World Ocean Review: Living with the oceans

world ocean review

Living with the oceans. 2010

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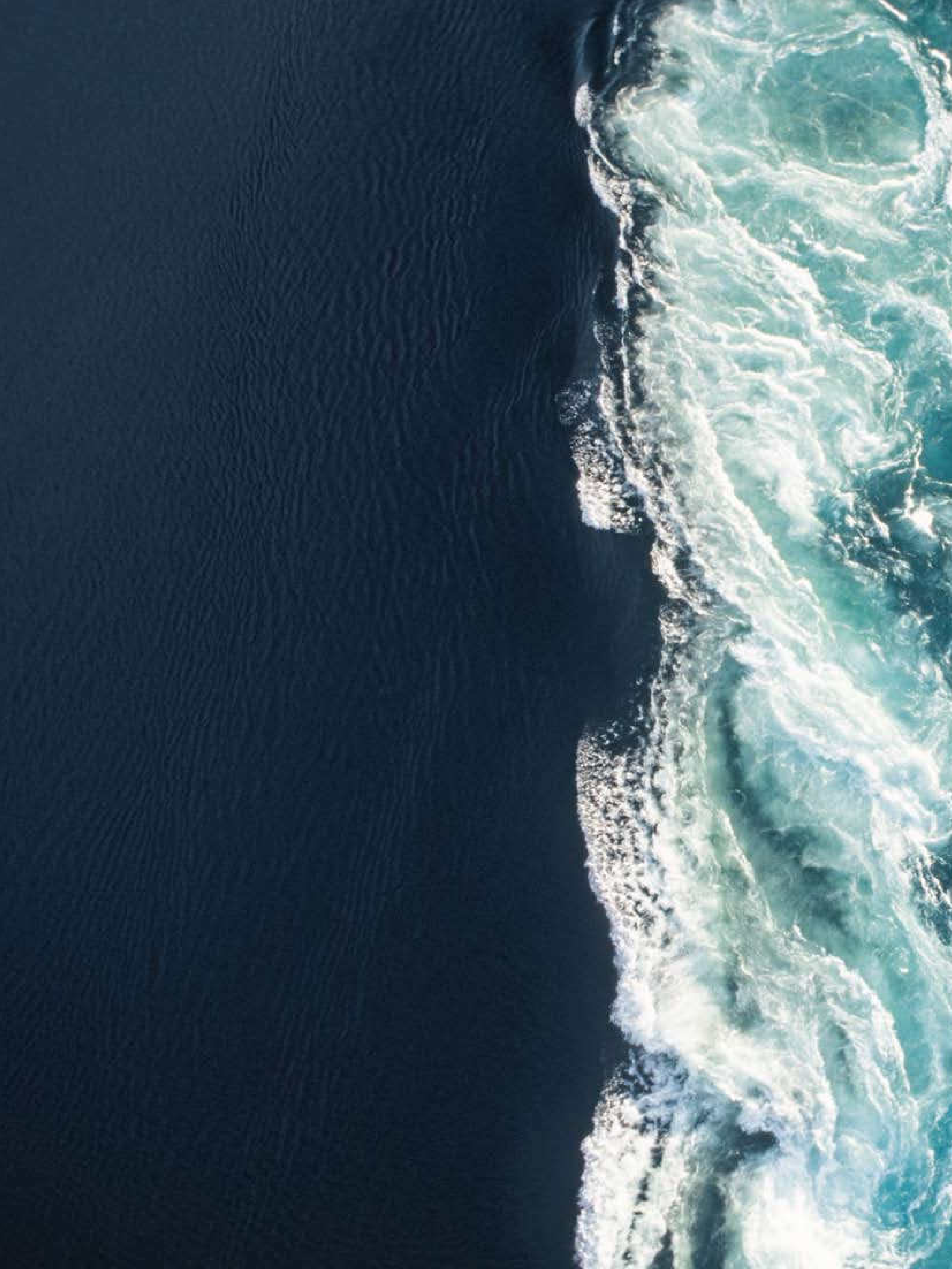

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Preface

Our environmental awareness is steadily increasing, albeit very slowly. This process began when we started to address obvious and visible problems. As a result, our streets, beaches, fields and forests became cleaner, industrial emissions decreased, and our chimneys produced less and less air pollution. When we see that there is a problem and there is scope for advocacy, we take action.

The oceans, however, are vast and largely inaccessible, and our awareness and understanding of them are correspondingly small. What's more, they have hardly any advocates or lobby to represent their interests. This is especially remarkable when we consider that the seas crucially influence our climate and are an increasingly important source of food.

The Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and the Stern Review, published in 2006, created an unprecedented level of awareness worldwide of the problems and impacts of climate change. This sparked the idea of producing a similar type of report for the oceans, which cover three-quarters of the Earth's surface, thus focusing attention on some of the most urgent issues facing us today.

To that end, the publishing house *mareverlag* in Hamburg set up the non-profit company *maribus* two years ago. This was motivated not by commercial interest but by the desire to focus maximum possible attention on the state of the world's oceans. Partners were sought to support the pursuit of this objective, and the International Ocean Institute (IOI) and the non-profit Ocean Science and Research Foundation (OSRF) – both founded by Elisabeth Mann Borgese – joined the project. The IOI provides logistical support, its close association with the work of the United Nations playing an important role in this context. The OSRF provides financial backing for the project.

The key scientific partner is the Cluster of Excellence "The Future Ocean" – a research group made up of more than 250 scientists investigating climate and ocean change at a number of research institutions in Kiel. Drawing on their outstanding expertise and applying an interdisciplinary approach, more than 40 scientists within the Cluster have authored this first *World Ocean Review* (WOR).

