal regions previously covered by glaciers can be attributed to meltwater from the former large ice masses penetrating into the sea floor and collecting there (subglacial/proglacial injection). Some known offshore reservoirs are also fed from the land, for example by precipitation on land percolating downward and then being carried underground toward the sea by deep-lying rock layers (meteoric recharge 1).

Most of the groundwater reservoirs found under the sea, however, originated during past cold intervals, such as the last glacial period around 20,000 years ago. During that period the ice sheets in the Arctic and Antarctic regions grew. Due to the great amount of water that was thus bound in the ice sheets, the global sea level dropped by more than 100 metres compared to today. As a result, the shallow coastal waters around the world retreated and the shelf areas of the continental margins dried up. When it rained or snowed on these areas, the water percolated into the soil and collected in hard, porous limestones, where it was stored in a manner similar to being absorbed by a sponge. This process is known as meteoric recharge 2. At the end of the glacial period, as sea level began to rise again, the shelf areas were flooded once more. Since then, the groundwater reservoirs have been located underwater beyond the coasts, and have become especially interesting for countries with limited water resources such as South Africa, Mexico, New Zealand and Malta.

In the waters of Malta, studies led by German scientists have revealed that the water-bearing limestones in the region lie around 400 metres below the sea floor. Off the New Zealand coast of Canterbury (eastern part of the southern island), by contrast, the researchers only had to drill 20 metres into the sea floor to find freshwater-bearing rocks. This is one of the shallowest groundwater reservoirs in the world. It extends to as far as 60 kilometres from the coastline, and is thought to hold up to 200 cubic kilometres of water. By comparison, Germany's largest inland lake, Lake Constance, holds 48 cubic kilometres of water. The volume of groundwater discovered off the coast of New Zealand is around four times as large.

Researchers have been able to obtain such detailed knowledge of the freshwater systems beneath the sea recently through a combination of various geophysical and geochemical research methods. With the help of marine electromagnetics, they can measure electrical resistivity below the seabed. Using these measurements, it is possible to determine whether the rocks in the subsurface have saltwater or freshwater stored in their pores. Saltwater is an excellent conductor, while freshwater has three times the electrical resistance.

In order to determine the salinity of the pore water with a great degree of accuracy and, furthermore, to estimate the volume of the groundwater, the geologists then combine the electromagnetic data with seismic profiles of the sea floor layers. This integration is essentially a statistical-mathematical process that links numerical models with machine learning algorithms. The method puts scientists in a position to characterize and map offshore freshwater systems in extraordinary detail. Strictly speaking, this research field is actually a bit more mathematics than geology and hydrology.



5.18 > Groundwater reservoirs have now been discovered in the coastal areas of all continents. They are formed by the breakdown of gas hydrates, by the consolidation of sediments (diagenesis), through the input of glacial meltwater, and by rainwater input from the land, but most commonly by the formation of groundwater reservoirs during past glacial periods.

The ocean as energy source – potential and expectations

> The ocean is being promoted as a component of the energy transition. The principal advocates for this include large oil corporations. They are investing in the expansion of offshore wind energy and developing concepts for storing carbon dioxide beneath the sea floor. These technologies provide a ray of hope in efforts to shift away from coal, oil and natural gas. But for the ocean, this development means that many of its regions will be even more intensively and permanently exploited by humans in the future.

A new era in the energy sector

Energy makes our lives much easier. In the form of electricity, it runs machines, trains and increasing numbers of automobiles. It allows real-time communication around the globe with pictures, and lights up apartments and entire cities after the sun has sunk below the horizon. In the form of heat, energy can melt ice and iron ore, and it keeps our homes cosy and warm when it is cold outside. Released by burning fuel in motors, it allows traffic to move and airplanes to fly.

Due to expansion of the world's population, with growing numbers of people owning heaters, home electrical connections and automobiles, and with ever widening fields of their daily lives being electrified, there is also a rapid growth in global primary energy consumption. Experts define this term as the total amount of energy required to supply the global economy. Up to now this need has been mainly produced by burning fossil fuels. In Germany, for example, roughly 80 per cent of the energy used in the year 2018 came from coal, natural gas and petroleum products.

Looking at the production of electric current alone, two-thirds of the electricity used globally is still generated by burning fossil fuels. The greenhouse gas emissions of the energy and traffic sectors are correspondingly high. More than one-quarter of the oil and gas burned is produced from the sea.

However, the energy sector is facing a radical transformation in two areas. The present power grids have to be expanded, modernized and intelligently managed in order to address the growing needs. At the same time, renewable energy sources such as wind, sun, biomass and hydropower are to replace conventional ones. Here, the ocean will also play a key role: for one, as a location for giant wind farms, and for another as a driver of wave energy converters and water-current power plants. There is also some discussion as to whether depleted natural-gas reservoirs beneath the seabed might be a suitable place to store carbon dioxide that has been captured from industrial operations and subsequently liquefied. At any rate, the storage potential would be enormous, and it is presently of great interest to a number of oil- and gas-producing companies.

Deep and ultra-deep water
The term "deep water" originated during the time when offshore drilling platforms still stood on the sea floor. It referred to the maximum water depth at which this kind of bottom support was possible. But the number assigned to this depth increased with advancing technology. While a water depth of 300 metres was considered to be "deep water" in the 1990s, today the term indicates a depth of more than 500 metres. When resource experts speak of "ultra-deep water", on the other hand, they are talking about water depths greater than 1500 metres.

Oil and natural gas production in the sea

Many of the Earth's oil and natural gas deposits are located beneath the sea. Formed over millions of years, the first of these to be drilled were in the Santa Barbara Channel off the coast of the US state of California at the end of the 19th century, although they were still within sight of the coast at that time. But shallow waters and close proximity to land ceased to be basic requirements more than 70 years ago. Due to improved exploration, drilling and production methods, oil and natural gas can now be retrieved from reservoirs in water depths greater than 3000 metres and more than 160 kilometres from the coast. However, the areas of deep-water and ultra-deep-water production are limited to the shelf seas on the continental margins. The deep-sea regions, which by far make up the largest part of the marine area, are underlain by oceanic crust, and have a very low or non-existent potential for the presence of oil or natural gas.

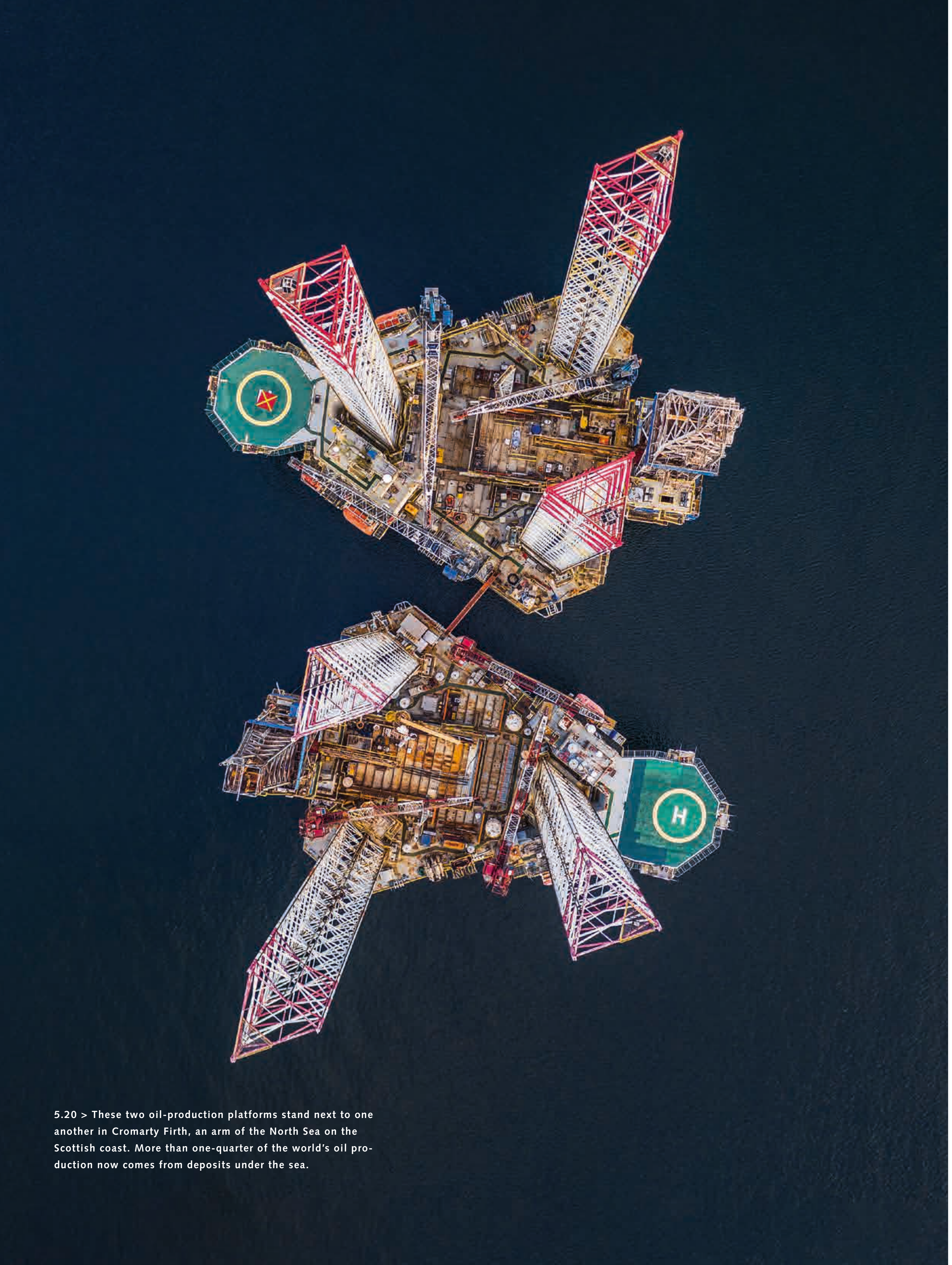
Drilling beneath the sea has now also achieved extreme depths. The deepest oil wells in the Gulf of Mexico, for example, extend for more than 6000 metres into the sea floor, and there are platforms whose drilling equipment could theoretically penetrate up to 11,400 metres below the bed under favourable conditions.

5.19 > A supply ship of the Norwegian energy company Equinor delivers technical equipment for oil production to the *Johan-Castberg* oil field in the Arctic. When the deposit in the Barents Sea goes into production it will be Norway's northernmost oil field.

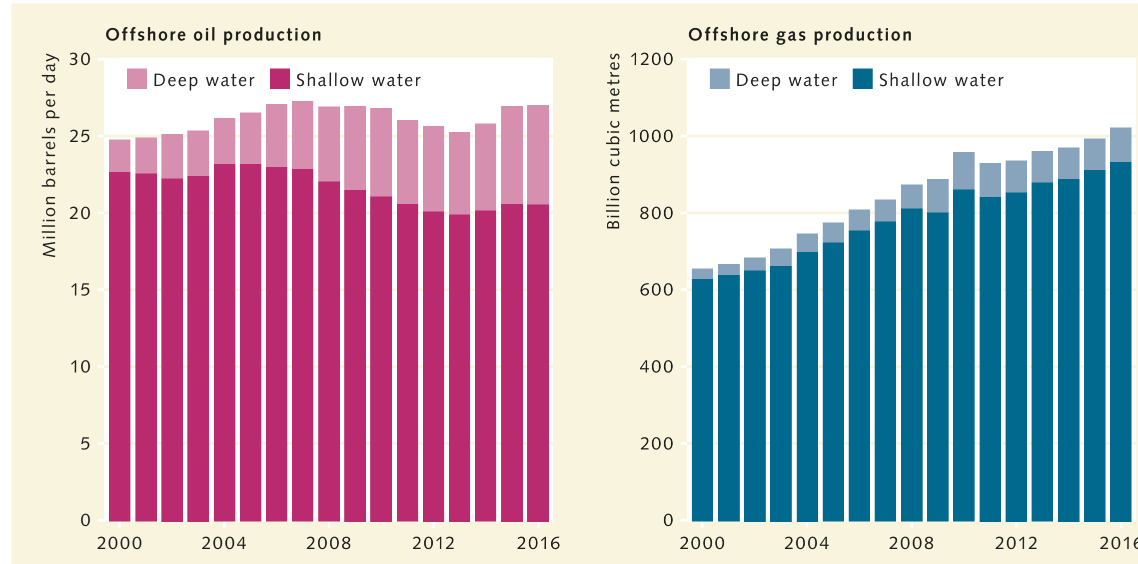
Technological advances have also allowed oil companies to expand their operations into areas where extreme weather or environmental conditions previously prevented production. In 2016, for example, the two Norwegian energy companies Vår Energi AS and Equinor (formerly Statoil) erected the *Goliat* drilling and production platform in the Arctic Barents Sea, thus developing the world's northernmost oil field to date. Development of another deposit, even further to the north, is already underway. Production in the *Johan-Castberg* oil field is projected to begin in 2023.

Oil and natural-gas production in the sea is very time-intensive, and also particularly cost-intensive. It can take up to ten years from the discovery of an offshore oil reservoir in ultra-deep water until the sale of the first barrel of oil. The costs for geological surveys and all of the necessary drilling and production technology typically total in the billions. The decision by a company to develop an offshore field or not is therefore not based on the current oil price, but with a view to projected price trends in the future. For this reason also, the levels of offshore production are not so closely tied to current price developments as are the amounts produced from deposits on land.

According to the International Energy Agency (IEA), the volumes of oil and gas produced from beneath the sea make up more than one-quarter of the total global production. There are now around 6500 offshore oil and gas production facilities in operation worldwide. The principal locations are the waters of the Near East, Brazil, the North Sea, the Gulf of Mexico, the Niger Delta and the Caspian Sea. While the amount of offshore oil production remained relatively stable at 26 to 27 million barrels a day from 2000 to 2018, gas production during the same time period increased by 50 per cent, to more than 1000 billion cubic metres. Another new development is that some operational steps, such as the liquefaction of natural gas, are



5.20 > These two oil-production platforms stand next to one another in Cromarty Firth, an arm of the North Sea on the Scottish coast. More than one-quarter of the world's oil production now comes from deposits under the sea.



5.21 > Since the year 2000, the amounts of fossil-fuel resources produced from the sea have been increasing, a trend that can largely be attributed to the rise in natural gas production. This takes place primarily in shallow waters. Oil, on the other hand, is increasingly being produced in deep water.

no longer carried out on land, but increasingly on special ships while still at sea.

In this setting, the search for new oil and gas reservoirs in the oceans is a continuing process. Over the past two decades, the largest deposits have been discovered in water depths greater than 400 metres. Altogether, these make up around half of all the oil and gas deposits discovered during the period from 2008 to 2018 worldwide. Considering the new reservoirs individually, it is clear that only a few of them can produce oil. More than half of the newly discovered occurrences are classified as natural gas fields.

In spite of all the new discoveries, many plans for offshore development were put on temporary hold following the *Deepwater Horizon* disaster in the year 2010 and the collapse of oil prices in 2014. During the same period, between 2013 and 2016, the number of active production platforms fell from 320 to around 220. One reason for this decrease was the enormous expansion of hydraulic fracking on land, especially in the USA. Fracking involves the deep injection of liquids at very high pressure, which produces cracks in the dense shale and petroleum source rocks. The shale gas and oil trapped in the rocks can then be extracted, and the entire procedure is much less expensive than offshore drilling.

The growing competition from fracking and the resulting price war forced adjustments in the offshore industry. Only highly promising drilling projects are now being carried out, and generally with much more efficient planning. The platform designs have been simplified, largely standardized, and in some cases even decreased in size. At the same time, the worldwide surplus of offshore equipment and services is contributing to a decline in operating costs. Whereas oil production facilities in Norwegian waters or in the Gulf of Mexico previously only made a profit when the market price for oil was above a threshold of USD 60 to 80 per barrel (159 litre capacity), modern facilities can now operate profitably at a price of USD 25 to 40 per barrel.

At present, companies are striving to further reduce costs by digitalizing certain processes of offshore production. They know that the reservoir for the next project will likely lie in even deeper waters or be further from the coast. It will therefore present the operator with more new challenges, be they technological, logistical or financial – whereby unexpected discoveries cannot be ruled out in coastal waters that have been sparsely explored so far. In 2018, experts from the USA compiled the following list of significant scientific and technological hurdles for the industry:

Methane hydrates – the price ultimately decides

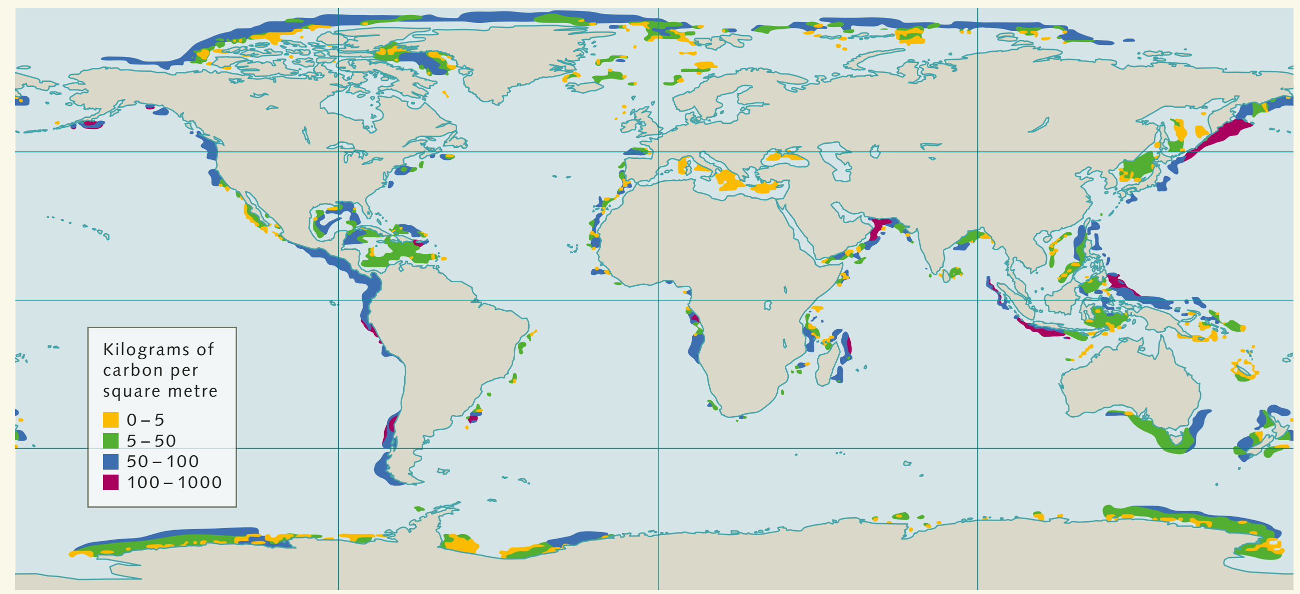
Natural gas in the sea floor occurs not only in the gas phase but also, and presumably much more abundantly, as gas hydrates, which are in solid form. Gas hydrates are composed mostly of frozen water molecules that form a solid crystal lattice. At first glance they therefore look just like ice. But unlike ice, there are one or more gases trapped within the crystal lattice of a gas hydrate. In many cases this gas is methane, but also nitrogen, carbon dioxide, hydrogen sulphide, ethane or propane may be present.

Gas hydrates therefore represent a highly concentrated form of natural gases. Roughly 160 to 180 cubic metres of methane gas can be obtained from one cubic metre of methane hydrate, which is why methane hydrates have been seen as an attractive potential energy resource for decades. Scientific studies suggest that there are between 100 and 1000 trillion cubic metres of methane gas in the form of hydrates in the sea floors of the shelf seas and continental margins. This amount would theoretically be sufficient to cover the current gas consumption of the world (2019: 4.088 trillion cubic metres) for at least another 24 years.

Realistically, however, only a comparatively small proportion of these deposits could actually be recovered because gas hydrates only form on the continental margins at water depths greater than around 300 metres. The reasons for this are twofold: For one, only on the continental margins does organic material settle from the upper water layers onto the bottom in sufficient amounts for microbes living in the sea floor to break it down and produce methane on a large scale. For another, only below a water depth of 300 metres is the pressure high enough that the gases generated in the sediments can combine with pore waters to form hydrates that remain stable. If the temperature on the sea floor changes or if the pressure decreases, the crystal lattice of the water molecules will break down and the trapped gases will escape. This physical process is known as dissociation, and it explains why it is possible to set fire to methane hydrates. The fire from a match first melts the ice and then ignites the escaping gas.

The extraction of methane hydrates has been technically possible for some time now. Japanese, US and European researchers have already developed and field-tested working methods. Their test results, however, were somewhat sobering. Compared to traditional natural gas production, it took far too much time for the drilled gas hydrates at depth to dissociate and for the escaping gas to rise through the pipeline. Considering the high investment costs projected by the tests, many experts concluded that industrial production is uneconomical. Nevertheless, Japan and China in particular are continuing to look at the development of new mining methods. If less expensive methods can be developed, Japan, for example, would be able to exploit the gas-hydrate deposits in its territorial waters and reduce its dependence on imported liquified natural gas. The experts working on it, however, have not yet achieved a decisive breakthrough. With the current world market prices for natural gas, extracting methane hydrates today would still be a losing proposition.

5.22 > When methane hydrates are brought up from the sea floor, they break down at atmospheric pressure. The methane released can then be easily ignited.



5.23 > Methane hydrates occur worldwide, especially on the continental slopes. The largest deposits are presumed to lie off Peru and the Arabian Peninsula. The figure illustrates only those hydrates in which the methane was produced by microorganisms. It does not include methane in the deeper sediment layers generated by the chemical transformation of biomass.

Looking through thick salt layers

In some regions, like the Gulf of Mexico and off the coast of Brazil, for example, oil deposits are present in the rock strata beneath thick layers of salt. However, these salt deposits, which can be up to two kilometres thick, are practically impossible to penetrate using conventional seismic methods. New analysis techniques and high-performance computers are needed that can analyse large numbers of geological datasets. Another problem is that salt dissolves when it comes into contact with drilling fluids. In some situations, it can even damage the drilling equipment or the borehole. Drilling through salt layers will therefore require new technology that is especially designed for salt.

Heat- and pressure-tolerant drilling technology

Conventional drilling equipment can be used at temperatures of up to around 175 degrees Celsius. In drilling for especially deep-lying deposits in the future, however, the ambient temperatures could be as high as 260 degrees Celsius. It would be hot enough in the borehole to bake a pizza. These temperature conditions would be destructive to many of the sensors and electrical components that are typically installed in the drilling system. For these kinds of operations, a drilling technology that is especially heat-tolerant, and that can withstand pressures 2000 times greater than the atmospheric pressure at the Earth's surface will be required.

New installation and observation systems

Companies are increasingly foregoing the use of floating platforms for producing oil and natural gas in deeper waters. This can be achieved instead by the installation of a subsea wellhead on the sea floor. Oil or gas flows from this through a pipeline directly to the shore. However, subsea systems still need to be monitored. This requires remotely controlled monitoring technology such as autonomous underwater vehicles with sensors and cameras that can examine the production systems for leaks or weak spots.

Storm-proof production facilities

Hurricanes are a growing safety issue because they are becoming stronger, particularly in the Gulf of Mexico. Oil and gas production facilities in storm-prone regions around the world have to be able to reliably withstand these weather extremes. The use of advanced technology or the installation of remotely operated underwater systems is therefore essential.

Another challenge is posed by production equipment that has been in use for decades. According to the IEA, around 2500 to 3000 oil or natural gas production systems will become obsolete by the year 2040. Many of these are steel platforms in shallow water. However, much more complex facilities in the deep sea are currently being added to these. The most environmentally friendly way to dispose of these would be to completely dismantle the systems and scrap them on land. But it is now conceivable that other solutions may be found such as using them as locations or foundations for offshore wind turbines in some situations.

The sea floor as a repository for carbon dioxide

The idea of using oil or gas platforms at the end of their service as sites for producing electricity from wind power, however, is just the beginning. With the advance of global warming and increasing pressure for action, governments and industry are intensively discussing whether it would be possible to store carbon dioxide in depleted oil or natural gas reservoirs beneath the sea to help prevent further warming of the Earth.

The idea of carbon capture and storage (CCS) is by no means a new notion. A number of concepts and approaches have been under consideration for several decades. But it has simply been much cheaper for industry to release greenhouse gases directly into the atmosphere than to capture them at great expense and store them underground.

One of two exceptions is provided by the oil industry itself. Particularly in the USA, oil companies sometimes inject carbon dioxide into partially depleted oil reservoirs in order to increase the pressure on the remaining oil and force it towards the production site.

As an added effect, the carbon dioxide improves the flow properties of the oil so that it can be produced faster. In this kind of oil production, known as Enhanced Oil Recovery (EOR), a portion of the injected carbon dioxide remains below the surface and is thus permanently stored. At present, however, only 30 per cent of the injected carbon dioxide comes from industrial capture projects. The rest, like the oil itself, comes from the subsurface.

Norway has gone a step further. As early as 1996, the country had already transformed one of its former marine natural gas fields into a carbon dioxide repository. As part of the *Sleipner* project in the North Sea, carbon dioxide that rises directly at the site of natural gas production is captured, liquified and then sequestered at a depth of 880 to 1100 metres below the sea floor. The responsible Norwegian oil company, Equinor (formerly Statoil), has also been operating under the same concept in the *Snøhvit* field in the southern Barents Sea since 2007. With these two CCS projects, the company now injects around 1.7 million tonnes of carbon dioxide into the sea floor each year. This amount is approximately equal to the emissions produced by a small coal power plant. But that is only the beginning.

According to its own reports, the company is now participating in more than 40 CCS projects and is developing concepts by which carbon dioxide can be separated during industrial production on land, liquified, and ultimately transported by ship or through pipelines to injection stations at sea. One of these is *Northern Lights*, a large Norwegian project that plans to capture carbon dioxide produced in cement production and waste incineration in the greater Oslo area and transport it by ship to the CCS terminal in Øygarden on the west coast of Norway. From there, it will be pumped through a 110-kilometre-long pipeline to an offshore temporary storage station south of the *Troll* natural gas field in the North Sea, where the liquified carbon dioxide will ultimately be injected to a depth of 2500 metres below the seabed. All of the necessary technological systems should be in operation by 2024.

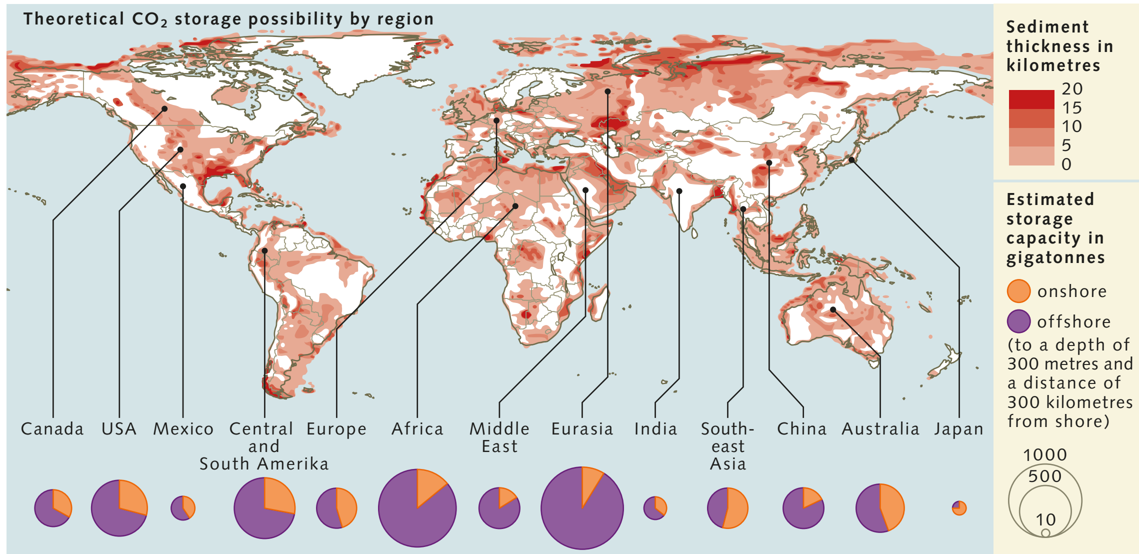
A group of companies in the Netherlands has similar plans. A depleted gas reservoir off Rotterdam (*Porthos* project) will serve as a carbon dioxide repository to store a portion of the 28 million tonnes of carbon dioxide released annually by the city's port and adjacent industrial area. The project plan estimates that two to five million tonnes of carbon dioxide can be injected into the *Porthos* reservoir annually. It remains to be seen, however, whether the emission-producing companies will actually follow through on their statements of intent and participate in the expensive process of carbon dioxide storage.

The cost of capturing one tonne of carbon dioxide at a cement plant, transporting it out to sea and injecting it into the sea floor is roughly estimated to be more than 50 Euros. CCS projects will not be economically viable until the cost for carbon dioxide emission exceeds the costs of capture and storage. For this to occur, however, the taxes on emissions will have to increase as drastically as the prices for the emission certificates. According to the World Bank, in 2019 companies paid between one and 19 US dollars for every tonne of carbon dioxide released, whereby more than half of the emissions were taxed at less than ten US dollars.

To date, initiators of CCS projects in Europe have been primarily focussing on the North Sea. This is partially due to the number of large industrial companies located in the coastal region, but also because of the ideal geological conditions beneath the floor of the North Sea. In order to store liquified carbon dioxide in the subsurface, a thick sandstone formation with abundant large pores between the individual sand grains is required, so that the carbon dioxide can easily disperse through the pore spaces. Overlying this sandstone formation, however, there must also be a layer of fine-grained clayey rock to seal it off and prevent the carbon dioxide from rising into the shallower layers of the sea floor.

After injection, the liquified carbon dioxide spreads through the porous region and slowly begins to dissolve in the pore waters of the sandstone formation. This process alone takes several hundred years. The dissolved carbon dioxide may eventually react with the surrounding rocks. It can dissolve them and form new rocks (limestone and other carbonates) in which the carbon dioxide is then per-

5.24 > In the *Sleipner* gas field in the North Sea, carbon dioxide that rises to the sea surface during the production of natural gas is captured directly on site, liquified, and then injected at a depth of 880 to 1100 metres back into the seabed.



5.25 > The greatest amounts of carbon dioxide could be stored onshore because the geological conditions are best there. Nevertheless, storage beneath the sea floor is being considered in many places, in part because the possible adverse consequences would be less severe than in inhabited regions on land.

manently fixed. Experts refer to this process as chemical neutralization of the greenhouse gas. It takes many millennia for this process to occur.

Reservoir rocks suitable for CCS are commonly located on the shelves and in marginal seas like the North Sea. The storage capacity of these alone is so large that they could contain an estimated 150 billion tonnes of carbon dioxide, which is roughly three times the annual total emissions from pre-corona times (2019: 42.3 billion tonnes of CO_2). Worldwide, there are at least 794 geological basins on land and in the sea where it would be theoretically possible to store carbon dioxide underground. Their combined storage capacity has been estimated at about 8000 to 55,000 billion tonnes of carbon dioxide. Of this capacity, 2000 to 13,000 billion tonnes are located in marine regions, whereby this calculation only takes into account the coastal waters (up to 300 kilometres offshore, maximum water depth 300 metres), and the polar seas are also not included.

Nevertheless, even large-scale CCS projects would not be enough alone to curb anthropogenic carbon dioxide emissions sufficiently to achieve the Paris climate goal of limiting global warming to significantly less than two degrees Celsius. For this, a much broader spectrum of measures for reducing carbon dioxide concentrations in the atmosphere will be required. However, experts at the International Energy Agency say that CCS will still play a key role as an interim solution. This process should principally be implemented in the industrial sectors where carbon dioxide emissions are currently considered to be unavoidable, such as in the manufacture of cement, steel production, production of chemicals, generation of electricity in biomass or coal-driven power plants, and in oil and natural-gas production and refinement.

According to calculations by the International Energy Agency, existing power plants and industrial facilities could be equipped with capture technology at a scale that allows around 600 billion tonnes of carbon dioxide to be captured globally within the next 50 years. That is equal to 17 times the current amount of total emissions from the industrial sector. The total quantity of captured carbon dioxide would not have to be stored underground. Some of it could also be used for the production of synthetic fuels. Raw-material experts also argue that inexpensive hydrogen could be produced from natural gas with the help of CCS. This could then be employed as a low-emission fuel or energy source for new applications in transportation, heavy industry or in buildings.

Finally, projects for underground storage of carbon dioxide could also be considered where the carbon dioxide is extracted directly from the atmosphere and subsequently liquified, a process known as direct air capture. This procedure is currently very energy-intensive and thus still too expensive. But for the long term, experts believe that unavoidable emissions will have to be offset by some degree of direct capture of carbon dioxide from the atmosphere. Otherwise, the goal of zero emissions will be no more than wishful thinking.

When comparing the advantages and disadvantages of storing carbon dioxide on land with storage options in the sea, the sub-seabed seems to be the lower-risk option because, as yet, there are virtually no infrastructures there that could be exposed to potentially serious damage. For example, if the sea floor is subjected to minor vibrations caused by the dispersion of carbon dioxide in the subsurface, the event would presumably cause very little disturbance to the biological communities on the sea floor. But on land these could cause damage to houses or roads. In addition, CCS projects on land could potentially affect the aquifers in the vicinity. These could be at risk of salinization, or acidification in some circumstances, and this could also be accompanied by the dissolution of toxic heavy metals from surrounding rocks. In the sea, such effects on possible groundwater reservoirs would be insignificant as long as these are not being used or planned as sources for drinking water.

The situation would be similar if carbon dioxide were to escape unintentionally from the subsurface. On land the greenhouse gas would be released directly into the atmosphere; but in the sea the escaping carbon dioxide would dissolve rapidly in the water, adding to its acidification. A large leakage experiment by European marine researchers in the Scottish North Sea suggested that this acidification is very localized, and only affects an area of ten to 20 metres around the site of seeping. If the site is in an area with noticeable currents or tides, the acidified water is diluted and its immediate detrimental effects on the marine animal and plant world are limited.

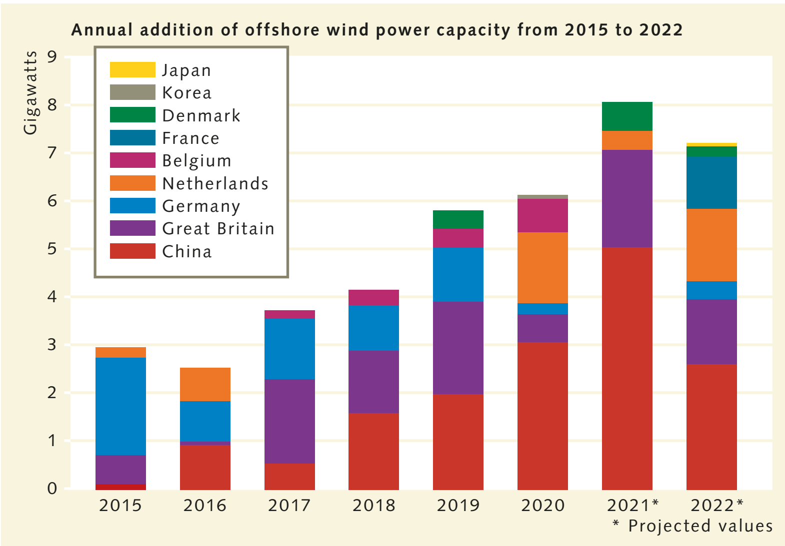
The leakage experiment has also helped to determine what kinds of technology will need to be employed to reliably and inexpensively monitor storage reservoirs of carbon dioxide in the sub-seabed over extended time periods. The operators of the two Norwegian CCS facilities in the sea perform regular seismic investigations of the subsurface. From the sea-floor profiles generated, the scientists can determine which rock layers the liquid carbon dioxide has penetrated. According to the experts, an observation network of geophones and passively listening robotic systems would be a beneficial addition to this. The geophones could be distributed on the sea floor and record the sounds of pressure-compensating motions, cracks or quakes in the subsurface. The robots would have the same function but, unlike the geophones, they would be mobile. They could thus move along the sea floor above the reservoir and check for signs of weakness, vibrations or leaks.

It is a well-known fact that the sea floor of the North Sea is perforated by around 20,000 drill holes. Added to this, there are naturally occurring cracks, fissures and vents. The subsurface is therefore as porous as a sieve. Methane is already escaping from the sea floor through around 4000 of the drill holes. Injecting carbon dioxide into the sub-ground near these holes would only induce additional leakage. Therefore, for the North Sea at least, it will not be a simple task to find potential reservoirs for carbon dioxide that satisfy all of the requirements. These are:

- located close enough to the coast to avoid high transport costs;
- located in a marine region where carbon dioxide storage is legally allowed;
- having reservoir rocks and an overlying caprock layer intact over a large geographic area;
- not already being used or planned for other purposes, such as shipping lanes, conservation areas or sites of future wind parks.

In the case of the North Sea, this does not leave very much suitable marine area. This situation has prompted the German government to initiate a national research project to study the possibilities and legal framework for CCS projects in German territorial waters. The experts

Terawatt-hours
One terawatt is equal to 1000 gigawatts, or one million megawatts. All three units express the power output that, in the case of a wind turbine, for example, specifies the maximum amount of energy that the unit can feed into the grid at a given instant in time. Tera-, giga- and megawatt-hours, on the other hand, are expressions of how much energy the wind turbine produces in one hour. These, therefore, address the question of how much current has actually flowed within one hour, rather than the peak output.



5.26 > The offshore wind sector is growing, but at very different rates in various regions of the world. The greatest annual growth in capacity during the period from 2015 to 2020 was seen in countries like Great Britain, China, Germany and the Netherlands.

began work in August 2021. A summary of their findings is expected in 2024.

However, whether the large-scale storage of carbon dioxide in the seabed will ultimately become a reality for Germany, Europe and areas beyond is, and will remain, primarily an economic decision. If the levies for greenhouse gas emissions do not continue to increase, industries will have absolutely no incentive to invest in and press forward with expensive CCS projects.

Promising sector — offshore wind power

An analysis by the International Energy Agency sounds promising: If wind turbines were to be actually built in all of the near-coastal marine areas that are suitable for their construction, and connected to the electricity grid, these offshore wind parks could generate a total of around 36,000 terawatt-hours of electricity per year.

This would be enough to supply the entire economy and all the world's households with power from a renewable source at least until the year 2040, and maybe beyond if electricity consumption doesn't continue to increase, which is not a realistic expectation. For comparison, in the year 2019, total global electricity consumption was 23,000 terawatt-hours. Roughly 0.3 per cent of this amount came from offshore wind turbines.

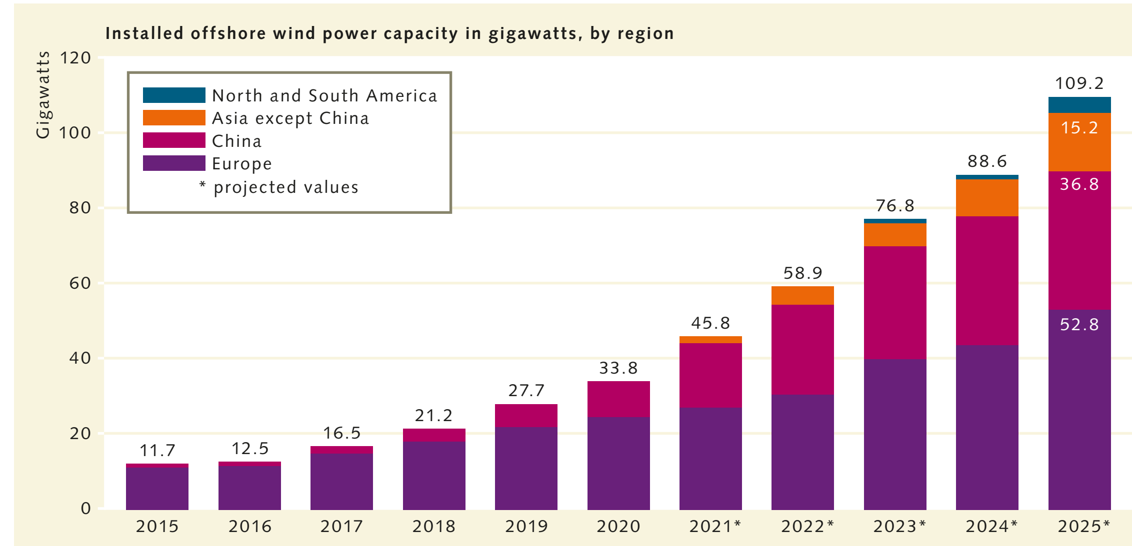
The urgency for producing electricity from renewable energy sources is growing every day. The reasons for this include more than just the steady advance of climate change. There is also the general increase in electrification of all aspects our lives and economies, including the transportation sector, heat supply and the growing need for cooling.

More than two-thirds of the electricity required for air conditioners, heating, robots, machines, e-mobility, computers and mobile telephones, however, presently comes from coal and gas power plants, although green electricity from renewable sources has become much cheaper. At the end of 2018, its share was 26 per cent of the electricity produced worldwide. If humankind is to meet the Paris climate target, it has less than 30 years to not only turn this ratio around, but to completely eliminate the generation of electricity and heat from fossil fuels by the year 2050.

Offshore wind turbines will play an important role in achieving this goal for four reasons. Firstly, they have the great advantage over onshore turbines that the wind at sea is generally stronger and more consistent. It can therefore generate more electricity for longer periods of time. Secondly, in many areas there is much less resistance from the population to offshore wind parks than to those on land. Construction projects thus have a greater chance of being approved. Thirdly, of all known technologies for generating electricity from renewable sources, offshore wind energy has the greatest potential for expansion.

And, finally, offshore wind farms can be constructed near small islands (small land areas that depend on imported fossil fuels) or in remote coastal regions (poor supply lines for fossil fuels) and thus significantly contribute to the energy needs of previously undersupplied areas with sufficient inexpensive and clean electricity, one of the 17 Sustainable Development Goals (SDGs) of the United Nations.

Because of the current state of affairs and the increasing societal pressure to act, the rate of expansion in offshore wind energy has risen significantly in recent years – driven primarily by investments from major oil-



5.27 > Worldwide, coastal states are investing massively in the expansion of offshore wind energy. If all of the projects presently planned are carried out, offshore wind parks with a total capacity of around 110 gigawatts will be connected to the electricity grids by 2025.

producing companies. During the period from 2010 to 2019, the offshore wind energy market grew by around 30 per cent per year, from three gigawatts of installed total capacity in 2010 to 29 gigawatts by the end of 2019. By that time, more than 5500 offshore wind turbines worldwide were connected to the electricity grid.

According to the International Energy Agency, another 150 offshore wind farm projects are expected to be completed by 2024, so that by the following year, one in five kilowatt-hours of wind energy will come from an offshore wind turbine.

The growing number of wind turbines in the German North Sea set a new record in 2020. According to the grid operator Tennet, with a combined capacity of 6679 megawatts, the turbines delivered a total of 22.76 terawatt-hours of electricity over the course of the year – an unprecedented yield. This is enough to supply around seven million households with green energy for one year.

The technology and expertise for the construction and operation of offshore wind turbines was developed primarily in Germany, Great Britain and Denmark. In 2019, Germany and the United Kingdom led the ranks of the largest offshore wind energy producers. However, China is presently making the largest investments in the construction of new offshore wind parks.

Larger wind turbines, lower electricity prices

The newest generation of offshore wind generators is equipped with larger turbines and many other improved technical functions that use the wind as efficiently as possible. For example, in 2023, when the first phase of the new *Dogger Bank* wind farm in the North Sea begins operation off the coast of Yorkshire, England, each of the 13-megawatt turbines will produce enough electricity with a single complete rotation of its rotor (blade length: 107 metres) to supply an English household with energy for two days.

In addition, new wind farms like *Dogger Bank* will be built at greater distances from the coast (100 kilometres and more), because the wind conditions are better further offshore. Because foundations on the sea floor are more expensive and technically difficult in deeper water, wind farm operators are now advancing the development of floating platforms like those used in offshore oil production. There are already 13 test sites globally, including in France, Portugal, Japan, South Korea and Scotland. Their initial performance results are promising. According to the Scottish operators, their five floating wind turbines produce more electricity than comparable facilities with fixed foundations. Experts therefore believe that floating wind farms could soon go into serial production.

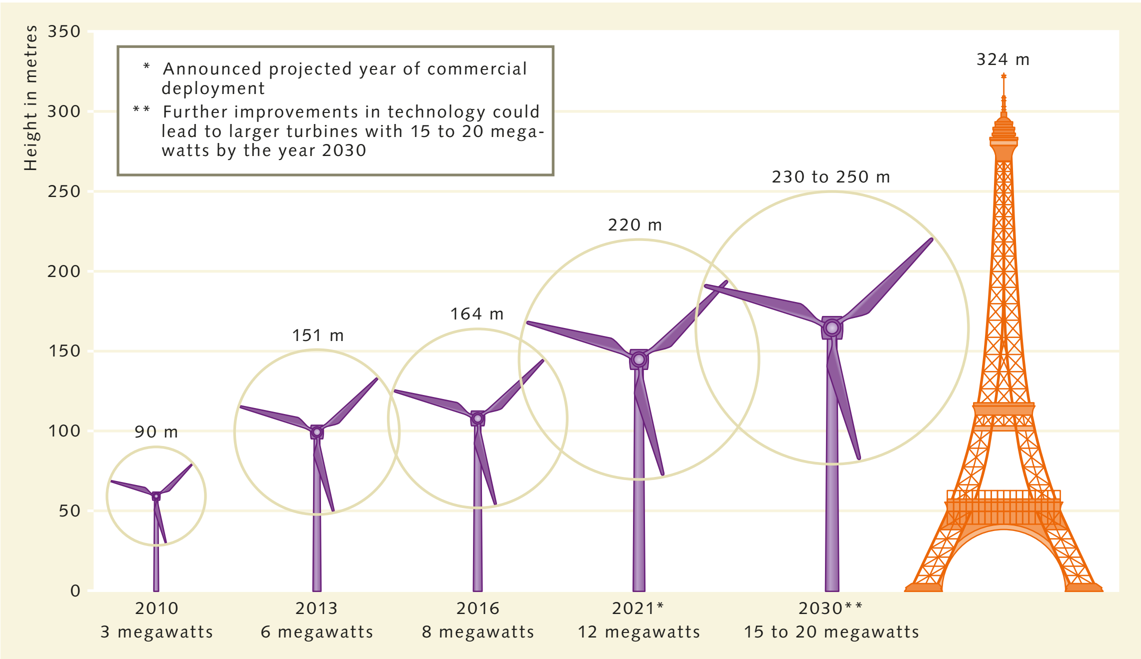
Due to numerous technological improvements, modern offshore wind turbines can now achieve a capacity factor of 40 to 50 per cent, and thus generate electricity with the same efficiency as many coal- or gas-fuelled power plants, even though the wind does not blow constantly. Offshore wind turbines are also more efficient than those on land, and have twice the capacity factor of photovoltaic systems. An additional advantage is that, unlike photovoltaic cells, offshore wind parks also generate electricity at night and under almost all weather conditions. In Europe, the USA and China, offshore wind parks produce particularly large amounts of electricity during the winter months. In India, the largest quantities of electricity are generated during monsoon periods.

Calculations by the International Energy Agency suggest that the cost of constructing and operating offshore wind-energy facilities will drop by more than 40 per cent by the year 2030, so that green wind electricity from the sea will soon be cheaper to produce than electricity from coal and natural gas. It will also probably be able eventually to compete strongly with onshore solar and wind generation. The IEA experts are therefore predicting huge growth for offshore wind power. By the year 2040 the amount of energy generated in this manner is to increase by a factor of fifteen. The European Union alone wants to install facilities with a total capacity of 300 gigawatts by 2050.

Because of the falling prices for wind energy from the sea, it is also being increasingly considered as an energy source for the production of green, or low-emission, hydrogen. This will be crucial for a number of uses that require a shift to low-emission energy sources, including the decarbonization of industry, transportation and heat supply. Just as one example, the output of a one-gigawatt offshore wind farm with present technology could produce enough hydrogen to heat around 250,000 homes. In January, 2021, the German government commissioned a large research project (H2Mare) to investigate the possibilities for producing green hydrogen and its by-products such as methane, ammonia and methanol directly at sea with the help of offshore wind turbines, and thus keep the costs of hydrogen production down.

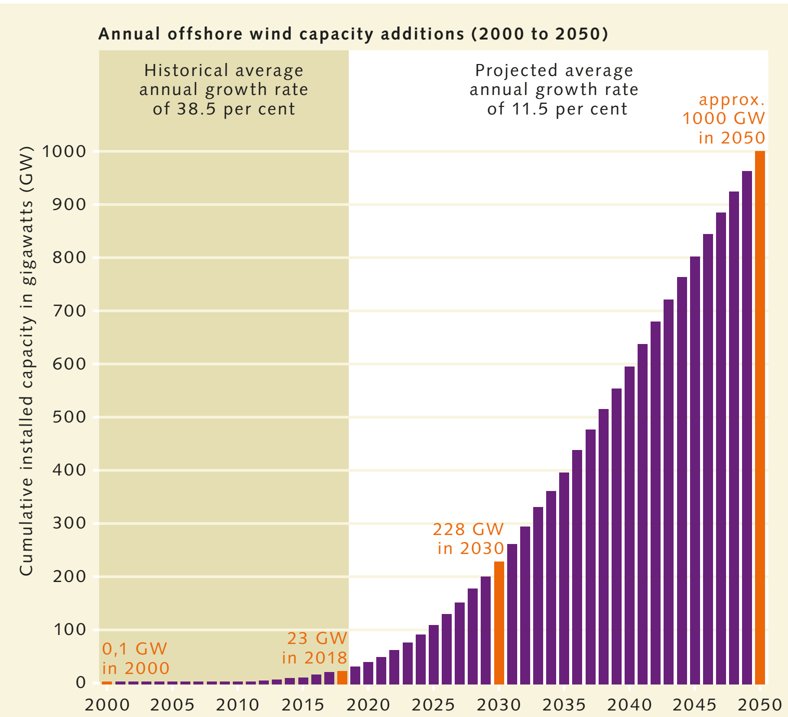
However, this is no reason for euphoria. In order to achieve the climate and sustainability goals of the inter-

Capacity factor
The capacity factor of a wind turbine is defined as the proportion of its maximum power output that it has generated within one year. The maximum value is the amount of energy that would have been generated if optimal wind conditions had prevailed throughout the entire year.