The primary purpose of this first review is not to focus on spectacular new findings or launch high-profile appeals. Rather, with its judicious combination of well-researched and substantive content presented in a clear and accessible style – thanks to the cooperation with *mareverlag* – the *World Ocean Review* aims to paint a clear and compelling picture of the complex state of the world's oceans and underline the urgent need for action.

It is up to us to act on this knowledge. We hope that as we look to the future, the *World Ocean Review* will inspire advocacy to protect and preserve our blue planet.

Nikolaus Gelpke
Managing Director of *maribus gGmbH* and *mareverlag* publisher

The scientists in the Cluster of Excellence "The Future Ocean" undertake research in a range of disciplines, evaluating the complex interactions between the oceans and global change and assessing opportunities and risks. But how much do we really know about the state of the oceans today? What do we know about the many influences that come into play in relation to the increasing overexploitation of the seas or climate change, both of which have a direct and indirect impact on the marine environment? What are the limits to our understanding? And can sustainable solutions be devised for the future use of the seas?

Journalists, teachers and interested members of the public often ask us, the scientists, these questions, but they are difficult for individual marine researchers to answer comprehensively. The Kiel-based Cluster of Excellence "The Future Ocean" therefore brings together researchers from many different disciplines – marine scientists, earth scientists, biologists and chemists, as well as mathematicians, economists, lawyers and medical scientists – to engage in joint interdisciplinary research on the marine environment. How can unresolved questions be investigated and reliable answers provided? The diversity of disciplines and research institutions involved in the Cluster of Excellence comes into play here and helps to provide a comprehensive overview of the state of the world's oceans.

The *World Ocean Review* is our attempt to present as realistic a picture as possible of the current state of the oceans. The aim is to draw together findings from the various disciplines and share our knowledge with the general public. We began by identifying the major issues of relevance to the state of the oceans. We asked scientists within the Cluster of Excellence to write about the current situation and topical issues from a variety of perspectives. Professional journalists were on hand to guide the experts with helpful advice on style and the choice of photographs and illustrations.

Readers will observe that many of the topics covered in the various chapters focus on humankind's use and overexploitation of the marine environment. This apparently infinite resource has become finite. As the *World Ocean Review* makes clear, the state of the oceans, as depicted here, gives frequent cause for concern. The outlook on possible developments and consequences of further overexploitation and pollution of the marine environment sadly only reinforces our concern and highlights the important role that preventive research in the field of marine sciences has to play for the future of humankind. The scientists in Kiel wish to make a contribution here.

We wish all the users of this first *World Ocean Review* an interesting and informative read.

Prof. Dr. Martin Visbeck
Chairman, Cluster of Excellence "The Future Ocean"





1 The world oceans, global climate drivers

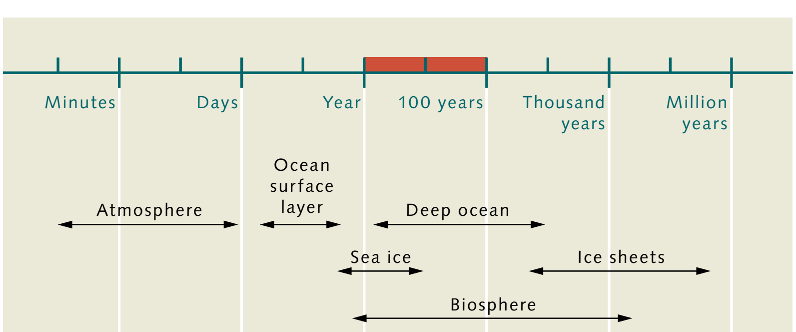
> The oceans cover around 70 per cent of the Earth's surface. They thus play an important role in the Earth's climate and in global warming. One important function of the oceans is to transport heat from the tropics to higher latitudes. They respond very slowly to changes in the atmosphere. Beside heat, they take up large amounts of the carbon dioxide emitted by humankind.

Earth's climate system – a complex framework

> The Earth's climate is influenced by many factors, including solar radiation, wind, and ocean currents. Researchers try to integrate all of these influencing variables into their models. Many of the processes involved are now well understood. But interaction among the various factors is very complex and numerous questions remain unresolved.

The inertia of climate

As we all learned in school, the world's oceans are one of the most important elements in the global climate system. But what does "climate" actually mean? The difference between weather and climate can be expressed in a single sentence: "Climate is what you expect; weather is what you get." This reveals a fundamental difference between weather and climate. Weather research is concerned with the formation, movement, and prediction of the individual elements of weather, such as a particular low-pressure system or a hurricane. Climate research, on the other hand, deals with the more comprehensive totality of low pressure systems and hurricanes, and is dedicated to addressing questions such as how many midlatitudinal storms or hurricanes will occur next year, or whether they will become more frequent or intense in the coming years as a result of global warming. So the term "weather" refers to short-term events in the **atmosphere,** while "climate" relates to longer time periods. For describing climate, as a rule, a time span of 30 years is generally used as a frame of reference.