5.28 > Advances in technology make it possible. Modern offshore wind turbines are becoming larger and taller. Each new turbine, with its long rotor blades, catches more wind than its predecessors. The result is that electricity from wind energy can be generated in greater amounts and, above all, less expensively.

5.29 > The European Union is focussing strongly on green offshore wind energy. Member states aim to install facilities with a total capacity of 300 gigawatts by 2050.



5.30 > The Paris climate goal can only be achieved if humankind transforms its energy sector to renewable forms of energy. For this to be successful, calculations indicate that the offshore wind sector needs to be expanded to a total capacity of around 1000 gigawatts by the year 2050.

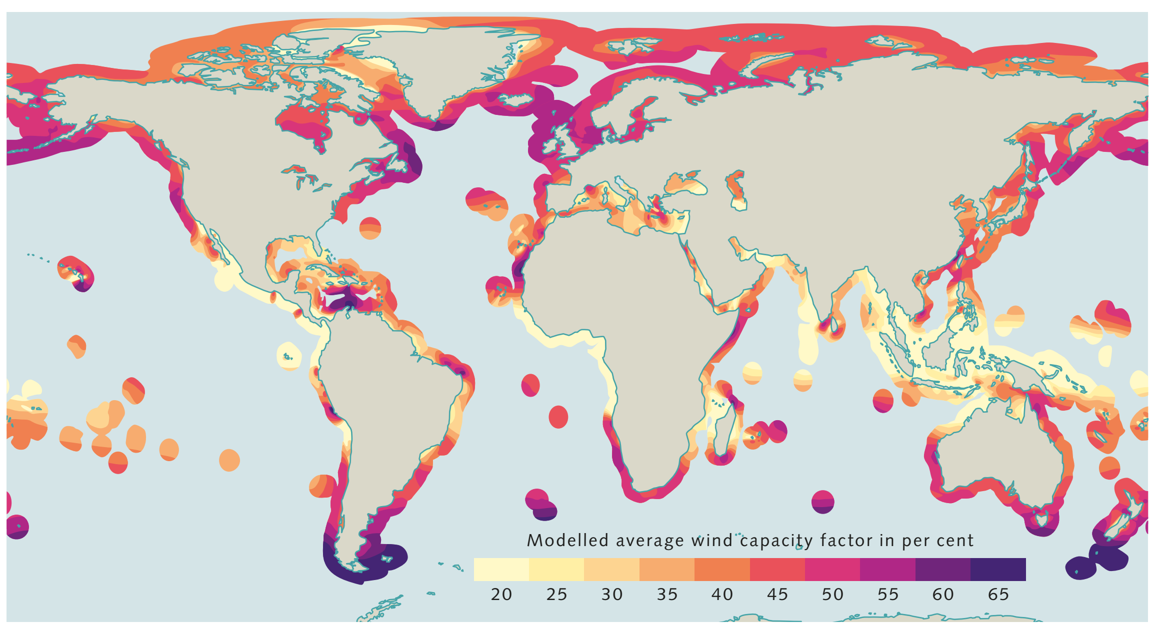
national community, the expansion of offshore wind farms will have to proceed twice as fast as it has been so far. For this to happen, the following are necessary:

- the explicit political will and a relevant offshore energy strategy,
- a clear legal framework,
- large investments, and
- progress in competitiveness, research and technology development.

Policymakers must lead the way

For a long time, the construction of offshore wind farms has been a national concern. But as the wind farms become larger and the sites shift further from shore, there is an increasing need for cooperation among multiple countries. This is necessary for the purpose of regional spatial planning, as well as for addressing the question of which grid the green electricity should be delivered to. An explicit commitment by every coastal state to advance the expansion of offshore wind energy and to cooperate with others in large-scale projects is therefore crucial.

Such an expression of intent is manifested by the formulation of national or joint offshore wind strategies by individual states or communities of states. These set the various expansion goals, characterize development trajectories and outline research, technology development and



5.31 > In the temperate and higher latitudes the winds blow stronger and more steadily, so wind capacity factors would be significantly greater than in the tropics.

knowledge transfer approaches. This establishes a setting for companies and investors that is reliable over the long term. The European Commission, for instance, published its strategy to harness the potential of offshore renewable energy in November 2020.

A fundamental component of the EU strategy is its commitment to a systematic and transnational planning of all activities on and in the sea (spatial planning), by which a significantly larger number of areas and sites are designated for the installation of bottom-fixed or floating wind farms that do not interfere with other kinds of usage such as fisheries, shipping and tourism. Furthermore, the European Commission recommends that the EU member states use best-practice examples to guide them in their planning, especially successful pilot projects that allow multiple use of the wind farms or the areas occupied by them, such as combining them with fish, shellfish or algae cultivation in aquaculture farms.

Moreover, it is important to include everyone affected by offshore wind power in a dialogue from the beginning. According to the European Commission, offshore energy technology can only be truly sustainable and thus viable for the future if it does not have a negative impact on the environment and does not endanger economic, social and territorial cohesion in the affected region.

A uniform legal framework

The rapid expansion of offshore wind energy requires planning and legal certainty for all participants, as well as clearly laid out and transparent approval procedures. Among other things, this implies:

- uniform procedures for evaluating and minimizing possible environmental impacts (especially underwater noise, damage to bird and marine mammal habitats, electromagnetic fields around sea-floor cables);
- uniform standards, regulations and approval procedures for the planning and construction of offshore wind farms;
- uniform regulations for connecting the offshore wind farms to the mainland and efficient transmission of current into the grid;
- uniform standards and regulations for the operation and maintenance of offshore wind power facilities, as well as for protection of the safety and health of all workers.

High investments

The construction of offshore wind turbines consumes a lot of money. In 2018, building a wind farm with a nominal capacity of one gigawatt would have required an investment of USD four billion. Since then, however, construction costs have been dropping and investments in offshore wind farms have been growing. In 2020 they rose drastically by 56 per cent compared to the previous year, ultimately reaching a total of USD 50 billion. The European Union estimates the cost of targeted power expansion to a total capacity of 300 gigawatts to be up to 800 billion Euros.

A large proportion of that money will be used to expand the electrical grid and trans-border connection lines because without them the green wind power cannot be distributed over a wide area. States bordering on the North Sea are also planning to combine several offshore wind farms in clusters or hybrid projects whose connection networks can supply multiple countries with electricity simultaneously.

Competitiveness, research and technological advances

Lowering the costs of green electricity from offshore wind farms will require efficient and competitive supply lines for all the necessary components and services. Furthermore, supply of all the metals required for construction of the wind turbines (especially the rare earth metals) needs to be guaranteed far into the future. There must also be progress in research and technology. The following questions, for example, still need to be addressed:

- In a large wind farm, how do the individual turbines need to be arranged in order to make optimal use of the wind without interfering with one another?
- How do large wind farms influence each other, and how do they affect the local weather?

Green hydrogen
Hydrogen is a colourless gas. Depending on its origin, however, it is named by various colours. Grey hydrogen is obtained from fossil fuel by the splitting of natural gas. Carbon dioxide is also produced in this process and released into the atmosphere. With blue hydrogen, the carbon dioxide produced is captured and stored, and thus does not enter the atmosphere. Green hydrogen is produced by the electrolysis of water using electricity from renewable sources. This process is carbon dioxide free.

Energy from the sea – technologies promoted by the European Union

Offshore wind turbines are not the only kind of technology that can be used to obtain green energy from the sea. There is a wide range of other types of emission-free energy technology in this category that are at various stages of development, but which, in the long term, certainly have potential applications at the local, regional or even global levels. In its offshore energy strategy, the European Commission is considering the following technologies for marine energy:

Power plants driven by currents and tides

Electricity plants powered by water currents and tides are presently among the most technologically advanced concepts for the production of energy from the sea. They use the motions of water-mass flow from tides or other natural marine currents to produce electricity.

For tidal power plants of the dam-construction type, marine basins are separated from the open sea by a dyke. Large ducts with turbines are installed in the dykes, through which the rising or falling water flows. Electricity is produced each time this happens. The principle works in both directions, but requires especially high tidal ranges that are found only on a few coasts of the world. Because the damming of bays and estuaries is very costly and has extensive environmental impacts, only a few dam-type tidal power plants have been constructed. These include a 240-megawatt plant in France and a 254-megawatt facility in South Korea.

The construction of more power plants of this type is unlikely. Experts are now focussing on marine current power plants, in which large rotor turbines attached to a mast or cable are positioned in the current. Modern current turbines are similar to the rotors of wind turbines and can now produce up to 1.5 megawatts of power. The largest marine current power plant in the world to date is the *MeyGen* project in northern Scotland. Its first four underwater rotors officially started operation in April 2018 and now reliably and predictably generate electricity for 2600 households. Other water-current power plants are presently under construction; the total global installed capacity is to surpass the one-gigawatt mark by the year 2025. Theoretically, however, many times more than that would be possible. Experts believe that as much as 1200 terawatts could be generated with current and tidal power plants. At present, however, the costs for this type of electricity generation are still too high.

Wave power plants

Up to 29,500 terawatt-hours per year could theoretically be generated using wave-energy power plants, with the greatest potential in the high-wind regions of the temperate latitudes in both hemispheres (30 to 60 degrees latitude). A few technologies have been trialled, but so far none of them have been fully convincing. Experimental systems have typically consisted of a device floating on the surface of the sea that is anchored to the sea floor and produces electricity by rising and falling with the waves. Pilot systems now installed worldwide have a total capacity of 2.5 megawatts. As the technology advances, however, experts believe that wave energy capacity will soon increase to 100 megawatts or more. The European Union aims to expand its wave, current and tidal power capacity to 40 gigawatts by the year 2050.

Floating photovoltaic

The idea of installing photovoltaic modules on the water is not new, and it is already being practised on dammed reservoirs and dredged lakes. The time-tested solar technology is now being progressively adapted to the sea. In February 2018 a Dutch consortium installed a pilot system with a capacity of 8.5 kilowatts on the North Sea and is planning to expand this to 100 megawatts. But South Korea is already a step ahead. The country is constructing a vast floating offshore photovoltaic plant with a total capacity of 2.1 gigawatts off the southwest coast of the Korean peninsula. According to press reports, the first phase of this plant, built at a total cost of USD 3.96 billion, should be connected to the grid by 2022, and the second phase three years later. India, Thailand, Vietnam, Singapore and the Seychelles are also pushing their own pilot projects in this field. The European Commission acknowledges the promising potential of the technology for coastal and near-coastal areas, but also stresses that existing marine applications are still predominately in the research or demonstration phase.

Biofuels from algae

Technical solutions for producing biodiesel, biogas and bioethanol from large algae are also in the early stages of development. The European Commission has judged the potential to be very promising, and expects individual technologies to be ready for the market by the year 2030.

5.32 > One of the fastest marine currents of Scotland drives the underwater rotors of the MeyGen power plant. In the first phase, the operating company installed four turbines on the sea floor, which have been supplying around 2600 households with electricity since August 2018. Further turbines will be added.

- How should electric grids be built and managed to be able to feed in large amounts of electricity from different wind farms under high wind conditions, to distribute and, if necessary, store it, so that the current is always available when and where it is needed by industries and households?

The substantial expansion of wind energy also presents a great challenge to marine researchers in determining the short- and long-term environmental impacts of the intensive and large-scale use of wind offshore. It has long been known that the noise generated during construction work creates high levels of stress for marine organisms. But how, for example, is the wind-driven mixing of the surface waters and the consequent oxygen and nutrient exchange with deeper water layers affected when large numbers of wind turbines impede the flow of air on the sea surface to some extent? Would this result in decreased algal growth and ultimately lower biomass production? This kind of chain reaction is theoretically conceivable, but scientists will have to investigate it more thoroughly to determine whether it occurs in the real world.

What is certain, however, is that with the growth of the offshore wind energy branch new jobs are being created. In the EU today 62,000 people already work in this sector. According to calculations by the International Renewable Energy Agency (IRENA), by the year 2030 the wind energy branch, including both onshore and offshore, will employ up to 3.74 million people worldwide. By 2050 the number of workers could increase to more than six million. Offshore wind farms not only provide a vital contribution to transforming our energy supply to electricity from renewable sources, they also represent a key sector in the sustainable marine economy. Without offshore wind power, sustainable development in the world and comprehensive decarbonization of our economy would be inconceivable today.

5.33 > Photovoltaic arrays so far have been primarily located in shallow bays where they are protected from wind and waves. This installation in the Chinese coastal city of Zhangzhou is one example.

Conclusion

Our oceans – full of energy

Humankind is facing a huge task. If limiting global warming to less than two degrees Celsius is to succeed, the energy supply of the world, including transportation and heating, must be converted to low-emission or emission-free technology. According to our present knowledge, such a transformation is absolutely impossible without the world ocean. The world's oceans must be exploited for two processes simultaneously – almost certainly as a direct source of energy, and likely also as a source of raw materials.

Regarding the idea of energy production from the sea, mankind is now at a fork in the road. New oil and gas deposits are still being developed offshore. These new reservoirs mostly lie at greater depths than before, and at greater distances from the coasts. While the global production of oil from the sea is high but fairly static, natural gas production is steadily increasing. More than a quarter of global fossil resource production now comes from the sea.

At the same time, the primary investors in large offshore wind farms are oil producing companies. The wind farms are also being built at increasing distances from the coasts to take advantage of better wind conditions on the open sea. Technological advances have helped to build modern wind turbines much larger than their predecessors, and thus able to produce much more power. As a consequence, the prices for green offshore wind power are falling and demand is growing.

Because of the high potential of offshore wind energy, its production is one of the most important pillars of national and international strategies for sustainable energy production. Other systems, such as wave and current power plants, offshore photovoltaic arrays, or biofuels from algae are all still in the developmental stages. But, over the long term, these too must be employed to meet the increasing electricity requirements of modern societies.

However, the expansion of renewable offshore energy, as well as the distribution and storage of electric power, can only succeed if the necessary power plants, power lines and battery systems are installed. These require increasing amounts of raw materials, whose extraction on land destroys habitats for mankind and animals on a large scale. The mining of large raw-material deposits in the ocean, especially in the deep sea, which contain a greater variety of metals and minerals than the deposits on land, would be a conceivable alternative. Our knowledge of these deep-sea occurrences has grown significantly over the past 20 years. The International Seabed Authority (ISA) with headquarters in Kingston, Jamaica, has awarded 31 contracts for exploring the sea floor for mineral raw materials since the year 2002. Preliminary designs in mining technology have been tested on site. These were accompanied by extensive expert investigations of the environmental consequences of possible deep-sea mining and the development of monitoring systems. The ISA is presently drafting and negotiating a set of rules for deep-sea mining in international waters. This could commence, according to experts, within five to ten years.

Environmentalists are calling for a general ban on mining in the seas. They point out that in view of the tense situation regarding resource supply, developing further natural resource deposits is not a solution. Instead, the enormous consumption of resources must be reduced to a minimum. This, however, would require a fundamental restructuring of the consumption-based economic system and significant changes in the behaviour of each individual consumer.

6 Pollution of the oceans

> Whether deliberately discharged or unintentionally introduced, plastic waste, pharmaceuticals, toxic heavy metals, insecticides and other chemicals have found their way to every corner of the oceans. The consequences are catastrophic and often lethal, especially for marine organisms. The only good news is that international prohibitions of some pollutants are beginning to have an effect. Without radical changes in industry and commerce, however, the pollution crisis in the oceans cannot be overcome.

A problem of immense scale

> The United Nations has estimated that humankind discharges around 400 million tonnes of pollutants into the sea annually. Evidence of this persistent pollution can now be found in all regions of the world's oceans – on remote islands, in the polar regions and in the deepest ocean trenches. Substances that are concentrated in the food chain are especially harmful because these pose a real danger to marine organisms as well as to people.

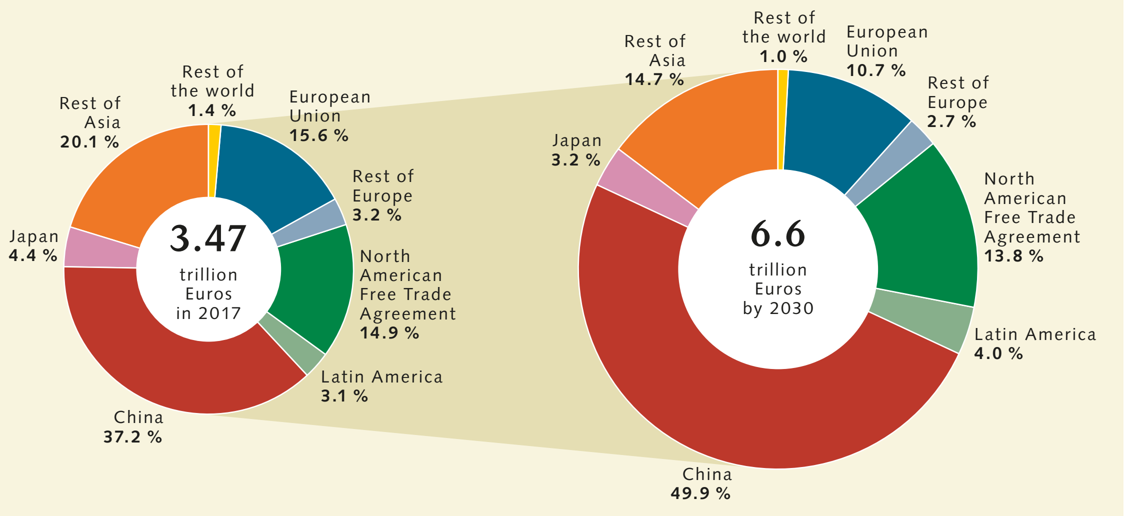
Contamination everywhere

Just like water and carbon, most natural substances move in giant cycles around the planet. Sometimes they are carried by flowing water and sometimes by the wind. In other cases, living organisms pick them up and transport them from one location to another. Geological processes may also convey previously deposited material back to the surface after thousands of years. The fact that materials are carried from the land into the sea is therefore just a part of the natural scheme. But since people have inhabited the Earth and have built cities, established global industries, practised intensive mining and agriculture and employed an estimated 40,000 to 60,000 different chemicals worldwide, the input of substances and materials into the world ocean has increased massively.

The terms "pollutant" or "environmentally hazardous material" refer to all substances and compounds that themselves or whose products of decay are capable of altering the properties of water, soil, air, climate, animals, plants or microorganisms in such a way as to pose an immediate or long-term risk to the environment. These criteria are fulfilled by many substances now found in the environment. In their current *Global Environment Outlook (GEO-6)*, experts of the United Nations Environment Programme (UNEP) concluded that humankind has never before lived in a world as contaminated with pollutants as it does today.

Humans themselves are responsible for this. Every year up to 400 million tonnes of pollutants are still being discharged into lakes, rivers and seas. These include thousands of chemicals, nutrients, plastics, toxic heavy metals, pharmaceutical substances, cosmetic products, pathogens and many more substances that have practical uses for humans but can cause harm when released into the environment. Around 80 per cent of these pollutants originate from sources on land. The remaining input is generated by fisheries, marine shipping, drilling platforms and aquaculture, even though the disposal of harmful waste and other substances at sea, with very few exceptions, is prohibited by the London Convention of 1972 and its supplement, the London Protocol of 1996.

Projected growth in worldwide chemical sales (excluding pharmaceuticals), 2017 to 2030



6.1 > Growth market: More and more chemicals are being sold worldwide. According to the United Nations, turnover in this sector will grow to USD 6.6 trillion by the year 2030. By that time, around 70 per cent of all chemical sales will be carried out in Asia.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) now lists pollution as the fourth-strongest driver of species extinction in the oceans. The only factors that are more detrimental are climate change, direct forms of exploitation like overfishing, and fundamental changes in usage of the seas. The latter include, for example, the destruction of natural coastal systems and river deltas, the expansion of marine aquaculture and ruinous bottom-net fishing.

UNEP experts refer to the high levels of contamination on land and in the sea as a global pollution crisis that is depriving humanity of its own livelihood. In the long run, only nature in a healthy state will be able to provide people with sufficient food, drinking water and other vital services. Globally, three times more people are dying today from the effects of environmental pollution than from the deadly diseases AIDS, malaria and tuberculosis combined.

The steady input of pollutants into the oceans is a direct result of the increasing production and use of these substances on land. Every year more fertilizer is being produced around the world, and more crop-protection products (pesticides) are being applied to increase the harvests and provide the Earth's growing population with food, plant-based fibre, animal feed and biofuels. From 2002 to 2018, for example, the amounts of crop-protection products used per hectare of farm land rose by 30 per cent. During the same period, farmers around the world increased their use of artificial fertilizers by 13 to 56 per cent in order to enrich their lands with nitrogen, phosphorus and potassium.

The London Convention and its Protocol

The London Convention of 1972 was one of the first treaties in international law to make marine conservation an international obligation. It was amended by the London Protocol in 1996, which is applicable to those states that had previously agreed to the Convention. Both treaties were developed to regulate the discharge of hazardous wastes and other substances into the ocean. As of January 2021, however, only 87 states had acceded to the Convention and only 53 to the Protocol, which means that coverage is less than universal for both of them.

Nevertheless, the London Convention sets internationally binding standards for marine conservation, in part because it is reinforced by the UN Convention on the Law of the Sea, the charter for the oceans that is recognized by almost all countries. The UN Convention on the Law of the Sea indirectly holds the standards of the London Convention and potentially also those of the Protocol to be applicable to all states, including those that have not signed the treaties.

The London Protocol came into force in 2006 and generally prohibits the discharge of waste into the sea. Exceptions to the ban include dredged material, sewage sludge, fish waste, derelict ships and drilling platforms, as well as natural organic and geological material.

Household products, furniture and electronic products are being manufactured with increasing amounts of plastic, and thus contain a large variety of environmentally hazardous chemicals. The wealthier people are, the greater their perceived needs become and the more they consume. However, our consumption-oriented lifestyle is producing mountains of waste, while people in the industrialized nations in particular are consuming more and more medicines to treat common ailments such as diabetes or headaches and back pain. And as more hazardous chemicals are bought and sold, the risk of accidents during their transportation increases, often resulting in severe environmental damage – both on land and at sea.

The great variety of applications for the known pollutants clearly illustrates that only a portion of the chemicals known today to be hazardous were initially developed with the intent that they be toxic, such as pesticides. Many were intended to fulfil completely different purposes and be used primarily for the well-being of people. The harmful effects of these substances were often not

Chemicals of special concern
Chemicals have a very large range of physical and chemical (physicochemical) properties and can have a wide variety of effects on living organisms. Substances that cannot be naturally degraded (longevity, persistence), those that are enriched in organisms (bioaccumulation) and poisonous substances (toxicity) are particularly hazardous. Substances with hormone-like effects, called endocrine disruptors, also fall into the category of "special concern" because of their problematic properties, and are thus considered to be highly hazardous.

realized until they appeared in increasing amounts in the rivers, lakes and oceans and scientists began to recognize their connections with diseases in aquatic organisms.

The use of these chemicals is expected to continue to increase, even though for many of them the potential danger to the environment is completely unknown. To make matters worse, the prohibition of especially hazardous substances is never even considered until after the first catastrophic environmental impacts are observed. But no one can presently really say how much of these substances will have already reached the lakes, rivers and oceans by then, and what long-term consequences they will have. It is a known fact, however, that winds and ocean currents are distributing the pollutants to every corner of the world's oceans, and that they are thus reaching the most remote and inaccessible regions.

A few years ago, while studying deep-sea amphipods in the Mariana Trench (the deepest ocean trench in the world) for environmental pollutants, scientists found that the animals there contained 50 times more persistent organic pollutants (POPs) than shrimp taken from the estuary of one of China's dirtiest rivers. Toxicity levels similar to those in the Mariana Trench amphipods have only been found in animals from Japan's Suruga Bay, a highly industrialized coastal region where chemicals with organochlorine compounds (chlorinated hydrocarbons) were previously used on a large scale. Many of these chemicals, primarily used in pesticides or flame retardants, have now been banned.

Pollutant accumulation in the food chain

Scientists have not been able to provide a clear explanation for the high contamination observed in the deep-sea amphipods from the Mariana Trench. But the bioaccumulation of toxic substances could play a part. Bioaccumulation is defined as the uptake of a substance from the environment and its subsequent enrichment in an organism. Not only do the marine organisms ingest the chemicals with their food, the substances can also enter the organisms through the skin or gills and then be deposited in their fatty tissue. Accumulation is facilitated by the fact that most of the harmful substances do not dissolve in water at all, but are readily soluble in fats and oils. Fats, in turn, are important building blocks for plant and animal cells. Furthermore, marine organisms form fatty tissue as an energy reserve in times of scarce food supply. But with the bioaccumulation of pollutants, fat reserves like the blubber in whales and seals can become veritable repositories of poisons.

The degree of bioaccumulation is usually reported as the ratio of the chemical accumulated in the organism relative to its concentration in the environment. According to the German Federal Environment Agency, accumulation factors of up to 100,000 have been observed for some highly accumulating chemicals. This means that the animals take up these chemicals from their surroundings and can enrich them in their bodies up to 100,000 times the concentration present in the environment.

The consequences for the animals are many and they vary from one species to another. The numerous toxic substances in the sea can:

- trigger diseases like cancer,
- lead to deformities,
- cause hormonal changes (for example, female fish form male genitalia) that affect the reproduction of many species,
- damage the genetic make-up of an animal or cause genetic mutations,
- cause behavioural changes,
- often lead to the death of the contaminated marine organism.

Predatory animals at the top of the marine food chain are often severely impacted by this. These include sharks, toothed whales, seals and seabirds – and humans when we eat fish or seafood that is heavily contaminated with environmental pollutants. This high risk to the predator is due to the fact that the poisons are passed up through the food chain. The heavily contaminated amphipods are eaten by a small fish, which then ends up in the stomach of a predator fish that is eventually eaten by a killer whale. The more often this sequence, known as biomagnification, is repeated, the more the body of the killer whale is enriched in toxic substances and damaged by them.

6.2 > The deep-sea amphipod *Eurythenes plasticus* carries the word "plastic" in its name. The reason is that when biologists first discovered the species in the Mariana Trench, they found fibres made of polyethylene terephthalate (PET) inside the intestines of one animal, a kind of plastic that is present, for example, in disposable bottles and in sports clothing.

European scientists observed record rates of poisoning several years ago when they studied tissue samples and examined reports on the cause of death of more than 1000 striped dolphins *(Stenella coeruleoalba)*, bottlenose dolphins *(Tursiops truncatus)* and killer whales *(Orcinus orca)*. They were addressing the question of the degree of contamination by pollutants such as chlorinated hydrocarbons in the mostly dead animals that were washed ashore (carcasses from 1990 to 2012). This group of substances includes some pesticides (such as lindane and DDT) and polychlorinated biphenyls (industrial chemicals). The recorded poisoning rates exceeded all previously measured levels for marine mammals, although the production and use of the toxic substances involved had been banned in the USA in 1979, in Great Britain in 1981 and in the Mediterranean countries in 1987.

The scientists reported that the extremely high levels of poisons in the animals were a primary reason why many of them were sick and infested with parasites. Dolphins and killer whales from the Mediterranean were hardest hit by the poisons. This landlocked sea is a toxic hotspot that is so heavily contaminated by chlorinated hydrocarbons, mostly from the group of polychlorinated biphenyls, but also by other pollutants, that the dolphin and killer whale populations have been declining for the past 50 years. This is mainly because wale offspring has become rare due to infertility caused by the poisons.

The six females of the only remaining killer whale family existing in the Mediterranean Sea at the time of the study, for example, gave birth to only five calves during the period from 1999 to 2011 that were able to survive past the age of one year. Up to the time of the publication of the study in 2015, a single group of killer whales that were regularly sighted off the northwest coast of Scotland

6.3 > Although there are hardly any people living in the rainforest-covered region of northern Columbia, thousands of fragments of plastic wash ashore with every wave surge and pollute the remote coastal strip.

and in western Ireland produced even fewer offspring. Over the 19 years that the scientists had observed these whales up to that time, the animals did not have a single young animal with them, although the group comprised both male and female individuals.

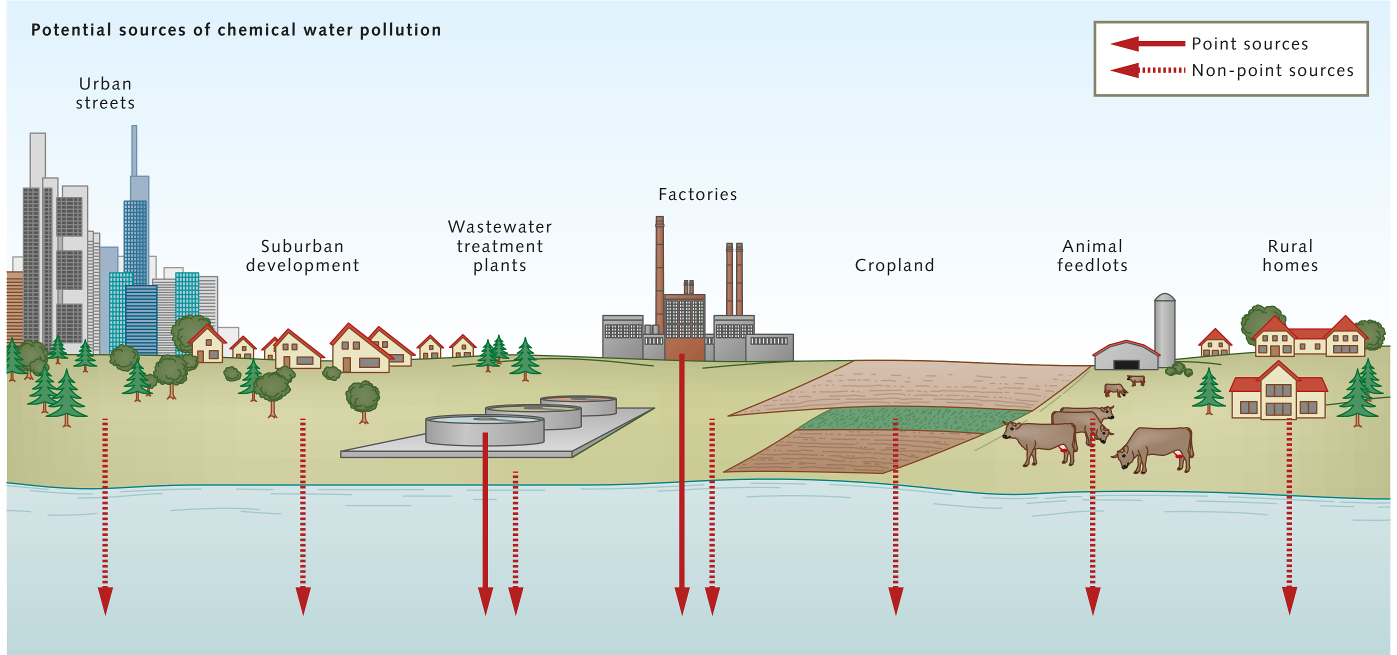
Pollutants in the sea

In eight of ten cases, marine pollution begins on land. Only occasionally is it possible to trace it back to a single source. These point sources include chemical plants or mines that discharge waste or effluent into rivers or directly into the sea, but also ships that discharge their garbage before entering a port. Point sources also include wastewater treatment plants that collect all of the wastewater from a region, treat it to some degree and then discharge it into a river or directly into the sea. In addition, there are still many communities that dispose of their wastewater without treating it, according to the old maxim: the best way to get rid of filth and waste is to dump it into the sea.

But much more often, marine contamination comes from more diffuse sources. There are many offenders and, as a rule, they are not easily identified. Furthermore, the pollutants do not always enter the sea through direct discharge, but may also be transported through the air or by rainwater.

On the west coast of the USA, scientists have recently discovered that a chemical additive in car tyres meant to protect them from degradation by ozone has caused the death of up to 90 per cent of the population of coho salmon *(Oncorhynchus kisutch)* in rivers after a strong rainfall. The chemical is present in the fine particulates from tyre wear that are produced when cars drive over asphalt. When it comes into contact with ozone, its chemical structure changes to produce a poison. The particles are then washed into the rivers during the next rainfall; the poison escapes from the tyre rubber and becomes fatal for the coho salmon.

Once they have reached the sea, environmental pollutants act in highly diverse ways. Water-insoluble substances, such as polychlorinated biphenyls, adhere quickly to the tiny remains of animals and plants and sink with them to the seabed, provided the particles are not broken down by microbes or eaten by animals on their way to the bottom. Other substances, such as the highly toxic organic



6.4 > Eighty per cent of the pollutants in the ocean originate from onshore sources. Experts distinguish between point sources and non-point sources. The former category includes factories or water treatment plants that discharge their effluent directly into the sea. The latter refers to those sources that discharge pollutants into the ocean by more indirect pathways.

tin compounds (including tributyltin, TBT), which have long been used in marine paints, evaporate easily and can thus enter the atmosphere when water evaporates at the sea surface. They are carried away by the wind and eventually condense with the water vapour and fall as rain somewhere else. They are therefore only redistributed and not decomposed.

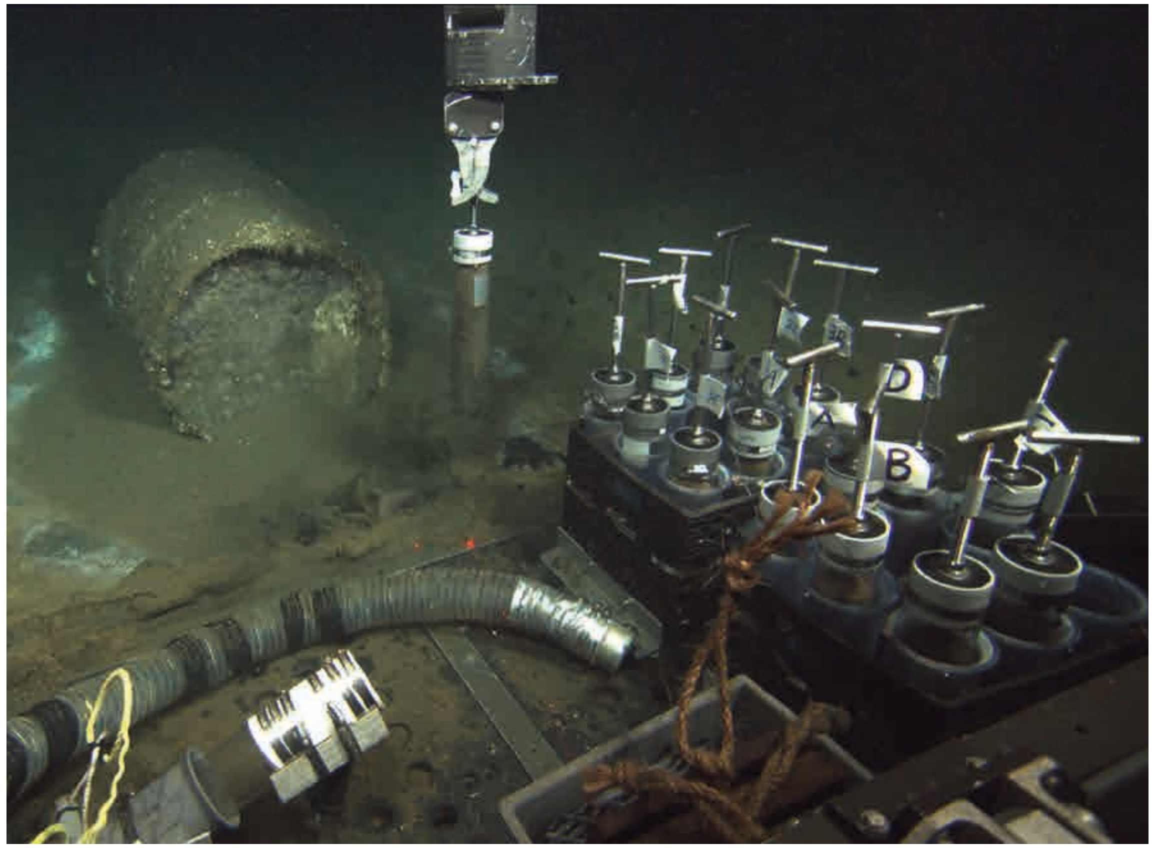
This situation, along with the fact that marine currents can distribute pollutants around the entire globe, makes their input to the sea an international issue that crosses all borders. The solutions thus require international cooperation and the use of joint and coordinated measures.

The most relevant groups of pollutants in the sea under scrutiny by environmental scientists include:

- polychlorinated biphenyls (PCBs), pesticides and other groups of substances that fall into the larger category of persistent organic pollutants (POPs),
- pharmaceuticals (medicines) as well as hormones and hormone-like substances,
- heavy metals,
- polycyclic aromatic hydrocarbons (PAHs),
- per- and polyfluorinated alkylated substances (PFAS),
- radioactive materials,
- plastic waste.

Persistent organic pollutants

The collective term "persistent organic pollutants" (POPs) encompasses a large group of organic chemicals that can contain halogens such as fluorine, chlorine, bromine, iodine or astatine. Because of their chemical compositions they are not readily degraded in nature and are thus very long-lived. POPs can thus be transported over long distances. They accumulate in suspended organic matter in the water and in the fatty tissues of organisms, and they are toxic to humans and animals. Even very small amounts of these contaminants can cause cancer. They damage the central nervous systems of living organisms, weaken their immune systems and cause problems with reproduction. The development of children who were exposed to POPs at an earlier age is signifi-cantly impaired compared to their peers who were unexposed.



6.5 > From 1930 to 1972, in the marine region between the US metropolis of Los Angeles and Santa Catalina Island, industrial waste was dumped on a large scale at water depths of up to 900 metres, including many containers filled with the insecticide DDT (dichlorodiphenyl-trichloroethane). Because of this, the sea floor as well as all the higher life forms in this region now contain dangerously high concentrations of DDT.

Experts distinguish between two kinds of persistent organic pollutant. The first comprises synthetically produced POPs that were used in the past for a great variety of purposes and still have many applications today. These toxic chemicals were sprayed as plant protectants, used as flame retardants, refrigerants and solvents, or in the production of varnishes, paints, adhesives, sealants, plastics and insulation (such as polystyrene insulation material). The second category of POPs comprises those that were unintentionally produced and includes the by-products of various combustion processes.

Although the devastating effects of this large group of pollutants has been known since the 1960s, and the production of some POPs was already prohibited at the national level by the 1980s, it was not until 1997 that negotiations toward an international agreement to limit the production and application of these substances began. The Stockholm Convention was finally adopted in May 2001 and came into force on 17 May 2004. To date 184 countries have acceded to the agreement.

The text of the convention lists three groups of pollutants:

- POPs that should be systematically eliminated;
- POPs whose production and use should be restricted;
- POPs whose unintentional generation as by-products should be reduced.

Waste containing or contaminated with POPs, according to the convention, must be disposed of in a way that destroys the POPs or irreversibly transforms them so that they lose their hazardous properties.

When the convention was adopted in 2001, there were only twelve POPs on the lists, which were known as the "dirty dozen". These included:

- pesticides (herbicides and insecticides) such as aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, mirex and toxaphene;
- industrial chemicals like hexachlorobenzene and polychlorinated biphenyls (PCBs); and
- by-products such as dioxins and furans.

As a part of the convention process, a group of experts known as the Review Committee was formed which meets annually to compile and discuss research findings on the effects of POPs that are still unlisted. If these chemicals are deemed to be of special concern – i.e., particularly hazardous – the Review Committee commissions risk assessments and subsequently proposes their listing to the member states of the convention along with specific recommendations for their elimination or restriction.

Since the Stockholm Convention first came into force, bans have been adopted for 19 additional pollutant groups. The focus of the Review Committee has changed significantly over the past two decades. In the early years of its existence the committee was primarily focussed on pesticides that were already banned by many countries, but it is now more involved in addressing much newer, complex industrial chemicals. Many of these are still being used in large quantities and are thus economically significant for a number of countries. The task is made more difficult by the fact that these substances have been in use for a relatively short time and it is virtually impossible to compile data and build knowledge about their possible dispersal pathways and environmental impacts. An accurate understanding of their potential harmful effects usually only becomes possible when it is too late, after excessive quantities of the chemicals have already been discharged into the oceans.

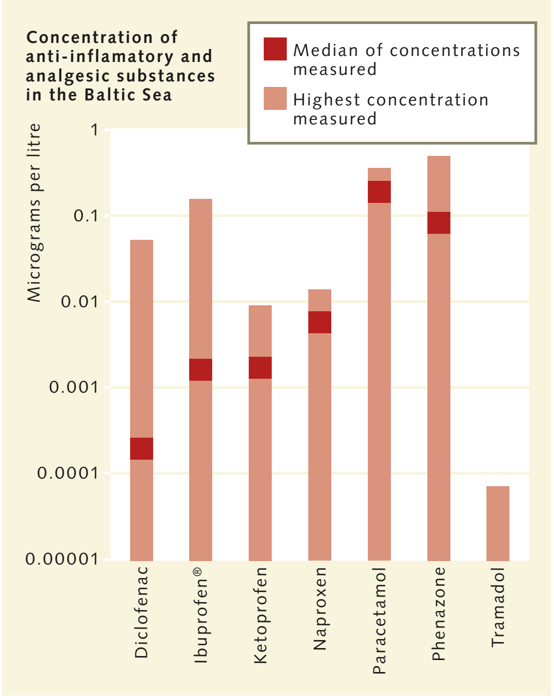
Nevertheless, international bans are having the desired effect. The concentrations of POPs that have been banned by the Stockholm Convention and by national and

Chlorinated hydrocarbons
The mass production of chlorinated hydrocarbons (CHCs) began in 1929 and peaked in the 1960s and 1970s. Around 97 per cent of the CHCs produced were applied in the northern hemisphere, which is why the seas on this half of the globe are especially heavily polluted with these persistent environmental poisons. By the end of the 1990s it was estimated that six to seven per cent of the total production up to that time was already stored in the seabed.

transnational agreements are gradually decreasing in the oceans.

Pharmaceuticals (medicinal products)

Pharmaceuticals, or medicinal products, are man-made chemicals developed for a specific purpose: targeting cells, influencing an organism's hormone levels or regulating the uptake and processing of nutrients, for example. In some instances, pharmaceuticals even regulate intercellular communication. In order to maximize their therapeutic effect, pharmaceutical products that are administered orally must reach the intestine, where they are absorbed into the bloodstream. Before that, however, they must pass unscathed through the highly acidic, and hence destructive, stomach environment. Most active pharmaceutical ingredients (APIs) are therefore designed to be highly stable and degrade very slowly, or not at all.



6.6 > Common analgesics such as diclofenac, ibuprofen and paracetamol are just some of the pharmaceuticals that are excreted by humans into wastewater and then enter the rivers and finally, in this instance, the Baltic Sea.

When these highly stable active substances enter the environment, they are referred to as environmentally persistent pharmaceutical pollutants (EPPPs) – and they pose a growing threat. The antibacterial effect of antibiotics, for example, can cause bacteria and other microbes to develop resistance to these substances, which means that these antibiotics can no longer be used to treat bacterial infections. According to the United Nations, the number of antibiotic-resistant bacteria is increasing, with antibiotic resistance now one of the greatest threats to human health.

Pharmaceuticals enter the sea by a variety of routes. Some are direct inputs from pharmaceutical companies, hospitals, hotels and restaurants discharging their untreated industrial waste or wastewater contaminated with active substances and disinfectants into rivers and sea. Another source is feed containing pharmaceuticals, which is distributed in cages in marine aquaculture. However, pharmaceuticals also leak into the environment when humans or animals take medication to treat a condition or disease and then excrete the active substances in their urine or faeces. With livestock, the active substances may be present but undetected in manure or slurry, which is then spread on fields, only to leach into nearby watercourses when it rains. And while human excrement is normally flushed down the toilet, the number of sewage treatment plants that filter out active pharmaceutical substances is still far too low. More than 80 per cent of the world's wastewater is still discharged into the environment without any treatment, making animal and human urine and faeces the main source of pharmaceutical residues in rivers and seas.

According to the United Nations Environment Programme (UNEP), approximately 4000 active pharmaceutical ingredients are administered worldwide in therapeutic and veterinary drugs, including prescription medicines and over-the-counter products. These active substances are removed from wastewater in sewage treatment plants with an efficiency of 20 to 80 per cent. The rest enters the rivers and seas. As a rough estimate, around 1800 tonnes of pharmaceutical residues enter the environment annually from sewage treatment plants in the Baltic Sea region alone. And year after year, China's longest river, the Yangtze, carries the sewage of more than 400 million people, containing some 152 tonnes of pharmaceuticals, out to sea.

Water pollution by pharmaceuticals is now present on such a scale that scientists are able to use water samples to draw firm conclusions about a nation's health. In a large-scale study conducted in the USA in 2014 to 2017, for example, researchers detected a total of 111 pharmaceutical compounds in headwater streams; some water samples contained mixtures of up to 60 different active pharmaceutical ingredients. The most common substances identified by the scientists were:

- nicotine, the stimulant found in tobacco;
- metformin, the diabetes and cancer drug, for which around 81 million prescriptions were issued in the USA in 2016 alone. It is excreted in human urine in a more or less pure form;
- caffeine, the stimulant contained in coffee, energy drinks, etc.;
- lidocaine, an anaesthetic.

The researchers also detected pharmaceutical mood enhancers (antidepressants) and anti-histamines; indeed, the latter were identified in seasonally varying concentrations (in step with the risk of hay fever being particularly high in spring).

Similar results were produced by a large-scale study on pharmaceutical pollution in the Baltic Sea, published in 2017. In this instance, however, analgesics and anti-inflammatories, such as paracetamol, ibuprofen and diclofenac, and cardiovascular and central nervous system agents topped the list of most frequently detected substances. In total, the researchers detected 167 pharmaceutical substances in the marine environment of the Baltic Sea region. Again, the main sources identified by the researchers were human and animal urine and faeces, whose pharmaceutical contents were not adequately removed during sewage treatment processes. Out of 118 pharmaceuticals whose filtering out was assessed by the researchers at various treatment plants, only nine were removed from wastewater with an efficiency over 95 per cent and nearly half of the compounds were removed only partially with an efficiency of less than 50 per cent.

Some medicinal products, such as the anti-inflammatory diclofenac (the active ingredient in Voltaren and other analgesics), are bio- and photodegradable (i.e. they decompose when exposed to light). These pharmaceuticals are not thought to bioaccumulate in living organisms. When present in high concentrations in water bodies, they are certainly harmful, however. Diclofenac, for example, is reported to cause damage in the internal organs of fish. Laboratory studies have shown that the diabetes drug metformin affects behaviour in the Siamese fighting fish *(Betta splendens)* and disrupts growth in the Japanese rice fish *(Oryzias latipes)*. Even in low concentrations, hormones such as those contained in the contraceptive pill (e.g. 17-alpha-ethinyl estradiol) cause transgenderism in fish, threatening reproduction and leading to population decline.

Mussels appear to be particularly vulnerable to exposure to pharmaceutical residues as they are known to filter seawater in order to extract the nutrient particles that it contains. Researchers have detected the antidepressant sertraline in roughly two-thirds of the mussels collected along the coast of the US state of California, while in the Bohai Sea of China, 142 of 190 mollusc samples were found to be contaminated with antibiotics. Traces of pharmaceuticals have also been found in squid from the Central Pacific, in herring from the North Atlantic and in sharks from the Eastern Central Atlantic. These findings indicate that these active pharmaceutical substances have biomagnified in the food web.

It is extremely difficult to trace the mechanisms by which pharmaceuticals affect marine ecosystems and to attribute these effects to specific products, particularly when mixtures of drugs are present, possibly causing reciprocal amplification of their effects. Researchers have already observed such forms of mixed toxicity in phytoplankton and some freshwater organisms. The research community cannot currently provide a conclusive answer to the question of what the specific effect of drug cocktails in the marine environment may be. Research on this topic is ongoing.

As a further challenge facing scientists, many pollutants are only detectable using specific analytical methods. This means that researchers must generally decide beforehand which substances they intend to investigate. Screening studies, which involve the application of all known methods in order to ascertain which substances may be present in seawater, are extremely complex and therefore less common. Furthermore, the chemical evidence that a substance is present in seawater does not, in itself, reveal any information about its impact on marine life. That would require further analyses to study the effects on individual organisms, with scientists investigating whether tumours are present, whether there is any disruption of the endocrine system, or whether enzyme activity in living organisms has changed.

The increasing consumption of pharmaceuticals and improved measuring techniques over recent decades mean that more pharmaceuticals are now being detected in the environment. Many are present in such high concentrations that they cause harm. For that reason, experts now recognize pharmaceuticals in the environment as one of the emerging policy issues in international chemicals management.

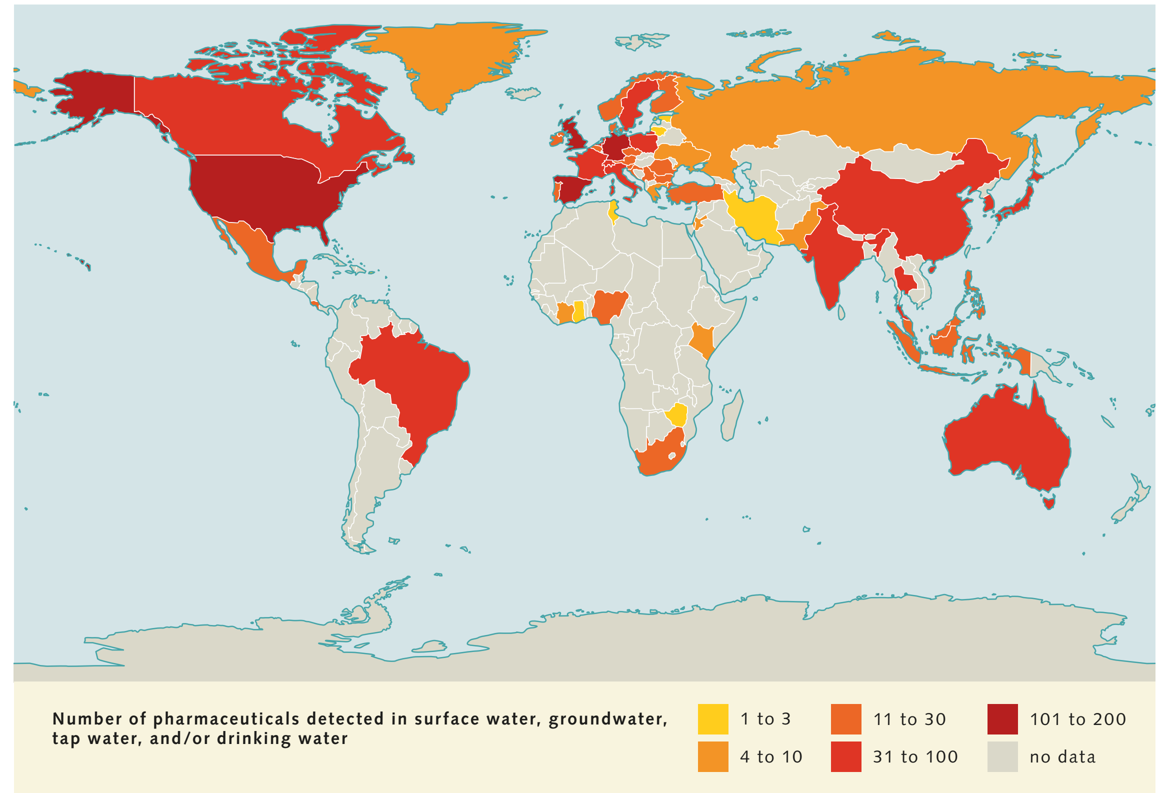
According to the definition provided by the Strategic Approach to International Chemicals Management (SAICM), pharmaceuticals in the environment are an issue which:

- affects all stages of a chemical's life cycle,
- has not yet been widely recognized,
- is inadequately managed,
- is the product of the "state of the science",
- has significant effects on human health and the environment,
- is a global problem.

SAICM was launched in 2006. It is a policy framework, non-binding under international law, which pursues a multi-stakeholder, multi-sectoral global approach, and whose overall objective is the achievement, originally by 2020, of the sound management of chemicals throughout their life cycle, from production to use and disposal. Various recommendations were adopted at a SAICM Workshop on Pharmaceuticals in the Environment, including the following:

- develop sustainable active pharmaceutical ingredients (i.e. active substances that are absorbed more efficiently in humans and animals and biodegrade more quickly, causing less damage if they enter the environment);
- run global campaigns to raise awareness of the harmful effects of pharmaceuticals in the environment, combined with information on safe disposal;
- develop well-functioning take-back and disposal systems worldwide for expired or partially used pharmaceuticals in order to curb illegal disposal;
- establish sufficiently large-scale wastewater treatment plants where none are currently available – particularly in the world's rapidly growing mega-cities, whose wastewater often contains pharmaceuticals in high concentrations;
- introduce new, highly efficient filtration technologies (Stage 4 treatment) in existing treatment plants in order to increase their purification efficiency;
- construct specialized treatment plants at point sources, such as hospitals;
- introduce strict separation of foul water and rainwater drainage systems (this avoids dilution of pharmaceutical concentrations in foul water, making it easier for treatment plants to filter out these pollutants);
- develop comprehensive monitoring systems, as well as international databases and networks for knowledge-sharing and the joint planning and implementation of protective measures.

In its Water Framework Directive (WFD), the European Union obliges Member States to assess the status of their water bodies to determine the presence of specific pollutants. In practice, however, the application of this policy requirement is proving extremely difficult in



6.7 > Analyses of groundwater and surface water show that the more developed the country, the more traces of pharmaceuticals are found in its immediate environment. In Germany, Spain and the USA, as many as 200 different pharmaceuticals have been detected.

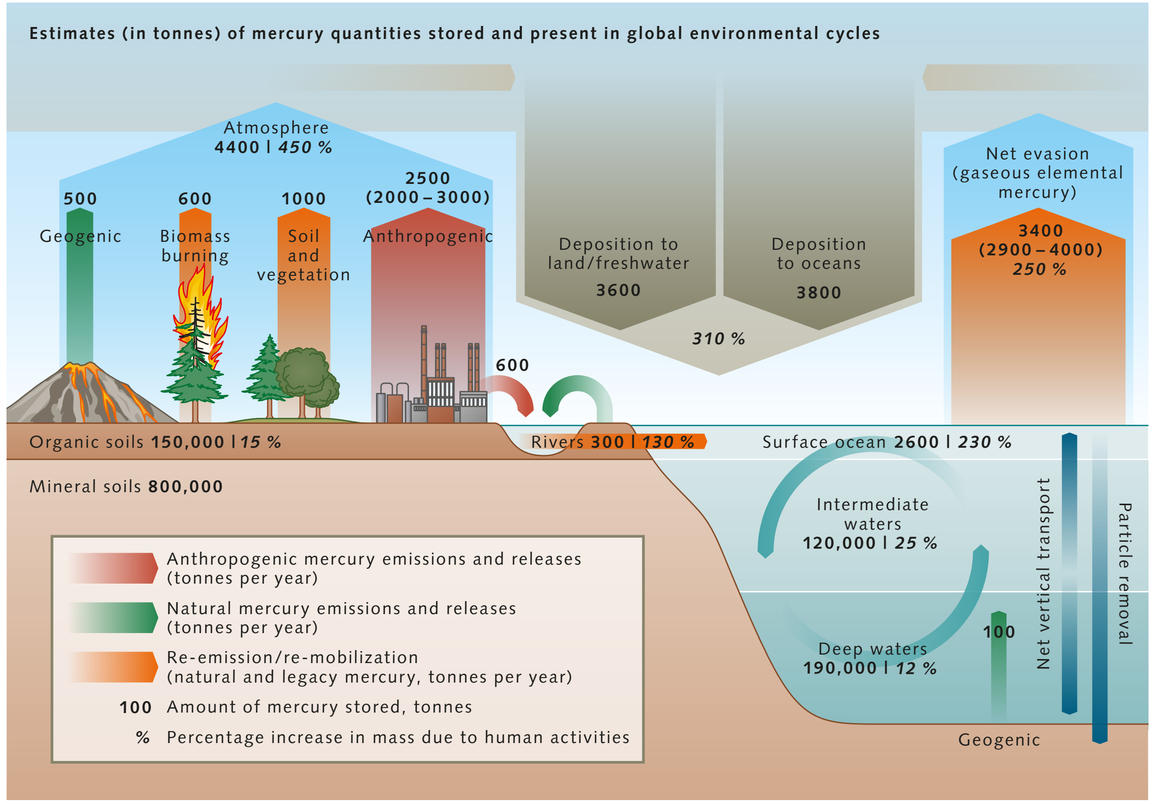
many instances, as the detection limits specified and required by the EU are extremely low; many laboratories lack the technical capacities to measure such small concentrations.

Heavy metals

Heavy metals are naturally occurring elements that are present in the Earth's crust. Their effect is twofold. Some of them – known as trace elements – provide essential nutrients and are therefore vital for the survival of almost every living organism on Earth; examples are iron, manganese, molybdenum, copper and zinc. Other heavy metals such as lead, cadmium and mercury are toxic and harmful to human and animal health.

Toxic heavy metals enter the environment by various routes. They are utilized in mining and some industrial processes, such as plastics manufacturing, and are present in sewage sludge and plant protection products, which are applied to crops. They are assembled into batteries and various types of measuring device, and are released into the atmosphere from vehicle emissions and coal-burning. The latter has caused a 300 to 500 per cent increase in mercury concentrations in the atmosphere over the past century. These heavy metal pollutants enter the marine environment via rivers and surface runoff, or are washed out of the atmosphere in rainfall and deposited in the sea.

According to experts, approximately half of the mercury released into the atmosphere by human activity has entered the ocean. This is borne out by the findings of a study which shows that mercury levels in surface water have doubled over the last 100 years. Mercury pollution has increased by a quarter in intermediate waters and by one-tenth in deep waters. The differences, according to the researchers, reflect the time it takes for particles and seawater to travel from the surface to the various depths.



6.8 > Human activities such as mining and coal-burning have resulted in a continuous rise in mercury releases since the 16th century. From 1900 to 2000 alone, the amount of mercury in the atmosphere increased at least threefold – along with mercury depositions to land and ocean. This figure shows the sources and sinks of this toxic heavy metal, along with global amounts for 2018.

In the sea, certain species of bacteria can convert the mercury into methylmercury compounds. These metallo-organic compounds are highly toxic; they are also fat-soluble and thus able to biomagnify in the food chain. The known effects of methylmercury poisoning in humans include damage to the nervous system, a weakened immune system response, vision impairment, respiratory failure and disorders of the liver, kidneys, skin and cardiac muscles.

Marine dwellers are generally exposed to lower mercury concentrations than wildlife in lakes and rivers. Nevertheless, in recent decades, researchers have observed an increase in methylmercury levels in marine fish, notably in species from the North Atlantic and the waters off West Greenland. In fish from the marine waters off East Greenland and the European Arctic, by contrast, methylmercury levels have generally decreased. Even so, in their latest *Global Mercury Assessment*, United Nations Environment Programme (UNEP) experts conclude that mercury loads in some aquatic food webs are worryingly high and pose a risk to the health of wildlife and human populations. Climate change amplifies this risk: in the Arctic, for example, the temperature-related decline in sea ice has influenced mercury distribution and transport and, in some areas, increased mercury methylation rates, which means that more mercury is being converted into methylmercury than before.

In light of these immense risks and the global distribution of mercury in the atmosphere and the terrestrial and marine environment, the international community – after many years of negotiations – adopted a multilateral convention in 2013 whose aim is to protect the environment and human health from mercury emissions. The Convention is named after the Japanese coastal city of Minamata, where, in the 1960s, a chemical factory discharged mercury-contaminated wastewater into the sea over an extended period of time, causing this toxic substance to bioaccumulate in marine fish. The fish were then caught and consumed by coastal communities, resulting in more than 2200 cases of methylmercury poisoning. Some of the victims were unable to walk, stand or swallow due to the severity of the damage to their central nervous systems.

The Minamata Convention entered into force on 16 August 2017. It is legally binding on all parties and, to date, has been signed and ratified by 127 countries and the European Union. Among other things, parties undertake:

- to refrain from opening any new mercury mines, and to phase out mining in existing facilities;
- to reduce the mercury content of many products and industrial processes;
- to establish a monitoring system for mercury emissions to the atmosphere, land and water;
- to ensure the safe storage of mercury at all times, including management of mercury-containing devices or products that were disposed of as waste some time ago (hazardous waste).

Thus far, however, the regulations derived from the Convention have had no impact on the international markets: mercury continues to be mined and traded to a similar or increasing extent, with no decrease in production seen yet. Nevertheless, experts predict a lasting transformation of the mining and trading of mercury in the longer term as a result of the Minamata Convention.

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are a group of more than 100 different chemicals. They occur naturally in coal and crude oil, but are also released as a by-product from the incomplete burning of coal, oil and gas, wood, waste and other organic material. This can happen naturally in forest fires and volcanic eruptions, for example. However, most of the PAHs that are present in the environment were produced in industrial combustion processes and can thus be attributed to human activity.

Many of these hydrocarbons have carcinogenic, mutagenic and reprotoxic properties. This poses a risk, particularly in the case of PAHs which do not break down in the natural environment but can bioaccumulate in living organisms.

Most PAHs are derived from oil and are used as softeners in the manufacturing of rubber and plastic products. These pollutants are therefore present in items such as flip-flops, bicycle handlebar grips, tyres, mouse mats, toys and anti-corrosion paints. They enter the environment mainly through dust particles, to which they adhere, and through abrasion of rubber products such as tyres. The particles are then deposited on land or water surfaces or are washed into the rivers and sea by rainwater.

Large quantities of PAHs are discharged into the sea as a result of oil leaks or oil tanker accidents, often causing the collapse of local marine ecosystems. A particularly striking example is the Niger Delta in Nigeria, where transnational corporations have operated oil production facilities since 1958. According to environmental experts, around 1.5 million tonnes of oil containing 3000 to

6.9 > Aerial view of a polluted river near Port Harcourt in Nigeria. In the Niger Delta, the contamination caused by decades of oil industry operations is so severe that it will take up to 30 years to clean up and restore the environment, according to a UNEP report published in 2011.

105,000 tonnes of toxic PAHs were released into the delta until 2006, with devastating impacts on all forms of aquatic life.

In order to protect human health and the environment from the harmful effects of PAHs, the EU Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) prohibits the supplying, to consumers, of substances classified as carcinogenic, mutagenic or toxic to reproduction. Eight PAH substances fall within the scope of this provision. In order to minimize PAH inputs into the environment, this group of pollutants is governed by the rules and limit values set forth in the Protocol to the Convention on Long-Range Transboundary Air Pollution on Persistent Organic Pollutants, the EU POPs Regulation and the EU Water Framework Directive.

Per- and polyfluorinated alkylated substances

The per- and polyfluorinated alkylated substance (PFAS) group now comprises more than 4700 chemicals which, due to their water-, grease- and dirt-repellent properties, are found in a wide variety of products, including outdoor clothing, cookware, paper and printed products, carpets, paints and fire-fighting foams. They enter the environment by various routes: during manufacturing, processing into products, subsequent use and final disposal. PFAS are dispersed by air, rivers and ocean currents, reaching remote regions of the world, and, like many other chemicals, are poorly degradable. Furthermore, some of these chemicals bioaccumulate in wildlife, plants and human tissue and are harmful to health. According to scientists, PFAS chemicals are now ubiquitous in the environment and are present in soil, in all the oceans, in the atmosphere, in flora and fauna, in human blood and even in breast milk.

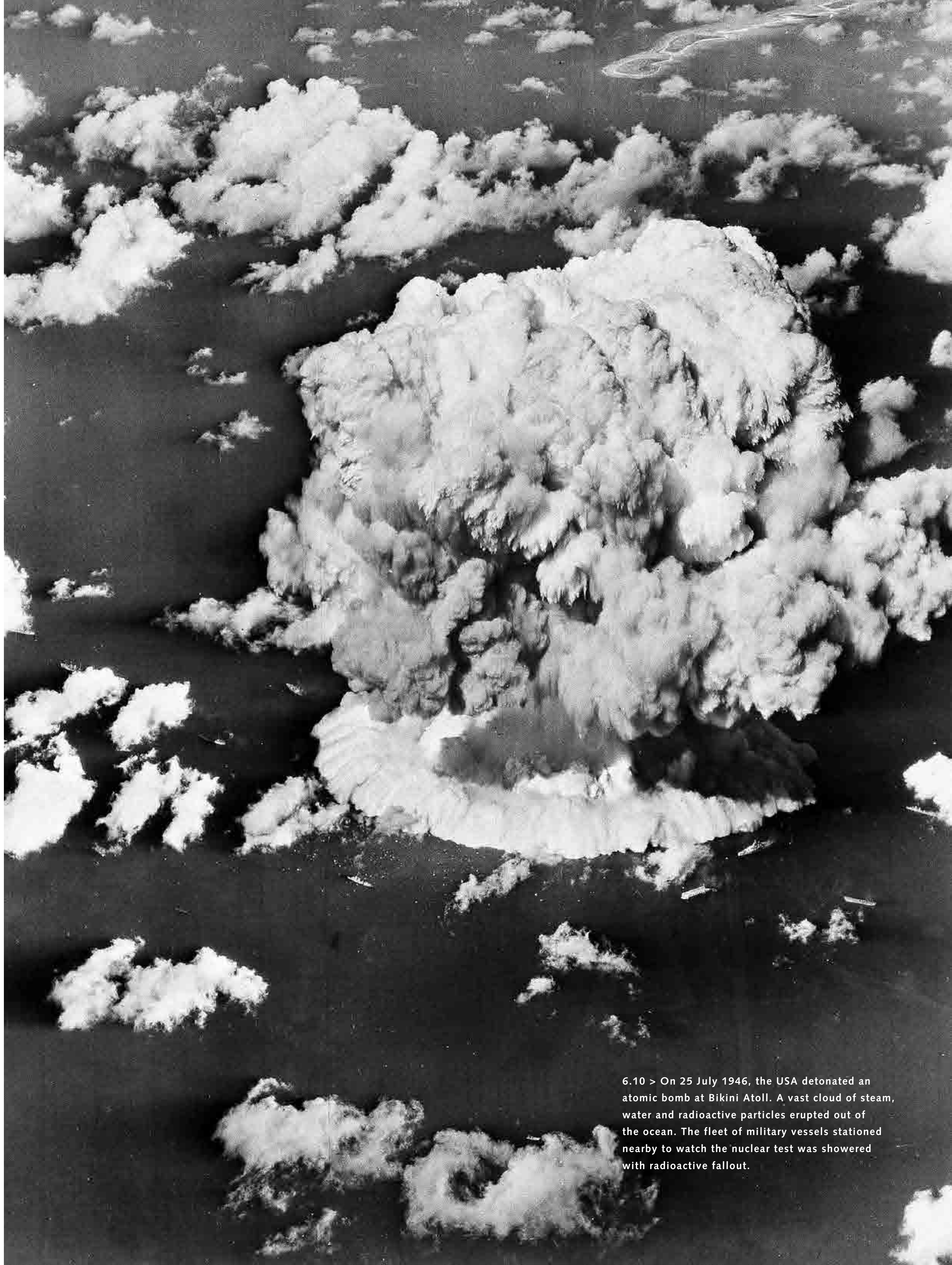
The PFAS chemicals whose names are most familiar to us have been in production and use since the 1950s. More recently, however, industry has relied mainly on new forms of these pollutants, with researchers and regulatory authorities having little to no information about their composition and environmental impacts. According to the German Environment Agency (UBA), around 40 PFAS can be detected using chemical proof procedures. However, no information is available about the precise chemical structure of most of the other chemicals in this substance group, and no analytical methods exist to detect them, making them far more difficult to regulate.

Due to their worrying properties, some PFAS chemicals already fall within the scope of the EU REACH Regulation. However, experts are calling for worldwide bans on their manufacturing and use, as well as for the development of eco-friendly alternatives. Global bans are enforceable under the Stockholm Convention, whose expert group recently added perfluorohexane sulfonic acid (PFHxS), which belongs to the PFAS group, to the list of prohibited substances. The experts also recommended that other PFAS chemicals be included in national and international monitoring programmes in order to assess whether regulatory measures are having the desired effect and PFAS contamination of the environment is decreasing.

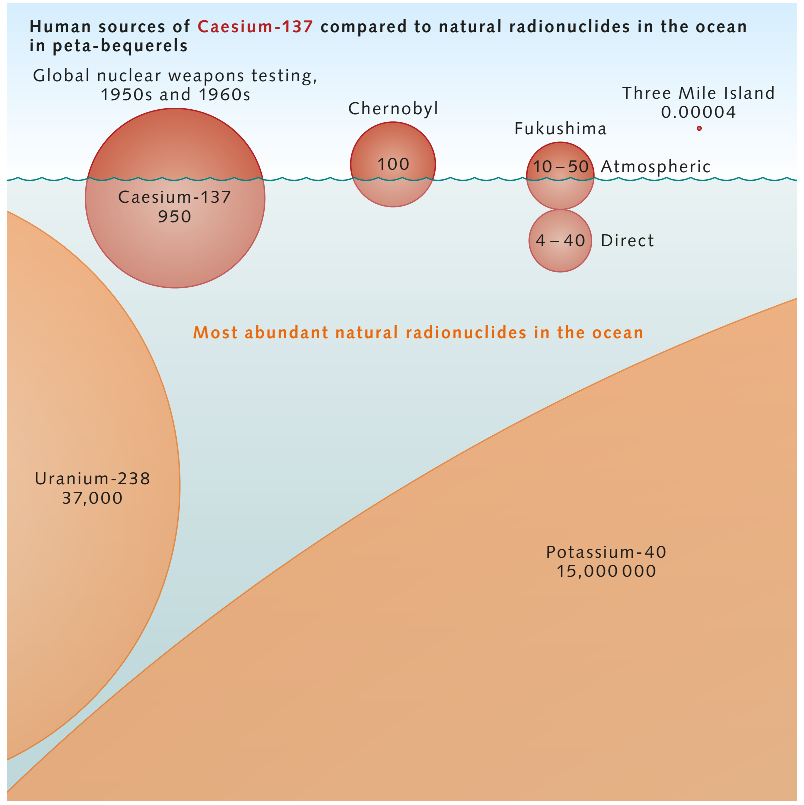
Radioactive substances

The ocean contains many naturally occurring radioactive elements, i.e. materials made up of atoms whose nuclei are unstable (known as radionuclides). This means that they break down or change and thus release energy, in the form of various types of radiation, into the environment. Some of these radioactive elements are the result of geological processes, such as weathering of rock, or are formed when cosmic radiation reaches the Earth. They include potassium-40, a radionuclide of the chemical element potassium. Potassium-40 accounts for approximately 0.0117 per cent of naturally occurring potassium and is responsible for the weak natural radioactivity of this alkali metal.

Potassium-40 is the predominant radioactive nuclide in the sea. Due to its low-level radiation, however, it poses no threat to marine dwellers or people – unlike the radioactive substances that are released and enter the marine environment in high doses as a consequence of human activity. These radiation doses may be fatal to humans and wildlife because they damage the cells of living organisms. People



6.10 > On 25 July 1946, the USA detonated an atomic bomb at Bikini Atoll. A vast cloud of steam, water and radioactive particles erupted out of the ocean. The fleet of military vessels stationed nearby to watch the nuclear test was showered with radioactive fallout.



6.11 > A comparison of the inventories of natural radionuclides and caesium-137 from human sources shows that the latter is present in the ocean in much smaller quantities.

who have been exposed to high doses of radiation are also more likely to develop cancer.

A particularly high radiation risk is associated with the following scenarios:

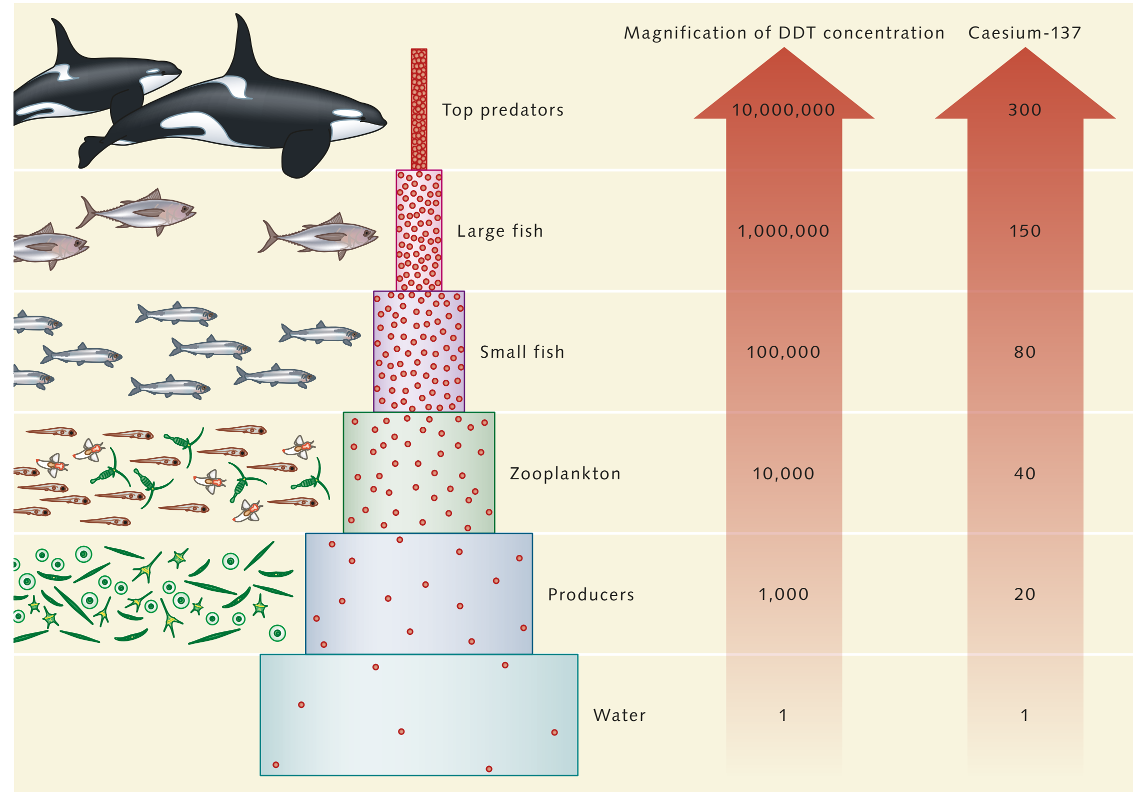
- nuclear weapons testing and use,
- accidents in nuclear power plants,
- if radioactively contaminated cooling water or wastewater from nuclear power plants or reprocessing plants is discharged into the sea,
- if radioactive waste is dumped in the ocean,
- if there is a radiation leak from nuclear-powered vessels and submarines, or
- if radiation used in medical settings and industry enters the sea by more indirect routes.

Nuclear weapons testing is the source of the largest inputs of radioactive substances in the ocean. From 1945 to 2017, more than 2000 nuclear warheads were detonated in tests worldwide. The tests were initially conducted above ground. However, as each of these blasts produced large quantities of radioactive dust, which showered down on numerous regions of the world as nuclear fallout, testing was moved underground from the 1960s onwards. Nevertheless, as a consequence of the fallout, a range of radioactive substances entered the ocean – including radionuclides which are harmful to health, such as caesium-137, strontium-90 and isotopes of plutonium and americium, as well as more innocuous substances such as tritium, carbon-14, technetium-99 and iodine-129.

Most of these substances are dissolved or diluted in water. Ocean currents and gyres thus disperse the radioactive nuclides and reduce the radiation dose. And as unstable nuclei undergo a constant process of decay, the radioactivity of these substances decreases over time, lessening the risk to health (keyword: half-life).

Nuclear weapons testing and accidents at nuclear power plants mainly release radioactive caesium-137, which is produced from nuclear fission in reactors and has a half-life of 30 years. In the aftermath of the tsunami and reactor accident at Fukushima, Japan, in March 2011, for example, caesium-137 entered the Pacific Ocean through the atmosphere (radioactive dust) and via groundwater, cooling water and firewater flowing into the sea. As a result, radiation levels off the coast of Japan near Fukushima quickly soared from just two to more than 50 million becquerels per cubic metre. For the purpose of comparison, the World Health Organization (WHO) advises against the consumption of drinking water with a radiation load above 10,000 becquerels per cubic metre.

In the sea, the masses of radioactive water were diluted and mingled with the Kuroshio Current, which flows along Japan's eastern seaboard. As a result of this process, the caesium-137 load in the coastal waters decreased significantly less than a month after most of the radioactively contaminated water entered the Pacific. At the same time, the caesium load increased at locations far from the Japanese coast. The radionuclides were transported by the main current towards North America, reaching its west coast two to four years after the reactor accident. In March



6.12 > Unlike the insecticide DDT, harmful radionuclides such as caesium-137 have limited biomagnification in marine food webs.

2019, researchers were still reporting raised caesium levels in the waters near Hawaii and along the Canadian and US Pacific Coast. The levels were extremely low, however – below 10 becquerels – and gave little cause for concern.

Near Fukushima itself, some of the caesium-137 adhered to particles drifting on the surface of the coastal waters and sank to the sea floor. These radioactive particles were then consumed by bottom dwellers or deposited in sediment, or were swept up and carried away by deep ocean currents, in some cases travelling distances up to 100 kilometres. Radionuclides also found their way into the deep ocean by more indirect routes – for example, in the faeces of fish, krill and other marine organisms that had ingested the particles in seawater or food.

When fish or small crustaceans ingest particles contaminated with caesium-137, the unstable atoms biodegrade surprisingly quickly. The radioactivity of caesium in fish tissue decreases by around 50 per cent within 50 days, provided that the fish leaves the contaminated area and is not exposed to further radiation. This also explains why tuna that were foraging off the coast of Japan at the time of the reactor accident and then swam away towards North America were found, just a few months later, to have a caesium load that was 15 to 30 times lower than fish species that had remained in Japanese coastal waters.

These latter waters, by contrast, were still so heavily contaminated with caesium-137 a year after the accident that radiation levels in more than half the fish specimens studied greatly exceeded the permitted maximum – probably because radioactively contaminated water continued to be discharged landside into the sea. Over time, however, the radiation load decreased, to the extent that random samples collected by Japanese fisheries inspectors in April 2015 showed no elevated levels for the first time. Thankfully, as caesium biomagnification in food webs is very limited, there was no additional risk to dolphins, sharks and other marine predators in the longer term.

Becquerel
The becquerel is the unit used to measure radioactivity. Named after the French physicist Antoine Henri Becquerel, it states how many nuclei decay per second. One becquerel corresponds to the amount of energy released by one single nucleus decaying.

6.13 > Off the coast of Indonesia, a seahorse clings to a cotton swab. In 2017, this photo circulated around the world and became a symbol of the pollution of the oceans by humans.

In spring 2021, TEPCO – the utility company which operates the Fukushima plant – announced plans to dump 1.24 million tonnes of radioactive cooling water and groundwater, currently stored in more than 1000 large onshore tanks, into the sea over the coming years. According to TEPCO, the water has been decontaminated, but it is unclear to what extent this decontamination process has been effective and which radioactive substances the water may still contain. For years, TEPCO had claimed that the water in the tanks contained nothing but tritium, a radioactive isotope of hydrogen which poses less of a health risk compared with other radionuclides. In October 2018, however, TEPCO was forced to concede that the water still contains other radioactive and environmentally harmful substances. TEPCO has yet to issue any clear and unequivocal statements indicating what these substances might be. This makes it difficult for experts to estimate what kind of impacts the discharge of these large volumes of water may have on the environment.

Littering the oceans

For many people, pollution by litter is the most visible environmental problem for the oceans. Trash washed onto the beach will quickly spoil the holiday feeling. Photos and videos of turtles with plastic bags in their throats, or of seahorses clinging to cotton swabs have been shared millions of times on social networks.

Around three-quarters of the litter in the ocean comprises synthetic polymers, commonly known as plastics. This group of substances includes a number of different materials that consist of carbon-based macromolecules called polymers. More than 90 per cent of all plastics are produced from petroleum but, depending on their purpose, also contain a variety of other chemicals such as softeners, solvents and hardeners.

There are now a number of types of biodegradable plastic that are being produced and employed on industrial scales. The overwhelming proportion of plastics, however, are the conventional types that require several centuries to degrade in nature. When these conventional plastics are deposited in landfills or dumped into the environment, they do not disappear. On the contrary, they are accumulating at an alarming scale.

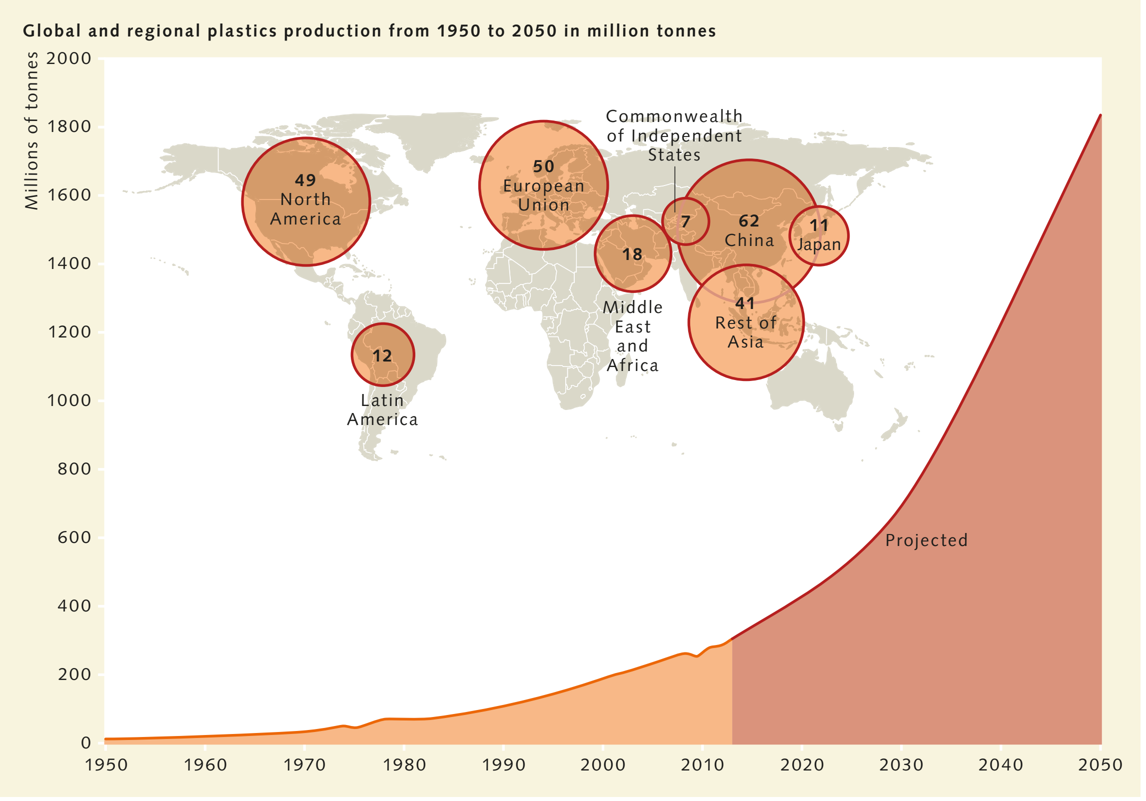
Plastics have a multitude of applications and are inexpensive to produce, which is why their worldwide production has increased so rapidly over the past 70 years. While 1.5 million tonnes of plastic were produced in 1950, this increased by a factor of 245 to some 368 million tonnes annually by 2019. In addition, more than 380 million tonnes of synthetic resins and fibres are used in textile production each year, and these are counted separately. If this trend continues, the annual production of plastics can be expected to reach two billion tonnes by 2050 and this estimate does not even include the resins and fibres.

Although now a large number of measures are in place for the recycling and reuse of plastics, especially in Europe, the greatest share of plastics is still disposed of as normal trash, in many places inappropriately, so that the amount entering the oceans is constantly growing. It is currently estimated that an additional 8.2 to 12.2 million tonnes of plastic end up in the ocean every year. This amount is equal to about three per cent of the total production. According to new research, if streams, lakes and rivers are added to the calculation, roughly eleven per cent of the plastic waste generated ends up in natural waters. In the year 2016, that was between 19 and 23 million tonnes of plastic.

What happens to the plastic in the oceans and, more importantly, the impact that this pollution has on the health of the marine organisms and of people, is only very slowly becoming understood by science. It is now generally agreed that plastic pollution in the oceans is a serious global hazard for humans and animals because creatures can become trapped in the floating waste, but also because the plastic pieces and particles are eaten or absorbed. Moreover, chemical pollutants adhere to and accumulate on these particles.

In their latest analysis, members of a UN expert group on trash and microplastics in the ocean have found that plastics not only make up the largest proportion of marine litter, but they are also the most long-lived and harmful compared to all other materials. It is estimated that the

6.14 > Enormous growth is projected for the plastics industry. In 2013 the sector produced 250 million tonnes of plastics (map). Four years later this had increased to 350 million tonnes. If this trend continues, it will be around two billion tonnes by 2050.



oceans are suffering a loss of services and functions equivalent to USD 500 to 2500 billion per year as a result of plastic pollution.

Plastics are introduced into the oceans in many different ways. The largest quantities, however, follow two major pathways:

- as clearly visible plastic waste (macroplastics) that people intentionally or unintentionally dispose of in the environment and is subsequently carried to the ocean by the wind or rivers (this includes fishing nets discarded or lost in the sea, called ghost nets);
- as microplastic particles hardly recognizable with the naked eye that are either intentionally added to commercial products (for example, cosmetic products like shower gel and toothpaste) or that are formed as unintentional by-products. The latter comprise mainly tyre-wear debris from street traffic and plastic fibres that are released when washing synthetic clothing.

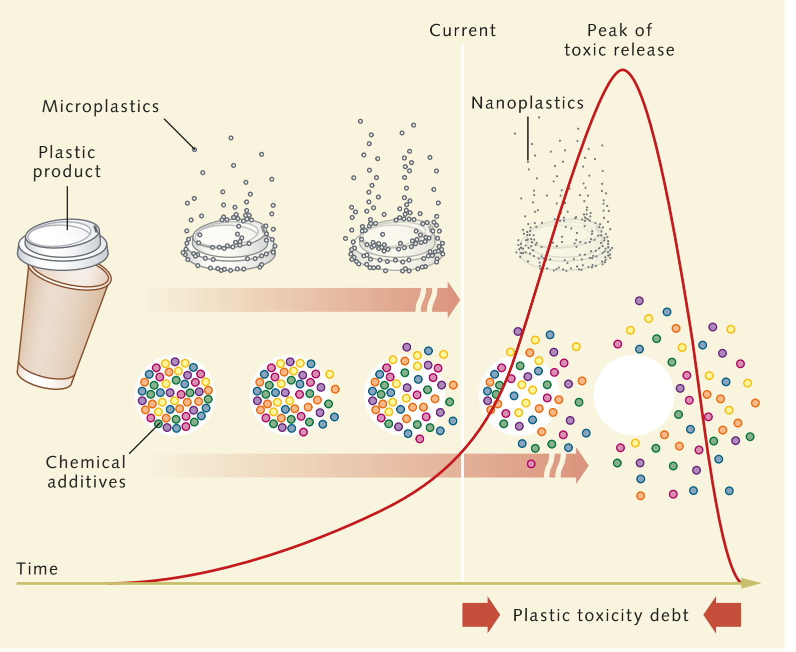
"Microplastics" are defined as plastic particles that are less than five millimetres in size. Experts distinguish between microplastics that are already micro-sized when they enter the ocean, and those that are the remains of formerly larger pieces of plastic. When they are exposed to sun and seawater, these pieces break down into progressively smaller particles, even down to nanoparticles less than one micrometre in size.

The main problem arising from this process is that as the plastic breaks down into smaller pieces, the total exposed surface area of the material increases, allowing more toxic substances and additives contained in the plastic to escape into the environment across these surfaces. Scientists are now referring to a toxicity debt that people incur when they use plastic, which means that the plastics we throw away today will generate their full toxic environmental impact only with the passing of time.

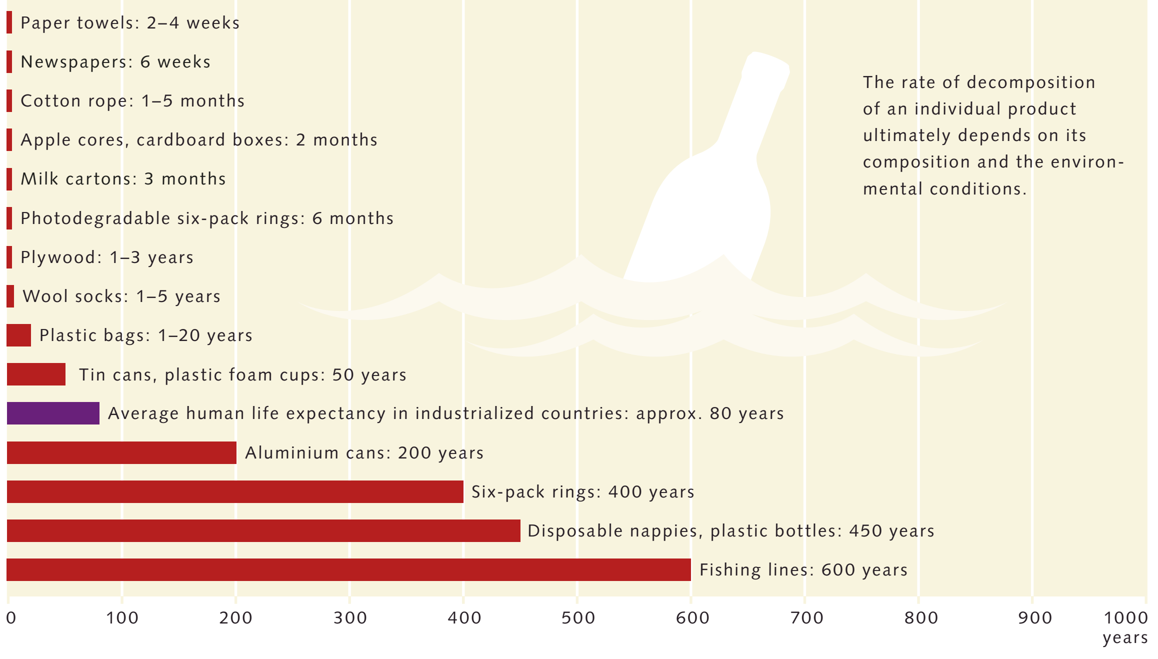
Macroplastics floating in the sea often originate directly from coastal regions, and especially from coastal states where waste management is not organized effectively. By contrast, microplastic particles may originate from regions far from the coasts. They may enter the rivers with wastewater, but can also be transported by rainwater, which washes the fine debris from tyre wear off the roads. A certain proportion of the particles is also transported through the air. Adding up the total weight of all the microplastic particles that have been introduced into the ocean, they now make up 15 per cent of the total plastics discharged into the sea.

Plastic can now be found in all ocean regions and at all water depths and is even present in the Arctic sea ice. Depending on its shape, size, density, weight and algal growth, the plastic may float on the water surface or in the water column, or it may sink to the bottom.

The ultimate destination of floating plastic litter, and whether it accumulates at a particular location, is primarily determined by the surface ocean currents and other water motions such as tides, storm floods or the flow of rivers into the sea. Computer models suggest that plastic litter in the sea is being concentrated in a number of naturally occurring gyres, especially the ocean's five large subtropical gyres. But it is a mistake to think that the litter is so densely concentrated in these regions that it can be easily recaptured. Even in those areas of the sea known as garbage patches it is mostly microplastic particles that accumulate, and those are difficult to observe with the naked eye.



6.15 > Because plastics release their additives and toxic constituents into the environment very slowly, the full damaging impacts are delayed. Scientists thus refer to a toxicity debt that we humans are incurring with the use of petroleum-based plastics.



6.16 > Much of the garbage in the ocean breaks down very gradually. Plastic products and nylon fishing lines are particularly resistant to degradation. Many of the plastic pieces do progressively break down into smaller fragments, but it can take centuries for these to completely decompose.

6.17 > A sperm whale has become entangled in a ghost net and is struggling with its last ounce of strength to reach the surface to breathe. After this photo was taken the whale dove deeper and was not seen again, despite an intensive search.

The catastrophic consequences of marine litter

Plastic pollution of the oceans has reached dramatic proportions. It is harmful to humans as well as animals in both direct and indirect ways. Plastic-clogged estuaries and bays are breeding grounds for disease and they diminish the quality of life and earning potential in many coastal towns. Tourists avoid such unattractive places. Fishermen and -women have trouble making a profitable catch. Coastal communities in vacation regions now have to spend a lot of money to keep their beaches clean. As a consequence of plastic pollution of the world's oceans, the total costs and revenue losses recorded by global tourism, fisheries and shipping alone are at least USD 13 billion annually.

The animal and plant worlds of the oceans suffer in a variety of ways from the litter. Problems result when:

- creatures are trapped by the plastic garbage or discarded fishing nets and fishing lines and die if they are not able to free themselves;
- marine organisms mistake plastic debris for prey, eat it, and eventually die of hunger with a full stomach – or they absorb the toxic substances that are released by the plastic or that have accumulated on the plastic during its time in the sea;
- marine predators ingest plastic by consuming prey that already have plastic in their digestive systems;
- primarily smaller marine organisms attach to floating garbage, drift with it over long distances, and can end up in other locations as invasive species;
- litter or floating nets destroy marine habitats by accumulating in them;
- chemical contaminants escape from the plastics and unleash their harmful effects in the sea.

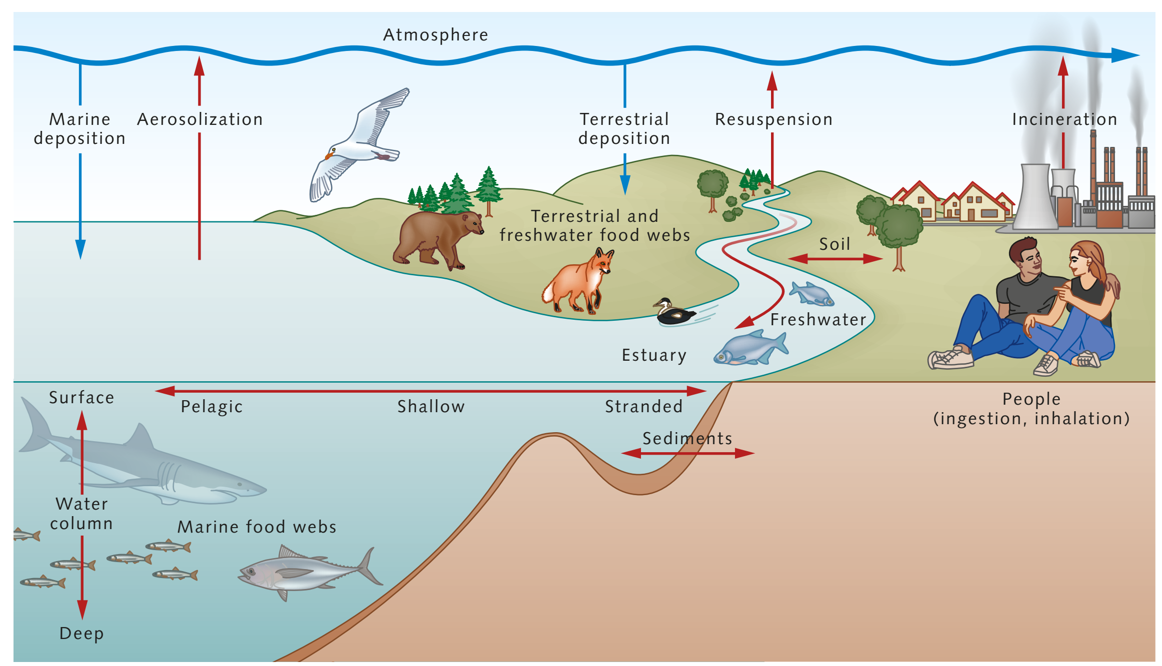
Researchers have so far identified at least 700 marine species whose lives are endangered when they come into contact with plastic garbage. Larger pieces of plastic (bags, nets, bottles, etc.) present the greatest risk for most of them. But there is now clear evidence that many marine creatures also ingest microplastic particles, including marine mammals, seabirds, fish, and some species of the zooplankton that form the base of the food web. Whether the microplastic particles also end up in the circulatory systems and ultimately in the muscle tissue of the individual animals, however, depends on their anatomy and the operation of their digestive tracts. Experiments with sea bass, for example, showed that this culinary fish excretes with its faeces almost all the microplastic particles it eats. The danger of humans ingesting plastic particles when eating filets of this kind of fish is therefore extremely low.

Nevertheless, there is an urgent need for action. If humans do not fundamentally change their consumption habits and attitudes with regard to plastic, it is estimated that by the year 2040 as much as 29 million tonnes of plastic garbage will find its way into the oceans each year. This amount would be equivalent to dumping 50 kilograms of plastic waste onto every metre of coastline in the world. New research shows that the ocean is no longer the final destination for microplastic particles. On the contrary, the tiny plastic particles travel in huge cycles through all levels of the Earth system and can now be detected in the air with the same confidence as in the soils and the depths of the ocean.

A patchwork of regulations

In view of the drastic impacts of plastic pollution on land and in the ocean, solutions are now being sought at many levels. In 1995, 108 states and the European Commission became signatories to the Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA), an organization for governments to discuss measures for the protection of the seas from solid waste, overfertilization and polluted effluent. In addition, in 2012, the United Nations launched the Global Partnership on Marine Litter (GPML), an international information and cooperation platform whose membership is open to representatives from politics, science, industry and civil society.

The United Nations Environment Assembly (UNEA) has so far adopted four resolutions on microplastics and litter in the ocean. In 2017 it decided to establish a UNEA expert group to study the topic. This shall identify innovative options for action at national, transregional and international levels, evaluate their feasibility and explore the factors that are still preventing the various stakeholders from effectively stemming the flood of plastics.



6.18 > Microplastic particles now migrate in a huge cycle through the individual components of the Earth system and can thus be found everywhere – in the air, in the soil, in the waters and in all food webs.

Munitions-contaminated areas in the sea – combatting the toxic legacies of war

More than 75 years have passed since the end of the Second World War. However, there is one legacy of the war that still affects the seas and oceans and has now become a serious environmental problem. Even today, millions of tonnes of explosives and chemical weapons from the second and first world wars are still rusting away on the sea floor.