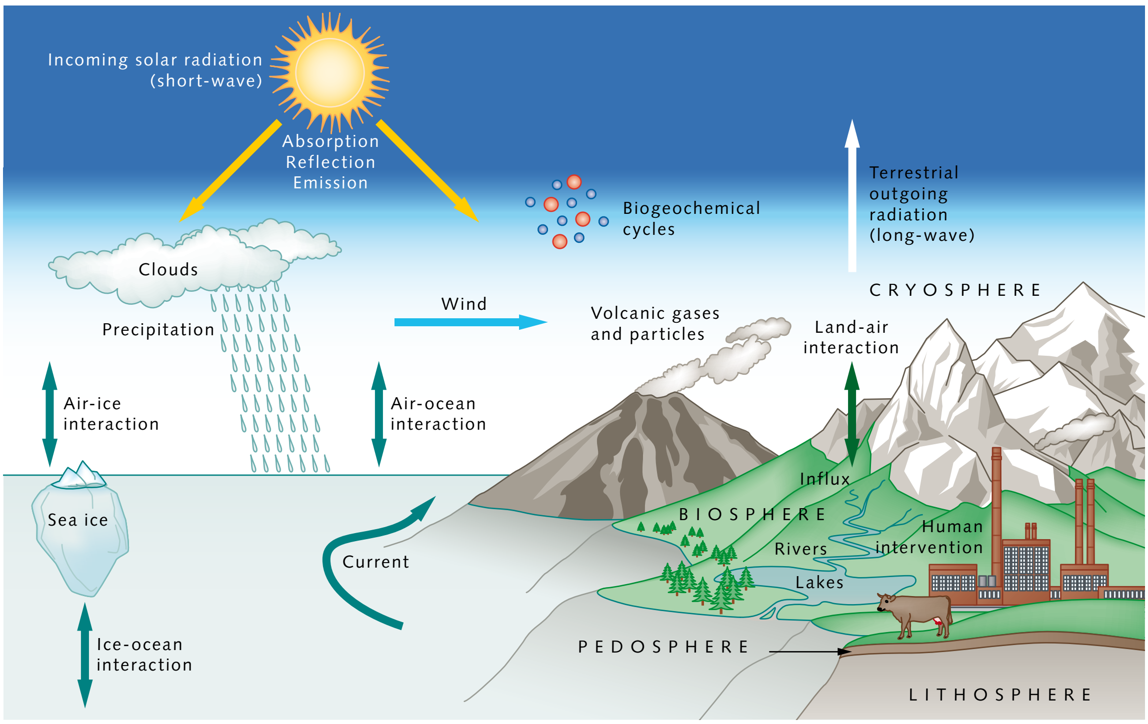


1.1 > Different components of the climate system react to perturbations at different rates. The deep ocean, for example, is an important cause of the slow response of climate. The coloured area on the top scale represents the short time span of a human life.

People mainly perceive climate change as changes in atmospheric variables, for example, variations in temperature or precipitation. In principle, due to its chaotic dynamics, the atmosphere itself can generate many natural climatic changes. One example of this is the **North Atlantic oscillation (NAO),** which significantly influences the climate over parts of Europe and North America. It is a kind of pressure fluctuation between the **Icelandic Low** and the **Azores High** that determines the strength of winter westerly winds across the North Atlantic. If these are strong, the result is mild and rainy weather in Western Europe; if they are weak it is dry and cold. These kinds of natural oscillations make it difficult to recognize anthropogenic climate changes due to an enhanced greenhouse effect.

The atmosphere is not an isolated system. It interacts with other components of the Earth system – the oceans, for example. But it is also in contact with the cryosphere (ice and snow), the biosphere (animals and plants), the pedosphere (soil) and the lithosphere (rocks). All of these elements together compose the climate system, whose individual components and processes are connected and influence each other in diverse ways.

These components all react to change at different rates. The atmosphere adjusts to the conditions at the Earth's surface such as ocean temperature or ice cover within a few hours to days. Furthermore, weather is variable and can only be predicted a few days in advance. In fact, it has been shown that the theoretical limit of weather pre-



1.2 > The climate system, its subsystems and relevant processes and interactions.

dictability is around 14 days. Currents in the deep sea, however, require several centuries to react fully to changing boundary conditions such as variations in the North Atlantic oscillation, which cause changes in temperature and precipitation at the sea surface and thus drive motion at greater depths. A large continental ice mass such as the Antarctic ice sheet, as a result of climate change, presumably undergoes change over many millennia, and without counteractive measures it will gradually melt on this time scale. The predictability of climate is based on the interactions between the atmosphere and the more inert climate subsystems, particularly the oceans. Within this scheme, the various components of the climate system move at completely different rates. Low-pressure systems can drift hundreds of kilometres within days. Ocean currents, on the other hand, often creep along at a few metres per minute. In addition, the individual components possess different thermal conductivities and heat capacities. Water, for instance, stores large amounts of solar heat for long periods of time.

Climate changes can be triggered in two different ways – by internal and external forces. The internal forces include:

- Changes in a single climate component, for example, an anomalous ocean current;
- Changes in the interactions between different climate components, for example, between the ocean and atmosphere.

Compared to these, the external mechanisms at first glance appear to have nothing to do with the climate system. These include:

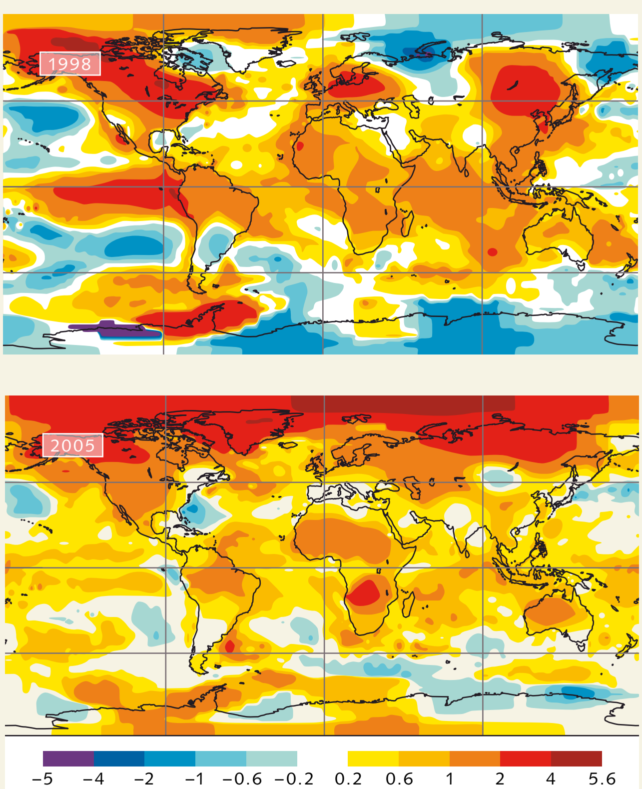
- The very slow drift of continents, which moves land masses into different climate zones over millions of years;
- The changing intensity of radiation emitted by the sun. The radiation energy of the sun fluctuates over time and changes temperatures on Earth;
- Volcanic eruptions, which inject ash and sulphur compounds into the atmosphere, influence the Earth's radiation budget and thus affect climate.

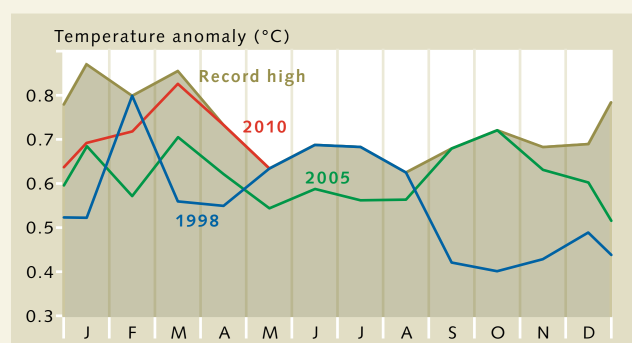
The difficulty of detecting anthropogenic climate change

Climate fluctuations are not unusual. In the North Atlantic Sector, for example, it is well known that the average temperatures and winds can fluctuate on decadal time scales. Climate changes caused by humans (anthropogenic) also evolve over the course of several decades. The natural decadal changes and those caused by humans are therefore superimposed upon one another. This makes it difficult to assess the impact of humans on climate with certainty. In contrast to the dynamic North Atlantic region, the effects of climate change are easier to detect in more stable regions such as the tropical Indian Ocean.

There is no doubt that the oceans drive interannual or decadal climate fluctuations. Decadal fluctuations of Atlantic hurricane activity or precipitation in the Sahel correlate remarkably well with oscillations of ocean temperature in the North Atlantic. Although the precise mechanisms behind these decadal changes are not yet fully understood, there is general agreement that variations in the Atlantic overturning circulation play an important role. This hypothesis is also supported by the fact that Atlantic sea surface temperature anomalies occur in cycles of several decades, with a pattern which is characterized by an interhemispheric dipole. When the rate of northward warm water transport increases, the surface air temperature rises in the North Atlantic and falls in the South Atlantic. If it becomes cooler in the north and warmer in the south, it is an indication of weak ocean currents. The air-temperature difference between the North and South Atlantic is therefore a measure of the overturning circulation strength.

Modern climate models can simulate the present-day climate and some historical climate fluctuations reasonably well. These models describe the climate with satisfactory reliability, especially on a global scale. But for smaller geographical areas the models are less