A small percentage of them are the result of actual combat operations in which marine areas were mined, or during actions in which torpedoes, aerial bombs or anti-aircraft shells sank to the sea floor unexploded. The vast majority of munitions, however, were intentionally dumped into the sea, at first by the German military who wanted to be sure during their retreat that their unused chemical weapons did not fall into the hands of the eventual victors. Later, when it was considered crucial to disarm Germany as quickly as possible at the end of the war, the allies sank shiploads of German munitions in selected dumping areas of the North and Baltic Seas.

Up until the 1960s, dumping into the sea was considered a safe and inexpensive way to dispose of munitions. For this reason, the British and US militaries also continued to discard their own outdated war materials in the sea during the post-war years. The British chose Beaufort's Dyke for this purpose, a 250-metre-deep trench between Scotland and Northern Ireland, which experts estimate now contains over a million tonnes of munitions. The Americans, on the other hand, dumped their remaining munitions in the waters off Hawaii, Nova Scotia, Newfoundland, and probably at other sites as well.

Researchers are rarely able to access these kinds of records abroad because of military security restrictions. They now know, however, that there are a great number of additional munition-contaminated marine areas around the world, including the Mediterranean and Black Seas, the west coast of the USA, the Gulf of Mexico, the east and west coasts of Australia, and around Japan. According to present knowledge, there are 1.6 million tonnes of munitions resting on the seabed in the dumping areas of the North and Baltic Seas alone.

A global environmental problem

Rusting munitions in the sea represent a worldwide threat for humans and marine inhabitants because they pose two kinds of danger. The first is that explosive ordnance can still detonate, for example, when mines are disturbed by bottom-fishing nets or when construction work for wind farms is initiated without prior examination of the sea floor for old munitions.

The explosion of a sea mine would trigger a shock wave that would kill all of the marine creatures in the close vicinity and shred the blood vessels and alveoli of whales, seals and other marine mammals over a greater distance. Divers and ships' crews would also be exposed to extreme danger, which is why the seabed has to be examined for explosive munitions prior to any construction being carried out in German waters. If munitions are found that can be moved, they are raised and placed on board a ship, transported to land and destroyed there. If lifting the ordnance safely is not possible, the munitions are carefully placed in a hoisting bag and towed to one of the dumping areas in the Baltic Sea where construction work is prohibited. In this case, permanent destruction is not an option, because there is currently no known procedure for neutralizing explosive ordnance in the sea in an environmentally acceptable way. In the North Sea, however, highly explosive munitions are sometimes towed to sandbanks that are above water at low tide. During low-water stands they can then be detonated without causing great harm in the sea.

The second danger to the environment is chemical in nature. Both explosive and chemical weapons contain various components that are increasingly leaking into the water due to the ongoing decay of the metal munition coverings, eventually dissolving in the water, and being distributed throughout the ocean by marine currents. Trinitrotoluene (TNT), the substance contained in explosives, for example, breaks down into as many as 50 different reaction products known as metabolites. The two most commonly occurring TNT metabolites, like their parent material, have been proven to cause cancer and have already been detected in mussels and the organs of fish in dumping areas of the Baltic Sea. The meat of the fish, however, was not significantly contaminated.

In 2018, when researchers from Kiel studied water samples taken from various regions of the German Baltic Sea, they found traces of TNT or its metabolites in every one of the approximately 1000 samples, because the substance first begins to metabolise in the sea and the process toward complete degradation proceeds very slowly. The long-term effects that the compounds used in explosives are having on biological communities of the North and Baltic Seas, and the concentrations at which they will cause demonstrable damage are now being studied by the researchers in various projects. So far, they have only been able to record notably high concentrations of TNT in the waters directly in the dumping areas.

Chemical munitions were dumped in barrels as well as in the form of bombs and grenades. Most of them contained nerve gases like tabun and phosgene, or the skin-damaging mustard gas. Tabun and phosgene degrade relatively rapidly in sea water. As a liquid, however, mustard gas goes through a process known as the coconut effect. It forms a hard crust and is encapsulated inside. If an angler happens to find one of these nuts and comes into contact with the liquid core, the carcinogenic chemical will still cause the same severe skin burns today that it did more than 100 years ago.

Time is pressing – possible solutions from science

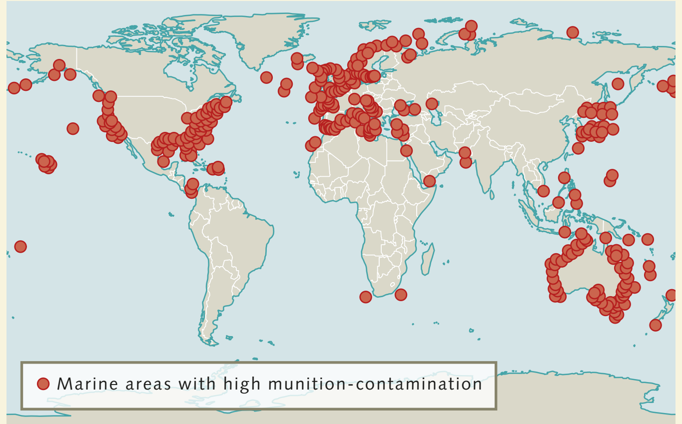
The longer the munitions lie in the sea, the further their casings continue to rust. They are thus becoming increasingly difficult to handle, and more and more of their contents are dissolving in the water. Because of this growing environmental threat, scientists are calling for the creation of long-term monitoring programmes for the piles of munitions in the dumping areas. These include:

- a scientific evaluation of historical records of combat operations and munition dumping (Where might munitions be located?);
- comprehensive mapping of the known munitions-contaminated areas (What quantities of known munitions are lying on the sea floor?);
- regular monitoring of the chemical contamination of the sea and its biological communities (What chemicals are being released and in what quantities?);
- accompanying studies on the effects of storms, marine currents, temperature, salinity and oxygen content on the munitions (mechanical attrition processes, shell degradation, displacement, covering by sediments, etc.);
- development of new methods for safe disposal of the weapons.

In recent years, the researchers have employed and refined a number of methods for mapping the sea floor. Through a combination of photography, multibeam echosounding and magnetic mapping, scientists can now produce impressively high-resolution images of the seabed in which mines, weapons boxes or torpedoes can be easily distinguished from rocks or other natural objects. Similar progress is being made in the development of rapid analysis methods. With the help of mobile mass spectrometers, scientists can now detect TNT and other compounds typical of explosives.

In the next step, German experts, along with many partners, want to develop technical methods for the safe and ecologically responsible clean-up of the munitions-contaminated areas directly at sea. The idea is to raise the munitions and load them onto a pontoon. Robots there would cut open the shells and remove all the chemical contents. The metal remains could be recycled and the chemicals would be thermally treated. The scientists want to have an initial prototype of this kind of system built and tested by the year 2025.

Scientists will soon make all the relevant data from international research on old munitions in the sea available online in a map-based information portal named AmuCad.org. The system uses artificial intelligence and other data-analysis approaches to identify regions with particularly high potential for risk. Using a colour-coded traffic-light system, decision-makers will be able to better identify marine areas where munitions are decaying especially rapidly, as well as zones with large quantities of munitions that are being used more intensively by humans. In both cases, it would be advisable to establish monitoring programmes and make plans for the removal of explosive ordnance.



6.19 > Ocean scrap yards in the form of dumped munitions are a global problem. Particularly former combatants such as the USA, Japan, Great Britain and Australia have dumped old stockpiles into the ocean and are now having to deal with the consequences.

Furthermore, the governments of the 20 largest industrialized nations agreed in 2019 to reduce the input of new plastic waste into the oceans to zero by the year 2050. This plan is to be achieved by the introduction of a circular economy for carbon-based plastics, improved waste management, and the development of new, more environmentally friendly materials. With this commitment, the industrialized nations are also retreating from the decades-long political strategy of viewing plastic pollution of the environment as a purely consumer problem and completely ignoring the true cause, which is the production and diverse application of long-lasting plastics.

At the transregional level, regulations on how to deal with terrestrial sources of waste have been stipulated in a number of regional marine conservation agreements, for example, in the Caribbean (Cartagena Convention), in the Mediterranean (Barcelona Convention), in western Africa (Abidjan Convention) and in the western Indian Ocean (Nairobi Convention). Those covering the Baltic Sea region (HELCOM Convention), the Northeast Atlantic (OSPAR Convention) and the seas of East Asia have even been able to agree on concrete plans for preventing or combatting the waste input to their respective waters. Ten regional marine agreements, furthermore, prohibit ship and platform crews from disposing of garbage in the sea, thus complying with an international ban prescribed by the MARPOL Convention, the international agreement to prevent marine pollution by ships. Experts, however, raise the concern that regional marine initiatives often lack the necessary money, human resources and contacts with local business communities that would be needed to fully and effectively implement their own regulations and decisions.

At the national level, countries are increasingly taking measures to reduce or completely prevent environmental pollution by plastics. Many of these measures aim to prohibit the use of disposable plastic products like bags or dishes, either through a ban on sales or by high taxes on the products. However, the outbreak of the corona pandemic at the beginning of 2020 has brought many of these efforts to a halt. Due to the fear of infection more food products worldwide are again being packed in plastic, drinks sold only in disposable cups, and generally more disposable dishes are being distributed.

6.20 > An eleven-year-old girl collects plastic waste from Jakarta's huge tip. Exposed mountains of trash like this generate a multitude of environmental problems. Methane escapes into the atmosphere and toxic water leaches into the ground. In addition, the wind blows away everything that is not heavy enough to remain in place.

There are many other basic questions that still need to be answered. One of the greatest challenges is to establish functioning waste management systems worldwide. In many countries there are still too few households connected to local waste-disposal systems. Without these services, discarded plastic products can neither be collected nor recycled. Researchers have made projections regarding this problem. In order to properly dispose of all plastic waste generated in the private sector by 2040, more than one million households would have to be added to waste collection systems every week, and this would have had to begin in the year 2020. This would be a huge task requiring enormous investments.

Experts also see an urgent need for:

- improvements in scientific monitoring systems for waste pollution, in order to learn where and over what pathways the garbage enters the environment;
- development of environmentally friendly alternatives for all non-biologically degradable types of plastics;
- producers to take responsibility that the products they manufacture are recycled and their components reintroduced to the circular economy;
- fundamental transformation of our economic system, so that it can fulfil the criteria for sustainable development. The prerequisite for this, however, would be for every individual consumer to fundamentally change their consumption patterns.

Parallel to these developments at the political level, there are now a number of initiatives by businesses and civil society. These include:

Worldwide litter collection actions on beaches and river banks

One of the best-known initiatives is International Coastal Cleanup Day, an event that the US environmental organization Ocean Conservancy has been holding each September for more than 30 years. In 2019 these marine conservationists and their partner organizations around the world cleaned almost 40,000 kilometres of coastline and collected 9.4 million kilograms of garbage, most of which was food packaging, cigarette butts, plastic bottles and plastic straws.

Developing new technologies for waste collection and disposal

Many small start-up companies are now developing a variety of new methods for removing plastics from the sea and, in the best-case scenarios, to profitably reprocess them. The spectrum of possible solutions ranges from giant plastic barriers that capture trash floating on the sea surface, to garbage-collection boats with large conveyor belts, water-filtering systems, and trash robots that patrol harbour basins collecting floating materials.

Initiatives to expand the circular economy

Industry and business are also now becoming more involved. For example, more than 500 businesses and organizations have joined the New Plastics Economy Global Commitment, a worldwide initiative of the Ellen MacArthur Foundation and the United Nations Environment Programme. The signatories plan to work together to significantly reduce the amount of plastic in the packaging industry, avoid unnecessary packaging and work specifically toward a closed circular economy so that plastic used for packaging purposes never has to be disposed of as waste.

In their annual report for 2020, the initiators write that the greatest progress has been achieved in the re-use of recycled plastic within the packaging industry. However, many of the plastics used are still not sufficiently recyclable. Moreover, the number of disposable plastic articles sold around the world is still much too high.

For this reason, scientists and a number of governments are also calling for an international agreement to reduce the plastic pollution of the planet, with clear joint objectives and binding commitments from all nations. The European Commission and other high-level political institutions support this initiative. At the international level, preliminary talks on how such an agreement should look have been underway since 2019. Critics respond that the lengthy negotiations for such an agreement are actually harmful to the struggle against plastic waste, because they prevent many stakeholders from taking immediate effective measures in the real world.

The United Nations Environment Assembly therefore advocates a dual approach. While their expert committee studies whether an international agreement would be effective and what guidelines it would have to include, the political, business and civil branches should continue to concentrate on implementing existing national regulations, establishing a circular economy, raising awareness within the general population and expanding research in the field of plastic in the oceans. There are actually two major aspects to be considered. Firstly, there is not a single correct solution for humanity's plastic problem; a variety of measures will be required. Secondly, time is pressing. As long as we humans continue to act as we have in the past, plastic pollution in the ocean will increase dramatically, with severe consequences for the health of all inhabitants of the ocean and all those who profit from it.

6.21 > The international community is attempting to regulate the way chemicals and waste are handled worldwide through a series of legally binding agreements. The following table lists the most important agreements, briefly describes their objectives, and gives the number of substances addressed and number of signatory states.

Multilateral agreements related to the sound management of chemicals and waste

Agreement	Adoption and entry into force	Goals	Number of chemical substances addressed	Number of Parties as of 14 January 2019
Montreal Protocol on Substances that Deplete the Ozone Layer	• Adopted at the Conference of Plenipotentiaries on the Protocol on Chlorofluorocarbons to the Vienna Convention for the Protection of the Ozone Layer in Montreal in 1987 • Entered into force in 1989	• Protect human health and the environment against adverse effects resulting, or likely to result, from human activities which modify or are likely to modify the ozone layer; • Protect the ozone layer by taking precautionary measures to control equitably the total global production and consumption of substances that deplete it, with the ultimate objective of their elimination on the basis of scientific knowledge, technical and economic considerations, and the developmental needs of developing countries.	144	197
Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal	• Adopted at the Conference of Plenipotentiaries in Basel in 1989 • Entered into force in 1992	• Effective implementation of Parties' obligations with respect to transboundary movements of hazardous and other wastes; • Strengthening the environmentally sound management of hazardous and other wastes; • Promoting the implementation of environmentally sound management of hazardous and other wastes as an essential contribution to the attainment of sustainable livelihood, the 2000 Millennium Development Goals, and the protection of human health and the environment.	124 groups of wastes, according to Annex I, II and VIII List A, and wastes falling under the criteria of the list of hazardous characteristics in Annex III	187

Multilateral agreements related to the sound management of chemicals and waste

Agreement	Adoption and entry into force	Goals	Number of chemical substances addressed	Number of Parties as of 14 January 2019
ILO Chemicals Convention C170	• Adopted at the 77th Session of the International Labour Conference in Geneva in 1990 • Entered into force in 1993	• Reduce the incidence of chemically induced illnesses and injuries at work by ensuring that all chemicals are evaluated to determine their hazards; • Provide employers with a mechanism to obtain information from suppliers about the chemicals used at work; • Provide workers with information about the chemicals at their workplaces, and about appropriate preventive measures so that they can effectively participate in protective programmes; • Establish principles for such programmes to ensure that chemicals are used safely.	Not applicable	21
Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction	• Adopted at the 635th plenary meeting of the Conference on Disarmament in Geneva in 1992 • Entered into force in 1997	• Achieve effective progress towards general and complete disarmament under strict and effective international control, including the prohibition and elimination of all types of weapons of mass destruction; • Exclude completely the possibility of the use of chemical weapons, including prohibition of the use of herbicides as a method of warfare; • Promote free trade in chemicals, as well as international cooperation and exchange of scientific and technical information in the field of chemical activities for purposes not prohibited under the Convention; • Completely and effectively prohibit the development, production, acquisition, stockpiling, retention, transfer and use of chemical weapons, and their destruction.	15 toxic chemicals and 28 precursors	193
ILO Convention concerning the Prevention of Major Industrial Accidents C174	• Adopted at the 80th Session of the International Labour Conference in Geneva in 1993 • Entered into force in 1997	Having regard to the need to ensure that all appropriate measures are taken to: • Prevent major accidents; • Minimize the risks of major accidents; • Minimize the effects of major accidents.	Not applicable	18

Multilateral agreements related to the sound management of chemicals and waste

Agreement	Adoption and entry into force	Goals	Number of chemical substances addressed	Number of Parties as of 14 January 2019
Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade	• Adopted at the Conference of Plenipotentiaries on the Convention in Rotterdam in 1998 • Entered into force in 2004	• Promote shared responsibility and cooperative efforts among Parties in the international trade of certain hazardous chemicals, in order to protect human health and the environment from potential harm and to contribute to their environmentally sound use, by facilitating information exchange about their characteristics, by providing for a national decisionmaking process on their import and export and by disseminating these decisions to Parties.	50 substances and mercury compounds	161
Stockholm Convention on Persistent Organic Pollutants	• Adopted at the Conference of Plenipotentiaries on the Stockholm Convention on Persistent Organic Pollutants in Stockholm in 2001 • Entered into force in 2004	• Protect human health and the environment from Persistent Organic Pollutants (POPs); • Eliminate or restrict the production, use, import and export of listed POPs, and require measures to be taken with respect to waste and unintentional releases of POPs.	28 POPs and mentioned salts	182
WHO International Health Regulations (IHR) (2005)	• Adopted by the 58th World Health Assembly in Geneva in 2005 • Entered into force in 2007	• Prevent, protect against, control and provide a public health response to the international spread of disease in ways that are commensurate with and restricted to public health risks, and which avoid unnecessary interference with international traffic and trade (Article 2).	Not applicable	196
Minamata Convention on Mercury	• Adopted on the occasion of the Conference of Plenipotentiaries on the Minamata Convention on Mercury in 2013 • Entered into force in 2017	• Protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds. Commitments by Parties include: • Ban new mercury mines and phase out existing ones; • Phase out and phase down mercury use in a number of products and processes; • Establish control measures for emissions to air and releases to land and water; • Environmentally sound interim storage of mercury, and its disposal once it becomes waste.	Mercury and mercury compounds	101

Conclusion

Seas brimming with litter and pollutants

Not only does the world ocean play a major role in the climate and species-diversity crises of the Earth. It is also affected by a third global environmental crisis: the widespread pollution of terrestrial and marine areas. Every year as much as 400 million tonnes of pollutants end up in lakes and rivers, and ultimately in the seas. These include thousands of different chemicals, nutrients, plastics and other synthetic products, toxic heavy metals, pharmaceuticals, cosmetic products, pathogens, radioactive substances and much more.

In eight of ten cases, pollutants identified in the sea originate from terrestrial sources. As industrial or household waste, they are either discharged directly into the water, escape from poorly functioning wastewater treatment plants, are washed from the fields and streets by rainfall from above, or are leached from landfills and garbage dumps into subterranean water channels or streams. Litter and plastics are also carried to the sea by the wind. The remaining input of pollution occurs directly at sea, as a result of fishing and aquaculture or from shipping.

Winds and ocean currents transport garbage and pollutants to the most inaccessible regions of the world's oceans. Evidence of the pollution can be found on remote islands, in the polar sea ice and in deep ocean trenches. Pollutants especially hazardous for marine biotic communities are those that are long-lived and that accumulate in the food webs. These are characteristic, for example, of the group of persistent organic pollutants (POPs), which includes many pesticides and industrial chemicals.

The consequences of contamination are manifold and are distinguished according to the species affected and pollutant concerned. Known environmental pollutants cause diseases such as cancer, evoke deformities and behavioural changes in marine organisms, impair reproduction in affected species and can cause death in contaminated individuals. As a rule, predators at the highest trophic levels are especially impacted by environmental pollutants. These include sharks, toothed whales and seals. Animals that come into contact with plastic waste are in danger of being trapped, or of ingesting the plastic and starving with a full stomach. At least 700 animal species have now been identified for which plastic in the ocean can be a deadly hazard.

The international community is attempting to limit the input of pollutants into the seas through a variety of international agreements as well as transregional and national regulations. The prohibition of selected persistent organic pollutants by the Stockholm Convention, for example, is delivering results. The concentrations of these pollutants in the sea are declining.

But in many other cases, politicians and scientists are facing the problem that regulatory authorities are not always fully informed about the chemicals that are used in popular products, or about the impacts these ingredients would have should they someday end up in the sea. In many cases, the risk analyses required for a ban on dangerous substances are only possible after excessive quantities of them have already been introduced into the ocean and researchers are able to demonstrate the links between pollutant input and ecosystem destruction.

An end to the crisis of marine pollution will not be possible until a large proportion of the households and businesses around the world are connected to functioning sewage and solid-waste management systems, until substances toxic to the environment and carbon-based plastics are replaced by biodegradable alternatives, and the use of chemicals and plastics is limited to closed-loop systems.

7 The race for the oceans' genetic diversity

> In the course of evolution, marine life has developed an astonishing variety of ingenious forms, functions and survival strategies. Marine-derived natural products and pharmaceuticals may therefore deliver progress and profit in many different economic sectors. However, it is still largely unclear who exactly may profit from the oceans' genetic diversity, how it can be used fairly and, above all, how its conservation can be guaranteed in the long term.

Marine-derived active compounds

> The expectations are huge: since the first successes of marine biodiscovery research, scientists have been hoping to find solutions to humankind's most pressing problems in the genome of marine organisms – from pharmaceuticals to treat previously fatal diseases to cosmetics for eternally young skin to formulas for environmentally friendly adhesives and paints. However, to decode genetic information is still a complex undertaking, even if modern high-throughput methods have enormously accelerated the process.

Unparalleled diversity

Marine life is unique and exceeds terrestrial species diversity many times over. In part, this diversity is owed to the fact that life on Earth first evolved 3.7 billion years ago in the oceans and only subsequently conquered the land. In retrospect, marine life had about three times more time to conquer the many niches of the ocean and adapt to the prevailing environmental conditions than land-based plants and animals. At the same time, marine organisms were forced from the outset to adapt to particularly extreme habitats. Deep-sea dwellers, for example, have to cope with the enormous pressure exerted by the water column, constantly low temperatures, little food and constant darkness. If they also live at one of the many hydrothermal vents, extreme chemical stresses are added – for example, a carbon dioxide content that can exceed by a factor of 1000 the concentration in the air we breathe.

Quorum Sensing
"Quorum" sensing is the term used to describe a bacterial cell-to-cell signalling process that is dependent on cell densities and only takes effect when the concentration of certain signalling molecules emitted by the bacteria exceeds a certain threshold value in the medium.

Challenged in this way, marine life has developed a wide range of ingenious forms, functions and strategies in the course of evolution and encoded the information for the formation of these characteristics in the marine organisms' genetic material. There are an estimated 2.2 million different species of marine animals, plants and fungi today, and about 230,000 of them have been scientifically described. The number of bacterial, archaeal and viral species is unknown. But it is known that, measured by their weight, they make up the bulk of life in the ocean. One drop of seawater can contain up to 350,000 different species of bacteria and other microorganisms.

The genetic diversity of marine animals, plants and various microorganisms is the foundation of life in the ocean. It influences, for example, how much biomass marine biocoenoses produce, to what extent they reproduce and how resistant they are to stressors. Species with high genetic diversity have greater fitness, adapt more quickly to environmental change and recover faster on foot of an environmentally induced population collapse. The ocean's gene pool thus helps determine how much food and other services the sea can provide to humans in the long term.

For scientists, the oceanic genome, i.e. the genetic resources present in all marine biodiversity as well as the many pieces of information they store, is akin to a gigantic library. Here they search for information on the development of marine organisms and their ability to adapt to their respective habitat and the changes therein. But also encoded in the genome are the blueprints for what are known as secondary metabolites, which are of particular interest to chemists and molecular biologists. In contrast to primary metabolites (e.g. nucleotides, amino acids), which serve to build vital biomolecules (e.g. DNA, proteins), secondary metabolites are not considered essential for the survival of the organism that produces them. They can however fulfil important ecological functions.

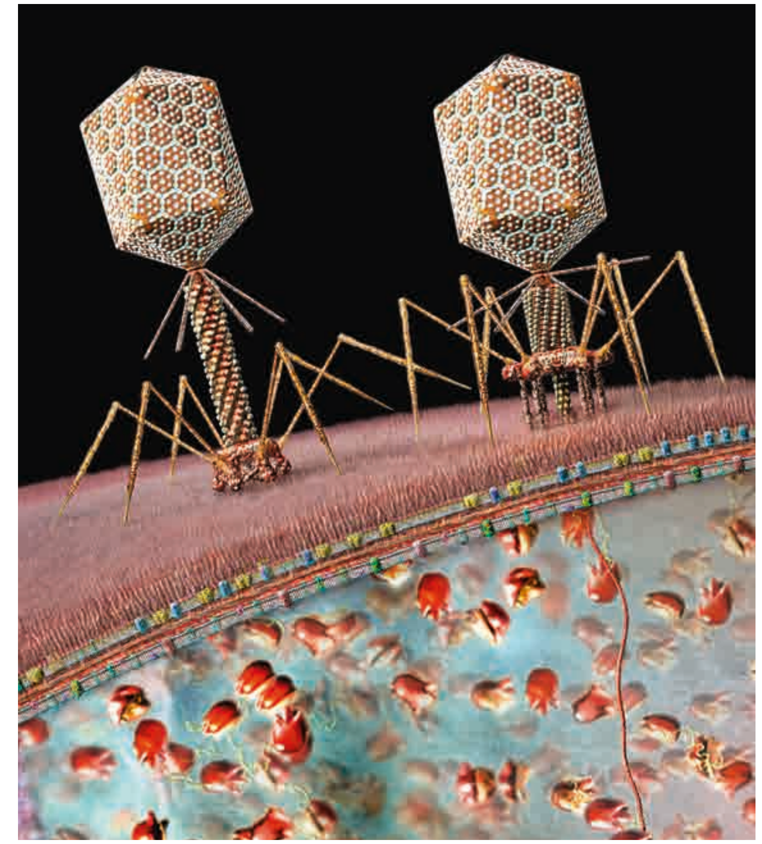
Secondary metabolites are produced by marine animals, plants, fungi, bacteria, archaea and viruses for various purposes. They serve, for example, as a chemical weapon for catching prey (as in the marine cone snail of the genus *Conus*), and also aid communication between organisms by means of chemical signals (quorum sensing in bacteria) or protect against extreme temperatures, UV radiation, pathogens, fouling, intrusive neighbours or predators. Secondary metabolites therefore noticeably improve the performance and adaptability and thus the chances of survival of marine organisms and are generally – and this is what is so special about them – enormously effective even in very small quantities.

For a little over two decades, marine scientists working in the field of marine natural products chemistry and the closely linked field of marine biotechnology have been actively researching marine secondary metabolites and their use by humans in the form of marine-derived active compounds. The scientists involved in this field examine marine organisms for the presence of bioactive, i.e. effective, molecules and components, extract them, describe their chemical structure, explore their function and look for possible commercial uses – ranging from the feed and food industries to the production of cosmetics and pharmaceuticals.

In addition to molecular research, biotechnologists investigate the extent to which fish waste, marine algae and microorganisms could be used as natural products for industrial purposes. German scientists, for example, are currently investigating whether edible food packaging can be produced from macroalgae. These could replace plastic packaging and disposable tableware and could also be enriched with bioactive ingredients that prolong the foods' shelf-life. Collagen can be extracted from fish scraps and used in a variety of ways – as a food supplement, as an agent to help repair tissue damage, as an additive in cosmetics production and as an agent against the formation of biofilms on surfaces. Scientists even suspect the presence of valuable active compounds in the ink of octopuses and cuttlefish.

The potential range of applications for marine-derived active compounds is so vast that experts are looking to the ocean for solutions to some of humankind's greatest problems. These include, among others:

- combating previously incurable diseases by developing new pharmaceutical compounds based on marine-derived active compounds;
- improved preventive healthcare by adding marine-derived active compounds to food products in order to make them more nutritious, vitamin-rich or digestible;
- development of biodegradable substitutes for plastics and other petroleum-based materials;



7.1 > There is as yet insufficient scientific knowledge about bacteriophages – viruses that are specialized on bacteria as host cells. Ten billion of them can be found in a single litre of seawater.

- development of environmentally friendly anti-fouling paints, adhesives and biofilters modelled on marine microorganisms;
- development of new methods for environmentally friendly ocean cleaning after chemical or oil spills, based on marine-derived natural products;
- development of alternative energy sources from natural substances, such as the production of biofuels from algae.

Marine biotechnology had its beginnings in the 1930s. At that time, carrageenan and other polysaccharides (multiple sugars) began to be extracted from macroalgae and used in the production of food and cosmetic products. Four decades later, in the 1970s, scientists began to intensively search for and extract active compounds from mostly sedentary marine organisms such as sponges and cnidarians, but also from snails, bryozoans and tunicates.

The basics of genetics: how genetic information is encoded

The genetic information of every living organism is contained in its chromosomes. These are microscopically small filamentous components of every cell, whose structure and location vary and constitute one of the fundamental differences between viruses (not counted as living organisms), bacteria and archaea (prokaryotes, single-celled organisms without a cell nucleus), and plants, animals and fungi (eukaryotes, living organisms with a cell nucleus in the cell).

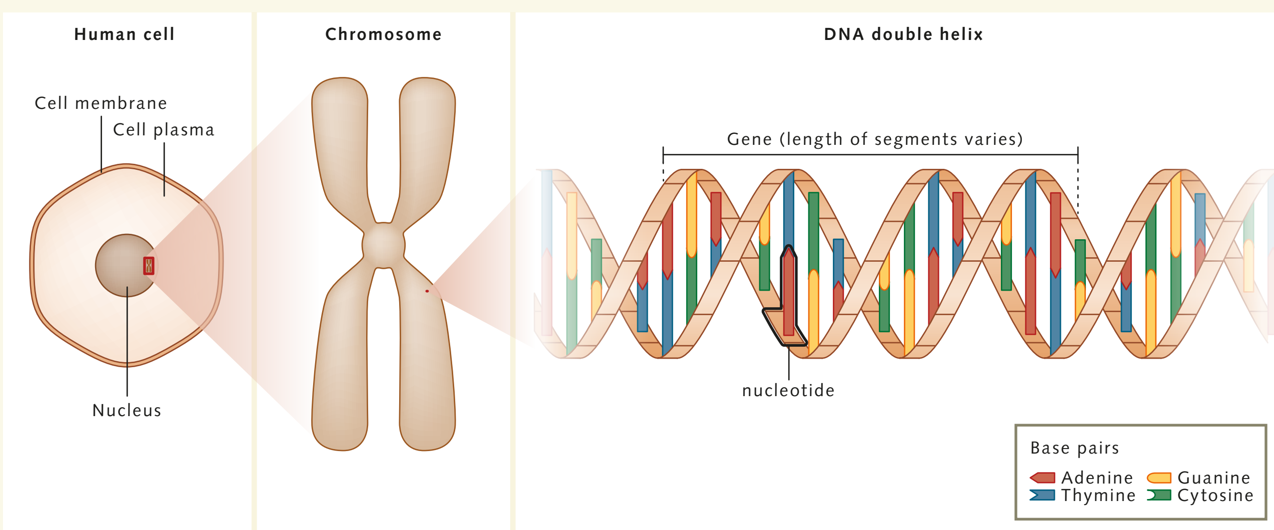
The chromosomes of viruses can consist of DNA (deoxyribonucleic acid) or RNA (ribonucleic acid). In prokaryotic unicellular organisms, only one ring-shaped chromosome made of DNA is found and this lies freely in the cell. In contrast, animals, plants and fungi have several chromosomes, often even a species-specific number of them. These consist mainly of DNA, but can also contain RNA and are located in the cell nucleus. This means they are enclosed by the membrane of the cell nucleus.

The chromosomes are nothing more than the tightly packed version of the long DNA molecule they are made of. If, for example, the 46 human chromosomes were to be unpacked, their genetic material in the form of DNA strands would come to a total length of about two metres. Each DNA molecule, in turn, looks like a twisted rope ladder. It consists of two parallel, interconnected polynucleotide chains. The backbone chains (the “ladder’s” outer sides) consist of sugars and phosphates; the “rungs” consist of two interconnected nucleotide bases each, with exactly four different bases occurring in each strand, each of which combines with only one other to form a base pair – adenine (A) with thymine (T) and guanine (G) with cytosine (C). Because its two nucleotide strands wind around each other like a helix, the DNA molecule is also called a double helix.

A gene is a specific section of the DNA molecule that stores specific genetic information. Different species vary in the number of genes in their DNA. The human genome consists of an estimated 30,000 genes, while scientists have identified precisely 5416 genes in the bacterium *Escherichia coli O157:H7*.

If in the cell the information of a gene is needed for a certain process, the DNA double-strand splits at the relevant section. Free complementary RNA nucleotides from the cell now attach themselves to the exposed nucleotide bases of the DNA molecule: adenine to thymine, guanine to cytosine and vice versa. The only difference is that in RNA uracil replaces thymine as the complementary base to adenine. In this manner, the RNA nucleotides copy the DNA information and then, as messenger RNA (mRNA), migrate to the part of the cell where the information is needed.

There, in a process called translation, the mRNA is translated into a sequence of amino acids from which proteins are then produced and cellular processes can be set in motion. For this reason, mRNA is also called bioactive.



7.2 > A human’s genetic information is stored in the cell nucleus, or more precisely in the 46 chromosomes whose individual DNA strands, strung together, would come to a length of two metres.

But research at that time and today’s modern biotechnology are scarcely comparable: New deep-sea research technology, modern DNA sequencing, replication and chemical analysis methods as well as advances in bioinformatics have revolutionized this branch of research and generated step changes in knowledge. Today, marine biotechnology is a pillar of the “blue bioeconomy”; that is, entire economic sectors have it as their foundation. Experts speak of a golden era and estimate that by 2025, pharmaceutical and chemical products worth USD 6.5 billion will be traded worldwide, the origin of which can be traced back to the genetic diversity contained in the oceans.

New technologies revolutionize research

Deciphering the entirety of a living being’s genes was first achieved in 1995, when the complete genome sequence of the bacterium *Haemophilus influenzae* was published. Only six years later, scientists almost completely decoded the human genome sequence. It consisted of approximately three billion letters (nucleotides) and raised the hopes of many experts that they may finally hold the key to understanding the complex human organism.

However, only a short time later, it became evident that deciphering the genome sequence of a living being is only a first big step, as the expression of genes depends on numerous environmental factors as well as the complex interplay of genes with each other and with the environment. Nowadays, experts use bioanalytical high-throughput methods, referred to as omics technologies, to elucidate these many interrelationships. These largely automated procedures allow for the parallel, comprehensive investigation of biomolecules contained in a biological sample in a relatively short time. They are named after the biomolecules investigated (genomics, transcriptomics, proteomics, metabolomics). This means that with their help, scientists not only sequence the complete genetic information of a living organism (genome), but can also decode the totality of all RNA molecules (transcriptome), proteins (proteome) or metabolites (metabolome) present in the cell at a given time.

These genetic blueprints are stored in digital form in genome databases and with the help of computer algorithms they can be analysed and studied in terms of their functions. Aided by high-throughput gene/genome sequencing methods, marine researchers not only identify a large number of microscopically small species that had previously always been overlooked in water samples. They also gain deep insights into the molecular basis of many life processes and an ever greater understanding of what has to happen for an organism to live and function in its characteristic manner. This knowledge then enables them to copy certain processes or blueprints, or else to rewrite gene sequences so that, for example, selected species of bacteria are able to produce a variety of medically effective substances to be used to manufacture pharmaceuticals.

If a living organism’s genetic information is to be changed in a targeted manner, scientists use “genetic scissors”, the CRISPR/Cas9 technology. They can use it to edit the genetic material of cells as desired, meaning they can specifically switch off genes, alter them or even replace them. Methods like this are referred to as genome editing. CRISPR/Cas9 actually works in all cells and all organisms, in humans as well as in animals, plants and microorganisms. Used together, omics technologies and genetic scissors therefore offer scientists almost unlimited possibilities to utilize marine genetic resources or to render them usable by means of targeted modifications of their genetic material.

These new technical possibilities also prompt desires. The better the marine gene pool is understood, the more frequently biotechnology companies apply for patents on potentially useful genetic information, thus securing exclusive usage rights for a certain period of time. When in October 2017 scientists investigated the number of patents now revolving around marine organisms and their genetic material, they counted 862 affected species and approximately 13,000 genetic sequences the use of which was protected by patent. The listed species ranged from marine giants such as the sperm whale *(Physeter macrocephalus)* and the giant oceanic manta ray *(Manta birostris)* to fish and mussels as well as tiny creatures such as

7.3 > Jellyfish, salps, crustaceans, worms, algae and thousands of other plankton species were fished out of the sea by researchers on the Tara Oceans Expedition (2009 to 2013) at more than 210 different locations. Their genetic material is now being analysed using modern high-throughput methods.

How do CRISPR-Cas9 genetic scissors work?

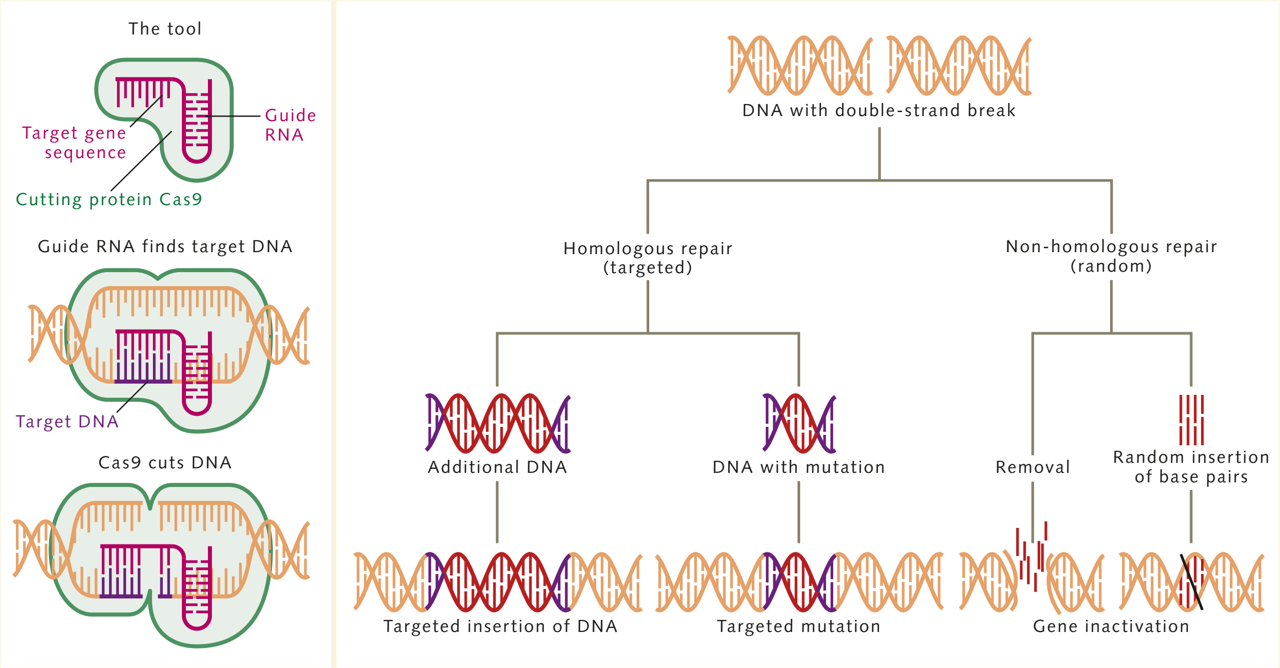
Programmable genome editing using CRISPR-Cas9 genetic scissors is a new molecular biological method allowing scientists to sever any DNA strand at a very specific point and, in the course of the subsequent repair, cut out, exchange or even insert individual DNA building blocks and thus rewrite individual genes.

CRISPR stands for "Clustered Regularly Interspaced Short Palindromic Repeats" and refers to sections of DNA repeats. The genetic scissors were developed by Emmanuelle Charpentier and Jennifer Doudna, two molecular biologists who were awarded the Nobel Prize for Chemistry in 2020 for their work on this technology.

The basic CRISPR-Cas mechanism originates from bacteria. It serves there as a kind of immune system, allowing the bacteria to recognize and fight off hostile viruses on the basis of previously stored DNA fragments. Scientists have now found ways to make use of this fascinating mechanism. In order to localize the site where the double strand is to be cut, the scientists provide the cutting protein Cas9 with a selected target sequence known as guide RNA. The protein then searches the double-stranded DNA for exactly this sequence. When it reaches the target sequence, in other words the cleavage site, it docks at the double-strand and cuts it.

Once Cas9 has cut the double strand of DNA, the cell's natural repair programme kicks in and rejoins the severed ends. This repair can be random (non-homologous) or targeted (homologous). In the case of non-homologous repair, individual DNA building blocks are removed or incorrectly assembled at the cleavage site. As a result, the gene in question can no longer be read correctly and is therefore no longer active. In homologous repair, a new gene segment or a short new DNA sequence can be inserted at the cleavage site and the gene function can thus be altered.

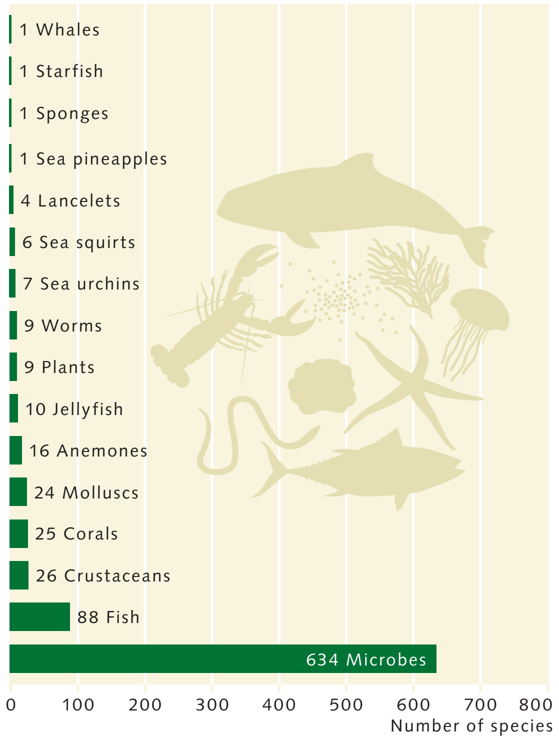
Both the guide RNA and the cutting protein Cas9 are produced synthetically and then introduced into a cell. Compared to other genome editing methods, the CRISPR-Cas9 genetic scissors are easier, faster and more cost-effective to use. This method is also far more precise than others: unintentional cuts in the DNA strand are rare and can largely be ruled out. Moreover, CRISPR-Cas9 can be used to make several changes to the genome simultaneously.



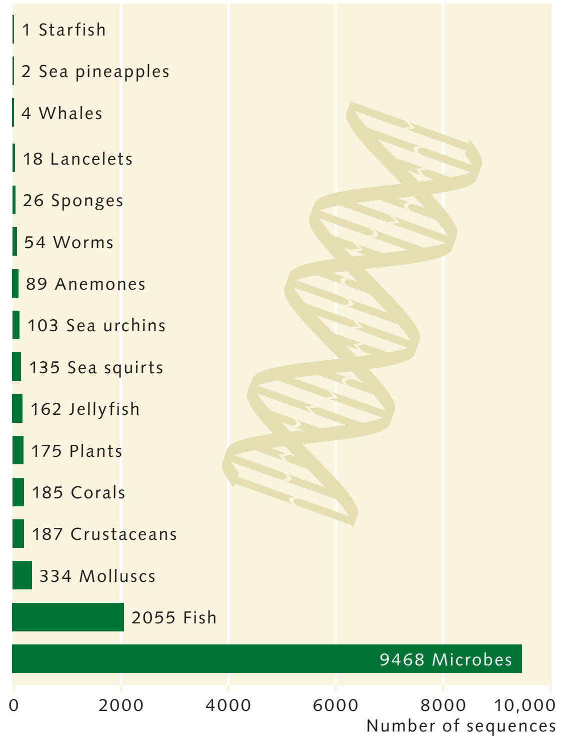
7.4 > The CRISPR-Cas9 genetic scissors are a molecular biological method for cutting and modifying DNA with pinpoint accuracy. The method can be used to insert, remove or modify individual DNA building blocks. It works with all organisms and is used in animal and plant breeding as well as in biotechnology.

7.5 and 7.6 > In October 2017, scientists investigated the number of patents registered for genetic information of marine organisms at that time. They counted 862 affected species and approximately 13,000 genetic sequences the use of which was protected by patent.

Marine species with patent sequences



Patent sequences from marine species



archaea and plankton. Ninety-one of the listed species were deep-sea dwellers, especially species occurring in biocoenoses at hydrothermal vents.

The patents surveyed had been filed by a total of 221 companies. However, almost half of the patents were held by a single large corporation, the German chemical company BASF, even though BASF itself does not conduct marine research. This major corporation and its subsidiaries instead search the public gene databases for promising sequences and check their commercial potential. The analysis also showed that the majority of patent claims were made by institutions from only 30 countries and the European Union. The remaining 165 countries of the world virtually did not appear in the statistics.

The great diversity of marine organisms means that basically every single species holds genetic information that could potentially be commercially exploited in one way or another. Biotechnologists and chemists are currently primarily looking for bioactive molecules that can be used as pharmaceutical compounds, as food supplements, as fertilizers or energy sources, as raw materials for the production of cosmetics and for various other industrial applications.

Medicine from the sea

The success story of medicine from the sea began in 1945, when a young chemist named Werner Bergmann was diving off the coast of Florida and discovered an inconspicuous, previously unknown brown sponge in shallow water. A colleague of Bergmann's scientifically described the Caribbean sponge and gave it the Latin name *Cryptotethya crypta*, today also known as *Tectitethya crypta*. Werner Bergmann extracted two previously unknown organic substances from the sponge – spongothymidine and spongouridine.

At that time, the chemist already suspected that these substances could one day be useful in medical research. How accurate his suspicions were became evident in particular in 1987, when the US Food and Drug Administration (FDA) approved the first drug to treat the immunodeficiency disease HIV. The drug was called azidothymidine (AZT) and its structure was modelled on the two substances that Werner Bergmann had extracted from sponge tissue more than 40 years earlier. Only two years after its approval, AZT had become the most expensive drug in the world. At that time, patients paid up to USD 8000 per year, which generated more than USD 100 million in annual profits for the manufacturing company.

Following Bergmann's example, scientists have discovered approximately 34,000 different secondary metabolites in marine organisms, many of which are of particular interest for pharmaceutical research. They kill bacteria or viruses for example, fight cancerous tumours and fungal diseases, strengthen the immune system, inhibit

7.7 > All marine organisms possess genetic information that can potentially be exploited. This table shows some of the most intensively researched groups of organisms, possible areas of application for their active compounds or extracts, and the greatest challenges to industrial use.

Source	Use	Representative phyla (exemplary genera/species)	Challenges
Metazoans	Medicine, cosmetics	Tunicates – Chordata *(Ecteinascidia turbinata)*, Mollusca *(Conus magus)*, sponges – Porifera *(Mycale hentscheli)*, Cnidaria *(Sinularia sp., Clavularia sp., Pseudopterogorgia sp.)*	Sourcing and supply sustainability
Macroalgae and seagrasses	Food, feed, medicine, cosmetics, nutraceuticals, biofertilizers/soils conditioners, biomaterials, bioremediation, energy	Rhodophyta *(Euchema denticulatum, Porphyra/Pyropia spp., Gelidium sesquipedale, Pterocladiella capillacea, Furcellaria lumbricalis, Palmaria spp., Gracilaria spp.)*, Chlorophyta *(Ulva spp.)*, Ochrophyta *(Laminaria hyperborea, Laminaria digitata, Ascophyllum nodosum, Saccharina japonica, Saccharina latissima, Sargassum, Undaria pinnatifida, Alaria spp., Fucus spp.)*, seagrasses *(Zostera, Cymodocea)*	Sourcing and supply sustainability, yield optimization, large-scale processing and transport, disease management
Microalgae	Sustainable energy, cosmetics, food, feed, biofertilizers, bioremediation, medicine	Chlorophyta *(Chlorella, Haematococcus, Tetraselmis)*, Cryptophyta, Myzozoa, Ochrophyta *(Nannochloropsis)*, Haptophyta *(Isochlysis)*, Bacillariophyta *(Phaeodactylum)*	Bioprospecting and yield optimization (1 – increase in biomass/volume ratio, 2 – increase yield of compound/extract production, 3 – Improve solar-to-biomass energy conversion)
Bacteria and archaea	Medicine, cosmetics, biomaterials, bioremediation	Actinobacteria *(Salinispora tropica)*, Firmicutes *(Bacillus)*, Cyanobacteria *(Arthrospira, Spirulina)*, Proteobacteria *(Pseudoalteromonas, Alteromonas)*, Euryarchaeota *(Pyrococcus, Thermococcus)*	Culturing for non-culturable species, yield optimization
Fungi	Bioremediation, medicine, cosmetics, food/feed, biofertilizers	Ascomycota *(Penicillium, Aspergillus, Fusarium, Cladosporium)*	Limited in-depth understanding, yield optimization
Thraustochytrids	Food/feed, sustainable energy production	Bigyra *(Aurantiochytrium sp.)*, Heterokonta *(Schizochytrium sp.)*	Limited in-depth understanding, yield optimization
Viruses	Medicine, biocontrol	Mycoviruses, bacteriophages	Limited in-depth understanding, yield optimization

inflammation or diabetes, lower the risk of heart disease or protect an organism from UV radiation. Chemists and pharmacologists working with marine-derived active compounds are now developing 2.5 times as many new drugs as the industry average.

The scientists often produce synthetic copies of the natural active compounds, meaning that not only can consistent quality of the active compound be guaranteed, but the substance can also be produced in sufficiently large quantities. Both are basic prerequisites for industrial application, which are rarely met by the original substances. The secondary metabolites usually only occur in such small quantities in the marine organisms in question that, for example, several tonnes of a selected sponge, snail or algae species would have to be caught or harvested to obtain just a few grams of active compound. And even then, there would be no guarantee that the specimens collected would indeed contain the coveted compounds, given that the production of the active ingredient often depends on the season and the interactions of various environmental conditions on site. Just a few metres away or a few weeks later in the year, these conditions may be completely different and the target organism may do just fine without the specific active compound.

For the same reason, the cultivation of marine organisms for targeted mass production of active ingredients presents major challenges. Attempts to keep sponges in aquaculture systems in order to produce active compounds have failed repeatedly. And even in modern laboratories, the complex natural marine living conditions can only be simulated inadequately. While some progress has been made – among other things in the cultivation of microalgae, whose secondary metabolites may prove useful in the development of antibiotics and cancer drugs – more than 85 per cent of all microorganisms are still considered unculturable.

Scientists are now also able to explain why sponges, cnidarians and other molluscs living on the seabed display such particularly high diversity of marine-derived active compounds. Once firmly anchored to the sea floor, these usually very long-lived animals are hardly able to escape – neither from intrusive neighbours who want to overgrow them, nor from predators, intrusive fungi or algae. The sessile animals therefore need to produce effective deterrent substances. They are actively supported in their production by highly specialized microorganisms with which they live in close symbioses. Scientists are therefore no longer surprised when it turns out that secondary metabolites found in tissue samples of a sponge or other mollusc actually have a bacterial origin.

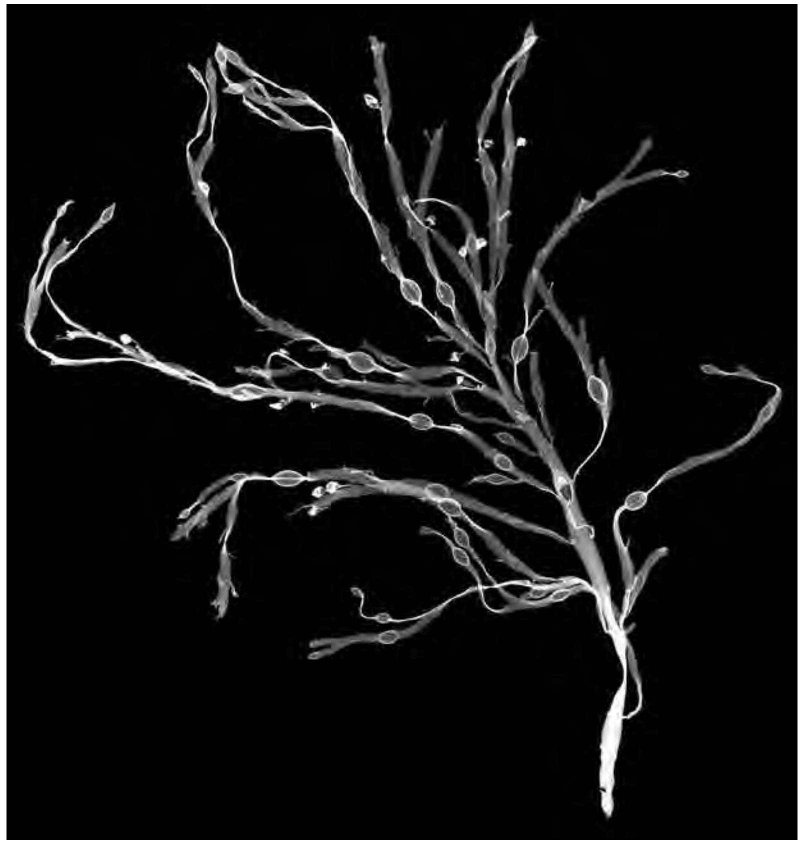
In some cases, however, marine organisms take up the secondary metabolites with their food. The antitumour agent Kahalalide F, for example, is now known to be produced by *Bryopsis spp.* algae – in very low concentrations. Scientists originally found this active compound in the sea snail *Elysia rufescens*. This species consumes Bryopsis algae and accumulates the compound in its body. Its concentration in the snail's tissue can be up to 5000 times higher than in the algae themselves.

Since the market launch of the antiviral drug AZT in 1987, the US Food and Drug Administration has approved a total of 13 pharmaceuticals containing marine-derived active compounds; globally there are 17 approved pharmaceuticals of marine origin (as of March 2021). The AZT models spongothymidine and spongouridine, for example, led to the development of the two compounds vidarabine and cytarabine, which are used in the treatment of blood cancer and viral infections. Researchers extracted the natural active compound ecteinascidin 743, also known as trabectedin, from the mangrove tunicate *Ecteinascidia turbinata*. A replica of this active compound is contained in the drug Yondelis, which is used to treat cancerous tumours.

Currently, an additional 23 drugs made from marine-derived active compounds are in the clinical trial phase. Pre-clinical studies are underway for 313 marine-derived active compounds, including eight anti-malarial compounds. Nearly two out of three of all new marine-derived natural products are now derived from microorganisms.

This highlights their increasing significance for biotechnology research. Given these statistics, experts have hailed marine biotechnology research a success story.

7.8 > Since the 1970s, the blue blood of the Atlantic horseshoe crab ***(Limulus polyphemus)*** has been used to test new vaccines for purity. It contains blood cells as part of the crabs' immune system that are particularly sensitive to toxic bacteria. If new vaccines are contaminated with such bacteria, the cells attack the bacteria and form clots. The good news for the animals is that there is now a synthetic alternative to their blood.



7.9 > The Baltic brown alga *Fucus vesiculosus* contains 44 effective components of interest. However, their quantity or concentration fluctuates through the seasons. The alga produces some active compounds mainly in winter, others almost exclusively in summer.

Normally, researchers have to extract, purify, identify and study the biological activity of around 15,000 different secondary metabolites in order to find the one active compound that will eventually be approved as a drug. The marine researchers' success rate stands at 17 approvals out of 34,000 secondary metabolites. However, the development of pharmaceuticals from natural substances remains a very expensive and lengthy process. It usually takes 15 to 20 years before a drug is approved.

Nevertheless, commercial interest in genetic material from the sea is growing steadily. Industrial research on natural products is, however, mainly driven by medium-sized and smaller pharmaceutical companies. Despite the vast potential of marine-derived natural products in particular, but also terrestrial natural products, most large corporations closed their natural product research departments in the 2000s in favour of "blockbuster drugs". These promised fast and high profits through large market shares. Today, large corporations often pursue a strategy of closely following the progress made by research companies and buying up these mostly smaller companies as soon as they can present initial promising results. If the large corporations invested directly in basic research, the pharmacologists' and chemists' yield rate would certainly be quite a bit greater still.

Use in cosmetics production

Due to their many positive properties, marine-derived natural products are often used in the production of cosmetics. These are frequently derived from marine bacteria, microalgae or fungi. However, there are also products on the market containing active compounds produced from macroalgae, fish and corals. Manufacturers are particularly interested in substances such as:

- Amino acids that protect marine organisms from high UV radiation near the ocean surface. The cosmetics industry often advertises these as anti-ageing compounds;
- Substances called exopolysaccharides; these are multiple sugars secreted by various microorganisms. When used as cosmetics, they increase the skin's moisture content;
- Carotenoids (fat-soluble pigments) and polyphenols (secondary phytochemicals), which have antioxidant or anti-inflammatory properties, slow down the skin's ageing process and make it more resistant to environmental factors;
- Enzymes and peptides that protect the collagen stores in the skin and in this way also slow down skin ageing.

Alginates (salts of alginic acid) and the polysaccharide fucoidan from brown algae, chitin from the carapace of shrimp, powder from oyster shells, carrageenan from red algae, collagen and gelatine extracted from jellyfish and fish are all widely used in the cosmetics industry. But manufacturers also use extracts from microalgae, fungi, soft corals and deep-sea microorganisms to create products that are supposed to prevent the formation of wrinkles, moisturize the skin and slow down its ageing process. Despite the great variety of products, scientists assume that the cosmetics industry is far from knowing and using all the marine active compounds. According to the scientific community there is still plenty of room for new discoveries.

Marine-derived natural products as food and feed additives

Their functional diversity makes marine-derived natural products a popular additive in food and feed production. Chemical components obtained from fish waste, microalgae and macroalgae, marine bacteria and fungi are used in the industry as natural preservatives, pigments, stabilizers, thickeners and binding agents, as food supplements and as prebiotics. Foods with bioactive additives are said to have a wide range of health-promoting effects. Food and beverage manufacturers also use cold-active enzymes from marine organisms in the production of heat-sensitive products. These enzymes prevent, for example, temperature-related changes in a product's smell, taste, appearance and feel. Antifreeze proteins are used to improve the quality of frozen foods. They prevent the formation of ice crystals and are produced, among other organisms, by algae living in sea ice. This property allows the algae to survive the long polar winter undamaged.

Manufacturers of fish feed are currently urgently searching for alternatives to fishmeal and fish oil and microalgae might give them what they are looking for. Selected species produce not only the essential fatty acids, which are vital yet cannot be produced by the human body, but also amino acids, which are needed to ensure the health and good growth of farmed fish. Moreover, microalgae are the main food source of saltwater crayfish (Artemia), rotifers (Rotifera) and copepods (Copepoda), which in turn are needed as live food for fish larvae. Researchers are working on optimizing the microalgae. The aim is for them to produce so many essential fatty and amino acids that both the zooplankton and, in the next step, the fish larvae can grow most favourably.

Possible applications in agriculture

Seaweed is the prime candidate for use in agriculture. Scientists are currently investigating its suitability as a fertilizer and animal feed as well as a raw material for biogas production, which in turn can be used as fuel (bioethanol) or for electricity generation. Small farmers in many coastal regions have always used washed-up macroalgae as a natural soil conditioner. Regularly applied, seaweed improves the soil structure as well as the humus content and thus the soil's nutrient content. Nevertheless, scientists see scope for improvement. Among other things, they hope that controlled composting of the algae could accelerate their subsequent release of nutrients to the soil and the crops growing therein. If this were successful, com-

7.10 > On the Scottish Orkney island of North Ronaldsay, a breed of sheep feeds almost exclusively on seaweed and kelp washed up on the rocky coastline or which the animals can reach at low tide.

7.11 > Workers rake up Sargassum seaweed, huge carpets of which have recently been washing up on Caribbean beaches where they rot away. In Mexico alone, the army and volunteers removed more than 57,000 tonnes of smelly heaps of seaweed in the summer of 2019.

posted macroalgae could replace conventional fertilizers. The vast quantities of Sargassum, a genus of brown macroalgae, which the sea now regularly washes up on the coasts of the islands and ocean-facing countries in the Caribbean, could potentially be used in this way. When the algae carpets rot in the surf zone, they not only harm the tourism industry but the nutrients released also overfertilize the sensitive coastal ecosystems and severely damage the coral reefs. In some instances farm animals also accept macroalgae as a feed. In this respect, the sheep on the Orkney island of North Ronaldsay are certainly a special case: seaweed is their main food source.

Microalgae and cyanobacteria also hold great potential. They produce biostimulants that promote the growth, development and resilience of crops such as cereals. These biostimulants include polysaccharides, minerals, vitamins, oils, fats, acids, pigments and hormones. Extracts from microalgae are therefore increasingly used as biofertilizers in farming.

Chitin is extracted from the shell of the Arctic prawn *(Pandalus borealis)* and used to produce chitosan. Chitosan binds fats and suspended solids and is therefore not only used in medical products and food supplements, but also in wastewater treatment plants as well as in the beverage industry in a variety of large-scale applications. In agriculture, chitosan can serve as a coating for fertilizers, pesticides, insecticides and herbicides and, due to its properties, ensure that nutrients or toxins are released into the soil in a controlled manner. Seeds and leaves can also be coated with chitosan to protect them from microbial attacks.

Aids for dealing with environmental pollution

The genetic diversity of marine organisms offers us humans a wide range of tools for detoxification and for the elimination of environmentally harmful pollution, a process known as bioremediation. Metabolites produced by sponges are used as anti-fouling agents in the fight against algal growth on ship hulls and other surfaces. Various strains of bacteria are able to break down hydrocarbons, aromatics and carbohydrates at a particularly fast pace and are thus suitable for cleaning up soils or marine regions affected by oil spills. Scientists are also aware that certain marine microorganisms produce enzymes that can break down plastics and other petroleum-based synthetic materials. However, the mechanisms and extent of such decomposition in the marine environment and the manner in which these processes can be used in the fight against marine litter are still being studied.

Enzymes from marine fungi are used to clean soils polluted with copper and zinc. The same substances are also used to decolourize textiles or paper. Microalgae and macroalgae are known to filter nutrients, heavy metals and even pharmaceutical compounds from seawater. As it is relatively cheap to grow macroalgae and seagrasses, these are being considered for large-scale use as biofilters in wastewater treatment. Microalgae, in contrast, are already in use today to combat heavy metal contamination. Purification by means of microalgae is a two-step process. First, the algae adsorb the heavy metals, i.e. the toxic substances accumulate on the tiny organisms' cell walls. Then the algae absorb the heavy metals into their cells and neutralize their toxic effect with the help of metal-binding peptides (organic compounds).

Marine-inspired materials

Marine-inspired natural materials bring with them a number of desirable properties: they are salt-tolerant to a certain degree, withstand high (water) pressure and endure heat as well as cold. Depending on their provenance, they may also possess previously undiscovered physical, chemical or biochemical properties. Experts believe that marine-derived natural products could, for example, be put to excellent use in the development of materials for medical applications. Examples would be materials for the production of artificial heart valves, bone implants or artificial joints.

However, there are still some hurdles to be overcome before this becomes feasible. For example, processes are needed that allow for the target substances to be isolated and prepared at the requisite high quality. It must also be ensured that sufficient quantities of the required substances are available at all times and that the properties of these source substances do not change over the course of the seasons.

Economically interesting sources of new biomaterials include algae, jellyfish, sponges, tunicates, mussels and crustaceans. They contain polysaccharides, enzymes, lipids (water-insoluble natural substances), pigments, minerals, ceramic materials (bioceramics) and toxins that could quite possibly be utilized in medical applications. Bioactive ceramic materials, for example, are extracted from corals, calcareous shells and sea urchins. They are then used as source materials for the production of hydroxyapatite, which is the main component of the inorganic substance in bones and teeth.

Glass sponges also serve as a model for designers and developers. These form a skeleton of needles, also called spicules (singular spiculum) that consist of highly pure silicon oxide, which the sponges form with the help of enzymatic processes from dissolved silicon in the surrounding seawater. Experts are trying to imitate these processes in order to use the material obtained for medical or optical applications. Silicon-containing materials are also used in high-tech products in the fields of microelectronics and optoelectronics.

In the search for alternatives to plastics and other petroleum-based synthetic materials, scientists are banking on macroalgae and microalgae. Cleaned, treated, dried and pressed into shape, macroalgae can be used as disposable tableware, for example. Various substances contained in the algae can also be used to make foils and other packaging materials. Carbohydrate-rich macroalgae and microalgae could also serve as a starting point for the production of polylactides.

To date, most biodegradable plastics are made from these synthetic substances. However, since polylactides decompose very slowly, scientists are still searching for better options.

Who should benefit from the marine gene pool?

There are numerous potential areas of application for marine natural products (MNPs) – and much of the genetic diversity contained in the ocean has not been decoded at all. This raises a multitude of questions. For example, who should benefit from the marine gene pool? Should the benefits accrue solely to states which fund this costly research? Doesn't the ocean belong to everyone? How should access to the sea's precious genetic resources be regulated at the international level – and what can be done to ensure that despite more intensive human use of marine resources, conserving biological diversity is the focal point of all action?

The search for answers to these questions starts with the United Nations Convention on the Law of the Sea (UNCLOS). It establishes the legal framework for all human activity in and on the oceans and seas, covering topics such as research, utilization of resources, and conservation of the marine environment, including – albeit without mentioning this specifically – biodiversity. Crucially, UNCLOS defines which maritime zones are classed as national territorial waters and are thus administered by the coastal states, and which parts of the ocean are defined as Areas Beyond National Jurisdiction (ABNJs).

The water column in the maritime regions beyond the limits of national jurisdiction is referred to in UNCLOS as the "high seas", while the adjoining seabed is known as "the Area". In relation to marine genetic resources, the distinction between national and international waters or areas is critical, since there is already a binding international treaty on terrestrial and maritime zones under national jurisdiction, namely the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (ABS) (abbreviated to "Nagoya Protocol"). The Protocol was adopted by the international community at the 10th meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD) in October 2010. It entered into force on 12 October 2014 and to date (April 2021) has been ratified by 130 countries.

The Nagoya Protocol was initially negotiated with the intention of establishing rules which ensure that profits arising from access to and utilization of genetic resources and the traditional knowledge associated with them are shared with their respective countries of origin in a fair and equitable manner. As the Protocol's underlying principle, each state has the sovereign right to determine access to the genetic resources originating on its territory. However, the Protocol also aims to ensure that access to such resources is possible under fair and transparent conditions. It therefore stipulates minimum standards which states must consider when developing their national regulations.

The Protocol is also informed by the principle that countries of origin have a right to share fairly and equitably in the benefits arising from utilization of their genetic resources. Here too, the Protocol establishes guidelines under international law.

At the same time, it obliges all Parties to ensure that access to and extraction of genetic resources are in compliance with any permit requirements adopted by the country of origin. The terms and conditions applicable to benefit-sharing must be negotiated with the country of origin prior to any extraction of material.

In practice, however, these legal provisions create a considerable administrative burden: if scientists from one country wish to extract marine genetic resources from another country's national waters, an application must be lodged and approval obtained beforehand – in addition to, and separately from, the diplomatic research permits that are also required.

Furthermore, the issue of what form any subsequent benefit-sharing will take must be regulated with the supplier country months or even years before any research is conducted. Options include not only monetary remuneration but also the sharing of research results, the inclusion of local scientists in research projects, or the provision of training for junior scientists. Inclusion and training are fundamentally positive as they promote international scientific cooperation and motivate coastal states in species-rich maritime regions to actively protect their coastal waters.

7.12 > The needle-like spicules forming the skeleton of glass sponges such as the species *Pheronema giganteum* consist of highly pure silicon oxide, which the sponges form by means of enzymatic processes from silicon dissolved in seawater. Experts are trying to mimic these processes in order to use the material thus extracted for medical or optical applications.

Access solely for cash? The dispute over public genetic databases

Until now, most of the genetic information that researchers have decoded has been made available by them via publicly accessible digital sequence information (DSI) databases. This genetic information is useful for conducting comparative analyses and is vital for biodiversity research, as well as for research on natural products and active substances. Pharmaceutical companies and other businesses use these freely available gene sequences to identify active substances, register patents, develop new products and generate profits. However, they are under no obligation to remunerate the data producers or the country of origin of this genetic material – a fact which has outraged an army of critics worldwide in recent years. As a result of their protests, a debate is currently under way about the implementation of the Nagoya Protocol and how the economic benefits arising from the use of this data can be shared in a fair and equitable manner at the international level. Restrictions on access and payment of fees are options being discussed.

The German National Academy of Sciences Leopoldina is opposed to restrictions on access. According to a statement released by the Academy, to enable free research worldwide, DSI databases must continue to be openly accessible. The coronavirus pandemic, in particular, has shown that the exchange of sequence information, in this case of novel pathogens, contributes significantly to scientific progress. In addition, DSI databases are a key tool for biodiversity conservation because, for example, changes in ecosystems can be tracked with their assistance.

The Academy's experts are in favour of equitable sharing of benefits arising from the use of biological diversity; however, this must be done in a way which does not jeopardize either biodiversity conservation or Open Science. The situation is also complicated by the fact that, to date, information on the geographical origin of the data is missing for almost half of all digital sequence information. The scientific community should therefore develop solutions to make this information traceable in the databases in the future.

Ideas on how to resolve this dilemma have been developed by an Open-Ended Working Group under the Convention on Biological Diversity (CBD). The framework developed by the Working Group will be discussed at the 15th meeting of the Conference of the Parties to the Convention on Biological Diversity in Kunming, China, in October 2021.

At present, however, the usefulness and effectiveness of the Nagoya Protocol are often still undermined by the differences in the Parties' implementation of its provisions.

In some countries, the application and authorization procedures relating to the Protocol are so complex and time-consuming that scientists abandon the research projects concerned or, where feasible, relocate them to maritime regions under other national jurisdictions, or to international waters. Others opt to focus on researching their own domestic waters instead.

A new agreement should provide clarity

The scientific community's experiences with the Nagoya Protocol rules, described above, play an important role in negotiations on the governance of genetic resources from international waters. As the reader will recall, the high seas cover more than two-thirds of the ocean and more than 40 per cent of the Earth's surface. They are the largest ecosystem on Earth and therefore also the largest reservoir of species diversity.

Under UNCLOS Articles 256 and 257, all states, irrespective of their geographical location, have the right to conduct research in international waters, both in the water column (high seas) and on the seabed (the Area). Theoretically, then, states or corporations could carry out marine scientific research in these international waters at any time, extract active substances from the sampled material, reproduce these substances and use them to develop pharmaceuticals or other revenue-generating products – without sharing any of the profits with other countries.

In order to prevent conduct of this nature, the United Nations General Assembly decided, in December 2017, to elaborate a new legally binding additional protocol under UNCLOS to regulate not only the conservation of marine biological diversity in areas beyond national jurisdiction in general terms but also the utilization of marine genetic resources in these areas. Its official title in English is: International legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ).

After several years of preparation, an intergovernmental conference, involving representatives of all the UN member states, was convened for the negotiations. To date, three formal sessions of the conference have been held; a fourth session, which was postponed from 2020 to 2021 due to the coronavirus pandemic, has not yet taken place. Although an initial draft of the instrument is now available, progress in the negotiations has been limited so far. One of the contentious issues is whether the water column, like the seabed, in international waters forms part of the common heritage of mankind, such that all the world's countries should benefit from potential revenues arising from it. This argument is presented mainly by developing countries which cannot afford to fund their own costly marine scientific and deep-sea research. Many developed nations, by contrast, argue that the water column in the high seas is not part of the seabed; they claim that the benefit-sharing requirement established by the International Seabed Authority (ISA) for profits from deep-seabed mining does not apply in the water column.

The position adopted thus far by the European Union (EU) is that sea areas beyond national jurisdiction (ABNJs) are part of the global commons – in other words, they form part of the common-pool resources that may be utilized by all nations of the world. Nonetheless, as regards the commercial utilization of genetic resources from ABNJs, compensation for non-participant countries should be considered; feasible options, from the European Unions' perspective, include scientific cooperation, training programmes for marine researchers from developing countries, and support for the establishment of a marine science infrastructure in these countries. Compensation payments as a form of benefit-sharing are rejected by the European Union, however.

Alongside all these fundamental questions, a series of detailed issues is hampering the negotiations. For example, how can it be ensured that all nations are kept fully informed about who is extracting genetic material from international waters, where they are doing so, and what happens to this material? To date, the discussion has focused on the establishment of an information and cooperation platform (clearing-house mechanism), e.g. for mandatory notification of planned research projects and the provision of a form of match-making service for potential partners. There is also some debate about the establishment of formal policy and science bodies and a secretariat, tasked with monitoring and coordinating compliance with all the provisions of the future agreement.

There is still a lack of clarity, however, on the powers to be granted to these individual bodies and where the secretariat might be located. It is likely that a separate Conference of the Parties (COP) will be established under the new agreement; representatives of all the signatory states would convene in this forum on a regular basis to review the implementation of the agreement, adopt any amendments that may be necessary, or regulate further details.

A further open question relates to sampling and how it can be proven that the biological material collected genuinely originated in international waters. In the case of organisms that are attached to the seabed, this question may be relatively easy to answer: the coordinates of the place of extraction would presumably suffice. In the case of plankton or migrating shoals of fish, however, determining the place of origin is more difficult. In such cases, is it, once again, the place of sampling that counts, or is the determining factor the location where a marine organism first saw the light of day, if this is known at all? The latter option is favoured mainly by states whose coastal waters are particularly species-rich and whose mangrove forests, reefs and seagrass meadows serve as a nursery for numerous marine species. However, a conclusive answer to this question is still awaited, along with solutions to issues of international patent protection and its validity for patents on gene sequences from the ocean.

It is also important to note, at this juncture, that access to and utilization of marine genetic resources and fair compensation mechanisms are just one out of a total of four overarching topics to be regulated by the new instrument on the conservation and sustainable use of marine biological diversity in international waters. The negotiating package also addresses rules on:

- Area-based management tools (ABMTs), this includes marine protected areas;
- Environmental Impact Assessment (EIA);
- Knowledge and technology transfer.

These negotiating packages often overlap; this is the case, for example, with knowledge transfer and the debate about benefit-sharing for marine genetic resources. The challenge facing the chief negotiators is how to achieve a balance of interests across all four topics. With regard to marine genetic resources, it is crucial that all nations have the opportunity to carry out genetic research, to access international databases and to utilize the vast amounts of data that the latter hold for universal benefit. At the same time, the rules must be framed in a way which ensures that research can continue and is not excessively burdened by technical and administrative complexities. The international community must also ensure that:

- research and development in marine biotechnology are conducted in a sustainable manner;
- no ethical and social boundaries are transgressed; and
- all demographic groups – including the poorest of the poor and marginalized groups, e.g. indigenous communities – genuinely benefit from biotech solutions, including active pharmaceutical ingredients.

These objectives can only be achieved if knowledge, research results and commercial successes arising from marine genetic diversity are shared in a fair and equitable manner; if current rules on patent protection are reformed; and if policymakers collaborate constructively – and more intensively – with the representatives of business, science and civil society. As their most important shared task, they must take decisions relating to the conservation and sustainable use of marine biological diversity on the basis of current knowledge, align these decisions to universal needs and, above all, never lose sight of their common responsibility for the ocean and its biotic communities.

7.13 > Artisanal fishers such as these men from Myanmar often belong to the poorest demographic groups. The instrument on the conservation and sustainable use of marine biological diversity in international waters, currently being negotiated, must ensure that they too ultimately benefit from potential biotech solutions.

Conclusion

The dawn of a golden age

The ocean's biodiversity is unique. Exposed to sometimes extreme environmental conditions, marine life has found remarkable ways to adapt. The information underpinning their species-specific survival strategies is encoded in marine organisms' genetic material. It includes the blueprints for the secondary metabolites which marine fauna, flora, fungi, bacteria, archaea and viruses produce for a variety of purposes – and which often take great effect even in low concentrations.

Chemists and molecular biologists are therefore particularly interested in secondary metabolites. In their studies of marine organisms, they look for and extract these bioactive molecules and substances, describe their chemical structure, investigate their functions and seek to identify potential commercial applications as marine natural products or active ingredients. In doing so, they make use of modern DNA sequencing, replication and chemical analysis techniques, enabling them to undertake rapid and comprehensive analysis of sampled material and digitally store all the genetic information that it contains.

These new technological options have sparked something akin to "gold-rush fever" in the interrelated branches of marine natural product chemistry and marine biotechnology. Experts now assume that every single marine organism may contain genetic information with potential for some form of commercial application in the future. The experts are calling this a "golden age" and project that the global market for chemical and pharmaceutical products derived from marine genetic diversity will reach an estimated USD 6.5 billion by 2025.

Marine natural products and substances are already found in a wide variety of applications. For instance, they are active ingredients in 17 licensed pharmaceuticals and are used in food supplements and fertilizers. They also provide raw materials for cosmetics manufacturing and various other industrial applications. However, their immense potential raises a number of issues that will need to be dealt with soon. The three most important questions are the following: Who should benefit from the ocean's genetic resources? How can these potential active substances and any profits generated from their commercial use benefit humanity as a whole? And finally, with commercial interest increasing, how can marine biodiversity be protected effectively?

Proposed solutions to the issues surrounding the access to and sustainable use of genetic resources from maritime areas under national jurisdiction are set forth in the Nagoya Protocol, an agreement in international law. In practice, however, they are proving difficult to implement, encumbering rather than encouraging research.

Rules governing international waters are currently being developed – at the United Nations level – as part of a new global agreement on the conservation of biodiversity in international waters. The negotiations on this agreement have been ongoing for years, and the current COVID-19 pandemic has further delayed the process. Furthermore, due to technological progress, the need arises for new items to be constantly added to the agenda. What kind of compromise will ultimately be reached by the international community? Will it fuel this "gold-rush fever" – or will it establish tight restrictions in the interests of marine conservation? Only time will tell.

8 Marine management – aspiration and reality

> Humankind has divided the ocean into artificial zones in order to lay sole claim to specific areas and their resources. Species and water masses, however, migrate undisturbed across the borders of these zones, as do heat, pollutants and litter. Successful marine management therefore requires collective solutions, which must be based on transnational, cross-sectoral thinking and aim for the protection and sustainable use of the seas.

A constitution for the seas

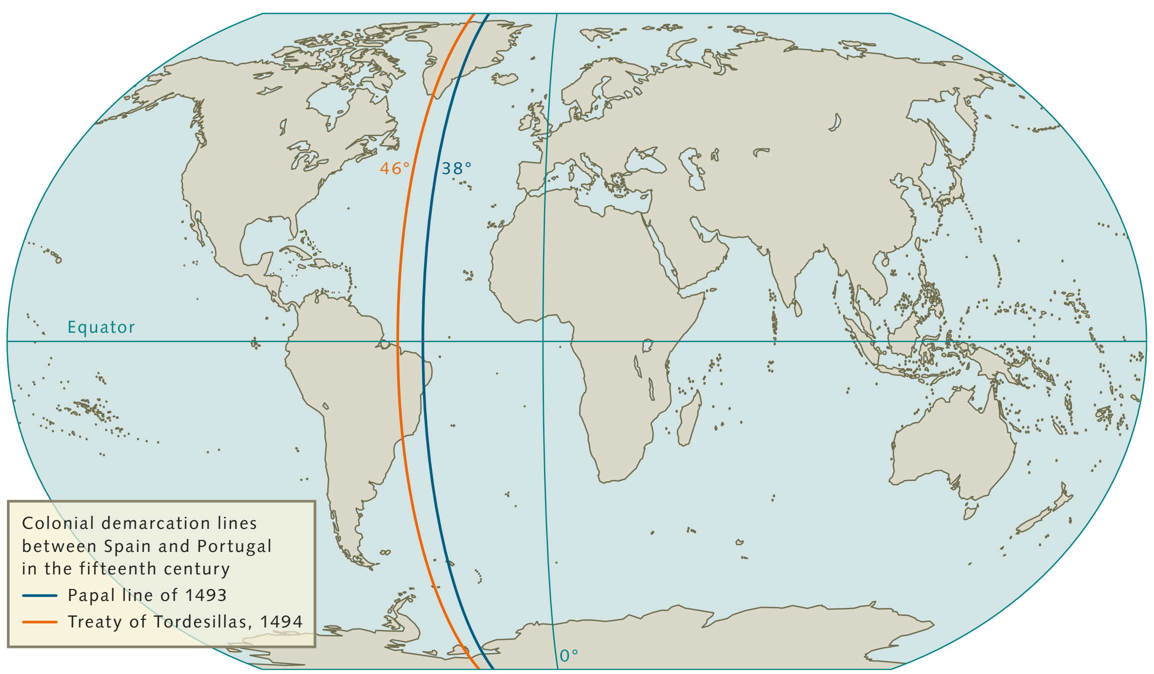
> Who owns the sea? Humans have been asking this question ever since they began to compete with one another over fishing rights or shipping routes. For almost four decades, a legally binding answer has been enshrined in the United Nations Convention on the Law of the Sea. It regulates who has jurisdiction over specific activities in the various maritime zones and obliges all actors to protect the marine environment – with little success so far, in the latter case, due to the failure to fully implement the Convention's provisions.

The origins of the law of the sea

December 2022 will mark 40 years since the international community agreed the United Nations Convention on the Law of the Sea (UNCLOS). The adoption of this major convention governing the use of the oceans is regarded as a historic milestone, for it answers the question of who may lay claim to the sea and its resources and thus establishes the basis for its collective and sustainable management under international law.

Progress towards the Convention was slow and fraught with difficulty, however. The origins of the international law of the sea date back to the time of the Roman Empire. In 529 AD, the Roman Emperor Justinian I decreed that the sea, like the air, was common to all and that no one may lay claim to it; it may thus be used by everyone. This quickly became the universal view; however, attitudes changed in the Middle Ages, when coastal states began to exercise sovereignty over the coastal waters adjacent to their kingdoms or territories. This development culminated in the signing of the Treaty of Tordesillas – a city in northern Spain – by seafaring nations Portugal and Spain on 7 June 1494. With the blessing of Pope Alexander VI, these two countries divided up the world and its oceans between them along a north-to-south meridian, with Spain receiving all the sea areas in the western Atlantic, the Pacific and the Gulf of Mexico and Portugal being granted the eastern and southern Atlantic and the Indian Ocean.

Just 100 years later, the treaty was largely obsolete: the Reformation, initiated by Martin Luther, had split the Church, and Protestant England and the Netherlands were now vying to establish themselves as seafaring nations and colonial powers alongside Catholic Spain and Portugal and were seeking to trade with territories overseas. The Treaty of Tordesillas was an obstacle to their endeavours. It prevented the Netherlands, for example, from sending ships across the Indian Ocean to its colony in the East Indies (now Indonesia). The dispute escalated when the Netherlands captured a vessel from the Portuguese in 1603. In order to provide a measure of post hoc justification for the attack, for which it was responsible, the United East India Company (Vereenigde Oost-Indische Compagnie – VOC) commissioned one of the country's best lawyers to produce a legal appraisal of the incident. The lawyer's name was Hugo Grotius (1583-1645).



8.1 > At the end of the fifteenth century, two maritime powers, Portugal and Spain, wielded such huge influence that Pope Alexander VI shared out the world between them. Territories to the west of the blue line in the Atlantic were awarded to Spain, and those to the east, to Portugal. The demarcation line was adjusted in the Treaty of Tordesillas.

Born in Delft in the Netherlands on 10 April 1583, Hugo Grotius was soon acclaimed as a child prodigy. At the age of 11, he was permitted to enrol at university; upon completing his studies just four years later at the age of 15, he went on to become a lawyer and diplomat. Grotius was happy to accede to the East India Company's request and composed a legal treatise, only one chapter of which would be published during his lifetime. In this treatise, entitled Mare liberum ("the free sea"), Grotius expounded his theory that unlike the land, the sea could be neither occupied nor defended by anyone; every nation should therefore have unrestricted access to the ocean and be free to use it.

A counter-opinion was presented by the English scholar John Selden (1584-1654) in 1635. In two volumes entitled Mare clausum ("the closed sea"), Selden defended the legal right of the English monarchy to dominion over all waters around the British Isles, concluding from this that among other things, this gave England exclusive fishing rights in these waters. On this basis, according to Selden's argument, the English monarchy also had the right to require foreign fishermen to acquire licences and pay taxes in order to fish in English waters. John Selden thus placed the interests of the coastal state above the principle of the "free sea" which everyone could use.

8.2 > The Dutch jurist and diplomat Hugo Grotius argued that the sea was no one's property; all nations should therefore have free access to the ocean.

The concepts of Mare liberum and Mare clausum propounded by Grotius and Selden, respectively, are still in use among experts in the law of the sea to this day: the former when the principle of the "free sea" is at stake, and the latter when national claims to jurisdiction over areas of the sea are at issue. In practice, however, the principle of the "free sea" has applied since the 17th century, albeit limited by the three-mile zone. This concept was developed by the Dutch jurist Cornelis van Bynkershoek (1673-1743), who posited that a state should be able to exercise sovereign jurisdiction over the area of their coastal waters which they could defend with a cannon shot from the land. At that time, the range of a cannon was approxima-

8.3 > The English scholar John Selden took a dispute over fishing rights as an opportunity to proclaim the British monarchy's dominion over all waters around the British Isles. He thus placed the interests of the coastal state above the principle that the seas were free for every nation to use.

tely three nautical miles (equivalent to 5.6 kilometres). Although this three-mile rule was never enshrined in writing, it was accepted by so many states that it soon came to be recognized as customary law.

As the coastal states steadily gained the ability to exercise effective control of the sea far outside the range of a cannon shot, the three-mile breadth of the territorial sea was increasingly called into question. In the first half of the 20th century, ever more states began to extend their claims to jurisdiction. These numerous "go-it-alone" approaches sparked tensions between coastal states and seafaring nations. If the breadth of waters under national jurisdiction were extended, this would create the risk that more than 100 straits and shipping routes of major significance worldwide would fall under exclusively national control – including hotspots of commercial shipping such as the Strait of Gibraltar. Alarmed that a multitude of diverse national rules for the territorial sea would make international shipping, fishing and resource extraction infinitely more complicated, the seafaring nations became fervent champions of freedom of the seas. Other voices entered the debate, calling for nation-states' rights to regulate in the territorial sea to be limited to specific topics: rules to protect the marine environment from pollution caused by shipping accidents, discharges from ships or fuel leaks, for example. Other experts, in turn, argued that coastal states should be permitted to regulate all human activities within their territorial waters.

In order to introduce a measure of agreement and order into this confusion of interests, the United Nations convened three successive international conferences on the law of the sea. The first of these conferences, held in Geneva, Switzerland, in 1958, was attended by 86 states. Together, they adopted four Geneva Conventions, thereby establishing a set of general rules governing the delimitation and exploitation of maritime areas and laying the key foundations for a collectively binding legal regime for the maritime space. The four agreements, known as the Geneva Conventions on the Law of the Sea, covered: (1) the territorial sea and the contiguous zone; (2) the high seas; (3) fishing and conservation of the living resources of the high seas; and (4) the continental shelf.

The second conference took place in 1960, again in Geneva. This time, the objective was to reach agreement on the territorial sea and fishery limits. The negotiations proved inconclusive, however. Among other things, the participating states proved unable, at that time, to reach agreement on the breadth of the territorial sea and thus failed to clarify one of the most pressing issues of the day. In 1973, the United Nations convened a further conference on the law of the sea, this time in New York, in order to consider aspects of marine mining. However, the 160 participating nations seized the opportunity afforded by the meeting to rewrite the rules on the use of the ocean. The process took a full nine years. After 11 sessions and a total of 585 days of deliberations, the international community signed the new constitution for the seas – the United Nations Convention on the Law of the Sea (UNCLOS) – in Montego Bay, Jamaica, on 10 December 1982. The Convention entered into force on 16 November 1994.

A convention like no other

The United Nations Convention on the Law of the Sea (UNCLOS) is perhaps the most complex and comprehensive international treaty ever concluded. It comprises 17 parts with a total of 320 articles, as well as an additional nine annexes containing supplementary provisions. It not only draws together the Geneva Conventions – the "old" law of the sea, which continues to apply – in a single unified treaty. It also divides the sea into various legal zones, regulates the use of these areas, e.g. for shipping, fishing and marine scientific research, includes provisions on seabed mining and the protection of the marine environment, and stipulates how disputes between two or more Parties are to be settled.

Four new institutions were established under the Convention for these and other purposes:

1. the International Tribunal for the Law of the Sea (ITLOS) in Hamburg, Germany; the Tribunal's jurisdiction is limited to legal disputes concerning the interpretation and application of the Convention;

8.4 > The judges at the International Tribunal for the Law of the Sea (ITLOS) in Hamburg rule solely on legal disputes concerning the interpretation and application of the United Nations Convention on the Law of the Sea.

2. the Commission on the Limits of the Continental Shelf (CLCS), which convenes in New York;
3. the International Seabed Authority (ISA) in Kingston, Jamaica;
4. the regular Meetings of State Parties to the Convention.

In addition, two supplementary agreements which deal with implementation currently exist:

- the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (abbreviated to "Deep Seabed Agreement"). This Agreement was adopted on 28 July 1994 and contains detailed provisions on mining in areas beyond national jurisdiction;
- the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (Fish Stocks Agreement). This Agreement was adopted on 4 December 1995 and limits all Parties' freedom of fishing in respect of highly migratory fish stocks and stocks in areas under and beyond national jurisdiction.

A third implementing agreement on the conservation and sustainable use of marine biological diversity in international waters, i.e. marine biodiversity in areas beyond national jurisdiction (BBNJ) is currently being negotiated by the international community. The aim is to establish a binding legal framework which draws together the many existing individual measures on the conservation of biodiversity and ensures the protection and sustainable use of ecosystems in the high seas on a cross-sectoral basis. Responsibility for this topic is currently divided among multiple agencies, including the International Maritime Organization (IMO) and the regional fisheries management organizations (RFMOs). In all cases, however, their jurisdiction is limited. There is also a lack of common guidelines and progress based on effective interinstitutional cooperation at all levels and across sectors. The new implementing agreement is intended to rectify this situation.

The rules and obligations set forth in the United Nations Convention on the Law of the Sea apply first and foremost to the 168 Parties, which include the EU (as at May 2021). However, most of the provisions are also binding on states which have not acceded to the Convention, including the US, as they constitute a body of established customary law which has been recognized and applied by these countries over a period of almost 40 years.

Dividing up the ocean

The United Nations Convention on the Law of the Sea attempts to achieve a balance between the interests of the nation-states and the freedom of the seas and defines various maritime zones and the corresponding extent of certain sovereign rights of the coastal states. These zones are:

- internal waters and the territorial sea,
- the contiguous zone,
- the exclusive economic zone,
- the continental shelf,
- the high seas and the Area.

Internal waters and the territorial sea
Saline waters landward of the baseline or low-water mark are defined as internal waters. The territorial sea, by contrast, is on the seaward side of the baseline and extends for up to 12 nautical miles (one nautical mile is 1852 metres). States have complete sovereignty over their internal waters because – like the territorial sea – they form part of its territory. Nations also have wide-ranging sovereignty over their territorial sea; this includes rights to the airspace, the water column, the seabed and the ground below the seabed. However, a coastal state may not prohibit the innocent passage of foreign ships through its territorial sea.

Passage is considered innocent if, while passing through the territorial sea, the ship in question does not use or threaten violence, does not spy on the coastal state and does not at any time pose a threat to the security of the coastal state in any other way. The United Nations Convention on the Law of the Sea defines potential threats in detail: for example, submarines must surface for the passage and hoist their flag. The Convention also prohibits unlawful discharges and other forms of marine pollution. The coastal state may designate shipping channels that must be used for passage and can levy charges if it provides services that enhance the safety of shipping. However, when designating shipping channels and traffic separation schemes, it must heed the recommendations of the International Maritime Organization (IMO).
Article 37 of the Convention on the Law of the Sea stipulates that the coastal state must grant foreign ships right of transit passage if the territorial sea is part of a strait or waterway that links parts of the high seas or different

8.5 > On 24 October 2014, German Foreign Minister Frank-Walter Steinmeier (right) and his Dutch counterpart Bert Koenders signed the German-Netherlands Treaty on the Use and Management of the Territorial Sea between Three and Twelve Nautical Miles from the Coast (known as the Ems-Dollart Treaty).

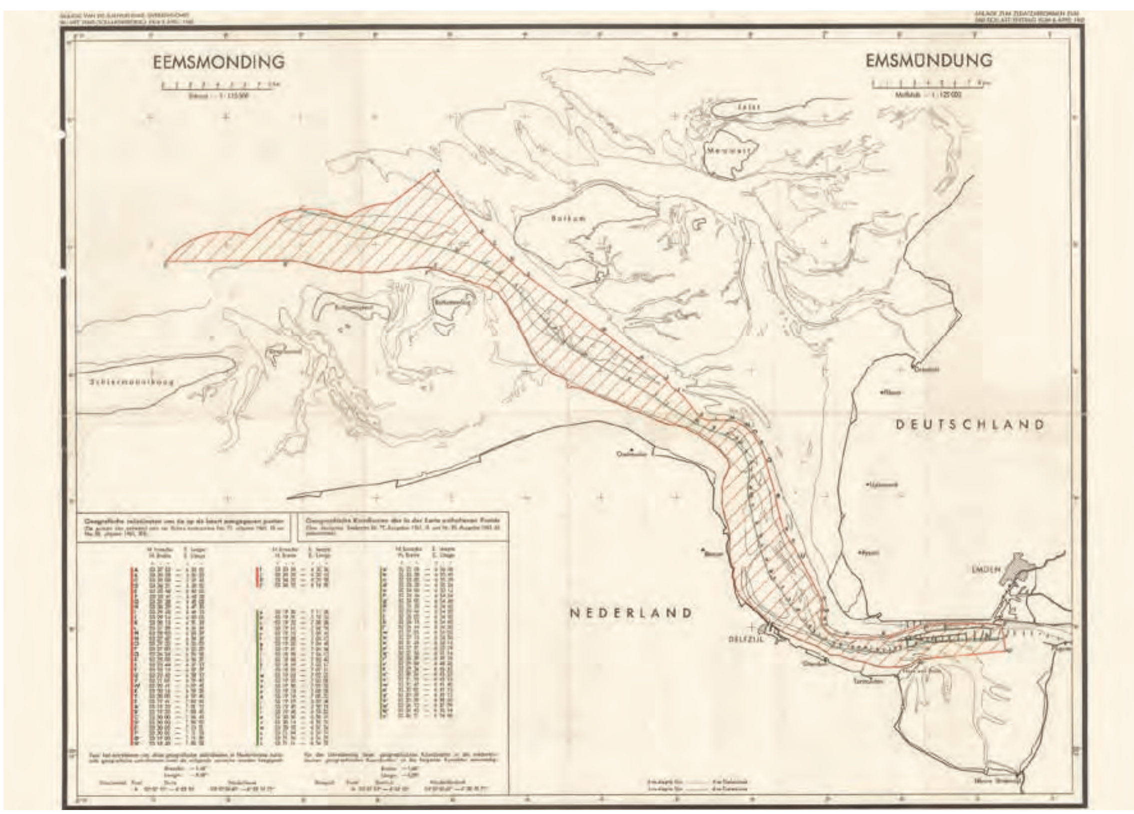
exclusive economic zones with each other and is used by international shipping. Coastal states have less scope for restricting the right of transit passage than for curbing innocent passage: in principle, transiting ships have the same freedom as on the high seas. Transit passage can be suspended or restricted only in the event of the threat or exercise of military force by the ship. Submarines can be submerged while passing through straits.

Defining boundaries in the territorial sea can become a contentious political issue. Germany and the Netherlands, for example, have been wrangling for decades over the precise delineation of the national border in the territorial sea. The two countries did not reach agreement until 2014, when they signed the German-Netherlands Treaty on the Use and Management of the Territorial Sea between Three and Twelve Nautical Miles from the Coast (known as the Ems-Dollart Treaty). Under its provisions, the two states maintain their divergent legal standpoints regarding the delineation of the national border in the territorial sea, but agreed a joint system for the management of maritime traffic in the navigation channel to and from their ports along the Ems.

Furthermore, under the terms of the Treaty, the Westerems Commission was established as a permanent commission to deal with shipping matters in the navigation channel, including decision-making on the precise route of the channel. With regard to non-living natural resources and the construction of installations, e.g. for renewable energy generation, the two parties reached agreement on a demarcation line to assist in determining which system of national law is applicable. The Netherlands has jurisdiction on the western side, while Germany has jurisdiction on the eastern side of the line.

The contiguous zone and exclusive economic zone

The contiguous zone adjoins the territorial sea, extending a maximum of 24 nautical miles beyond the low-water line. In this zone, coastal states may exercise certain



8.6 > The dispute between Germany and the Netherlands in the territorial sea stems from their divergent views regarding the delineation of the national border in the Ems estuary. While the Netherlands draws the border along the deepest points in the river, Germany refers to a letter of feoffment dating back to 1464, which places the border along the western low-water line of the Ems. As a pragmatic solution, in operation since 1960, the two countries have agreed an area of shared use in the territorial sea up to three nautical miles (and up to 12 nautical miles since 2014) with a clear midline (since 1962); the treaty between the two countries defines their respective responsibilities in relation to various management issues.

powers of inspection and, for example, enforce customs regulations vis-à-vis third countries. Beyond the contiguous zone is the exclusive economic zone (EEZ), which can extend up to 200 nautical miles from the low-water line. This zone does not form part of the coastal state's sovereign territory. However, the coastal state has exclusive rights to fish in this area, to extract resources, to engage in marine mining and to approve, erect and operate artificial islands and installations such as oil drilling platforms and offshore wind farms. In this zone, the coastal state also has jurisdiction over marine conservation and marine research. This means that foreign states must obtain the consent of the coastal state if they wish to conduct scientific studies in the exclusive economic zone. However, the Convention makes it clear that a coastal state may not assert any territorial claims to any part of the exclusive economic zone; in other words, it may not seek to incorporate the EEZ into its national territory. Third countries have freedom of navigation in this area and may also lay submarine cables and pipelines here. When doing so, however, they must take account of existing structures.

The continental shelf

The United Nations Convention on the Law of the Sea sets out special rules on the continental shelf, which in large part lies below the exclusive economic zone, but is regarded as a separate marine zone. A coastal state has exclusive rights within the entire continental shelf area provided that it lies within the 200-nautical-mile limit. Under the law of the sea, every coastal state is entitled to a continental shelf of up to 200 nautical miles, even if in geological terms the shelf is narrower than this. If the geological continental shelf extends beyond this 200-nautical-mile limit – which is the case with an estimated 85 coastal states – the coastal state may, under Article 76 of the Convention on the Law of the Sea, extend the outer limit of the shelf.