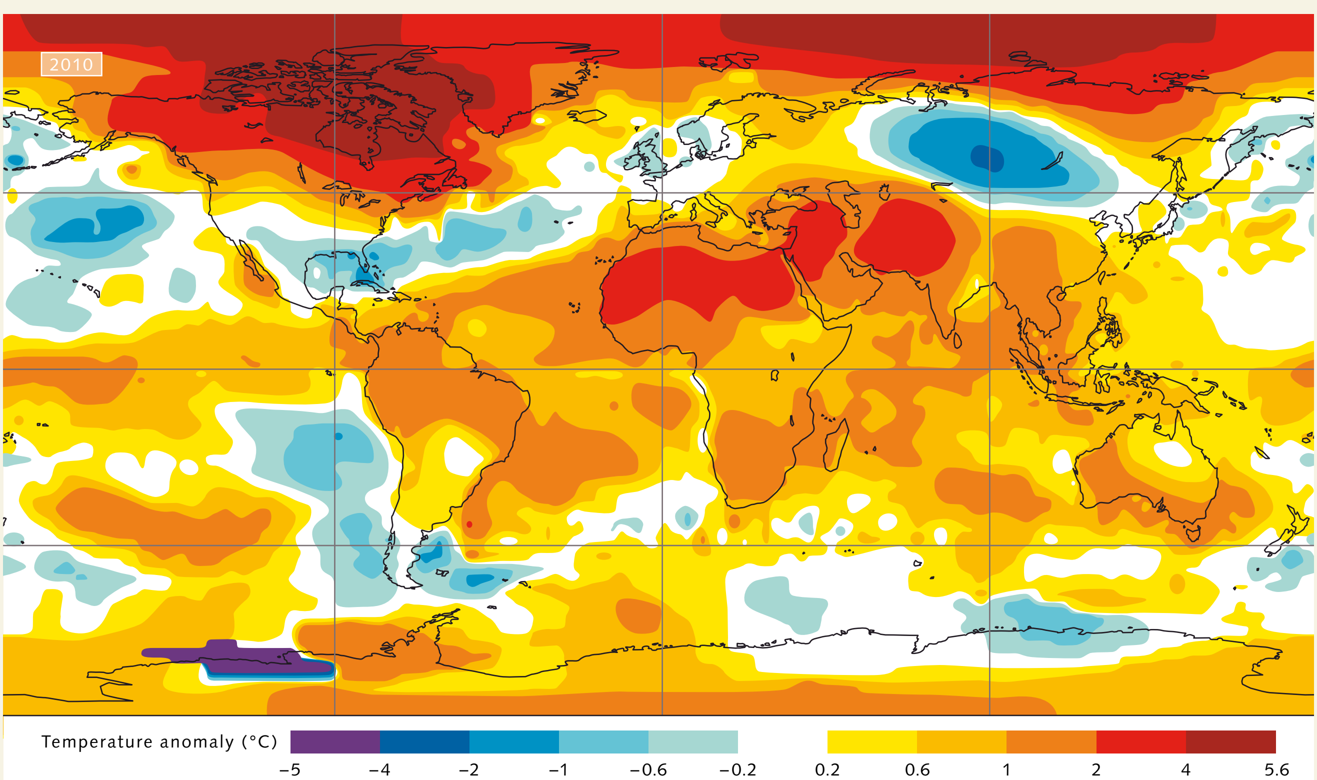


1.3 > Europe experienced an unusually cold beginning of the year 2010. But from a global perspective, the winter of 2010 was the third warmest in the past 131 years. If the first five months of the year are considered, then 2010 is actually the warmest, and it even reached the previous temperature record highs for the months of April and May (top). The years 1998 and 2005 have been so far the two warmest years in the annual mean (relative to the average of 1951 to 1980).

reliable. It is much easier to infer the globally averaged temperature than to predict the future precipitation in Berlin. Extensive measurement series are required to better understand regional climate. For many regions of the Earth, in the Southern Ocean for example, there are long time periods in the past with only a limited number of measurements. Today data are provided in these areas by satellites.

Many mathematical models now exist that can help to understand the impacts of human activity on climate. As one aspect, they simulate climate response to external natural and anthropogenic forcing, but they also reveal how climate interacts with the **biogeochemical** cycles such as the **carbon cycle** (Chapter 2). Climate research is thus developing into a more comprehensive study of the Earth system, and today's climate models are evolving into Earth system models. This is necessary in order to study the multiple interactions. For example, the impact of global warming on the **stratospheric** ozone layer can only be investigated when the chemical processes in the atmosphere are taken into account. Another example is acidification of the seawater (Chapter 2) due to uptake of anthropogenic CO_2 by the ocean.

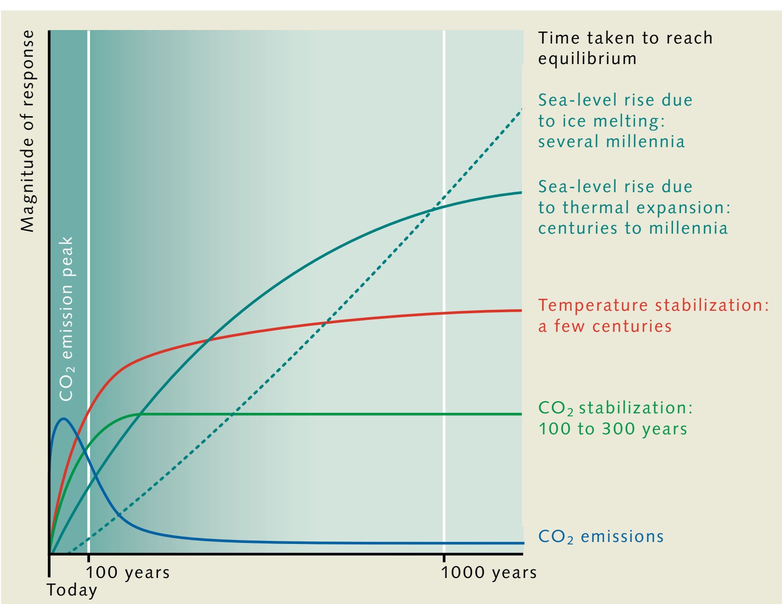
No one has yet been able to predict how the warming and acidification of the ocean will influence its future uptake of anthropogenic carbon dioxide, upon which the carbon dioxide levels in the atmosphere and thus the future temperature change depend. There is a mutual interaction between the ocean and the atmosphere. To a large extent the ocean determines the intensity of climate change, and its regional expression in particular. On average, warming is taking place globally. But individual regions, such as the area of the Gulf Stream, may behave in different ways. On the other hand, the ocean itself reacts to climate change. Understanding this complex interplay is a task that will take years to accomplish.



How humans are changing the climate

The human impact on climate has greatly increased over the past hundred years. We release vast amounts of climate-relevant trace gases into the atmosphere. This changes the radiation balance of the atmosphere and leads to global warming.

In addition to carbon dioxide, these trace gases include methane, nitrous oxide (laughing gas), halogenated fluorocarbons, perfluorinated hydrocarbons, and sulphur hexafluoride. But carbon dioxide (CO_2) is especially important for the Earth's climate system because the worldwide output is so enormous. It is released primarily through the burning of fossil fuels (oil, natural gas, and coal) in power plants, vehicle engines or in household heating systems. Its atmospheric levels have risen to almost 390 parts per million (ppm) today as compared to the pre-industrial value of 280 ppm. With this increase the temperature has also risen during the twentieth century. The internally driven changes in the oceans such as changes in the **Gulf Stream** also occur within a time frame of decades or a few centuries. These have a decisive influence on climate and on the concentration of greenhouse gases in the atmosphere because they are strongly involved in global mass cycles such as the carbon cycle. For example, CO_2 dissolves easily in water. However, the oceans have taken up about half of all the carbon dioxide produced by the burning of fossil fuels since the beginning of the industrial revolution, which has clearly dominated the natural variations. Whether the climate will change in the future, and by how much, can therefore be also deduced from the oceans.