To do so it must make a submission to the Commission on the Limits of the Continental Shelf (CLCS), setting out the scientific data that show that the relevant part of the seabed and subsoil thereof constitute a natural prolongation of its continental margin. As a result of this requirement, the continental margins are now some of the most comprehensively surveyed areas of the sea, with detailed data available on the topography and geology of the sea floor here. Elsewhere, particularly in the deep sea zones, there are still many large areas of white on the maps of the seafloor. By June 2021, just 20.6 per cent of the global seafloor had been mapped.

The extended continental shelf is an area of jurisdiction in which only the coastal state has the right to explore and exploit the natural resources of the seabed. The coastal state is, however, required to pay royalties from the profits generated by marine mining in these areas to the International Seabed Authority. Freedom of fishing and freedom of maritime navigation apply in the waters above the extended continental shelf.

However, there are legal limits to the extension of the continental shelf: the new outer limit of the continental shelf must not be more than 350 nautical miles from the coastal state's baseline or more than 100 nautical miles from the 2500-metre isobath. A combination of the two methods is permitted.

In the Arctic, where the coastal states have been making overlapping territorial claims for decades, the delimitation of boundaries is complicated by the fact that three underwater ridges – the Lomonosov Ridge, the Gakkel Ridge and the Alpha-Mendeleev Ridge – run along the floor of the Arctic Ocean. A special provision in the Convention on the Law of the Sea therefore applies: Article 76 of the Convention distinguishes between submarine ridges and submarine elevations.

Depending on whether a ridge or an elevation is joined to a coastal state's continental shelf, different rules apply. If parts of the continental shelf run over a submarine ridge, only the 350-nautical-mile rule can be applied; the rule on the 2500-metre isobath cannot be invoked. However, if the continental shelf extends over a submarine elevation, both rules apply, since it is assumed that the submarine elevation will generally consist of the same material as the continental shelf. Submarine ridges, by contrast, usually consist of volcanic rock and are therefore of a different material from the continental shelf.

Baseline
The baseline is normally the low-water mark – in other words, the lowest point reached by the sea at low tide – as marked on officially recognized nautical charts. However, as a standard nautical chart zero does not exist at the international level and the position and course of all low-water marks have never been formally established, the data used by coastal states to plot the baseline vary considerably. In the case of estuaries, islands along the coast or deeply indented or highly unstable coastlines, baselines may be plotted using natural points along the furthest seaward extent of the low-water line (promontories, fringes of islands, etc.).

8.7 > A Somali pirate by the wreck of a Taiwanese fishing boat which he and several other men have hijacked. Suspected piracy and human trafficking are two of the few circumstances in which the United Nations Convention on the Law of the Sea (UNCLOS) permits the use of force on the high seas.

These complex rules in the Convention on the Law of the Sea hamper the work of the Commission on the Limits of the Continental Shelf. The Commission considers all submitted applications and makes a recommendation. If the coastal state adjusts the outer limit of its extended economic zone in accordance with the recommendation, this outer limit is final and binding. What is not clear is what happens if a coastal state opposes the Commission's recommendation and sets an outer limit that is not in accordance with the recommendation. The Commission is not a body with judicial powers: its purpose is only to ensure that the delimitation of boundaries complies with scientific standards.

As the Commission is chronically underfunded, it generally takes several years, and in some cases several decades, to consider an application and reach a decision. Moreover, the Commission is not responsible for situations in which two coastal states with opposing or adjacent coastlines argue over the precise boundary of their continental shelves or over overlapping areas to which they lay claim. In such cases, the Convention on the Law of the Sea requires the countries involved to conclude one or more boundary agreements. In other words, the states concerned have to sort out these disputes among themselves. If this were to fail, the dispute could be settled by an international court such as the International Court of Justice or the International Tribunal for the Law of the Sea – provided that the countries involved recognize its jurisdiction.

In the Arctic, the willingness of the coastal states to negotiate and compromise has in the past enabled many disputes over boundaries and territories to be resolved. In September 2010, for example, Norway and Russia signed a cooperation agreement that put an end to four decades of argument over the boundary of their adjacent economic zones and continental shelves in the mineral- and resource-rich Barents Sea. The boundary that has been agreed gives equal weight to the claims of both countries.

The two parties also agreed that any new, as yet undiscovered resource deposits that straddle the boundary would be exploited jointly.

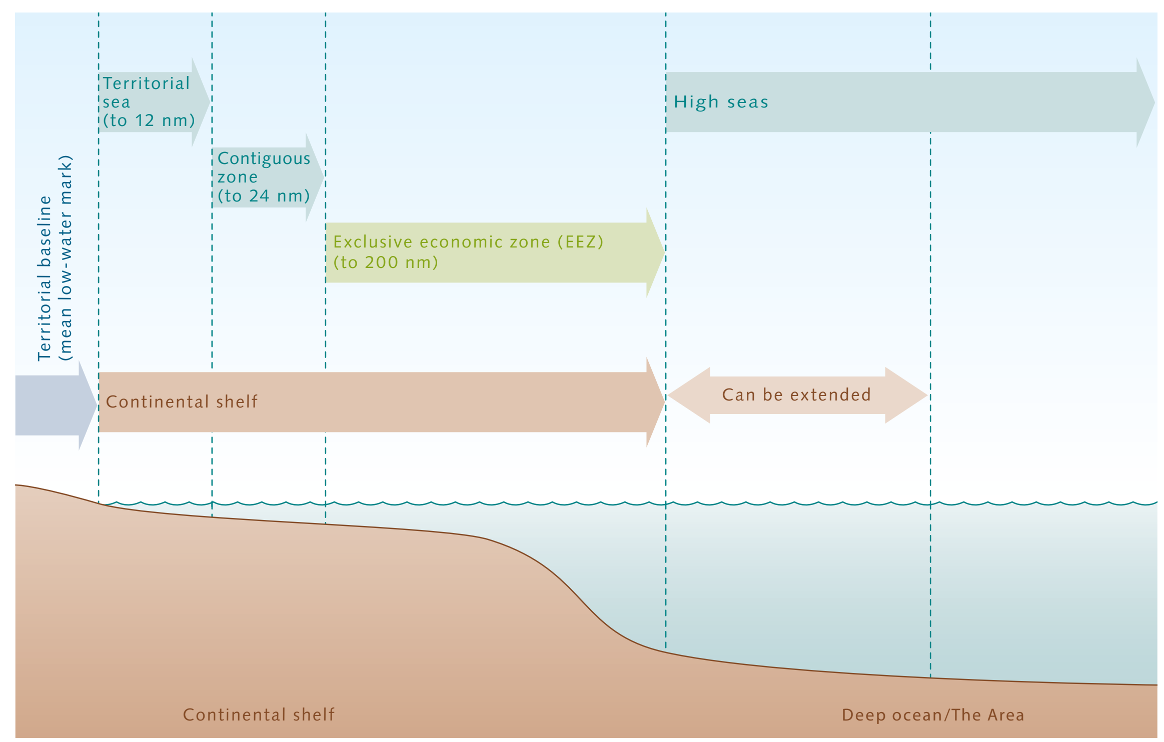
The delimitation of the continental shelf in the North Sea was also a subject of dispute for many years. Here, the European continental shelf is almost entirely covered by the sea. The International Court of Justice therefore instructed the parties to the dispute to agree a workable solution which ensured that each party would be granted all parts of the continental shelf that constituted a natural prolongation of its land territory in or under the sea, insofar as this was possible without detriment to the natural continuation of the land territory of another party. In 1972, the Federal Republic of Germany concluded an agreement with Denmark, the United Kingdom and the Netherlands on the delimitation on the continental shelf.

The high seas

The high seas commence at the outer limit of the exclusive economic zone. The term "high seas" applies to the entire water column but does not include the seabed. Experts in international law describe the high seas as "global commons", for they are open for use by all states on an equal basis. No state may claim sovereign rights over, or appropriate, any part of the high seas.

Within the limits of the high seas, all states have the freedom of the high seas: among other things, this means that ships have free passage and aircraft have the right to overfly. In addition, anyone can fish or conduct research in these areas, although certain aspects of freedom of fishing are now regulated in more detail by numerous international treaties and also by the Fish Stocks Agreement.

In accordance with the Convention, all human activities on the high seas must be peaceful in nature. However, all states have a duty to repress piracy and human trafficking. Furthermore, with the exception of marine distress signals, all ships are prohibited from engaging in unauthorized broadcasting, defined as the transmission of sound radio or television broadcasts, on the high seas intended for reception by the general public. Warships may not seize any other vessel unless there are grounds to



8.8 > The United Nations Convention on the Law of the Sea (UNCLOS) divides the sea into various legal zones, with the state's sovereignty decreasing with increasing distance from the baseline. See table overleaf.

	Maritime zone	**Extent of coastal state's jurisdiction**	**Rights of third countries / Freedom of the seas**
Part of the national territory	**Internal waters** Waters between dry land and the baseline of a coastal state.	• Subject to the coastal state's complete territorial jurisdiction; • No right of innocent passage; • A ship entering another state's internal waters falls within the territorial jurisdiction of the coastal or port state; • A state may reserve rights of fishing and cabotage (the operation of passenger and goods transport services between inland ports) for its own nationals.	
	The territorial sea Breadth up to 12 nautical miles on the seaward side of the baseline or low-water mark.	• The coastal state has sovereign rights to the airspace, the water column, the seabed and the ground below the seabed; • The coastal state defines environmental provisions, may provide for the safety of shipping and may designate shipping channels; • The coastal state has certain limited rights of intervention in respect of shipping and may levy charges for providing certain services (e.g. towage).	Right of innocent passage, including for warships on peaceful missions; submarines must surface for the passage and hoist their flag.
Zones that are not part of the national territory (i.e. zones of coastal state functional jurisdiction)	**The contiguous zone** Breadth may not exceed 12 nautical miles; outer limit may not extend more than 24 nautical miles from the baseline; zone does not include the airspace.	• The coastal state is granted rights of inspection, precedence or monopoly status vis-à-vis other states and their nationals, but only for a specific segment of jurisdiction; • The coastal state has rights of inspection necessary to prevent and prosecute violations of the financial, immigration or health regulations applicable on its national territory.	
	Exclusive economic zone (EEZ) Breadth up to 200 nautical miles from the baseline; zone does not include the airspace.	• The coastal state has certain exclusive rights and sovereign powers; • The coastal state has sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living; almost all economically relevant activities are reserved for the coastal state, including fishing, wind power generation, resource extraction, mining; • Right to conduct maritime spatial planning; • Duty to conserve fish stocks living in the EEZ and to take measures against illegal fishing.	Rights of third countries: • freedom of navigation, • freedom of overflight, • freedom to lay submarine cables and pipelines, and • other internationally lawful uses of the sea related to these freedoms.
	Continental shelf comprises the seabed that extends throughout the natural prolongation of the land territory to the outer edge of the continental margin; the extended continental shelf must not be more than 350 nautical miles from the baseline or more than 100 nautical miles from the 2500-metre isobath.	• The coastal state exercises sovereign rights over the continental shelf for the purpose of exploring it and exploiting its natural resources (monopoly of exploration and exploitation); however, the right to prohibit marine scientific research on the extended continental shelf (beyond 200 nautical miles) is limited; • A coastal state is required to make payments in respect of the exploitation of the resources of the extended continental shelf beyond the 200-mile limit; a developing state which is a net importer of a mineral resource produced from its continental shelf is exempt from making such payments; • The coastal state has the exclusive right to authorize and regulate drilling on the continental shelf for all purposes and to establish artificial islands, installations and structures (e.g. wind farms).	Waters above the extended continental shelf form part of the high seas. Rights of third countries: • Freedom of fishing, • Scientific research in the water column, • Navigation, • Overflight, • Laying of submarine cables and pipelines, and • other internationally lawful uses of the sea related to these freedoms.
Zones that are not part of the national territory (i.e. zones of coastal state functional jurisdiction)	**High seas** Directly adjacent to the EEZ; comprises the water column but not the seabed.	• No exclusive rights of use; • No state may claim sovereignty over the high seas or parts thereof; • Consideration is imperative: all states must contribute to the conservation of the living resources of the high seas; • The threat and use of force are prohibited on the high seas, which are reserved for peaceful purposes; • Ships on the high seas are subject to the jurisdiction of their flag state; • On the high seas, any state may take measures against ships that are engaged in piracy or slavery or misuse their flag.	• Prohibition of appropriation: no one may lay claim to the high seas; • Freedom of use for all interested parties on an equal basis, with due regard for the interests of other states and the activities conducted within the framework of seabed mining far from the coasts; • Freedom of navigation (may be restricted by rules adopted by regional fisheries management organizations); in situations of competition, the first comer has right of access; • Freedom of overflight, freedom to lay cables and pipelines; • Freedom to construct artificial islands.
	The Area The seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction, which have been declared part of the common heritage of mankind.	• Prohibition of appropriation: No state may claim or exercise sovereignty or sovereign rights over the Area or parts thereof.	• No unauthorized use of the Area and its mineral resources; permission is required for all activities (except for prospecting for mineral resources); • Exploration, use and exploitation of, and revenue from, this Area beyond national jurisdiction and its resources should benefit everyone, including non-industrialized countries and future generations; activities in the Area should therefore be conducted in a manner which protects the environment, resources and markets; • ISA to safeguard compliance with all legal requirements.

suspect piracy, human trafficking (slavery) or other offences subject to penalties under the Convention.

The Convention also establishes a duty of states to cooperate on the conservation and management of the living resources of the high seas, including, in particular, fish, marine mammals and seabirds. Decisions on species conservation and the management of resources should be taken on the basis of the best scientific evidence, the prerequisite being that this evidence is available to all states concerned.

The Parties' compliance with these and other marine conservation provisions set forth in the Convention is inadequate, however. It was therefore recognized some time ago that the principle of freedom of the high seas was not sufficient to hold Parties to account and ensure that they made adequate provision to protect the marine environment in international waters. In 2015, the United Nations General Assembly therefore voted to commence negotiations on a third implementing agreement, mentioned above, on the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction (BBNJ agreement), thus restricting the scope and freedom of the nation-states. This presupposes, of course, that the agreement is ultimately adopted and ratified by the member states.

The Area

The United Nations Convention on the Law of the Sea (UNCLOS) defines the "Area" as the seabed and ocean floor and subsoil thereof, beyond the limits of the continental shelf, as well as all the non-living resources contained therein. It is made clear that this definition does not include the water column or the air space above these waters. The Area and its mineral resources have been declared part of the common heritage of mankind and may be used solely for peaceful and beneficial purposes. Unlike the situation with the high seas, however, such use requires authorization, for which an application must be submitted to the International Seabed Authority, which oversees all human activity within the Area. All states have equal rights of access and benefit-sharing in respect of the Area and its resources. It is also important to note that states are liable for all activities undertaken by their nationals within the Area.

Balancing interests – an ongoing process

On the face of it, the division of the ocean into the zones defined in the United Nations Convention on the Law of the Sea provides the clarity sought by all stakeholders. A closer look, however, reveals that as a result of the human demarcation of these artificial zones, a specific area of the sea may be subject to several different legal regimes, depending on the type of use. In the waters of the exclusive economic zone, for example, the coastal state has exclusive usage rights where fishing and the construction of wind energy installations are concerned. However, in this same maritime zone, the freedom of the high seas applies when topics such as sea rescues or anti-piracy measures are the main focus of interest.

The situation is complicated by the fact that nature itself pays no heed to these artificial boundaries: shoals of fish, for example, migrate freely between the zones. In some cases, this may mean that a multitude of agencies is responsible for the sustainable management of one and the same stock, whose survival can only be guaranteed if all these agencies work together. On the other hand this example shows that when it comes to the sustainable use of marine resources, the interests of the coastal states must constantly be weighed in the balance against the freedom of the seas. And decision-making is rarely straightforward, least of all when stress factors such as climate change impacts, pollution, noise, coastal development and resource extraction likewise make themselves felt across every inter-zonal boundary.

Regional seas conventions

The United Nations Convention on the Law of the Sea includes special provisions on inland seas (enclosed seas) and semi-enclosed seas. A number of highly significant stretches of water, including the Black Sea, the North Sea, the Baltic Sea, the Mediterranean, the Persian Gulf and the Gulf of Mexico, fall into this category. The Convention

8.9 > The United Nations Convention on the Law of the Sea (UNCLOS) includes special provisions on inland seas such as the Mediterranean: it obliges all the coastal states to cooperate on issues such as the protection of the marine environment, fishing, scientific research and relations with other states and international organizations.

requires the coastal states to cooperate in a number of thematic areas, with shared responsibility for fisheries management, the protection of the marine environment and scientific research in their respective waters; it also calls for their collaboration with other states and international organizations.

One example of this type of regional cooperation in the European context is the Helsinki Commission (HELCOM), a framework in which all nine Baltic Sea states and the European Union work together to develop strategies to protect the Baltic Sea. Core topics include the conservation of biodiversity, fisheries and shipping, pollutant discharges and eutrophication of the sea by riverine inputs or airborne deposition. The representatives of all the Baltic Sea states collaborate in five permanent working groups and in a multitude of expert groups and projects, and develop recommendations and strategies with the aim of restoring the ecological balance in the Baltic Sea. These recommendations and strategies are not legally binding, however: implementation is a matter for the Contracting Parties.

Regional seas conventions and action plans now exist in at least 18 sea areas worldwide. They are regarded as one of the key instruments in international marine management, often also known as "ocean governance". The major advantage of regional conventions is that nations are often more willing to agree joint objectives and activities, and hence to cede some of their rights, at the regional level than in the much larger international arena. Furthermore, regional conventions allow the parties to make area-specific arrangements, which often offer far greater prospects of success than would be the case with more general international rules.

Rethinking coastal zone management

Regional seas conventions and action plans provide participating coastal states with a common framework and make it easier for them to develop and implement their own integrated management programmes for coastal areas and the territorial sea. The term "integrated coastal zone management" denotes a regulatory and governance approach in which coastal areas are recognized as a complex, dynamic system involving multiple interactions between human communities and marine and coastal ecosystems across zonal and sectoral boundaries. This means – according to one of the key principles of the integrated approach – that coastal issues can no longer be addressed solely within the parameters of the traditional sectors: their spheres of competence overlap far too often for that. Furthermore, stakeholders in the fisheries, tourism, energy, shipping, resource extraction and environmental sectors may well pursue competing or even conflicting interests; the resulting measures are almost always detrimental to the marine environment.

For that reason, integrated marine management aims to develop inter-zonal, cross-sectoral guidelines for sustainable use of the ocean and its resources. At present, this approach is mainly applied in regional action plans, e.g. in the European Union, where the European Commission has developed an Integrated Maritime Policy covering five major and converging policy fields: the blue economy, marine data and knowledge, maritime spatial planning, integrated maritime surveillance, and sea basin strategies. However, regional seas conventions are by no means a prerequisite for successful integrated coastal zone management. With good planning and implementation, coastal states can improve their coastal zone management and ocean governance with integrated approaches even if they act on their own.

Due to the division of the sea into separate zones under the United Nations Convention on the Law of the Sea and the multiple spheres of competence, however, even integrated marine management quickly reaches its limits. Experts note that one reason is the ever-increasing number of stakeholders and agencies involved. This system may still be relatively straightforward at the local level, but decision-making becomes ever more complex, cumbersome and ineffective with each successive tier (regional, national, transregional, international). A further obstacle, the experts say, is the lack of information-sharing between the numerous participating sectors and institutions, as well as a general lack of awareness of how measures or changes in one sector impact on all the others.

	Convention	Year adopted	Year entered into force	No. of States
UNEP Administered				
1. Mediterranean	Barcelona	1976/1995	1978/2004	22
2. Western and Central Africa	Abidjan	1981	1984	22
3. Wider Caribbean	Cartagena	1983	1986	28
4. Eastern Africa	Nairobi	1985	1996	10
5. East Asian Seas	None	1984 (Revised in 1993)	Action plan in force	9
6. North-West Pacific	None	1994	Action plan in force	4
7. Caspian Sea	Tehran	2003	2006	5
Non-UNEP Administered				
8. Regional Organisation for the Protection of the Marine Environment (ROPME)	Kuwait	1978	1979	8
9. South-East Pacific	Lima	1981	1986	4
10. Red Sea and Gulf of Aden	Jeddah	1982	1985	8
11. Pacific	Noumea	1986	1990	19
12. Black Sea	Bucharest	1992	1994	6
13. South Asian Seas	None	1995	Action plan in force	5
14. North-East Pacific	Antigua	2002	2010	8
Independent Regional Seas Programmes				
15. Baltic Sea	Helsinki	1974/1992	1980/2000	10
16. North East Atlantic	Oslo-Paris (OSPAR)	1974/78/92	1998	16
17. Antarctic	Antarctic Treaty/Commission for the Conservation of Antarctic Living Resources	1959/1980	1961/1982	32
18. Arctic	Arctic Council Protection of the Arctic Marine Environment Working Group			8

8.10 > Regional seas conventions are regarded as the jewel in the crown of environmental diplomacy as they facilitate regional cooperation and actions which would be almost impossible to implement at the international level. They are therefore one of the most important tools in the United Nations Environment Programme (UNEP) toolkit. The table above lists 18 regional seas conventions and action plans currently involving more than 146 nations.

New approaches to marine management

> Despite clear stipulations laid down in the international law of the sea, there is a gap between the aspirations and realities of marine management. There are many reasons for this. They include a lack of money, knowledge and political will to implement applicable law; rigid structures and overlapping responsibilities hinder effective action. We must break out of these limitations – with the help of new actors and networks and by means of goal-oriented cooperation across levels, sectors and national borders.

Ocean Panel
The Ocean Panel is a joint initiative of 14 coastal nations that was launched in September 2018 with the aim of developing pragmatic solutions for a sustainable marine economy. To this end, the initiative works with representatives from politics, science, business and civil society. Members are Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal.

An obvious contradiction

In essence, the United Nations Convention on the Law of the Sea (UNCLOS) places an obligation on the parties to cooperate at the regional, national, supra-regional and global levels and to effectively protect the marine environment in this way. As stated in the provisions, all measures and concepts applied to this end must be integrative in their substance and preventive and precautionary in their effects. But why then, one might ask, are the world's oceans in such a bad state? Why is there such a wide gulf between the ambition and reality of the international law of the sea and marine management?

The answers given to this question vary greatly. They range from pointing out the lack of implementation of many existing agreements to calling for a radical transformation of marine management. For example, the authors of the United Nations *Second World Ocean Assessment* argue that the ocean and its resources can only be protected and used sustainably if UNCLOS and its many complementary legal instruments are actually implemented worldwide. Among these complementary legal instruments, the authors include:

- *International treaties:* These include international agreements on sustainable fisheries management, on protection against pollution from ships, on the protection of certain marine habitats, and on the protection of crews, fishers and other workers in the marine sector;
- *Regional treaties:* This category includes the regional fisheries agreements as well as the regional marine conventions and programmes of action;
- *Soft law instruments:* The term "soft law" covers agreements, guidelines, resolutions or declarations of intent which, unlike "hard law", are not legally binding and compliance with which cannot be enforced in the courts. Nevertheless, they are frequently used at the international level and nations pay great attention to them, primarily because soft law regulations often serve as precursors for later hard law regulations in the form of treaties or agreements. In the area of marine management they include, for example, the various fisheries guidelines of the Food and Agriculture Organization (FAO) and the guidelines for marine spatial planning issued by the UNESCO Intergovernmental Oceanographic Commission (IOC). Also relevant are the Rio Declaration on Environment and Development as well as the 2030 Agenda and its 17 Sustainable Development Goals (SDGs) – in particular SDG 14, with which the community of nations commits to the conservation and sustainable use of the oceans, seas and marine resources.

The UN experts state that the implementation of this multitude of laws, guidelines and requirements constitutes a great challenge for all nations. The number of international conventions of significance for the sea now amounts to more than 100.

Especially the small island states and the world's economically weakest countries lack the expertise, financial resources and qualified personnel and the necessary institutions or authorities to implement effective marine management measures, the scientists say. The authors also emphasize that successful marine management begins on land. All terrestrial activities must be managed in such a way that the sea and its biotic communities ultimately bene-fit instead of being primarily harmed, as has been the case so far.

8.11 > Baye Cheikh Mbaye from Senegal labels sample bottles in the wet lab during an expedition on the German research vessel *Heincke*. At just under 55 metres, it is the second largest ship in the fleet of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI).

According to the UN experts, there are also numerous issues that are only partially covered by existing legal instruments – regulations on dealing with marine litter or fisheries management for example. Many areas need to be reworked. Another complicating factor is that even in relatively well-regulated and controlled areas, private-sector actors often find loopholes that give them financial advantages, but ultimately come at the expense of people and the marine environment.

A recent example of such a loophole can be found in shipping. New research shows that ship-owners in industrialized countries such as Japan, South Korea, the USA and European Union member states are increasingly choosing "flags of convenience", i.e. they are registering the ships in a foreign country in order to be able to scrap them cheaply at the end of their service life in countries with weak occupational health and safety standards and environmental regulations. Data from 2014 to 2018 show that 80 per cent of all retired ships were dismantled in ship graveyards or demolition yards in Bangladesh, India and Pakistan. All three countries are known for frequently scrapping ships right on the beaches, releasing large amounts of asbestos, oil and toxic chemicals into the environment in the process. Moreover, local employers and authorities pay scant attention to occupational health and safety conditions or compliance with environmental regulations during the dismantling of ships.

The option of registering ships in foreign countries was mainly used by ship-owners in EU countries: between 2002 and 2019 the proportion of ships that sailed under the flag of a developing country, even though their owners were EU citizens, increased from 46 to 96 per cent. This increase is also due to stricter rules on ship disposal that have been in force in the European Union since 31 December 2018. According to these rules, ships flying the flag of an EU member state must

8.12 > The Chittagong ship graveyard in Bangladesh is one of the many places where disused cargo ships, tankers and container ships are scrapped directly on the beach. Asbestos, oil, toxic chemicals and other substances are released into the environment in the process. The pollutants also affect the health of the approximately 20,000 workers at the ship-breaking yard.

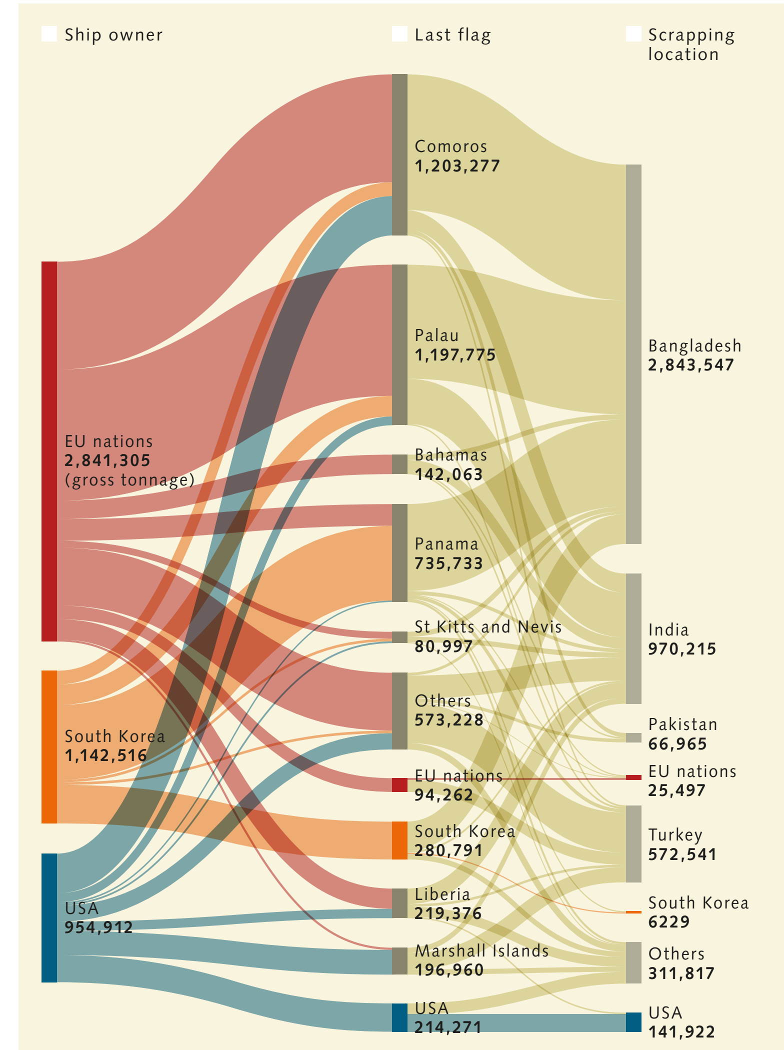
ultimately be dismantled and recycled at a dismantling facility that is on a list of approved facilities and thus demonstrably meets a number of safety and environmental standards. The standards required in the EU go beyond those set by the International Maritime Organization in its controversial Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships. Before this convention was signed in 2009, more than 100 environmental and human rights organizations as well as trade unions and representatives of numerous other institutions had jointly protested against the inadequate IMO minimum standards and called for improvements.

A fundamental transformation is needed

In view of these and many other discrepancies between the aspirations and realities of ocean governance, the approaches put forward by a growing number of experts go far beyond the United Nations' stance. They are calling not only for clear implementation of existing agreements, laws and guidelines, but also for a fundamental reform of marine management. These experts include, for example, members of the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services as well as a group of researchers who, on behalf of the Ocean Panel, developed strategies for a radical reorganization of marine management.

They state unanimously that the oceans' current situation demands a fundamental rethink, or in other words: a new relationship between humanity and nature and especially the ocean, guided by the awareness that the ocean is the common heritage of all, that it should not serve individual gain and only be utilized within its ecosystems' capacity to perform without coming to harm. All human activities should therefore primarily aim at the recovery and revitalization of marine ecosystems and not at their exploitation. At the same time, flexible and effective marine management processes must be identified that guarantee the protection and sustainable use of the oceans. This is the only way to prevent the imminent collapse of the ocean's biotic communities and thus its key functions for economies and societies.

To describe the scope of transformation that is called for, the Ocean Panel experts draw on examples from human history. In their opinion, the necessary societal change is roughly comparable to the fundamental changes that led to hunter-gatherers becoming sedentary farmers about 12,000 years ago, or to the upheaval in which Europe's peasant-based Renaissance and Reformation period (1450 to 1750) societies mastered the leap into the industrial age. In other words, to meet the objective of sustainable use of the sea, all aspects of our modern lives



8.13 > A study shows that the majority of ships scrapped in 2019 belonged to owners from the European Union, South Korea and the USA. However, the owners ultimately had the ageing ships registered under "flags of convenience", allowing them to be disposed of in countries with lax environmental regulations.

8.14 > The Great Blue Hole forms the entrance to an undersea cave system and is a major tourist attraction in the part of the Mesoamerican Reef administered by Belize. The country's integrated coastal management plan is considered exemplary. It banks on healthy, robust coastal ecosystems being of much greater benefit to humans than exploited and degraded ones.

must change fundamentally. There must be a rethink on almost everything, and almost everything must be redesigned with a view to sustainability. Humankind should regard nature's carrying capacities as a red line that is not to be crossed.

According to the scientists, the failure of the current marine management system is due to the fact that, firstly, the tasks are distributed among too many independently acting sectors and institutions. Secondly, there are no instruments or incentives for a jointly coordinated approach, although the Convention on the Law of the Sea does in fact provide the requisite framework. A content analysis of more than 500 international conventions on environmental protection and human activities in the world's oceans proved revealing in this regard. The findings showed that global agreements largely make reference only to individual marine sectors, such as fisheries, pollution, resource extraction or shipping. Only rarely do they cover two or more sectors. In contrast, regional agreements usually cover several such sectors. However, they too tend to mention only in passing cross-cutting issues such as the strengthening of marine biocoenoses.

A similar picture emerges when looking at the most important institutions in global and national marine management. These are also predominantly assigned to individual sectors and rarely have cross-border jurisdiction. They include institutions that:

- govern land use in coastal, rural or urban areas,
- manage inland waters and monitor their use,
- manage the use of natural resources (such as agriculture, forestry, mining, fisheries),
- are responsible for environmental protection,
- are tasked with promoting development (economy, energy sector, transport), or
- oversee and regulate human activities at sea.

The scientists find that there is an insufficient degree of cooperation between all these institutions. Moreover, climate change, technological change and the demands of a growing global population are exacerbating man-made pressure on the oceans. This makes the failure of current marine management all the more obvious, they note.

Ideas for new marine management

According to the experts, the search for ways out of this crisis should be learning-driven and knowledge-based. Research has shown that ecosystems on land, in rivers, and in freshwater or marine estuaries are closely interconnected and that none of the three global crises (climate change, species loss, pollution) can be solved on its own. Sustainable marine use therefore calls for a holistic approach to marine management. However, this requires a much greater willingness to cooperate on the part of all actors – from local through to international levels. It also requires a greater sense of responsibility, clear liability rules in the event of violations, transparent decision-making processes and new participatory procedures to ensure that conflicts over use are resolved and that all stakeholders benefit fairly from the resources and services provided by the sea, especially those outside of national territorial waters.

The experts have particular hopes for "niche solutions" that are devised and tested at a small or local scale, prove their worth and are then moved out into the world as best-practice examples and widely applied. For example, a cross-sectoral integrated coastal management plan adopted in Belize in 2016 has global appeal and serves as a role model. Its development was initiated by a newly created ministry that places under one roof the areas of agriculture, fisheries, forestry, environmental protection and sustainable development.

In the process of developing the new plan, the government sought advice from experts in integrated coastal planning. It also organized a co-creation process in which all stakeholders affected by coastal planning were able to participate. Ministries as well as non-governmental organizations, businesses and representatives of local communities participated in the process. The new management plan aims at more effectively protecting the coasts from storm damage and rising sea levels, increasing profits from fishing and tourism, and at strengthening protection for mangroves, coral reefs and *Zostera* beds, thus safeguarding the livelihoods of a large part of the coastal population.

The plan also highlights the need to coordinate and fund a wide range of different actors and measures for successful implementation – from coastal pollution, bottom-net fisheries, pelagic fisheries and aquaculture to tourism development, education, climate change adaptation and the preservation of cultural heritage. Moreover, the new management plan led to the Belize government banning oil exploration at the world's second largest coral reef, the Mesoamerican Barrier Reef. UNESCO praised the coastal management plan as one of the most progressive in the world and considered the country's great coral reef to be so well protected now that it removed the reef from the List of World Heritage in Danger.

Great progress in marine protection can also be achieved by eliminating subsidies. Without them, many deep-sea fisheries would be loss-making enterprises. Moreover, fertilizer-intensive forms of agricultural cropping are also subsidized, resulting in the eutrophication of rivers and coastal waters. And looking further, subsidized coastal reconfiguration, forest clearing and the sealing of soil surfaces ultimately harm the sea. They limit the ability of natural landscapes to remove carbon dioxide from the atmosphere, and thus drive climate change. They also destroy habitats important for species diversity and minimize their functional diversity, on which the oceans in turn depend in direct and indirect ways.

The first signs of an awareness shift in politics and business can be found in the increasing willingness of nations and companies to work towards self-imposed environmental and climate targets. The most prominent example of such voluntary commitments are the Nationally Determined Contributions (NDCs) to which the signatories to the Paris Climate Agreement have pledged.

Voluntary commitments with direct relevance to the ocean are made by governmental and non-governmental actors at the regular Our Ocean Conference or at the UN Ocean Conference. A remarkably large number of actors subsequently implement the projects they announced. In the 2014 to 2017 period, for example, one third of all com-

Our Ocean Conference
Our Ocean Conference (OOC) is an annual event that brings together government and business representatives as well as scientific and civil society leaders to exchange information on progress in ocean conservation and announce new projects. These always fall under one of the following six headings: (1) marine protected areas, (2) climate change, (3) marine pollution, (4) sustainable fisheries, (5) sustainable blue economy and (6) marine security.

mitments announced at the Our Ocean Conferences concerned marine protected areas. Of these 143 announcements, half were implemented by 2019, meaning that more than five million square kilometres of marine areas were newly protected worldwide, for example in Palau, Argentina, Chile, Canada, the USA, Norway, Ireland and Micronesia.

At the Sixth Our Ocean Conference in October 2019, governments, businesses and other stakeholders pledged a total of 370 actions at a combined cost of USD 64 billion. Among others, the actions covered:

- Commitments to let independent scientists conduct on-board monitoring of krill hauls (fisheries companies);
- Investment in Ocean Risk Initiatives (insurance);
- Funding commitments for projects on environmental transformation in maritime shipping (banks);
- A variety of research as well as knowledge and data transfer projects (research institutions and governments);
- Projects to prevent or reduce marine litter (NGOs and governments);
- Increased efforts to effectively implement conservation measures in designated marine protected areas (governments) and much more.

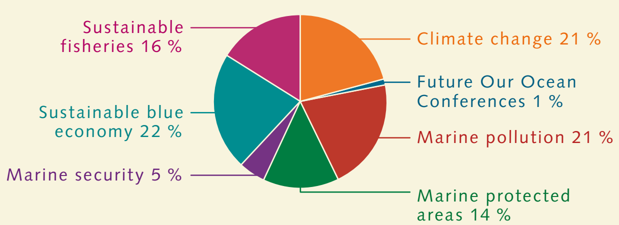
Overall, 23 per cent of the measures announced fell into the category of "sustainable blue economy" and 21 per cent dealt with marine pollution. Another 16 per cent targeted sustainable fisheries, while five and four per cent covered marine security and the hosting of future conferences respectively. In terms of pledged funds, 80 per cent of the funds were to be used for measures to combat climate change, followed by financial commitments for measures for a sustainable marine economy.

However, voluntary commitments alone are not enough to drive the necessary change. Experts say that ocean governance structures also need to change. While decisions have so far often been made at the highest national level and their implementation then pushed through to the lowest level (top-down approach), sustainable development requires network-like decision-making structures in which representatives from the political arena, the private sector, research and civil society participate and cooperate in a variety of ways across thematic boundaries and levels of responsibility. The strands of such a polycentric management network would therefore extend in all directions – with many linkages across sectoral, thematic and district, regional and national boundaries.

8.15 > At the Sixth Our Ocean Conference in 2019, participants made ocean protection pledges worth a total of USD 64 billion. The majority of project ideas were submitted by governments, while the most financially costly pledges came from the private sector.

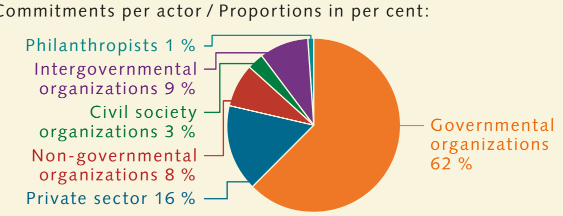
Commitments made at the Sixth Our Ocean Conference in October 2019

Commitments per theme / Proportions in per cent:



	Number of commitments	Budget in USD	Budget in %
	76	51,112,094,613	80
	4	911,200	0
	76	652,404,611	1
	53	1,307,751,906	2
	20	111,685,000	0
	81	10,239,386,637	16
	60	298,536,770	0
Total commitments	370	63,722,770,737	

Commitments per actor / Proportions in per cent:



	Number of commitments	Budget in USD	Budget in %
	229	4,556,588,343	7
	61	50,281,499,644	79
	30	39,582,750	0
	10	192,150,000	0
	35	8,418,950,000	13
	5	234,000,000	0
Total commitments	370	63,722,770,737	

8.16 > For some years now, abalone sea snails in Chile may only be caught by fishers who hold a fishing licence for the respective coastal area where the snails occur. Since the introduction of these exclusive fishing rights for artisanal fisheries, the once heavily overfished stocks have recovered in many places.

The scientists are convinced that such a complex management network with many cooperating decision-making centres has three major advantages:

- It is more open to innovative approaches and promotes shared learning.
- It involves all societal groups in decision-making, especially the local public affected by the decisions.
- It can therefore respond more effectively to the challenges of our time than an administrative system in which there is little diversity of interests and only one way of decision-making.

In practice, such network-like approaches already exist where, for example, the decision-making authority for local marine management has been placed in the hands of the local coastal population, meaning that the residents, supported by experts, jointly consult and decide on the use and protection of their waters. Another crucial factor for success is that the opinions and approaches of local actors are incorporated into regional and national decision-making processes and that the stakeholders at the various levels coordinate with each other.

In Chile, for example, after the collapse of the abalone stocks in 1991, the government introduced Territorial Use Rights in Fisheries (TURFs) for artisanal fisheries. This means that in more than 550 designated coastal areas, only certain groups of artisanal fishers have been allowed to catch Chilean abalone *(Concholepas concholepas)* and other species for several years – each in the section the group was allocated. The fisher cooperatives themselves decide on the quantities caught. They autonomously monitor compliance with the legal regulations in their area and are obliged to report regular stock assessments to the supervisory authorities. As a result of this local fisheries management, the artisanal fishers' catches have increased continuously in most regions, and as much as fivefold in some areas. The sector is once again reliably providing food for the coastal population and work for more than 17,000 fishers. In particularly well-managed

The WBGU criteria for a future system of ocean governance

As early as 2013, an expert panel of the German Federal Government (the German Advisory Council on Global Change, WBGU) developed ten criteria that can be used to analyse and realign existing marine management structures. The criteria have lost none of their value or relevance to this day. Ambitious marine management under this approach is based on the following principles:

1. *Adaptive management* aims to continuously improve the knowledge base for governance and to promptly use it in the conservation and sustainable use of the oceans. Adaptive management aims to broaden our knowledge of the structure and dynamics of ecosystems via a learning process and thus iteratively improves the protection and management of the seas.
2. *Incentives for innovation* encouraging a sustainable, low risk use of the oceans reward players who develop long-term, sustainable business models on the use and conservation of the seas instead of seeking short-term profit maximization.
3. A *clear assignment of rights of use* is necessary to prevent the overexploitation of the sea, which is a common good. This makes it possible to exclude certain users and thus to coordinate use – either via markets or by negotiation. Furthermore, the societal costs of use can be charged to the users according to the polluter pays principle, so that the external costs are internalized.
4. Neither the conservation nor the sustainable use of the oceans as a global public good is possible without an unprecedented level of *global cooperation* and global cooperation mechanisms. Global cooperation forms the foundation for the development of international treaties on marine conservation and use, and for the joint implementation of these treaties.
5. *Subsidiary decision-making structures* – i.e. assigning decision-making powers primarily to decentralized decision-makers at the regional or local level, and secondarily to central international agencies – are crucial for the acceptance of global and national regulations. Moreover, such an interpretation of subsidiarity makes regulations easier to enforce efficiently.
6. *Transparent information* ensures that all players have access to the relevant data.
7. *Participatory decision-making structures* make it possible to reveal interests; they lead to decisions that all stakeholders can understand.
8. *Fair distribution mechanisms* aim to ensure an equitable distribution both of the benefits of marine resource use and of the costs – e.g. of conservation, monitoring, surveillance and sanctions. This applies to the sharing of costs and benefits between countries and between different levels of a country's government.
9. *Conflict-resolution mechanisms* are necessary in order to coordinate the many and complex use interests of different stakeholders (e.g. governments and individuals).
10. *Sanction mechanisms* at the different governance levels are key instruments for enforcing compliance with regulations on use.

TURFs, stock densities and fish size have also increased, indicating that this approach is a valuable tool for sustainable coastal and fisheries management.

Furthermore, according to the Ocean Panel authors, an international ocean agency is needed as the highest level institution. This agency should define the norms and principles and thus the overarching rules for sustainable network-like marine management. It would also be tasked with offering rules and mechanisms for dispute resolution and enforcing compliance with important principles such as transparency, accountability and diversity of participation. A United Nations resolution would be needed to establish such an institution, as well as a group of nations that would put up the necessary funding, but without claiming special privileges in return.

Experts from the German Advisory Council on Global Change (WBGU) had already put forward a similar institutional proposal in 2013. They proposed the establishment of a World Ocean Organization as the global steward of the ocean as human heritage, and defined ten criteria against which ambitious ocean governance would have to be measured.

However, not all experts approve of the idea of a UN ocean agency. In view of the experiences with the negotiations on the Mining Code for the deep sea and the agreement on Biodiversity Beyond National Jurisdiction (BBNJ), critics point out that once again this body would probably be composed of representatives of the nation states. There would thus be a danger that their differences in interests would again delay elementary decision-making processes and severely hamper the work of the Ocean Agency. Moreover, it is questionable whether the industrialized nations would even agree to such an ocean agency. They would after all only have one vote each and would have to decide on fundamental questions of ocean use together with many developing countries and landlocked states, and may have to submit to majority decisions.

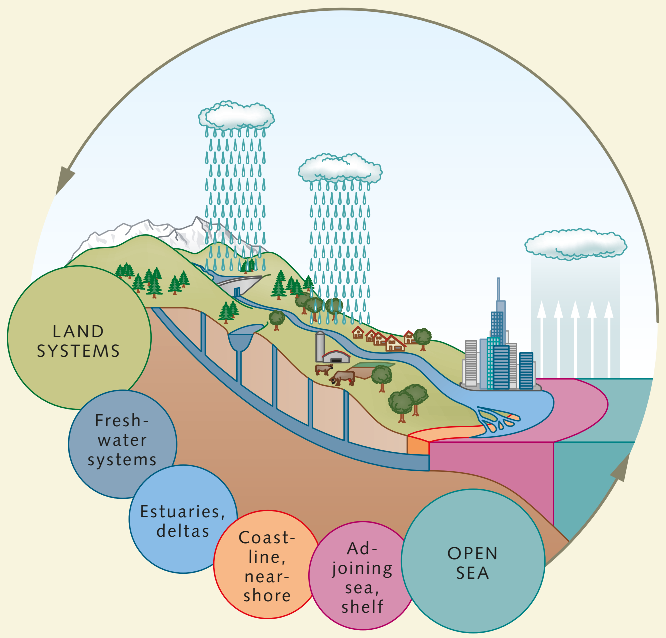
Nevertheless, the international community should certainly take note of the Ocean Panel authors' recommendations. The principles of a network-like sustainable marine management they developed could prove to be extremely useful – regardless of whether or not there will ultimately be an ocean agency. With these principles as guardrails, it may be possible to actually bring to life the framework provided by the United Nations Convention on the Law of the Sea and guarantee the sea the protection it needs to serve humanity in the best possible way. Once again and in brief, the most important recommended actions put forward for future marine management are as follows:

- All decisions should aim at sustainable use of the oceans and be based on the guidelines agreed upon by the international community in the UN Climate Convention, the Paris Climate Agreement and the Convention on Biological Diversity. In addition, the polluter-pays principle applies (polluter pays to remedy damage caused), as already laid down in the Rio Declaration on Environment and Development. The United Nations Convention on the Law of the Sea forms the legal basis for all action.
- Programmes and measures should go beyond sectoral and zonal boundaries and take into account information from all affected areas. This requires close cooperation between the many actors and institutions.
- Decisions should be science-based and always take into account the precautionary principle. To ensure that expert knowledge is reliably incorporated into decision-making processes, fixed procedures should be introduced that allow scientists to be heard or to participate. Moreover, the effectiveness and efficiency of all measures should be checked by means of large-scale monitoring and evaluation programmes.
- Sustainable marine management necessitates a flexible organizational framework within which it is also possible to react promptly and efficiently to unforeseen changes.
- Sustainable marine management should rely on a closely meshed network composed of many actors to ensure that all can participate in decision-making. Moreover, it is important to make all decision-making processes transparent.
- All knowledge about the state of the ocean, legal frameworks, use plans, research results, technology developments and best-practice examples should be freely shared among all stakeholders via knowledge and data portals.
- The process of marine management should be characterized by fairness and equality. It is crucial to this end that human rights are protected and enforced, and that actors take responsibility for their actions and are liable for adverse repercussions. Furthermore, a balance must be obtained between individual short-term goals and the common long-term goal of sustainable ocean use.

The authors also call on all governments, businesses and civil society representatives to strengthen the transformational ocean programmes established by the United Nations and its institutions. As a result of human activity, the ocean, a source of life, is in an extremely precarious situation. This is further exacerbated by climate change. To release it from this predicament and to guarantee a sustainable future for both the ocean's biocoenoses and the billions of people who benefit from the sea requires the support and cooperation of all – a plea that is quite in the spirit of the Convention on the Law of the Sea.

Source-to-sea approach – marine protection starts far inland

An example of new forms of environmental and marine management is the "source-to-sea approach" which was developed by an international organizational network of the same name. Its basic idea is to think of marine protection in such a way that all physiographic regions from which substances enter the sea are included in the management, i.e. from the source of the (material) flows to the ocean. Geographically, this approach starts at the headwaters of streams and rivers, extends through forests, fields, wetlands, lakes and settlements along their course, and extends beyond the delta or estuary to the coastal sea and finally to the open sea.