1.4 > Even if it is possible to significantly reduce the emission of greenhouse gases, and CO_2 in particular, by the end of this century, the impact will still be extensive. CO_2 has a long life and remains in the atmosphere for many centuries. Because of this, the temperature on the Earth will continue to rise by a few tenths of a degree for a century or longer. Because heat penetrates very slowly into the ocean depths, the water also expands slowly and sea level will continue to rise gradually over a long period of time. Melting of the large continental ice sheets in the Antarctic and Greenland is also a very gradual process. Melt water from these will flow into the ocean for centuries or even millennia, causing sea level to continue to rise. The figure illustrates the principle of stabilization at arbitrary levels of CO_2 between 450 and 1000 parts per million (ppm), and therefore does not show any units on the response axis.

Climate will change very slowly in the future because the oceans with their immense volumes of water react very gradually to change. Therefore, many but not all of the consequences of climate change triggered by human activity will only gradually become noticeable. Some of these consequences could actually be irreversible when certain thresholds are crossed. At some point it will no longer be possible, for instance, to stop the complete melting of the Greenland ice sheet and the resulting seven-meter rise of sea level. The position of the threshold, however, is not precisely known. But one thing is certain: Even if the emission of carbon dioxide were stabilized at today's levels it would not lead to a stabilization of the carbon dioxide concentration in the atmosphere, because carbon dioxide is extremely long-lived and the carbon dioxide **sinks**, mainly the oceans, do not absorb it as quickly as we produce it.

The situation is different for short-lived trace gases like methane (CH_4). If methane emissions were stabilized at the present level, the methane concentration in the atmosphere would also stabilize, because methane diminishes in the atmosphere at about the same rate as it is emitted. In order to maintain the carbon dioxide concentration at a given level, the emissions have to be reduced to a fraction of the present amounts.

1.5 > To bring attention to the threat of global warming, the government of the Republic of Maldives held a meeting on the sea floor in autumn 2009 just before the Copenhagen summit.

A looming catastrophe

Long after the stabilization of carbon dioxide levels, the climate will still further continue to change because of its inertia. Climate models indicate that the near-surface air temperature will rise for at least a hundred years. Sea level will continue to rise for several centuries because seawater expands slowly as a result of the gradual warming of the deep sea, and because the continental ice sheets in the Arctic and Antarctic will probably react very slowly to the warming of the atmosphere, and the glaciers will continue to melt for many millennia. It will therefore be a long time before sea level achieves a new equilibrium. But scientists also believe it is possible that, if the warming is strong, the Greenland ice sheet could completely melt within this millennium and disappear into the ocean. The ice sheet could actually break apart and giant pieces fall into the sea. The enormous amounts of fresh water could cause a critical change in ocean circulation, for example, in the Gulf Stream. In an extreme scenario, sea level could rise by more than a metre per century, regionally by even more

The inertia of the climate system and the danger that the trend is irreversible should be sufficient reasons for forward-looking action. One should always keep in mind that the impacts of climate change that are measurable today do not yet reflect the total extent of climate change already caused by humans in the past. Humankind will only begin to feel them sharply in a few decades but has to take action right away.

Carbon dioxide and the greenhouse effect

The atmosphere is becoming more enriched in carbon dioxide (CO_2), or to be more precise, carbon dioxide and other climate-relevant trace gases. Initially they allow the incoming short-wave radiation of the sun to pass through. This energy is transformed to heat at the Earth's surface and is then emitted back as long-wave radiation. The gases in the atmosphere, like the glass panes of a greenhouse, prevent this long-wave radiation from escaping into space, and the Earth's surface warms up.

The great ocean currents – the climate engine

> Ocean currents transport enormous amounts of heat around the world. This makes them one of the most important driving forces of climate. Because they respond extremely slowly to changes, the effects of global warming will gradually become noticeable but over a period of centuries. Climate changes associated with wind and sea ice could become recognizable more quickly.

What drives the water masses

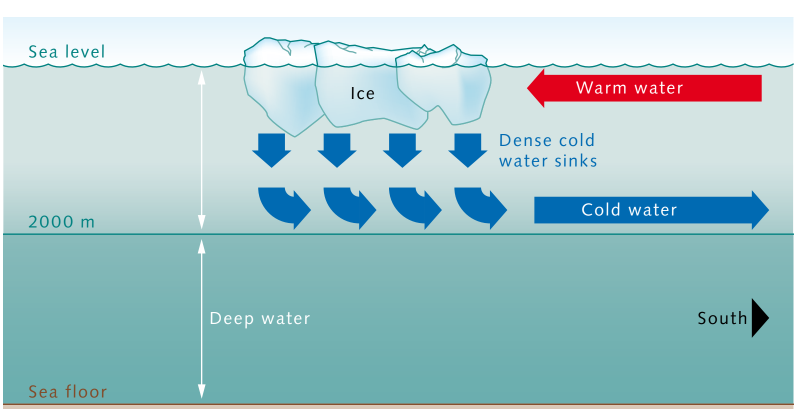
Water plays a central role in the climate system. Its density varies depending on salinity and temperature. Cold, salty water is heavy and sinks to great depths. This causes the circulation of millions of cubic metres of water in the ocean. This powerful phenomenon, which primarily occurs in a few polar regions of the ocean, is called convection.