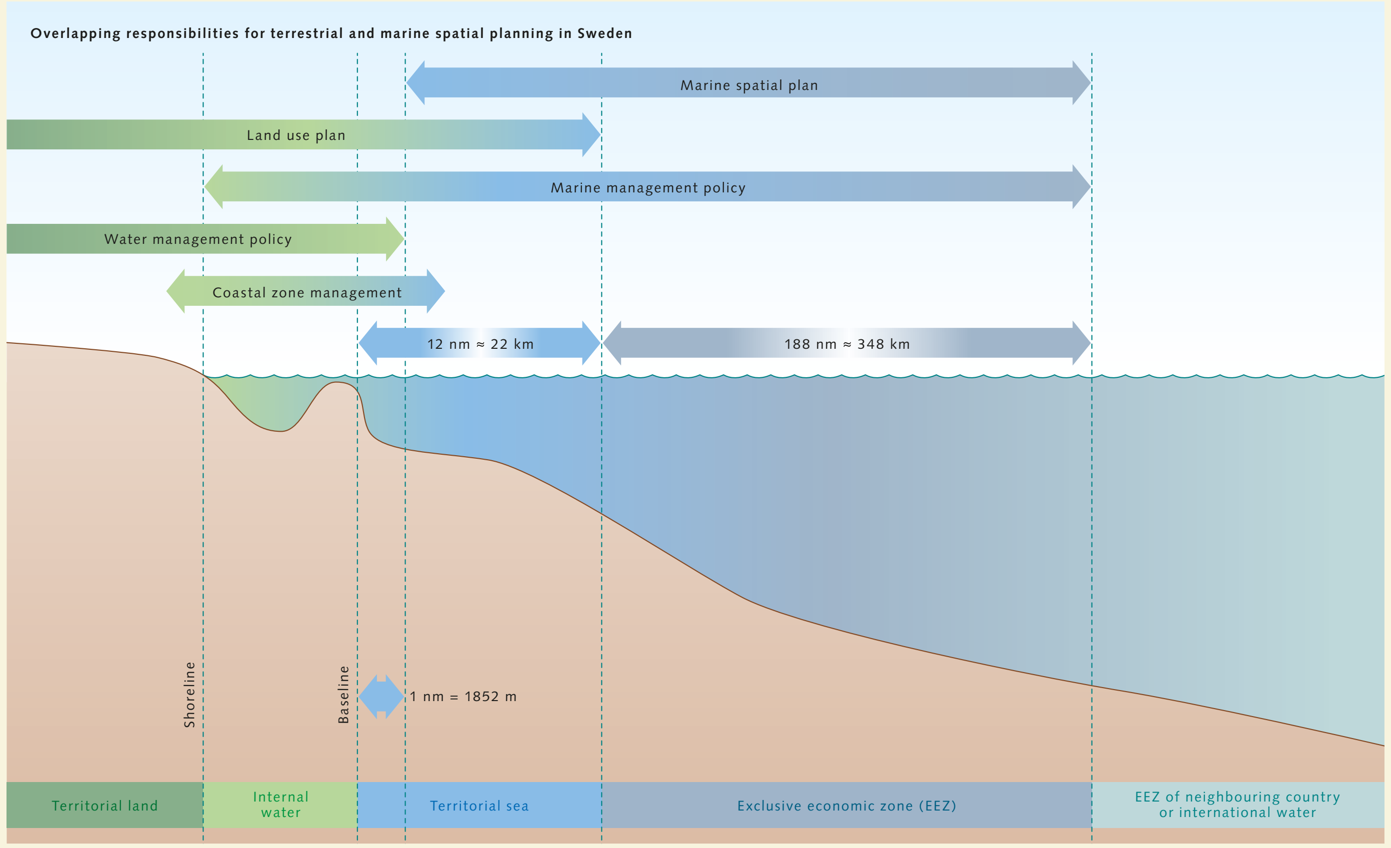


8.17 > The source-to-sea approach takes into account the many material flows from land to sea and vice versa. It therefore involves all inland physiographic regions and inland actors in coastal and marine protection.

All these spaces are interlinked through movements of water, sediments, organisms, pollutants and materials and through various ecosystem services. Additionally, humans are active in all physiographic regions, utilizing their resources with a primary focus on self-interest. This means that they are less interested in what happens further downstream. For this reason, the initiators of the source-to-sea concept developed a structured process that can be used to analyse this system consisting of different spaces, actors, interests, forms of use and regulations, thus broadening the individual actors' perspectives and generating opportunities for supra-regional cooperation. Joint projects share the following characteristics: they (1) are holistically conceived, (2) initiate new partnerships, (3) set thematic priorities, (4) respond to the conditions on site, (5) act in a goal-oriented manner and (6) are adaptable. This means that measures are scientifically guided, results are documented, and methods and processes are evaluated so that appropriate adjustments can be made in the event of failure or regression.

This process tends to result in closer cooperation between actors across sectoral boundaries. Sweden even went so far as to merge its fisheries agency with parts of its environment agency. Together they have formed the new Swedish Agency for Marine and Water Management since 2011. It is tasked with implementing national and European guidelines for inland waters and for marine and fisheries management. By uniting these three subsectors under one roof, the staff are empowered to take a holistic view of streams, lakes, rivers and marine areas and the environmental problems that arise. This perspective is becoming increasingly important as the pressure to address problems holistically increases as a result of climate change and new national and international targets. Two examples: Sweden's energy sector is to be fully converted to electricity from renewable energy sources by 2040; a large proportion of the electricity supply is to be provided by hydropower plants, but these must first be modernized to meet important environmental standards. At the same time, the water quality in Sweden's inland and coastal waters is to be improved. Their status is still far from what would be considered a "good" status by the European Union or Sweden itself.

According to the source-to-sea initiators, eight years after the new authority started its work, not everything was going according to plan quite yet. The internal coordination of measures in particular as well as the cooperation with other national authorities still needed to be improved. Both were still hampered by different, partly overlapping areas of responsibility, programmes of measures and regulations, the initiators reported in 2019. But a start had been made and the structured process is now being applied in several coastal regions – for example in the Bay of Bengal, in 14 Pacific island nations and in the global quest for ways to solve the marine litter crisis.



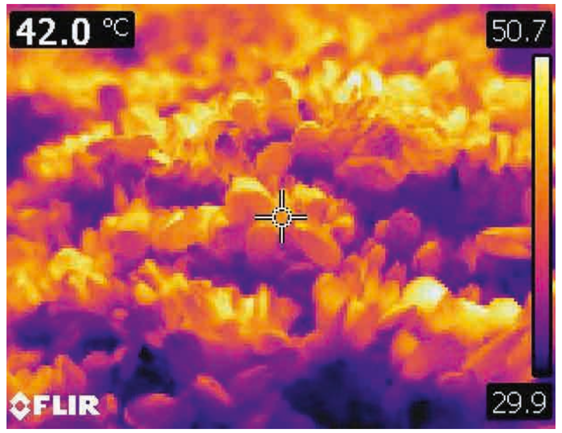
8.18 > This presentation by the Swedish Agency for Marine and Water Management shows how, in Sweden's coastal regions, programmes of measures and responsibilities for specific zones overlap and continue to hamper integrative and cross-sectoral management.

The ocean – flashpoint yet part of the solution

> As a consequence of climate change, overfishing, habitat destruction, species extinction, overfertilization, pollution, shipping and many other stress factors, the state of the ocean is steadily worsening today. And yet the world needs an intact and productive ocean now more than ever. The immediate and highest priority must be to drastically reduce these stresses. There is disagreement, however, on how this objective can be realized, and it is not clear whether humanity currently has the will to initiate the necessary changes.

In sharper fokus

First the good news: Since the turn of the millennium the ocean has been moving up the political agenda, and the world's leaders are now acknowledging that the state of the world's oceans is much worse than had long been assumed, with higher temperatures, sea-level rise, and more intense storms, as well as declining biodiversity. Acidity levels are rising, while oxygen concentrations continue to drop. The oceans are being severely overfished in many regions and are being polluted with tonnes of contaminants and garbage every day. In 2020, more than 80 per cent of the ocean's surface area experienced at least one heat wave. At the beginning of the United Nations Decade of Ocean Science for Sustainable Development, it is clear that the oceans are the setting for not just one, but three global environmental crises, all of which are entirely man-made – the climate crisis, the biodiversity crisis and the global pollution crisis.



8.19 > This thermal image of a mussel bed in Vancouver, Canada, indicates that the mussels heated up to 50 degrees Celsius during an extreme heat wave in summer 2021.

The impacts of these environmental crises are not equally distributed around the globe. Throughout the world, the disruptions, particularly those associated with climate change, are hitting poor people hardest, because they have little or no adaptive capacity. The hardships are exemplified by small-scale fishers who are not able to follow the migrating schools of fish with their small boats, or farming families in coastal regions, who are increasingly losing their lands and livelihoods to the rising seas.

There is also no question that social problems such as poverty, hunger and social injustice are fuelling the crisis. People who depend solely on the sea have no choice but to keep on fishing until the very last fish is caught. The extent to which marine conservation measures and programmes for sustainable use of the seas can be effective therefore always depends on the extent to which they take into account the needs of people impacted locally.

At the same time, however, the ocean itself offers a number of solutions, ranging from its great potential for wind energy and sustainable fishing and aquaculture to the immense amounts of carbon dioxide that could be fixed and sequestered by the restoration of mangrove forests and seagrass meadows, or through systematic large-scale kelp farming. Yet achieving these goals will require a fundamental paradigm shift in the way we interact with the sea. Instead of focusing exclusively on the objectives of extracting the maximum amounts of fish, shellfish, oil, gas, sand, ores and other resources, humankind will have to consider how the goals of marine conservation, sustainable use and a fair and equitable sharing of the ocean's bounty can be reconciled and implemented simultaneously.

8.20 > Dead mussels cover a stretch of beach in Vancouver, Canada. Under normal conditions, these rocky coast dwellers can survive temperatures of 35 degrees Celsius for short periods. However, these marine organisms were unable to cope with the record temperatures of 45 to 50 degrees reached in summer 2021; as a result, large numbers of them died.

The experts assembled in the Ocean Panel recommend five basic building blocks:

1. **Whenever decisions about the ocean are made in future, they must be based on data and scientific knowledge.** This requires open, accessible databases and technologies that facilitate the measurement of environmental parameters, simulation of processes, tracking of stakeholders, prediction of developments, monitoring of management measures and, finally, the sharing of data. Some of these technologies are already being applied on a small scale. A computer model, known as POSEIDON, allows scientists to simulate the interactions among various fishery management measures, fishing fleets and marine ecosystems, thus enabling them to compare alternative options. There is also a new Marine Manager portal developed by the marine conservation organization Global Fishing Watch. Almost in real time, the portal makes data available on key marine parameters, zone boundaries and human activities (e.g. fishing, mining, tourism) in marine protected areas, thereby facilitating the monitoring and protection of the various regions by area administrators and interested users. At present, this portal only covers five selected marine protected areas, but should be functioning globally by 2024 at the latest.
2. **Marine spatial planning should be guided by concrete goals and transcend sector boundaries.** Considering the many interactions among the individual sectors of the marine economy, new and coordinated policies for use are needed that include integrated, ecosystem-based management and science-based spatial planning for all marine regions. However, success can only be achieved when a balance is established between the interests of the various user groups. All of these groups must therefore be involved in the planning. Other requirements are that the ocean may only be exploited to an extent which does not harm its biotic communities, and that the local populations have fair access and usage rights. This includes exclusive fishing rights for local fishing communities.

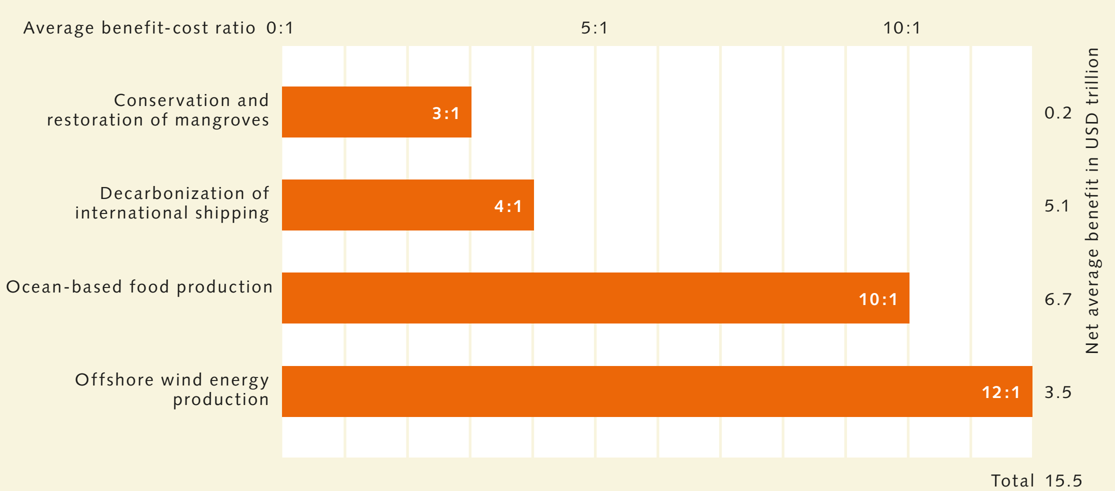
3. **More money needs to be invested in methods for sustainable use of the oceans.** To date, only one quarter of the funds needed to restore critical degraded ocean habitats is available. Governments are also being called upon to foster new kinds of sustainable marine use through subsidies. These could easily be financed through elimination or redirection of the existing harmful subsidies for industrial fishing and for subsea extraction of oil and gas. Correctly applied, investments in the health of the ocean offer the prospect of substantial financial returns in the long term.
4. **Land-based inputs of garbage and pollutants must be stopped,** especially by reducing the huge amounts of waste through smart recycling practices and the use of alternative packaging materials, and by introducing a circular economy in all sectors of business. Effective environmental protection measures also need to be introduced and implemented in agriculture.
5. **The many services provided by the oceans must be reflected in all economic accounting and product prices, in order to more clearly reflect the true value and importance of the ocean.** Conventional methods of calculating a country's economic performance (gross domestic product, for example) fail to consider the damage done by some industries, or the extent to which their activities accelerate climate change. This also still applies to calculations of the strength of the marine economy, perpetuating the perception that non-sustainable activities like industrial fishing are profitable, and leading to their being subsidized in many places. To realistically balance the damage caused by marine industries with the potential benefits provided by the ocean, new calculation criteria and procedures are needed. Their development is a task that needs to be addressed jointly by governments and their statistics authorities.

The Ocean Panel experts no longer automatically interpret the term "marine conservation" to mean that humans should completely refrain from using the sea in certain regions. What is proposed instead is a more responsible approach that preserves the biodiversity and important habitats in the oceans, strengthens the resilience of marine biotic communities, and allows their decimated stocks to recover – an approach which is now being advocated by many proponents of an expanding marine economy.

The threefold benefits of genuine marine protected areas

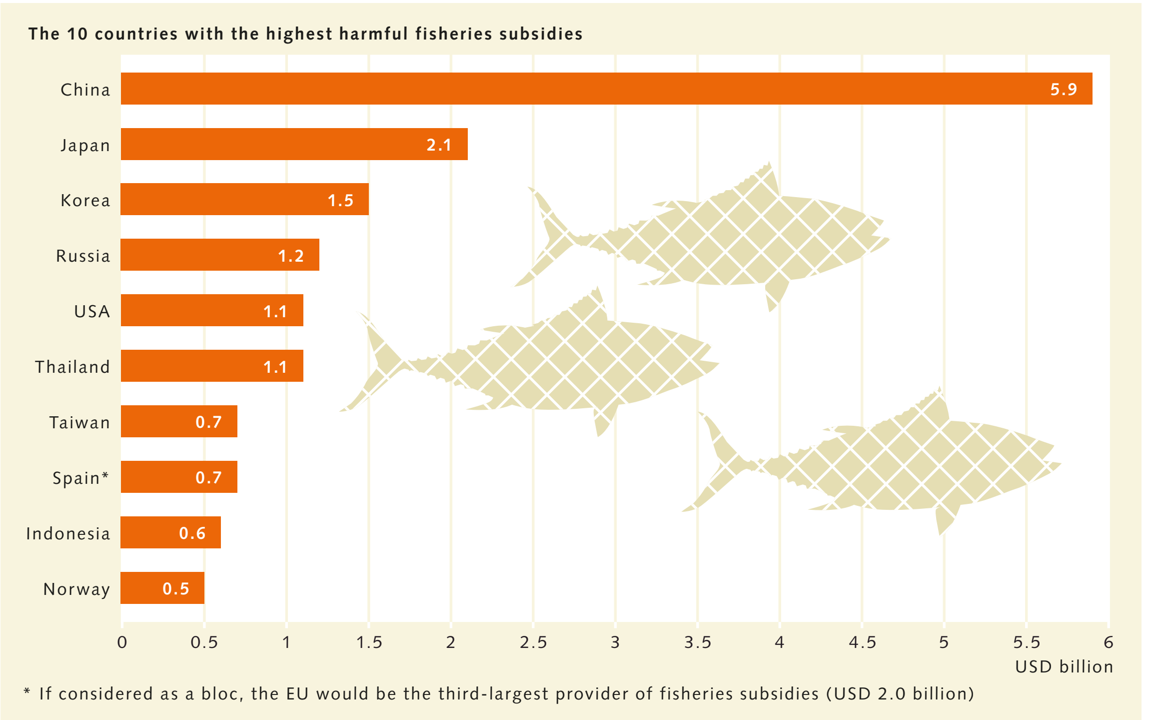
A new study, published in March 2021, shows that radical marine conservation, meaning the expansion of highly

Benefit-cost calculations for selected sustainable measures in the timeframe from 2020 to 2050



8.21 > Investments in sustainable forms of marine use pay off in the long term. Experts predict profitable benefit-cost ratios and high returns within three decades.

8.22 > Healthy seagrass meadows and mangrove forests, such as those that still exist in Cuba and elsewhere, are hotspots of marine biodiversity. Here, an American crocodile *(Crocodylus acutus)* rests on a seagrass bed near a red mangrove *(Rhizophora mangle)*.



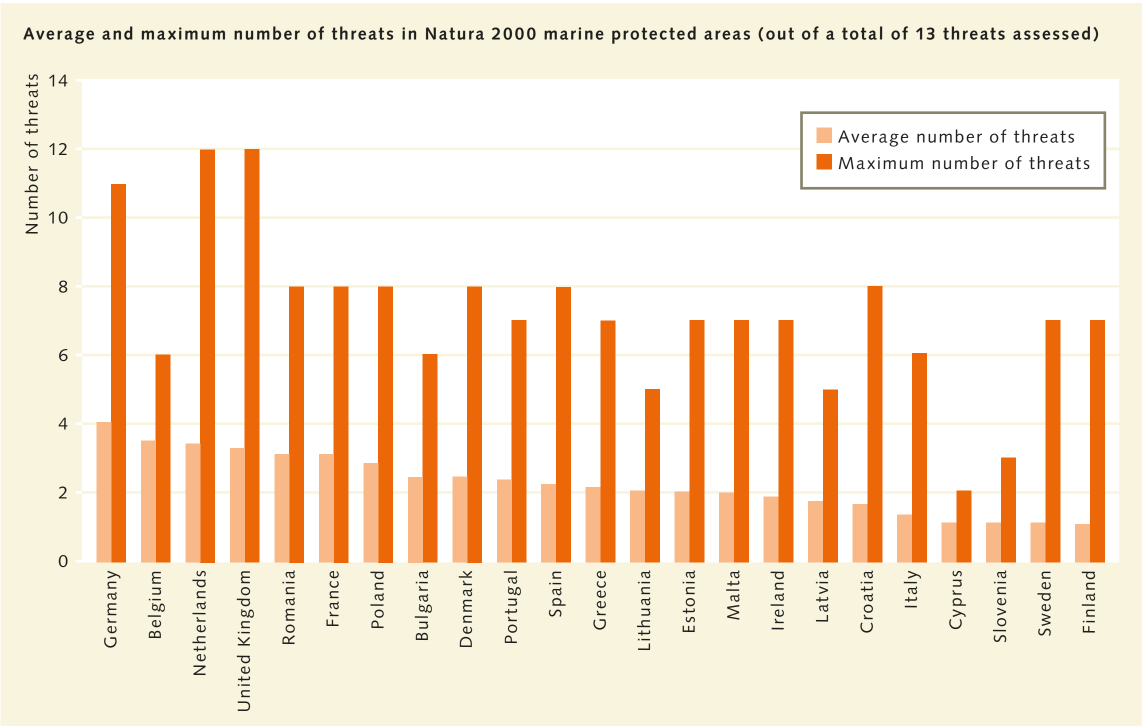
8.23 > Large fishing countries now pay high subsidies to allow their fleets to fish far from home, thus minimizing the risk of overfishing in their own waters. According to the most recent calculations, the 10 largest providers of subsidies spent around USD 15.4 billion on this item in 2018.

protected marine regions, can also help in tackling the climate and biodiversity crises. However, those involved with this issue must understand that widely different protection standards can be implied by the term Marine Protected Area (MPA). The International Union for Conservation of Nature (IUCN) defines six different types of marine protected area. They range from the most strictly regulated MPAs, where all activities are prohibited that destroy habitats or involve the removal of organisms or material from the sea (including fishing and mining, as well as oil and gas extraction), to areas in which sustainable use of natural resources is permitted.

As of June 2021, a total area of 7.7 per cent of the global seas had been officially granted marine protected status – an area equivalent to the size of North America. However, high fishery protection standards have actually been implemented in only 2.7 per cent of the global marine area. According to Oceana, an ocean conservation organization, activities harmful to the sea and its biotic communities are permitted in up to 96 per cent of the designated Natura 2000 marine protected areas in Europe. Areas such as these are therefore referred to in environmental conservation circles as “paper parks”. They are protected areas on paper only, providing little or no protection in reality. To take just one example from the Oceana report: in more than 500 European Natura 2000 areas that were explicitly designated for protection of the seabed fauna, fishing methods that destroy these very communities are still permitted.

But even disregarding the lack of effective protection in many marine protected areas, the number, size and connectivity of the areas, in the view of experts, are far from what is necessary to offer the many sea-floor dwellers sufficient habitats over the long term, or to enable them to adapt to climate change. Adaptation would generally require migration to areas closer to the poles, where the organisms would encounter conditions similar to those in their former habitats. Protected corridors between the old and new habitats are necessary to facilitate the colonization of new areas by these flora and fauna.

In the new March 2021 study mentioned above, an international team of scientists therefore investigated

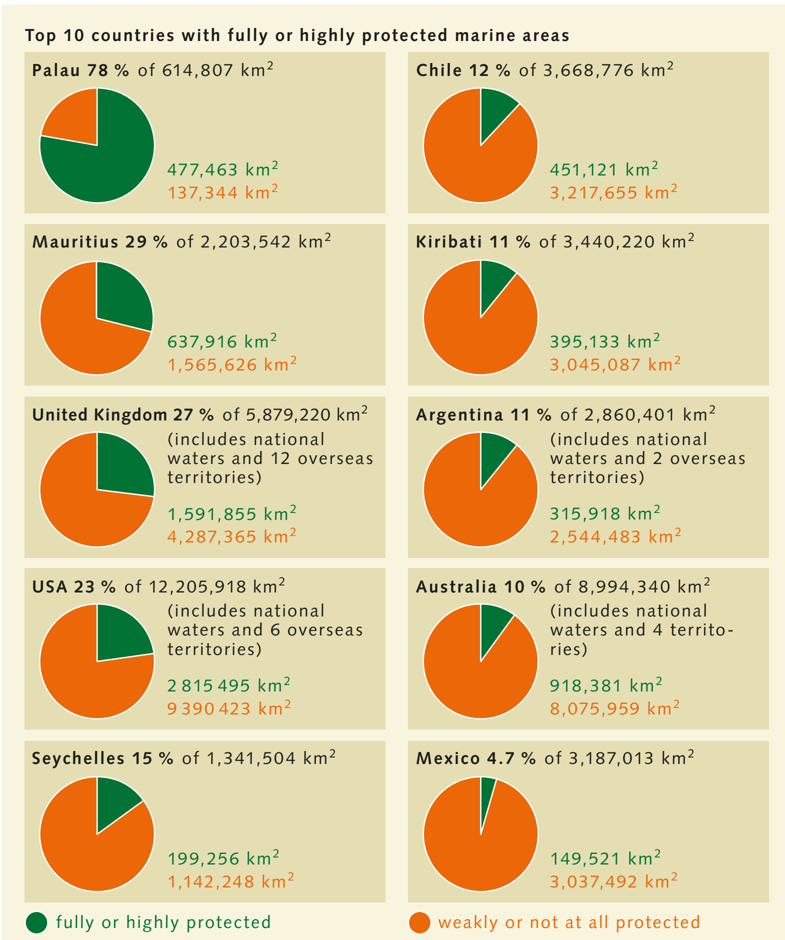


8.24 > When the marine conservation organization Oceana reviewed some 3450 European marine protected areas with regard to their protection standards in 2018, they found that in more than 70 per cent of the areas at least one of 13 environmentally harmful activities was permitted, including disruptive interventions such as aquaculture, fishing, oil and gas extraction, shipping, laying of subsea cables and pipelines, and the construction of wind farms.

which marine regions need to be urgently placed under protection in order to achieve the best possible outcomes in terms of species conservation, fishing and climate protection. For the latter, the most important question was in which regions bottom trawling should be prohibited, because this activity disturbs carbon reserves on the sea floor and encourages their breakdown by microorganisms. Over the long term, this process leads to the release of 15 to 20 per cent of the carbon dioxide that the ocean had previously removed from the atmosphere and trapped in sediments on the sea floor. Bottom trawling worldwide causes elevated emissions of greenhouse gases on a scale similar to the amounts released by soil changes in agriculture.

As a first step, the researchers calculated what proportion of the oceans would have to be strictly protected if only one of the three objectives at a time were prioritized (species conservation, secure fishing yields, maintenance of carbon stores on the seabed):

1. Species diversity would receive 90 per cent of the maximum possible benefit if around 21 per cent of the ocean’s area were protected from human intervention. This would require the granting of strict protected status for 43 per cent of national waters (exclusive economic zones – EEZs) and six per cent of the high seas. The result would be a much greater degree of habitat protection, particularly for endangered species and those threatened with extinction. While 1.5 per cent of the necessary area currently has protected status, after the expansion the proportion would increase to as much as 87 per cent.
2. Fishing yields would increase by up to 5.9 million tonnes if 28 per cent of the marine area were protected. For this objective, as for species conservation, the protection mandate would have to apply primarily to the EEZs, where 96 per cent of all wild catches are now made.
3. To effectively protect around 90 per cent of the carbon stores on the sea floor that are being subjected to bottom trawling, this activity would have to be prohibited in 3.6 per cent of the ocean area, again mainly inside the EEZs because most trawl fishers work in this



8.25 > Since January 2020, Palau has topped the list of countries with the greatest proportion of marine protected areas. It has placed 78 per cent of its exclusive economic zone under strict protection, an area larger than the US state of California. This means that fishing and all forms of resource extraction are prohibited there.

area. The researchers were not able to include the possible impacts of deep-sea mining on greenhouse gas emissions from the ocean in their calculations, because it is still largely unknown how this industrial sector will develop over time.

The selection of protected areas is considerably more complex when all three goals are addressed simultaneously, because in some places the goals may be incompatible. Measures to conserve biodiversity, for example, could entirely preclude fishing in certain areas.

Nevertheless, the results of the calculations illustrate the role that the ocean could play in tackling the current crises. Placing 45 per cent of the total marine area under strict protection could achieve 71 per cent of the possible benefit for biodiversity, 92 per cent of the possible benefit for fisheries, and 29 per cent of the possible benefit for maintenance of carbon stores. However, this would require intensive international cooperation, targeted selection of the marine regions to be protected, and financial compensation for countries that would have to close large areas of their species-rich coastal waters to fishing and resource extraction and thus lose these potential earnings. The scientists note that a coordinated network of marine protected areas could serve as an effective mechanism for more climate and species protection, and would also contribute to the recovery of fish stocks so that the sea would again produce more food for humans.

Both the World Biodiversity Council (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) support this approach. In their new Workshop Report on the interactions between biodiversity and climate change, they set the required proportion of natural areas at 30 to 50 per cent.

If exploitation were the exception

Environmentalists take these scientific recommendations much further. During the 2021 Monaco Ocean Week, a policy discussion forum on marine issues that is now held on a regular basis, one group presented novel and alternative ideas.

If the designation, implementation and management of marine protected areas are so complex and difficult, the group suggested, it might make more sense to place the entire area of the oceans under protection, and then just designate those areas where exploitation of the sea or its use for shipping lanes would still be permitted. The extraction of organisms and material from the sea would then no longer be the rule but the exception, and fishing, mining and shipping companies would have to apply for the necessary licences.

The consequence of such a step would be that anyone who wants to fish, extract resources or engage in long-distance shipping would have to provide evidence, in their application, that their activities would cause no harm to marine biodiversity or the marine habitat, or at least that the environmental footprint of these activities would be kept within acceptable limits. The approach would thus completely reverse the status quo, shifting the perspective and focus of the problem from exploitation of the oceans to their protection. The immediate consequence would be that the companies, rather than marine conservation organizations, would have to compete to be recognized and heard in the debate on sustainable marine management. It would also be easier to discuss which forms of fishing and other marine uses are acceptable, and which are not. Furthermore, it would be possible to ensure that an environmental impact assessment were carried out prior to any industrial use of the sea, and that the results of the assessment would genuinely count.

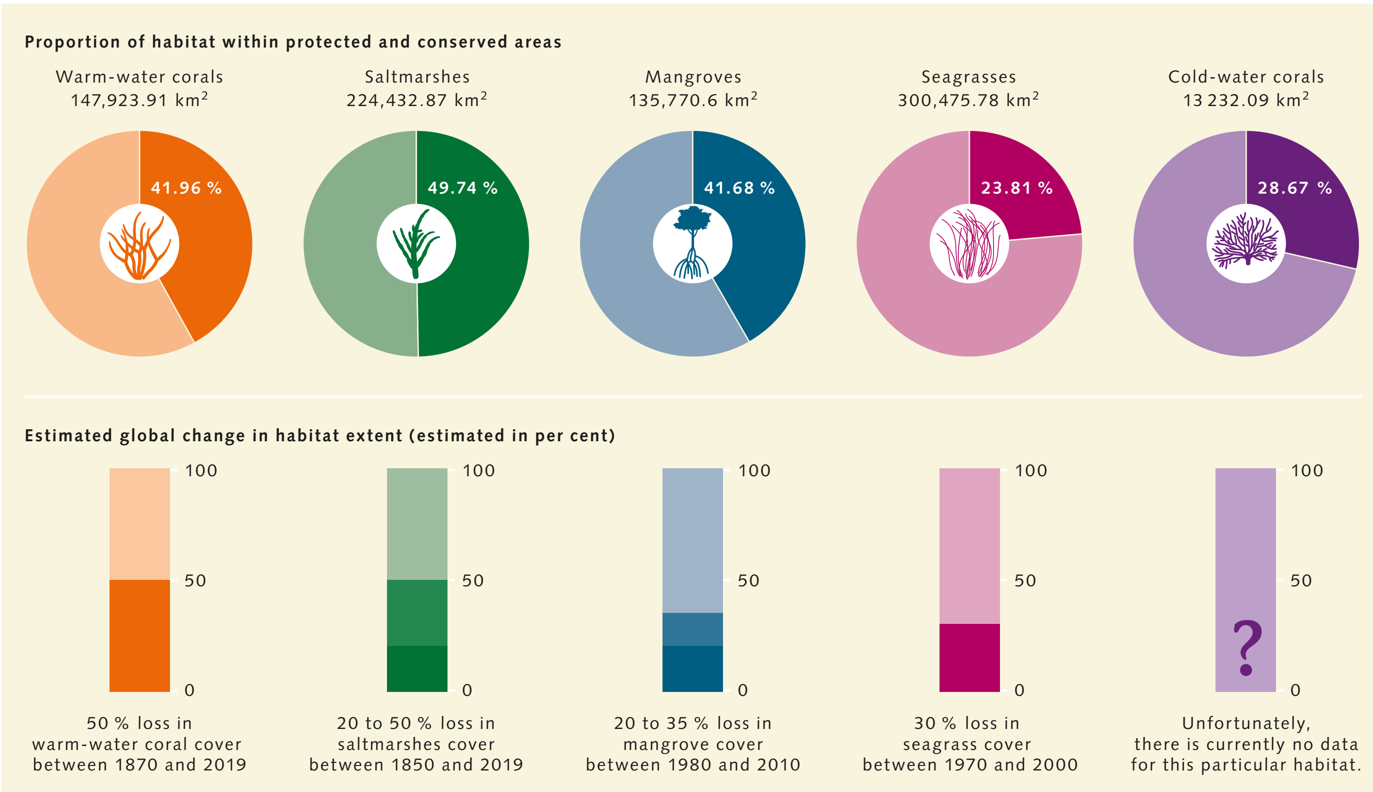
According to environmentalists, the current UN negotiations on the third implementing agreement on the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction (BBNJ agreement) offer a realistic opportunity to explore how such an approach could be put into practice – even though it would initially be limited to the high seas. Representatives of industry and governments will presumably reject the idea out of hand because such an approach would severely restrict the use of the seas. Given the current crises facing the Earth, however, humankind has no option but to search for new ideas. Or, to paraphrase a joint analysis by the Intergovernmental Panel on Climate Change and the World Biodiversity Council: Sustainable development for people and nature will only be achievable if humanity fundamentally reforms and reorientates its economic, social and governmental systems. This will necessitate measures on a scale never previously undertaken in human history. The idea of giving conservation the highest priority in global marine management would fit nicely within the framework of a reformed and realigned system of ocean governance.

The overriding goal – to restore the ocean

Today, more than ever, humanity is dependent on a healthy and productive world ocean. However, we are currently at a crossroads: while the pressure of human use

Nauru Agreement
The eight member states of the Nauru Agreement are Kiribati, Nauru, the Marshall Islands, the Solomon Islands, Palau, Papua New Guinea, Tuvalu and Tokelau, as well as the Federated States of Micronesia. Among other species, half of the world's skipjack tuna, the most commonly fished tuna species in the world, is caught in the territorial waters of these nations.

8.26 > A desperate search for food: A Florida manatee *(Trichechus manatus latirostris)* searches for edible seagrass beneath a thick carpet of algae in the waters of Florida. The algae are spreading because Florida's rivers are carrying more and more fertilizer and untreated wastewater into the sea. In the first five months of 2021 alone, 761 manatees starved to death in Florida. This was 10 per cent of the total population.



8.27 and 8.28 > **The coastal zones of the oceans are among the Earth's habitats that have been most extensively altered by humankind. In the *Ocean+Habitats* project, experts at the United Nations Environment Programme keep records of the extent to which coral reefs, mangroves, salt marshes and other vital coastal ecosystems are under threat.**

is steadily increasing, the diversity of life in the ocean is rapidly decreasing, and with it the range of ocean services. Scientists report that one third to one half of the sensitive marine habitats, including coral reefs, salt marshes and mangroves, have already been destroyed. Large stretches of coastline are suffering from rising levels of pollution, eutrophication (overfertilization), oxygen deficiency and heat stress. The number of marine species threatened with extinction is growing. IUCN experts have so far assessed the population figures for more than 14,000 marine species. There is a high risk of extinction for around 11 per cent, i.e. more than 1500, of these species. They are therefore classified as endangered, critically endangered or threatened with extinction.

In order to reverse this trend, first, the restoration of habitats with key functions for the ocean is vital. Foremost among them are the mangroves, seagrass meadows, salt marshes, coral reefs, kelp forests and mussel beds. The number of restoration projects around the world is growing, but they are still far too small to have a global impact. Second, the anthropogenic pressure on the oceans must be minimized. The highest priorities are a drastic reduction in greenhouse gas emissions and a shift from the conventional system of global fishing to truly sustainable fishing and management methods. If both these aims can be achieved, experts say, the prerequisites for the recovery of marine life within the next three decades would be met.

But scientists also agree that there is no single solution that will enable the ocean to recover its former health. On the contrary, success can only be achieved if a number of coordinated measures are taken that are tailored to local conditions:

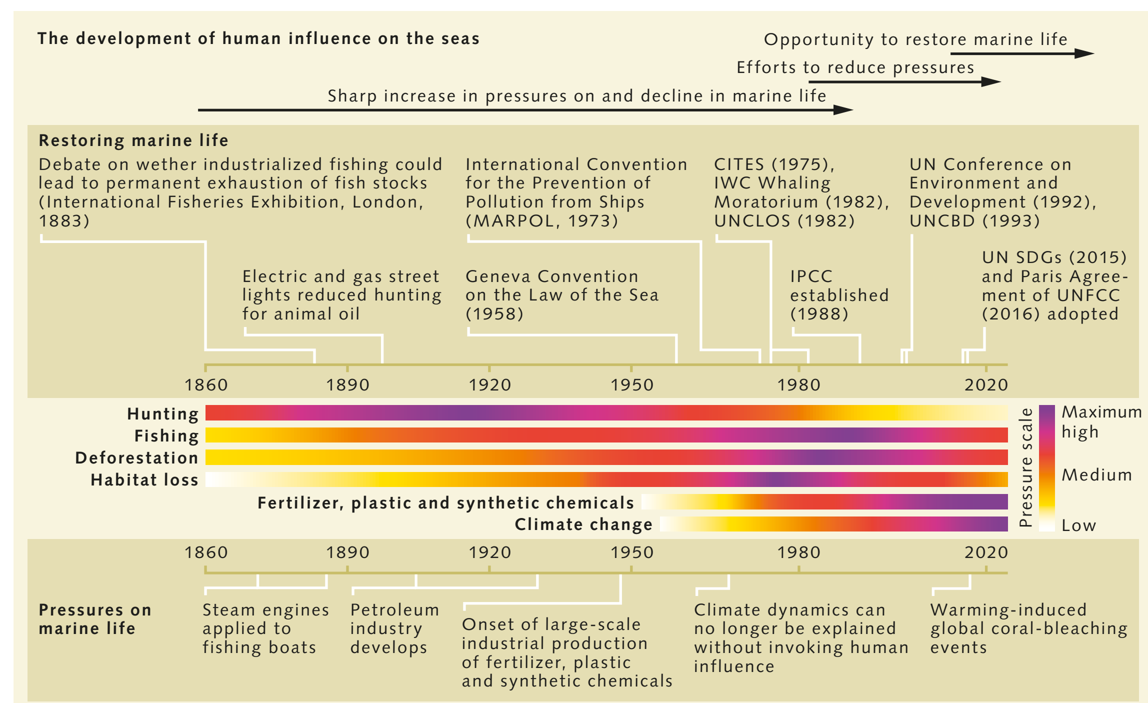
1. preserving and restoring habitats,
2. protecting endangered species and ensuring the sustainable use of healthy stocks,
3. effectively combating the causes of pollution, and
4. curbing climate change through drastic reduction of anthropogenic greenhouse gas emissions.

Many examples from a variety of regions show that protection, cooperation and the restoration of marine habitats pay off. Since commercial hunting of baleen whales was prohibited globally, the populations of humpback and blue whales have been recovering. In Vietnam, the area of mangrove forests is expanding in coastal regions where local communities have a voice in decisions on their use. In Bangladesh, scientists have been able to show that newly established mussel beds fully protect the salt marshes behind them from the destructive power of the waves, and this effectively stabilizes the coasts.

On the Kachelotplate sandbank, in the part of the Wadden Sea National Park in the territory of the German state of Lower Saxony, more grey seal pups are born every year. This is because the seals are able to find sufficient food and quiet in the park. While the staff counted only 40 young animals in 2010, the birth rate reached a new record high in 2020, with 372 newborns.

	Warm-water corals	Salt-marshes	Man-groves	Sea-grasses	Cold-water corals
Critically endangered	5	9	3	0	2
Endangered	25	16	3	1	1
Vulnerable	201	17	6	7	2
Near threatened	176	4	5	4	0
Least concern	297	124	45	44	15
Data deficient	135	8	2	4	15
Not evaluated	77	240	15	11	2153
Total	**916**	**418**	**79**	**71**	**2188**

8.29 > Hundreds of coastal organisms are now on the Red List of Threatened Species. These scientific assessments help local decision-makers decide which species are in most urgent need of habitat improvement.



8.30 > Fishing and the hunting of whales and other marine mammals were the first human activities to put heavy pressure on the seas. Since then, conservation agreements and technological advances have at least reduced this hunting pressure. However, economic development has resulted in the emergence of two new and deadly trends, climate change and marine pollution.

Affordable and effective –
coastal and climate protection using nature's tools

Nature-based solutions (NbSs) are among the most promising and cost-effective approaches in the fight to tackle the planet's triple crisis. These are measures for the protection, restoration or expansion of healthy natural areas with the objective of enhancing their many benefits and managing them sustainably.

In coastal zones this primarily involves the restoration, renaturalization or comprehensive replanting of mangroves, seagrass meadows, coral reefs, mussel beds, salt marshes, dunes and natural floodplains. These measures are effective in facilitating:

- **the removal of carbon dioxide from the atmosphere, thus limiting global warming** (Mangroves, for example, can store up to four times more carbon per square metre than tropical rainforests. Natural ocean-based measures to increase natural carbon storage are known as blue carbon.);
- **the creation of habitats for rich and resilient biodiversity** (Intact coastal ecosystems filter pollutants and suspended material from the water and provide organisms with protection, food and corridors for potential migration of species. The benefits: less stressed species have a better chance of adapting to climate change. For example, 4000 square metres of seagrass meadow provide a habitat and food for around 40,000 fish and 50 million invertebrates such as lobsters and shrimp.);
- **the reinforcement of natural coastal protection** (Coral reefs, mussel beds, seagrass meadows, kelp forests and mangrove forests help to absorb the force of waves, thus mitigating flooding and minimizing the destruction and degradation of inland coastal areas. An additional advantage: After a storm, the mangroves, mussel beds, etc. repair the damage themselves and, unlike dikes and protective walls, they grow naturally with rising sea level.);
- **mitigation of the severity of local ocean acidification** (By absorbing carbon dioxide from the water, seagrass meadows reduce local acidification in the ocean, for example by up to 30 per cent off the coast of the US state of California.);
- **food security for coastal communities** (Healthy coastal ecosystems provide a habitat and nursery for many marine organisms and seabirds. If their offspring can develop successfully as a result of favourable habitat conditions and sustainable management, the yields achieved by fishers, hunters and gatherers will increase.);
- **provision of new livelihoods for people** (The beauty and biodiversity of healthy coastal ecosystems attract tourists and may enable local communities to generate new sources of income and escape poverty.).

Nature-based solution for the coastal zones

8.31 > The restoration of wetlands, along with coastal and mangrove forests, can be effective in protecting populated coastal areas from storm surges, rising sea levels and erosion.

The prerequisite for all of these functions, however, is that human societies drastically reduce their greenhouse gas emissions. For mangroves, seagrasses, kelp forests and mussels react sensitively to heat stress, extreme storms and rapidly rising sea levels. In light of the current global warming, it is also vital to allow species and biotic communities viable routes for migrating polewards. Dikes, protective walls and coastal cities paved in concrete often present insurmountable obstacles. And finally, the restoration and preservation of these natural coastal bulwarks require a considerable amount of specialized interdisciplinary knowledge, adequate funding and local communities' participation and support. If only one of these aspects is missing, projects will fail.

8.32 > A bright idea: Women from a village on the southeast coast of India are planting mangrove seedlings along the bank of a river. Each family that takes part in this restoration project receives a goat and some chickens as payment. This incentive improves the villagers' food supply and motivates them to participate.

Critical delay – marine conservation as a development goal

Everything that is currently happening in marine research and policy-making is based on the 2030 Agenda for Sustainable Development. This was signed by the leaders of the UN member states in September 2015 and includes 17 development goals. Marine protection is dealt with in Goal 14, which reads: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

The priorities are reflected in ten targets, which set the following objectives:

1. By 2025, significantly reduce marine pollution;
2. By 2020, sustainably manage and protect marine ecosystems;
3. Minimize the impacts of ocean acidification;
4. By 2020, end overfishing, illegal fishing and destructive fishing practices and implement science-based fishing management plans;
5. By 2020, conserve at least ten per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information;
6. By 2020, prohibit harmful fisheries subsidies;
7. By 2030, increase the economic benefits to island states and least developed countries from the sustainable use of marine resources;
8. Increase the transfer of scientific knowledge and technology and enhance the research capacity of small island states and developing countries;
9. Provide access for small-scale artisanal fishers to marine resources and markets;
10. Implement the UN Convention on the Law of the Sea and its associated agreements in order to propagate conservation of the seas and sustainable use of its resources.

For four of the targets, the deadline – the end of 2020 – has already passed, with no significant progress being reported. According to a recent UN interim report, the current efforts to protect the marine environment, and the small-scale fishers in particular, are by no means sufficient to conserve the fragile resource that is the ocean. A first interim assessment was to be made at the second UN Ocean Conference, but this was postponed from June 2020 to the summer of 2022 due to the coronavirus pandemic.

United Nations analysts say that the pandemic has demonstrated what it means to live on a planet where nature and the climate are out of balance. It can only be hoped that this experience will further motivate the international community to work together and with resolve towards the realization of the 2030 Agenda. Less than ten years remain.

Eight small island states in the West Pacific provide an example of what sustainable fishing can look like. Within a period of 40 years, the member nations of the Nauru Agreement developed a common set of rules by which they now successfully and profitably control tuna fishing in their national waters. The core of the Agreement is a process of auctioning off a fixed number of fishing days to foreign fishing vessels. Beforehand, however, the island states carry out a precise assessment of the tuna stocks to determine how many tonnes can be caught without endangering the populations. From this amount, the number of fishing days is calculated and taken into account in the bidding process. In addition, strict conditions are imposed by the member states. Fishing vessels that use purse-seine nets are required to have observers on board who, among other things, ensure that neither dolphins nor whale sharks are caught. The use of anchored or free-floating platforms that attract tuna, marlin and other highly desirable edible fish, and make their capture easier, is also prohibited.

For the past 10 years, these measures have allowed the association of island states to protect its tuna stocks from overfishing by the large fishing fleets from Europe, China, the USA, Japan and Thailand, and to generate an income of up to USD 500 million annually from fishing licences. Prior to the agreement, when each member state was still issuing its own fishing licences, less than five per cent of the sale value of the tuna flowed into the national coffers of the country of origin. Since the bidding procedure has been in operation, this share has risen to 25 per cent for the skipjack tuna *(Katsuwonus pelamis)*, for example.

The many successes at the local level illustrate that sufficient tools and knowledge for sustainable marine management are available. The task now is to make use of them, to involve all stakeholders in the process, make the required funds available, and to always consider the ocean in relation to the climate and humanity. Protecting the ocean, enhancing its biodiversity and using its services sustainably is also climate action. Performing such marine protection activities at one location, however, should never be used as an excuse to allow emission-intensive activities to be carried out elsewhere.

CONCLUSION

Sustainable marine management – a Herculean task

For nearly four decades, the United Nations Convention on the Law of the Sea has provided a clear framework in international law for all human activities on the seas and oceans, thus establishing a strong foundation for communal governance of the ocean. The convention classifies the marine areas into zones, regulates who can lay claim to the ocean and its resources in the various regions, and includes provisions on shipping, seabed mining and conservation of the marine environment. Furthermore, it calls upon all nations to work together regionally and globally to address issues relating to the ocean, and provides guidance to the international community on how disputes between parties should be resolved.

To date, 168 countries, the vast majority of states, have ratified the Convention and undertaken to comply with its provisions. However, the present state of the oceans provides ample evidence that so far, the international community has in fact largely missed its goal of sustainable use. There are many reasons for this failure. Developing countries, for their part, often lack the necessary structures, funding, know-how, personnel and technology to implement international regulations and agreements at the national level. In industrialised countries and at the international level, cross-sectoral cooperation is often lacking, resulting in conflicting goals and measures that have less impact than was originally planned. Industry and business, in turn, are still seeking to exploit legal loopholes in order to maximize their own profits at the expense of the marine environment.

In view of the global impacts of climate change and the ongoing biodiversity and pollution crises, it is now widely accepted that recovery of the oceans cannot be achieved simply by applying stand-alone solutions. Instead, integrated approaches are necessary at all levels of marine management. This means that programmes for marine use must be planned and agreed using transparent procedures that involve all stakeholders and transcend sectors, zones and often borders as well. Marine conservation, in other words, does not begin at the coastline, but much further inland.

Decisions on marine use should always be made on a scientific basis, and local community interests must be considered in all cases. In this way, it can be ensured that innovative local solutions receive recognition at higher levels, and can then be implemented on a broader basis.

Subsidies for activities that are harmful to the environment should be abolished. The public funds previously used to finance those subsidies should be employed instead to promote projects that restore marine and coastal ecosystems. Such approaches will have the added benefit of enabling communities to nurture and use ecosystems sustainably. In that vein, the measures that promise the greatest success are those which revitalize biotic communities while simultaneously contributing to climate protection and improving local living conditions.

Opinions naturally differ on the scope of the changes required. While some experts believe that restructuring the economic and value systems is absolutely necessary in order to significantly reduce anthropogenic pressure on the oceans, others point out that a great deal would have been achieved already had the existing rules and regulations been implemented consistently. In any event, it will not be a straightforward process. Progressing ocean recovery is a great challenge to humankind. Indeed, it is a task on a scale similar to that of mitigating climate change. The two must go hand in hand for humanity and the oceans to have a future.

world ocean review
Living with the oceans. 2021

7

The Ocean, Guarantor of Life – Sustainable Use, Effective Protection

The outbreak of the coronavirus pandemic in January 2020 marked a turning point for the world ocean. International merchant shipping collapsed, at least for a time; cruise ships were forced to abandon their voyages; beach hotels stood empty; large-scale marine projects such as the construction of new oil and gas production facilities in the Arctic were delayed. The international negotiations on improved marine conservation and more sustainable use also stalled when major political conferences could not go ahead as planned.

However, the pandemic also turned the spotlight on the oceans to a greater and more varied extent than ever before. This interest was driven firstly by the rapid progression of global warming and the role of the ocean as a heat repository, and secondly by a new wave of digital publicity for marine topics. Conferences, lectures and symposia were suddenly all moved online and were often open to everyone. Researchers held webinars to share new information and their latest research findings; marine conservation organizations and societies shifted their campaigns and events to the virtual space. Anyone who wished to and who had a knowledge of the relevant language could access these information formats on a daily basis, including events run by small, local cooperatives which, before the pandemic, rarely had an opportunity to reach a transregional, less still an international audience.