The surface water in the North Atlantic region sinks to a depth of around 2000 metres due to convection. There it settles on an even denser deep-water layer from the Antarctic that extends down to the sea floor. As the cold and salty surface water sinks by convection, salty water flows in from nearby warmer regions, from the direction of the equator. This water is then cooled in the Arctic air and also begins to sink, so that the convection is continuous. Before sinking, the water absorbs enormous amounts of gases such as carbon dioxide at the sea surface, and then transports them rapidly to much greater depths. That is why the highest concentrations of carbon dioxide in the ocean are found in the convection areas.

The high carbon dioxide concentrations pumped into the water by convection have been shown to reach depths today of around 3000 metres. Carbon dioxide is transported relatively rapidly by convection to a depth of 2000 metres. In the North Atlantic the transport to greater depths takes significantly longer because carbon dioxide and other gases can only penetrate the deep water by slow mixing processes.

Low temperature and high salinity are the primary driving forces of convection. They pull the dense water of the polar regions downward, which drives a worldwide convection engine called thermohaline circulation (*thermo* – driven by temperature differences; *haline* – driven by salinity differences). The cold, salty water submerges primarily in the Labrador and Greenland Seas, and then flows southward toward the equator and beyond. Although convection only occurs locally in the polar regions, it propels thermohaline circulation, which spans the globe like a giant conveyor belt. Even the Gulf Stream and its branches are driven by convection and thermohaline circulation. Although wind also influences the transport of water masses, its contribution is significantly less.

But how do the water masses of different densities that drive ocean convection actually originate? Air temperature, evaporation and precipitation are among the



1.6 > The convection process in the North Atlantic: Cold, salty water sinks in the Labrador and in the Greenland Sea. This water forms a layer above the denser deep water from the Antarctic at a depth of around 2000 metres and flows toward the equator. Warmer waters from the upper ocean layers move into the convection area to replace the sinking water.

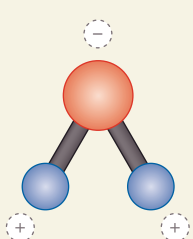
Water – a unique molecule

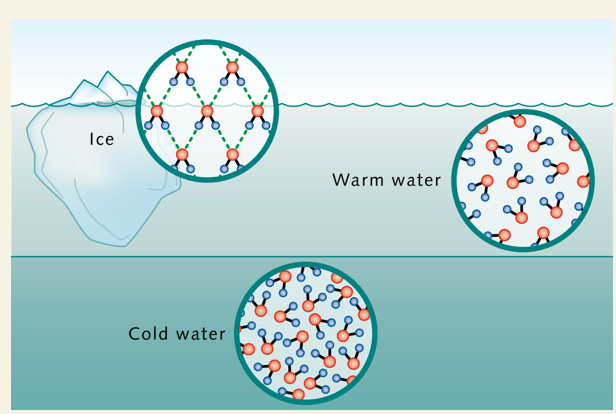
Water behaves differently from most other chemical compounds. In almost all substances the atoms and molecules move closer together as they get colder. They then solidify. Water, however, attains its greatest density at four degrees Celsius because the water molecules are packed closest together at this temperature. Many freshwater lakes have a temperature of four degrees at their deepest point because the heavy water sinks to the bottom. But surprisingly, to reach the solid ice phase, the water molecules again move farther apart. This phenomenon is referred to as the water anomaly. Ice is lighter and floats at the surface. This is seen in the large ocean regions at polar latitudes, which are partly covered by ice. The reason for this anomaly lies in the unusual properties of the water molecule (H_2O). Its oxygen atom (O) and the two hydrogen atoms (H) are asymmetrically arranged. This produces a dipole, a molecule with one negatively and one positively charged end.

Depending on the temperature, these dipoles align themselves into aggregates according to their charge, for example, in the formation of an ice crystal. The dipole character of water is a critical factor for climate. Because the water dipoles tend to hold together like small magnets, water reacts sluggishly to warming or cooling. In fact, water has the highest heat capacity of all liquid and solid substances with the exception of ammonia. This means that water can absorb large amounts of heat before it boils. Both, the freezing and boiling points of water (zero and 100 degrees Celsius, respectively), so much a part of our daily lives, are really rather unusual. If the water molecule were symmetrical (not a dipole), then water (ice) would melt at minus 110 degrees Celsius and boil at minus 80 degrees. The inertia of climate is a result of the high heat capacity of water in the first place.

Water influences climate not only in its liquid and solid states. H_2O in the form of water vapour in the atmosphere has a decisive impact on the heat budget of the Earth; water vapour alone is responsible for about two thirds of the natural greenhouse effect. In addition, it amplifies the impact of other substances on climate. For example, if the temperature rises as a result of higher carbon dioxide levels, then the water vapour content also increases because the warmer atmosphere can sustainably hold more water vapour. Because of its dipole molecule, water absorbs infrared radiation very efficiently. As a result, it approximately doubles the warming originally caused by carbon dioxide.

Another important property of water is its ability to dissolve salts, which significantly changes its density. The average salinity of the ocean is 34.7 parts per thousand (‰). At this salinity water has a greatest density of minus 3.8 degrees Celsius, which is below the freezing point of seawater with average salinity. This is, in fact, minus 1.9 degrees Celsius. So surface cooling can cause convection until ice is formed. This density trait is the engine for convection, one of the most important elements of the climate system; cold, salty water is heavy and sinks to great depths. It is replaced by water flowing in at the sea surface.