This growing public attention to the issues affecting the oceans did not come a moment too soon. The ocean is in a parlous state, which means that one of the fundamental pillars of our human existence rests on shaky ground, for the truth is that every person on Earth relies on the ocean in one way or another. The seas regulate the Earth's climate and ensure that our planet remains habitable and liveable. They distribute tropical heat around the globe, provide vapour to the water cycle, help to mitigate climate change by absorbing vast amounts of carbon dioxide and heat, and produce the oxygen for every second breath we take.

The ocean is the Earth's largest and most diverse habitat. It supplies animal protein for more than three billion people and provides livelihoods for millions more – in fishing, marine and coastal tourism, shipping, resource extraction, the renewable energy sector, and branches of the economy which process materials or substances from the sea.

Around 40 per cent of the world's people live less than 150 kilometres from the coast. For them, but also for the many visitors from further inland, the sea is a place for leisure and recreation, a source of inspiration and an element of identity. Today, it is clear that the healthier and more resilient the ocean, the greater human wellbeing will be, now and in future.

Currently, however, the ocean cannot be described as being in a healthy state. On the contrary, like the rest of the planet, our seas are the setting for not just one but three crises, all of which are entirely man-made – climate change, species extinction and growing pollution. On its own, each one of these three crises represents an existential problem for the ocean; taken together, the effects of this "trilemma" are amplified, reverberating, tsunami-like, far beyond their place of origin. The dramatic effects of these crises can now be felt not only in every area of the sea – from the surf zones to the deep-sea trenches, from the tropics to the remote polar regions – but also, and above all, on land, home to millions of people who are increasingly being denied the services that the ocean would normally provide.

In many regions, climate change is now the greatest threat, for it is altering living conditions in the oceans and coastal zones at a rate never previously experienced in human history. The oceans absorb more than 90 per cent of the excess heat and around 25 per cent of anthropogenic carbon dioxide emissions. As a consequence, the chemical and physical properties of the water masses are changing.

The ocean is currently warming more rapidly and to greater depths than at any time since the end of the last Ice Age. In 2020 alone, the upper 2000 metres of the water column in the world's oceans absorbed up to 20 more zettajoules of heat than in 2019. This is enough heat to boil 1.3 billion kettles, each containing 1.5 litres of water. Sea surface temperature has increased by an average of 0.88 degrees Celsius since the start of the 20th century. In 2020, 84 per cent of the global sea surface was affected by at least one marine heatwave.

Due to this warming, mixing of the water masses has decreased. As one outcome of this decline, the world's oceans lost around two per cent of their oxygen content between 1970 and 2010. Over the past four decades, their pH value has also fallen to the lowest level in 1000 years – a new record – while the global sea level is now rising by 3.7 millimetres per annum. In short, the seas are getting warmer, higher, more acidic and more oxygen-depleted, and their water masses are no longer circulating around the globe by their normal routes and at the normal speed. At the same time, the frequency and intensity of extreme events such as heatwaves and storms are increasing. Oxygen-depleted zones are now emerging in increasingly eutrophic coastal waters and, due to the more pronounced stratification of the water masses, in the open sea as well.

Marine organisms can barely cope with these additional stresses, which far exceed their physiological boundaries, often resulting in local mass mortality. Scientists are therefore observing fundamental changes in life in the ocean: mobile species such as cod, lobster, krill and many others are abandoning their traditional territories and migrating poleward or to greater depths; sedentary or less

Overall-Conclusion

mobile species such as molluscs face death from heat exposure.

As a result of these two developments, biodiversity, especially in previously species-rich tropical waters, is declining dramatically, species composition in the middle latitudes is changing and the cold-adapted organisms which inhabit the polar seas are now rarely able to find suitable refuges.

Key events such as algal blooms are occurring earlier in the year in response to the warmer temperatures, disrupting the sea's biological calendar and adversely affecting vital predator-prey relationships. Biodiversity hotspots such as kelp forests, seagrass meadows, mangroves and tropical coral reefs are dying off. The general fitness and reproduction statistics for many species are declining, as is the body mass of individual animals. This shrinking of stocks and populations causes a drop in biomass production. The ocean thus produces less food and material for potential human use. Modelling shows that all these trends will continue unless humanity succeeds in drastically reducing its greenhouse gas emissions and curbing global warming.

Fisherfolk are clearly feeling the effects of climate change already. As a result of marine warming, ocean acidification and oxygen depletion, the productivity of many marine fish species decreased from 1930 to 2010 and in parallel, the global fishing potential shrank by 4.1 per cent over the same period. This is a substantial reduction if it is considered that marine fish and seafood are a staple part of the diet in many regions of the world and that according to official figures, around 179 million tonnes of fish are caught wild or raised in aquaculture facilities annually. Some of the worst-affected regions, such as the North Sea, the Sea of Japan and the Asian seas around the Pacific, have even recorded productivity decreases of 15 to 35 per cent. In other words, as a result of climate change, local fishing communities – assuming that they manage their stocks in accordance with FAO criteria – are catching around one third less fish than their predecessors 90 years ago.

However, this development does little to change the status quo in marine fishing. Oversized fishing fleets continue to chase declining fish stocks, while numerous countries still subsidize the depredation of the seas. In 2018 alone, the ten largest providers of subsidies granted more than USD 5.3 billion in financial support for the operation of their fishing fleets in foreign waters. It is difficult to quantify the resulting damage because half of the fish caught come from stocks that are not subject to any kind of scientific monitoring. According to FAO data, more than one third of the scientifically assessed stocks are now considered overfished. Other studies which also take illegal, unreported and uncontrolled fishing into account assume an even higher figure.

New technologies and information portals now make it easier to control industrial marine fishing. Local projects in the USA, Chile and the Philippines show that previously overfished fish and mollusc populations are often capable of recovering if sustainable, science-based management strategies are introduced or local cooperatives are granted exclusive fishing rights. By contrast, depletion of fish stocks due to overfishing mainly affects regions where there are no controls, and no regulation of industrial fishing.

Will it be possible for the world's growing appetite for marine fish and seafood to be satiated primarily from marine aquaculture in future? Only time will tell. For decades, the construction and operation of aquaculture facilities have resulted in large-scale environmental degradation, and the vast demand for fishmeal has led to the overfishing of wild stocks. What's more, the impacts of climate change are already taking their toll. For these reasons, intensive research is being conducted on strategies, feedstuffs and technologies that would support sustainable and resilient aquaculture. Integrated or ecosystem-based approaches with closed nutrient cycles currently offer the best prospects of success. Major growth potential is also currently predicted for the cultivation of macroalgae – at least in areas where marine warming, ocean acidification and oxygen depletion still allow this to take place.

Macroalgae such as seagrass and kelp not only produce oxygen and sequester carbon; they also filter out nutrients from the water and thus help to clean the ocean. With eutrophication and marine pollution increasing, however, these natural filtration systems are overwhelmed. According to United Nations estimates, every year, around 400 million tonnes of pollutants are discharged into the sea. They include thousands of chemicals, nutrients, plastics and other synthetic materials, toxic heavy metals, pharmaceutical substances, cosmetic products, pathogens, radioactive substances and many more. The drivers include the increasing production and use of these substances, but also their incorrect disposal. Around 80 per cent of pollutants identified in the sea originate from land-based sources.

Evidence of this worsening persistent pollution can now be found in all regions of the world's oceans. Wastes and substances toxic to the environment are not only a hazard to marine life; they also pose a threat to the health and livelihoods of anyone who relies on the ocean as a source of food or income. Particular damage is caused by toxic substances which are not readily degraded in nature and therefore bioaccumulate in food webs. These and other pollutants cause disease, deformities and behavioural changes in marine organisms, impair reproduction and can cause the death of affected individuals. Plastic pollution is particularly significant nowadays: experts have identified at least 700 animal species for which plastic in the ocean can be a deadly hazard. Like water and nutrients, microplastic particles now migrate in their own separate cycle through all the individual components of the Earth system.

Although various initiatives have been launched, the international community has not yet succeeded in curbing the input of pollutants into the seas, partly because the environmentally harmful effects of new chemicals are generally recognised far too late. Only the global ban on selected persistent organic pollutants (POPs) is having an effect – the concentrations of these pollutants in the sea are gradually declining. Long-term progress in tackling marine pollution will therefore only be achieved once there is a substantial reduction in fertilizer use, a large proportion of households and businesses around the world are connected to well-functioning sewage and solid-waste management systems, substances toxic to the environment and oil-based plastics are replaced by biodegradable alternatives, and the use of chemicals and plastics is limited to closed-loop systems.

In view of the crises facing the planet, a radical transformation of international merchant shipping is necessary as well. This ever-expanding branch of the economy accounts for around three per cent of global greenhouse gas emissions, while noise from ships, sewage, garbage and invasive species put pressure on coastal ecosystems around the world. Equipping the merchant fleet, comprising almost 100,000 vessels, with low-emission propulsion systems or replacing the fleet with new ships would be a mammoth, global-scale project in both technological and financial terms.

It would require very substantial investment in the development of new propulsion systems and alternative fuels, as well as legal and fiscal measures to provide investors with planning security, a supranational tax on greenhouse gas emissions and strict controls by the flag and port states to verify compliance with uniform regulations.

The International Maritime Organization (IMO) aims to reduce the merchant fleet's carbon dioxide emissions by 2050 to half of the amount released in 2008. At the same time, coastal nations are facing the challenge of protecting their ports from the impacts of advancing climate change while minimizing greenhouse gas emissions from port operations. Some of the direct environmental impacts of shipping are already being addressed through international regulation; with others – noise pollution from shipping traffic, for example – there is still a great deal of catching up to do.

The more the Earth warms, the more important the ocean becomes for humanity, for it is clear that the ocean has a vital role to play in achieving the greenhouse gas

Overall-Conclusion

emissions reductions that are such an urgent necessity. The world's oceans are needed for at least two transformation processes – as a direct source of energy, and likely also as a source of raw materials. Despite the expansion of renewable energies, the age of offshore oil and gas production is far from over. New marine deposits are still being developed, most of them at greater depths than before, and at greater distances from the coasts. More than a quarter of global fossil resource production now comes from the sea. Another option being considered at present is to make more use of exhausted subsea natural gas deposits as storage sites for liquefied carbon dioxide. The necessary technologies already exist and initial pilot projects are under way, with more currently at the planning stage.

At the same time, more offshore wind farms are being constructed worldwide, also at increasing distances from the coasts to take advantage of better wind conditions on the open sea. Due to technological advances, modern wind turbines are much larger and produce more power than earlier models. As a consequence, the prices of green offshore wind power are falling and demand is growing.

Due to the immense potential of offshore wind energy, it is one of the key technologies for sustainable energy production. Alternatives such as wave and current power plants, offshore photovoltaic arrays, and biofuel production from algae are all still in the developmental stage but play a significant role in long-term forward planning.

However, the expansion and large-scale use of renewable offshore energy will fail unless an adequate and appropriate infrastructure and storage systems are in place. Their manufacture requires vast amounts of raw materials, whose extraction on land destroys habitats for human communities and wildlife.

Resource extraction in the ocean, especially in the deep sea – where deposits contain a great variety of metals and minerals – is a conceivable alternative. The exploitation of these deposits is becoming increasingly likely, despite worldwide protests by environmentalists. The International Seabed Authority (ISA) has already issued 31 licences for the exploration of mineral resources on the sea floor. Initial extraction technologies have been tested on site and studies on environmental impacts and environmental monitoring have been conducted. The ISA is currently drafting a set of rules for deep-sea mining in international waters, which, according to experts, could commence within five to ten years.

Humanity's growing claims on the sea are also the subject of negotiations on a new international agreement to regulate the conservation of marine biological diversity. One of the topics being discussed in this context is the question of who should benefit, and to what extent, from marine genetic resources, i.e. the blueprints encoded in the genome of marine organisms that determine the unique diversity of their forms and functions. Nowadays, scientists are successfully decoding this information ever more rapidly in order to extract the formulas for marine natural products or active ingredients. The range of their potential applications is substantial, as are the profits which, it is hoped, will be generated as a result.

Marine natural products and substances are already found in a wide variety of applications. They are active ingredients in 17 licensed pharmaceuticals and are used in food supplements and fertilizers. They provide raw materials for cosmetics manufacturing and various other industrial applications. It is likely that many more applications will be feasible and sustainable in future. However, the international community must agree collective rules on conservation and use which would guarantee that the benefits of marine biodiversity are shared as widely as possible rather than accruing to a few select individuals.

If the pressure of human use increases while the three crises facing the ocean continue unabated, the collapse of marine ecosystems is surely only a matter of time. And yet the ocean's biotic communities often show remarkable resilience. They are able to recover if humanity gives them enough time and space and drastically reduces all the various stress factors.

For nearly four decades, the United Nations Convention on the Law of the Sea (UNCLOS) has provided the overarching legal framework for governance of the ocean. It classifies the marine areas into zones and regulates in which zones coastal states may exercise sovereign jurisdiction and in which areas international rules apply. It also requires the international community to protect and preserve the marine environment and establishes mechanisms for conflict resolution.

Detailed provisions on the sustainable use of the ocean are absent from the Convention. Instead, this topic is regulated in numerous national, transregional and international conventions or agreements, which generally focus on a single issue or economic sector and do not take interacting factors into account.

The same tunnel vision also afflicts many marine management organizations. A lack of cooperation and coordination across sectors causes conflicts of interest and lessens the prospects that any action taken will be successful. Furthermore, poorer coastal states in particular often lack the expertise, financial resources and the necessary technologies and structures to implement international rules in their national waters.

The lack of transparency in decision-making on marine policy and the failure to provide for the – crucial – involvement of local communities have been identified as other drivers of the crises facing the seas.

If the current crises affecting the ocean have taught us anything, it is this: they cannot be viewed in isolation from what is happening on land, in the atmosphere and within society. Ocean recovery will therefore only succeed if humanity makes change happen on multiple fronts. Sustainable marine management faces a mammoth task: it must overcome multiple challenges simultaneously. For example, it must:

- be designed, funded and implemented on a trans-zonal, trans-sectoral and, where appropriate, trans-boundary basis;
- genuinely involve all stakeholders – including affected local communities, above all – in decision-making from the outset;
- be transparent, socially just and open to innovative niche solutions;
- aim to strengthen marine ecosystems and, as far as possible, restore degraded marine and coastal habitats;
- apply measures that offer the greatest benefits for climate change mitigation, biodiversity conservation and local communities;
- abolish environmentally harmful subsidies and invest the funds in projects that focus on sustainability;
- ensure that as far as possible, all decisions are science-based, and that evaluation measures are planned to ensure regular monitoring of progress.

In short, humanity must decide collectively how it wishes to strengthen the marine environment and make sustainable use of its many spaces and resources.

Expert opinions differ on the scope of the structural changes required to initiate this process and achieve all the goals. While some experts believe that a radical transformation of our economic and value systems is necessary in order to halt global climate change, species extinction and the pollution crisis, others argue that the existing rules and regulations pertaining to the marine environment should first be implemented consistently. Only then, they say, will it be possible to assess whether more far-reaching changes are necessary in ocean governance.

Whichever path is chosen by those responsible, progressing ocean recovery can only succeed through collective action. A further prerequisite is recognition of the acute problems facing the ocean, along with an understanding of how the effects of the many anthropogenic stress factors are amplified through their interaction and which potential solutions are available. Just like ten years ago, when we published the first *World Ocean Review*, we hope that this new edition will "make at least a small contribution towards steering a sustainable course".

Glossary

Intergovernmental Panel on Climate Change (IPCC): This is a United Nations body founded in 1988. It tasks hundreds of scientists around the globe with compiling, at regular intervals, the current state of research on climate change and assessing it. In other words, these scientists present the causes, implications and risks of climate change and identify ways in which humankind can mitigate and adapt to it. The three working groups of the IPCC publish their findings in Assessment Reports that are sometimes called *World Climate Reports*.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES): This is a scientific council established in 2012. It is an organization within the United Nations system. IPBES advises policy-makers on the issues surrounding the sustainable use of nature and its biodiversity and services, and publishes regular assessment reports on biodiversity-related topics. Its work is supported by more than 1000 scientists around the globe. They all contribute their expertise without pay and on a voluntary basis.

Paris Climate Agreement: The Paris Climate Accords, as the treaty is also known, form the first comprehensive and legally binding climate agreement by the international community. Adopted by 196 states on 12 December 2015 at the United Nations Climate Change Conference in Paris, the Agreement sets a global framework for combatting climate change. It aims to hold the increase in the global average temperature to well below two degrees Celsius above pre-industrial levels by means of drastic reductions in greenhouse gas emissions. In the best case, the temperature increase is to be limited to 1.5 degrees Celsius. Moreover, the developing countries in particular are to be assisted in efforts to adapt to the impacts of climate change. The Agreement entered into force on 4 November 2016 after 55 countries had ratified it which are jointly responsible for at least 55 per cent of global emissions.

Precautionary principle: This is a guiding principle of international environmental policy. It calls for human societies to act in good time and with foresight when intervening in natural systems, in such a way that environmental hazards do not arise in the first place. Germany's Federal Environment Agency notes that the principle has two dimensions: risk foresight and resource foresight. Risk foresight (also termed risk prevention) means that, in the event of incomplete or uncertain knowledge about the nature, extent, probability and causality of environmental damage and hazards, a precautionary approach must be taken that prevents such damage or hazards from the outset. Resource foresight means handling natural resources such as water, soil and air with a view to their long-term conservation in the interest of future generations.

Representative Concentration Pathways (RCPs): The term refers to four selected scenarios that were utilised in international climate modelling and in the *Fifth IPCC Assessment Report* to facilitate simulations with diverse climate models and render their outcomes comparable. Scenarios set certain parameters for the climate models and thus define a certain scope that would otherwise need to be determined at considerable cost and effort. The scenarios consist mainly of numerical tables. These combine times series of the potential future trajectories of greenhouse gas emissions, aerosol concentrations in the atmosphere, land use and vegetation – all to the year 2100. Furthermore, they take account of assumptions concerning the trajectories of population growth, economic development and fossil energy consumption. On this basis, the RCP scenarios provide time series of anticipated greenhouse gas concentrations and of the radiative forcing that results from each concentration.

Shared Socioeconomic Pathways (SSPs) are selected scenarios that were produced to supplement the Representative Concentration Pathways (RCPs) and are thus slightly more recent. They take socioeconomic factors into account, depicting five different societal development trajectories – ranging from a future characterised by active climate policy to one in which there is no climate or environmental protection policy at all. In the latter trajectory, termed SSP5-8.5, humankind puts its faith entirely in market forces, technological progress and fossil resources such as coal and mineral oil. In other words, the SSP scenarios can be employed to test the climate impacts of policy decisions. The SSP scenarios provide a basis for calculating the future development of temperatures in a manner complementing the RCP scenarios.

The Glossary explains the meaning of specialist terms which are particularly important for an understanding of the text but which cannot be defined in the individual chapters due to space constraints. Glossary terms are printed in **bold** in the body of the *Review*, making them easy to identify.

Abbreviations

ABMT Area-based Management Tools

ABNJ Areas Beyond National Jurisdiction

AIS Automatic Identification System

AMOC Atlantic Meridional Overturning Circulation

ARGO Array for Realtime Geostrophic Oceanography

ASC Aquaculture Stewardship Council; quality label for socially and ecologically sustainable aquaculture

AZT Azidothymidine; medication

BASF German chemical group

BBNJ Biodiversity Beyond National Jurisdiction

BGR Bundesanstalt für Geowissenschaften und Rohstoffe; German Federal Institute for Geoscience and Natural Resources

BSH German Federal Maritime and Hydrographic Agency

CAMLR Convention on the Conservation of Antarctic Marine Living Resources

CARA Circum Arctic Resource Appraisal

CBD Convention on Biological Diversity

CCAMLR Commission for the Conservation of Antarctic Marine Living Resources

CCS Carbon Capture and Storage

CCZ Clarion-Clipperton Zone

CKW Chlorinated hydrocarbons

CLCS Commission on the Limits of the Continental Shelf

CLIA Cruise Lines International Association

CMI China Merchants Industry Holdings

COSCO China Ocean Shipping Company

DDT Dichlorodiphenyltrichloroethane; insecticide

DNA Deoxyribonucleic acid

ECA Emission Control Area

EEZ Exclusive economic zone

EIA Environmental Impact Assessment

EOR Enhanced Oil Recovery (for example injection of gases)

EPA Environmental Protection Agency

EPPPs Environmentally Persistent Pharmaceutical Pollutants

EU European Union

FAO Food and Agriculture Organization of the United Nations

FDA U. S. Food and Drug Administration

GFCM General Fisheries Commission for the Mediterranean

GPML Global Partnership on Marine Litter

HELCOM Baltic Marine Environment Protection Commission (Helsinki Commission)

ICCAT International Commission for the Conservation of Atlantic Tuna

ICES International Council for the Exploration of the Sea

ICS International Chamber of Shipping

IEA International Energy Agency

ILO International Labour Organization

IMO International Maritime Organization

IOC Intergovernmental Oceanographic Commission

IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC Intergovernmental Panel on Climate Change

ISA International Seabed Authority

IUCN International Union for the Conservation of Nature

IUU-fishing Illegal, unreported and unregulated fishing

IWC International Whaling Commission

JOGMEC Japan Oil, Gas and Metals National Corporation

LED Light-emitting diode

LNG Liquefied Natural Gas

MARPOL International Convention for the Prevention of Marine Pollution from Ships

MOU Memorandum of Understanding

MPA Marine Protected Area

MSC Marine Stewardship Council; non-profit organization, founded of WWF and Unilever for certification of products from sustainable fishing

MSY Maximum Sustainable Yield

NAFO Northwest Atlantic Fisheries Organization

NATO North Atlantic Treaty Organization

NbS Nature-based Solutions

NDCs Nationally determined contributions

NEAFC North East Atlantic Fisheries Commission

NSR Northern Sea Route

OECD Organisation for Economic Co-operation and Development

OMZ Oxygen Minimum Zone

OOC Our Ocean Conference; annual event

OSPAR Oslo and Paris Conventions; Convention for the Protection of the Marine Environment of the North-East Atlantic

PAHs Polycyclic aromatic hydrocarbons

PCBs Polychlorinated biphenyls

PFAS Per- and polyfluoroalkyl substances

POPs Persistent organic pollutants

ppm Parts per million

PSMA Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing

RCPs Representative Concentration Pathways

RFB Regional Fisheries Body

RFMO Regional Fisheries Management Organisation

RNA Ribonucleic Acid

RP Reference point

SAICM Strategic Approach to International Chemicals Management

SCR Suez Canal Route

SDGs Sustainable Development Goals

SOLAS International Convention for the Safety of Life at Sea

SSPs Shared Socioeconomic Pathways

TAC Total Allowable Catch

TBT Tributyltin

TNT Trinitrotoluene; explosive material

TURFs Territorial use right in fisheries

UNCLOS United Nations Convention on the Law of the Sea

UNCTAD United Nations Conference on Trade and Development

UNEA United Nations Environment Assembly

UNEP United Nations Environment Programme

UNFCCC United Nations Framework Convention on Climate Change

USGS United States Geological Survey

UV Ultraviolet

WBGU Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen; German Advisory Council on Global Change

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Chapter 1
Our oceans – source of life

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Contributors

Many experts have contributed their specialized knowledge to the compilation of the *World Ocean Review* in 2021. These included, in particular, scientists working in one of the member institutions of the German Marine Research Consortium (KDM).

Dr. Martina Blümel is a microbiologist working under the direction of Prof. Dr. Deniz Tasdemir in the Marine Natural Products Chemistry research unit of the GEOMAR Centre for Marine Biotechnology at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. Her investigations concentrate on the components of marine fungi from which medicines and other multi-functional agents may be derived. As an expert in biotechnological processes, however, she also assists team members who are working with other marine organisms, including brown algae from the Baltic Sea. She also develops new techniques for cultivating fungi and other marine microorganisms in the laboratory. She is actively involved in the project management of the working group, and is responsible for the smooth workflow of all laboratory work at GEOMAR Biotech.

Dr. Kathrin Fisch is a chemist working as a post-doc in the Marine Chemistry section at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW). Her primary interest is the analysis of modern pollutants in the marine environment and, in connection with the *MEGAPOL* project, she is presently investigating the distribution of pharmaceuticals, body-care products (e.g. UV filters), and pesticides in the sediment layers and water column of the South China Sea. These studies are basically a continuation of her doctoral thesis, in which she developed new detection methods for pesticides, pharmaceuticals and cosmetic products in marine waters.

Dr. Dieter Franke is a research specialist for energy resources at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover. One of the objectives of BGR research and analysis is to contribute to the security of Germany's supply of energy resources. To this end, within various projects, Dieter Franke not only investigates potential natural gas and oil resources on land and in the sea, but also works with colleagues to prepare country studies and methodology reviews, and regularly reports on market developments in the energy sector. In addition to publishing their findings in scientific journals, the specialists produce a newsletter in the form of the annual *BGR Energy Data*, and also publish the *BGR Energy Study – Data and Developments Concerning German and Global Energy Supplies*, which appears every two years.

Torsten Frey studied environmental and economic sciences. He is now a research specialist for management issues at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, focussing on munition waste sites in the sea. Currently, in collaboration with partners in the European *BASTA* (Boost Applied munition detection through Smart data inTegration and AI workflows) project, he is working to improve methods for detecting submerged munitions. These efforts have two major goals: First, the scientists want to facilitate the search for underwater munitions by optimizing tools like high-resolution echosounders or submersible vehicles for visual and magnetic detection of the materials. Second, they store all of the measurement data obtained in a database, and analyse them with the help of artificial intelligence and machine learning. This should make it possible to find and identify the sites of dumped munitions in the sea more quickly, efficiently and economically than ever before.

Dr. Rainer Froese a fisheries biologist at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, investigates the condition of fish stocks around the world, develops approaches towards sustainable fisheries management, and is a co-founder of the FishBase database (fishbase.org), the largest scientific database for fish species in the world. One of his areas of focus is the assessment of fish stocks for which sparse data is available. Because this is true for three-fourths of all the fish stocks in the world, he and his colleagues have developed methods to estimate stock sizes and levels of fishing that work with only a fraction of the data normally required. These have made it possible to carry out at least preliminary surveys for many fish stocks. Rainer Froese has authored or co-authored more than 100 scientific publications, is one of the most frequently cited of marine scientists, and, in 2020, received the Ocean Award in the category "Most Influential Scientist for Marine Conservation in 2019".

Prof. Dr. Jens Greinert is a geologist, a recognized expert in the development of instrumentation, and leader of the Deep Sea Monitoring Research Unit at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. After many years of building and testing new research technology for exploring the deep sea, he is now concentrating on developing new methods for detecting, monitoring and recovering dumped munitions in the sea. He coordinates several German and European research projects on this topic, particularly those related to the German Baltic and North Seas, devises recommendations for politics and administration, and manages the development of databases and information portals. One of his major goals is to establish a European-level centre of excellence for munitions to investigate the ecological impacts and provide competent guidance in the monitoring and disposal of the millions of tons of old munitions and explosives in European waters.

Dr. Lars Gutow is one of Germany's best-known experts on the impacts of microplastics on marine communities. For more than a decade, the marine biologist, working at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven, has been researching the extent to which various marine organisms ingest plastic particles and the physical reactions that the foreign particles cause. He is co-editor of the widely read textbook *Marine Anthropogenic Litter*, and is an expert contributor to several working groups and technical commissions.

Prof. Dr. Julian Gutt is a marine ecologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. He studies benthic communities of the Southern Ocean in terms of their diversity, ecosystem functions and vulnerability to environmental change. To this end, he primarily uses imaging methods as they spare the ecosystem from damage and depict the benthic communities in their natural state. He has conducted these investigations in the course of numerous expeditions to the Arctic and Antarctic, twice as chief scientist on board of the German research icebreaker *Polarstern*. Julian Gutt contributes his expertise and many years of experience to numerous international organizations, such as the Scientific Committee on Antarctic Research (SCAR) and the policy-advising Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Dr. Stefan Hain heads the Environmental Policy Staff Unit at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. Among other roles as part of this function, he is the institute's contact person for the Federal Environment Agency (UBA), Germany's regulatory body for all activities within the remit of the Antarctic Treaty. The marine biologist completed his doctorate at the AWI and then worked at the interface of science and policy for more than 25 years – first as deputy secretary of the Oslo-Paris Commission (OSPAR) in London, then as Head of the Coral Reef Unit of the United Nations Environment Programme in Cambridge, United Kingdom. In 2009 he returned to the AWI and since then he has been working as the institute's environmental policy spokesperson, coordinating AWI's contributions to a variety of international processes which could potentially impact on the institute's research activities. In this capacity he vigorously promotes efforts to establish a Marine Protected Area in the south polar Weddell Sea, and monitors the international negotiations on the Third Implementing Agreement on the conservation and sustainable use of biological diversity in areas beyond national jurisdiction.

Dr. Amir Haroon is a marine geophysicist specializing in electromagnetics at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. He is a member of the working group of Dr. Marion Jegen-Kulcsar, and specializes in geophysical applications in coastal regions. His work primarily involves developing measurement technology to search for groundwater reservoirs beneath the seafloor and evaluating the data obtained.

Dr. Katja Heubel heads the Coastal Ecology working group at the Research and Technology Centre West Coast (FTZ) of Kiel University (Christian-Albrechts-Universität zu Kiel – CAU) in Büsum. In various projects, the biologist investigates the interactions among individual marine organisms, populations and communities, and how both individuals and entire communities react to anthropogenic stress factors such as noise and climate change. Her studies frequently involve gobies, whose behavioural changes and adaptive strategies she has analysed in detail. She is currently investigating the influence of underwater noise on acoustic communication and on predator-prey relationships between zooplankton and fish. She is also addressing the question of how species that have recently migrated or been introduced into the North Sea integrate with or alter the established communities.

Dr. Jan Hoffmann is a transportation and shipping expert who has headed the Trade Logistics Branch of the United Nations Conference on Trade and Development (UNCTAD) in Geneva since 2016. He and his team conceive and implement education and training programmes on trade and transport in Africa, Asia, the Pacific region, Latin America and the Caribbean. In addition, they publish the annual *UNCTAD Review of Marine Transport* and provide information on current developments in world trade and transport, especially in shipping, through a number of other publications.

Dr. Marion Jegen-Kulcsar is a geophysicist at the GEOMAR Helmholtz Centre for Ocean Research in Kiel and an expert in marine electromagnetics. She and her colleagues use these techniques, originally developed for deep-sea research, to explore for freshwater reservoirs beneath the sea floor. In one current research project, for example, they are mapping occurrences of freshwater off the coast of the Mediterranean island of Malta, whose water reserves on land are being depleted due to drought and increased consumption. Marion Jegen-Kulcsar and her team are developing the measurement technology themselves, which is why they are one of the few research groups worldwide using marine electromagnetics in this way.

Dr. Marion Kanwischer is a biotechnician and research scientist in the marine chemistry section of the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), and heads the Analytics Group of the institute's organic trace substance laboratory. With her team, she regularly examines water samples from the Baltic Sea for the presence of persistent organic pollutants, such as chlorinated hydrocarbons and polycyclic aromatic hydrocarbons. Marion Kanwischer also develops and tests new methods for detecting organic trace substances in the marine environment. These include pesticides such as glyphosate, for example, but also natural organic phosphorus compounds like methylphosphonic acid.

Dr. Ulrike Kronfeld-Goharani is a physical oceanographer and interdisciplinary marine researcher. As a research fellow, she teaches and carries out research in the group for International Political Sociology at the Institute of Social Sciences of Kiel University (CAU) in Kiel. The focus of her research is sustainable development. She is especially interested in socio-ecological transformations in coastal regions due to maritime tourism, business sustainability in the maritime economy, and the development of approaches towards a more sustainable management of the high seas. She is currently exploring the roles that narratives play in the prevalent discourses about the ocean, and how new narratives can be developed to promote more sustainable use of the ocean.

Dr. Thomas Kuhn is a researcher in marine geology at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover and is a recognized expert on mineral resource deposits in the deep sea. His scientific career began in 1999 with a doctoral thesis on the geochemistry of ferromanganese crusts and deep-sea sediments. Since 2010 he has been studying the geology of manganese nodules in the Pacific and regularly participates in research expeditions to these marine regions. He contributes his expertise to assessing the deposits and is involved in projects to develop methods for the metallurgical processing of marine mineral resources. Since 2020 he has been in charge of the exploration for massive sulphide occurrences in the German contract area of the Indian Ocean.

Dr. Holger Kühnhold is a scientist in the Experimental Aquaculture working group of the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. As a marine biologist, he performs research at the interface between ecophysiology and aquaculture. His research is centred on utilizing marine invertebrates (for example, sea cucumbers and jellyfish) and aquatic plants (such as duckweed) for human consumption. One aspect of this involves the determination of optimal culture conditions for highly promising target species in a variety of aquaculture systems. Another is the extent to which environmental parameters such as temperature, light quality and UV radiation must be manipulated in order to increase the specific production of important nutrients. His research work should contribute to an improved use of biomass at the lower end of the marine food chain for long-term global food security.

Dr. Andreas Kunzmann is a marine and fisheries biologist, and heads the Experimental Aquaculture working group at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. His research focusses on the development of sustainable, environmentally sound methods in aquaculture, but also on the issues of the altered living conditions that fish and invertebrates are exposed to in aquaculture farming, the extent to which they are able to adapt, and how much fish and seafood can be produced in marine aquaculture in the future. For these purposes, the investigations of Andreas Kunzmann and his working group include ecophysiological studies of the stress metabolism of fish (oxygen consumption, energy production) at different life stages. In addition, the researchers are studying whether and how new aquatic food sources known as "novel foods", such as jellyfish, sea cucumbers or green caviar, can be cultivated and used as healthy food in the future.

Dr. Felix Mark is a marine biologist and research scientist at the Integrative Ecophysiology Section of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. He has specialized in physiological adaptation mechanisms of marine ectotherms and investigates the organisms' responses to marine warming, ocean acidification and oxygen depletion, from the organism as a whole down to the molecular level, and with a particular focus on polar fish. Felix Mark undertakes regular expeditions to the polar seas and was the consortium leader of "Theme 3: Ocean Acidification and Warming Impacts Across Natural Systems and Society: From Mechanisms to Sensitivities and Societal Adaptation" as part of the major German research programme on Biological Impacts of Ocean Acidification (BIOACID). Furthermore, in recent months he co-authored the third chapter (Oceans) of the contribution of Working Group II to the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, which is due to be published in February 2022.

Prof. Dr. Nele Matz-Lück is a lawyer and has held a Professorship of Public Law, with a focus on international law and the law of the sea, at Kiel University since 2011. She is also co-Director of the Walther Schücking Institute for International Law. In addition, she serves as spokesperson for the "Future Ocean" network, was a member of the steering committee of Kiel Marine Science, the University Centre for Interdisciplinary Marine Science, for several years, and is a judge on the Constitutional Court of Schleswig-Holstein. In June 2020, at the recommendation of the German government, she was added to the list of arbitrators and conciliators under Annex V and Annex VII of the United Nations Convention on the Law of the Sea. Her research and publication activities are focussed on the international law of the sea, international environmental law and the law of international treaties.

Dr. Katja Mintenbeck was a marine biologist in the Integrative Ecophysiology section at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven until 2017. Her work there focussed on the ecology of Antarctic marine communities, and specifically on the sensitivity of Antarctic fish response to disturbances and environmental change. Since then, she has been working as the Scientific Director of the Technical Support Unit of Working Group II of the Intergovernmental Panel on Climate Change (IPCC). In this function, among other duties, she was responsible for the IPCC Special Report *The Ocean and Cryosphere in a Changing Climate*, which was published in September 2019, and Volume II of the *IPCC Sixth Assessment Report*, which is scheduled for publication in February 2022.

Prof. Dr. Christian Möllmann is a fisheries biologist and managing director of the Institute of Marine Ecosystem and Fishery Science at the University of Hamburg. His research examines structural and functional changes in marine ecosystems under anthropogenic pressures such as climate change and fishery exploitation. The aim of his work is to contribute to sustainable, ecosystem-based management. His approach to research is generally based on the natural sciences, but he is increasingly adopting transdisciplinary methods that involve direct interaction and knowledge-building with non-scientific individuals and groups. Christian Möllmann is one of the authors of the *Sixth Assessment Report* of Working Group II of the Intergovernmental Panel on Climate Change.

Prof. Dr. Andreas Oschlies is an oceanographer, and head of the department of Biogeochemical Modelling at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. His research interests include the physical, biogeochemical and ecological processes of carbon uptake by the ocean and possible changes in these as a result of climate change. For example, he and his team develop biogeochemical models to investigate changes in the oxygen content of the oceans and the resulting ecological impacts. In addition, Andreas Oschlies heads and coordinates large research projects related to the scientific assessment of potential climate engineering techniques, as well as a new collaborative project on marine carbon sinks.

Prof. Dr. Konrad Ott is a philosopher and Professor for Philosophy and Ethics of the Environment at Kiel University. In recent years, his research has focused primarily on "strong sustainability" issues, the practical dimensions of nature and biodiversity conservation, climate change, water resources, agriculture, restoration and the ethical aspects of geoengineering. He is currently elaborating the foundations of environmental ethics and sustainability in the realm of social theory. He further contributes to numerous transdisciplinary research projects addressing, for instance, management strategies for highly radioactive residues, climate ethics, natural climate solutions and the ethical foundations of marine conservation.

Dr. Elvira Poloczanska is a marine biologist and acknowledged expert on climate-induced changes in marine ecosystems. For over 15 years she has been studying the responses of marine biological communities, especially fish, to rising water temperatures, increasing acidification and persistent oxygen depletion. With the help of ecosystem models, she investigates the further climate consequences that can be expected in the course of progressing global warming, and the adaptive capacities of marine organisms as well as the people and economic sectors that depend on them. Elvira Poloczanska was a lead author on the *IPCC's Fifth Assessment Report* and is presently serving as scientific advisor to the two co-chairs of IPCC Working Group II, and the Technical Support Unit on the *Sixth Assessment Report* of that Working Group (impacts, adaptation and vulnerability).

Prof. Dr. Hans-Otto Pörtner is a marine biologist performing research at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven, where he heads the Integrative Ecophysiology Section. He is also one of the two co-chairs of Working Group II of the Intergovernmental Panel on Climate Change. During his scientific career Hans-Otto Pörtner has developed ground-breaking theories on the impacts of ocean warming, ocean acidification and oxygen deficiency on marine organisms and ecosystems, and has validated these in numerous studies. Two of his seminal topics involve the molecular, biochemical and physiological mechanisms that determine the tolerance, performance and adaptive capacity of marine animals, and whether and how these mechanisms apply universally to all animals, including humans. His technical publications are currently among the most-cited works in the field of climate and ocean research. He is an elected member of the European Academy of Sciences and was appointed by the German government to its Advisory Council on Global Change (WBGU) in 2020.

Dr. Carsten Rühlemann heads the Exploration Group of the Marine Geology section at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover. From 2006 to 2019 he coordinated the exploration of manganese-nodule occurrences in the German contract area in the Pacific. A globally recognized expert, he has been a member of the Legal and Technical Commission of the International Seabed Authority (ISA) in Kingston, Jamaica since 2020. The marine geologist is interested in all aspects of deep-sea mining, and he was a participant on the latest research expedition to the Clarion-Clipperton Zone in April 2021. On this MANGAN-2021 Expedition, the team of international scientists deployed the manganese-nodule collector *Patania II* made by the Belgian company Global Sea Mineral Resources (GSR) in its first two successful deep-sea operations, and conducted intensive accompanying research to learn more about the possible consequences of manganese-nodule mining for the marine environment.

Dr. Jörn Schmidt is a fishery ecologist and presently adjunct professor of the marine affairs programme at Dalhousie University. He was head of the Marine Food Security research group at the Center for Ocean and Society at Kiel University before taking over the Chair of the Science Committee of the International Council for the Exploration of the Sea (ICES) in August 2020. He had already chaired the ICES Strategic Initiative on the Human Dimension from 2015 to 2019. His work focusses on socio-ecological systems and concepts of sustainability in the ocean, fishery management, science communication, the development of practical management recommendations, and direct interaction with fishermen and women. For example, he is involved with the *Sustainable Nunatsiavut Futures* project, which focusses on the joint production of knowledge related to rapidly changing environmental conditions in Nunatsiavut, northern Canada, and the impact of these on the local communities. Jörn Schmidt was one of the German authors of the *Second United Nations World Ocean Assessment Report*, and since 2021 has been a member of the expert group for the *Third Assessment Report*, which will be published in 2025.

Prof. Dr. Corinna Schrum is an oceanographer and head of the Institute of Coastal Systems – Analysis and Modeling at the Helmholtz Centre Hereon in Geesthacht. Coupled system models are developed at the institute by which processes and complex interactions can be represented and changes in coastal systems can be described. Her research centres on the question of how the elements of land, sea and atmosphere interact in the coastal realm and how the activities of humans directly affect coastal systems. For example, Corinna Schrum and her team analyse the physical, biogeochemical and ecological effects of offshore wind farm construction, and examine the social and planning aspects that need to be considered in advance.

Dr. Klaus Schwarzer worked as a geologist and associate scientist in the Coastal Geology and Sedimentology group at Kiel University (CAU) until his retirement. He is an expert in coastal and nearshore processes and coastal development, and is still active today in investigating how both humans and the sea itself are changing coastal zones in the North and Baltic Sea realms, as well as other marine regions of the world, through sediment displacement or resource extraction. His work also examines the changes to coasts caused by sea-level rise, storm events and tsunamis. In joint projects with biologists, he addresses the extent to which sedimentological changes in coastal regions, on beaches, steep coastlines, mangroves in tropical regions or deltas in estuarine areas alter the living conditions for humans and the native animal and plant species in those areas. This topic also had a great influence on his teaching activities, both in classroom lectures and training sessions on research vessels and excursions. He taught at Kiel University, but also abroad (for example in Brazil, Vietnam and Malaysia) in the framework of research and teaching collaborations.

Prof. Dr. Deniz Tasdemir leads the Marine Natural Products research unit at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, and is also director of the GEOMAR Centre for Marine Biotechnology (GEOMAR Biotech). She has taught on the subject of marine natural products chemistry at Kiel University since August 2014. She began her scientific career researching sponges. She is an award-winning and globally recognized expert in natural marine active substances, now focusing her research on algae and microorganisms in the Baltic Sea and, with her research group, is pursuing the goal of developing drugs to combat cancer, highly contagious diseases, and pest infestation in plants. She also works as a scientific advisor, is on the editorial boards of a number of professional journals in the field of bioactive natural products, and serves on the scientific advisory boards of international research projects and centres.

Dr. Annemiek Vink works as a biologist at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover. She coordinates and is responsible for the numerous investigations there aimed at understanding the environmental impacts that possible deep-sea mining would have on the marine environment and its biodiversity. Since 2019 she has coordinated the exploration efforts for manganese-nodule occurrences in the German contract area in the Pacific. In April 2021, she led the MANGAN-2021 expedition to the Clarion-Clipperton Zone, which included accompanying scientific research on the first successful deep-sea operations of the manganese-nodule collector *Patania II* built by the Belgian company Global Sea Mineral Resources (GSR). She and her team hope that the many new measurement data will allow far-reaching conclusions to be drawn about the environmental risks of potential manganese-nodule mining at an industrial scale, possible measures to reduce the risks, and the monitoring procedures required to adequately oversee possible deep-sea mining.

Prof. Dr. Martin Visbeck is a physical oceanographer, heads the Physical Oceanography Research Unit at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, and acts as co-speaker of the Kiel "Future Ocean" network. In addition, he has been teaching at Kiel University (CAU) since 2004, and is one of the best-known science communicators in Germany on the topic of the world ocean. The scope of his research includes the influence of the ocean on natural fluctuations of the global climate as well as the variability of regional marine currents. Other areas of interest include deep-water formation and the origins of tropical oxygen-minimum zones. Martin Visbeck is active in various committees for the planning and implementation of the UN Decade of Ocean Science for Sustainable Development, and coordinates the international Digital Twins of the Ocean (DITTO) programme.

Prof. Dr. Klaus Wallmann is a geoscientist, leads the Marine Geosystems research department at the GEOMAR Helmholtz Centre for Ocean Research in Kiel, and teaches the foundations of marine biogeochemistry at Kiel University (CAU). His research interests include material turnover at cold seeps and mud volcanoes on the sea floor, the formation of gas hydrates, microbial degradation of organic matter in surface sediments, and the recycling of nutrients from the sediments into the ocean. In addition, he investigates the long-term geochemical evolution of the oceans and the atmosphere, led an EU research project on the consequences of carbon-dioxide storage below the sea floor from 2011 to 2015, and is now participating in a new large project on marine carbon sinks.

Uwe Wichert, is a retired naval officer and a member of the "Bund-Länder-Ausschuss Nordsee-Ostsee" (BLANO) expert panel on munitions in the sea. This group of specialists has taken on the task of compiling, evaluating and reporting all of the available data and information on the dumping of munitions in German marine waters. An important aspect of their work is the examination of historical documents stored in archives in Europe and the USA that contain relevant information. Uwe Wichert coordinates this task and evaluates the information retrieved. This is the starting point for all the steps that follow, from investigations of the current situation to the eventual removal of the munitions waste. All of the expert panel's findings to date are made available to the public in annual updates to the comprehensive report *Munitions in the Sea*.

Julian Wilckens is a certified lawyer focussing on international and administrative law, and heads the Department of Coastal, Marine and Polar Research at Project Management Jülich in Rostock. In this function he advises, among others, the German Research Ministry on international maritime law and assists in international processes, including negotiations within the framework of the Antarctic Treaty System, the International Seabed Authority (ISA), and the Third Implementing Agreement on the conservation and sustainable use of biological diversity in areas beyond national jurisdiction. His main focus in all processes is to secure the freedom of marine research in negotiations and international legislative procedures and to ensure that German marine research has the appropriate leeway to carry out its investigative projects.

Index

Page numbers printed in **bold** draw attention to passages within the text which are especially important for an understanding of the concept in question.

Partners

Future Ocean: The research network harnesses the collective knowledge of marine scientists, economists, medical scientists, mathematicians, IT experts, legal scholars and social scientists in pursuit of the study of oceanic and climate change. A total of more than 250 scientists working at Kiel University (CAU), GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design join forces to develop options for sustainable marine conservation and use.

IOI: The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

KDM: The German Marine Research Consortium combines the broad expertise of German marine research. Its membership comprises all of the research institutes that are active in marine, polar and coastal research. A primary objective of the KDM is to collectively represent the interests of marine researchers to national policy-makers and the EU as well as to the general public.

mare: The bimonthly German-language magazine *mare*, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. *mare's* mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine, which has received numerous awards for its high-quality reporting and photographs, its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

Acknowledgement

Producing a publication like the *World Ocean Review* is a collective effort which relies on the dedication and commitment of a large number of people. I would therefore like to first express my thanks to all the participating scientists for their contributions to this review. I am also most grateful to the organizational team of the German Marine Research Consortium and the The Future Ocean Network in Kiel for ensuring a smooth and uninterrupted communication process and for working so hard behind the scenes.

I further wish to express my particular appreciation to the scientific journalist Sina Löschke, who gave structure to the individual texts and ensured that they could be read and enjoyed by scientists and the general public alike. My sincere thanks also go to designer Anna Boucsein, photo editor Petra Koßmann and Anastasia Hermann, text editor Dimitri Ladischensky, and last but not least Jan Lehmköster, the project manager at maribus, who nurtured the *World Ocean Review* from the beginning and whose leadership helped to shape it into the publication it is today.

Nikolaus Gelpke
Managing Director of maribus gGmbH

Table of figures

Cover: mauritius images/Westend61/Konstantin Trubavin; p. 1 (map): after Athelstan F. 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Spilhaus; fig. 1.10 right: after Diercke-Weltatlas; p. 28/29: Ed Hawkins/Creative Commons, https://showyourstripes.info; fig. 2.1: NSF/US Antarctic Program/Rob Robbins; fig. 2.2: NASA Operation IceBridge/Jeremy Harbeck; fig. 2.3: after Arias et al., 2021; fig. 2.4: after Ed Hawkins/Climate Lab Book; fig. 2.5: Jim West/REPORT DIGITAL-REA/laif; fig. 2.6: after GRID-Arendal; fig. 2.7: after Cheng et al., 2020; fig. 2.8: after Deutsches Klima-Konsortium, 2019; fig. 2.9: Jes Aznar; fig. 2.10: after Vousdoukas et al., 2020; fig. 2.11: after Breitburg et al., 2018; fig. 2.12: after Laffoley and Baxter, 2019; fig. 2.13: Alan Duncan; fig. 2.14: after Laffoley and Baxter, 2019; fig. 2.15: after Schmidtko et al., 2017; fig. 2.16: after Laffoley and Baxter, 2019; fig. 2.17: after Fischer and Knutti, 2015; fig. 2.18: after Virginia Institute of Marine Science; fig. 2.19: after Gimeno et al., 2014; fig. 2.20: NOAA; fig. 2.21: after Hobday et al., 2016; fig. 2.22: after Gruber et al., 2019; fig. 2.23: Greg Rouse/Scripps Oceanography; fig. 2.24: after Dahlke et al., 2020; fig. 2.25: Paulo Oliveira/Alamy Stock Foto; fig. 2.26: © Rich Reid Photo; fig. 2.27: mauritius images/nature picture library/Jürgen Freund; fig. 2.28: Quantifying the Effect of Anthropogenic Climate Change on Calcifying Plankton, Author: Fox, L., Stukins, S., Hill, T. et al., Publication: Scientific Reports, Date: January 31, 2020, Sci. 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