1.7 > The water molecule is asymmetrical and is therefore oppositely charged at its two ends (left). This is called a dipole. It thus behaves differently from other substances in many ways. Ice is less dense (top) and floats on the surface. Freshwater has its greatest density at four degrees (bottom), and sinks to the bottom. This is then overlain by warm water (middle). Salty water has different characteristics.

most important factors in the answer to this question. The freezing of water in the polar convection regions also plays a central role. Because ice only contains about five tenths of a per cent salt, it leaves behind a considerable amount of salt in the water when it freezes, which increases the salinity of the surrounding ocean water and thus increases its density. The water mass produced by convection in the Arctic is called the North Atlantic Deep Water (NADW).

The path of water into the deep ocean

There is no other area in the ocean where the surface water finds its way so quickly into the deep as in the convection areas, and at no other place do changes at the sea surface or in the atmosphere become so rapidly apparent in the ocean's interior, for example, in the increased carbon dioxide levels in the water as a result of higher carbon dioxide concentrations in the atmosphere. Convection connects two distinctly different components of the ocean: the near-surface layers that are in contact with the variable atmospheric fields of wind, radiation and precipitation, and the deep regions of the ocean. At the surface, currents, temperature and salinity fluctuate on a scale of weeks to months. But at greater depths the environmental conditions change at time scales of decades or centuries.

In the consistently warm oceanic regions of the tropics (the warm regions of the Earth between 23.5 degrees north and 23.5 degrees south latitude) and the subtropics (the regions between 23.5 and 40 degrees in the northern and southern hemispheres), there is no exchange between the surface and deep waters that is comparable to polar convection. This is because, averaged over the year, there is a net radiation excess of the surface-layer waters. The warm water, with a minimum temperature of ten degrees Celsius, has a relatively low density and floats as a warm layer on top of the deeper, colder water masses. The two layers are distinctly separated with no gradual transition between them. At the boundary where they meet there is a sharp temperature jump, and therefore also an abrupt density difference that inhibits penetration of the heat to greater depths. The warm surface layer has an average thickness of several hundred metres, which is relatively thin compared to the total depth of the oceans. In very warm ocean regions such as the western equatorial Pacific, there is hardly any vertical mixing at all. Nearer to the poles, however, there is more vertical mixing of the oceans and layering is less well-defined. Because there is no abrupt temperature and density change there, changes in the sea surface can be transmitted to the interior depths of the ocean. But the convection areas are still the express elevator to the deep.

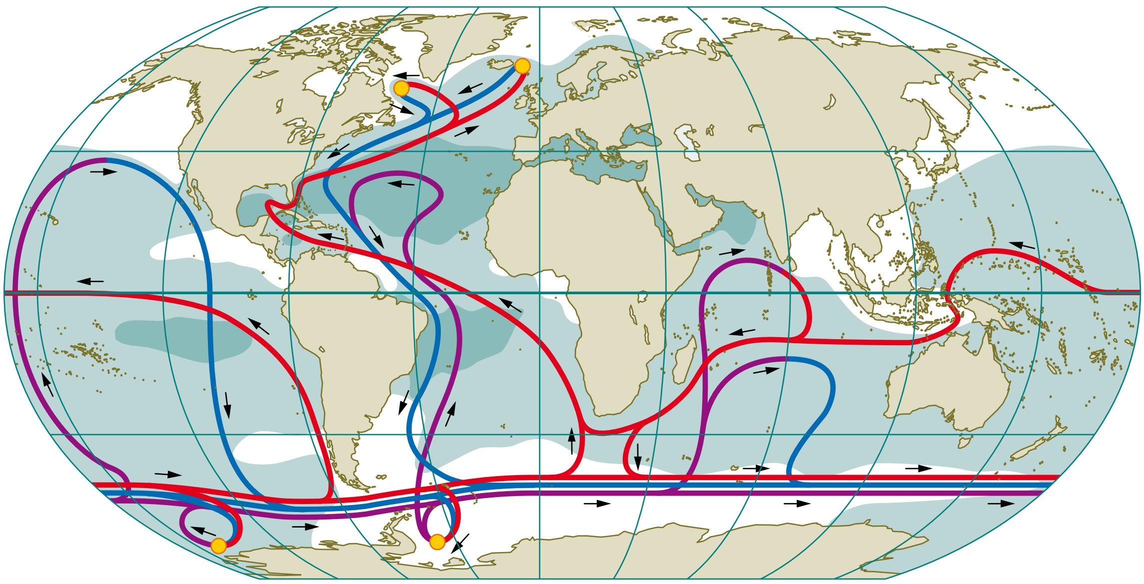
The global conveyor belt

Convection also occurs in the Antarctic regions. Because of their even higher salinity, the water masses produced here sink all the way to the sea floor. This is called the Antarctic Bottom Water (AABW), and it flows across the ocean floor halfway around the globe into the North Atlantic. The AABW is also the deep water layer that the thick intermediate NADW overlies when it sinks by convection. The NADW forms in the Greenland and Labrador Seas. Figure 1.8 schematically illustrates its flow path and the return flow of warm water in the near-surface layers, in the global conveyor belt of thermohaline circulation. The NADW, and especially the AABW, remain in the deep ocean for an amazingly long time. Radioactive carbon-isotope dating of the deep waters indicates that from the time of sinking into the deep until its return to the surface, a period of several hundred or even up to 1000 years will pass.

For most of this time the water remains in the colder deep regions of the thermohaline conveyor belt because there the flow rate is slow, at around one to three kilometres per day, due to its high density. The amount of water involved in this cycle is truly immense. Its volume is around 400,000 cubic kilometres, which is equivalent to about one third of the total water in the ocean. This is enough water to fill a swimming pool 400 kilometres long, 100 kilometres wide, and ten kilometres deep. The oceanic conveyor belt transports about 20 million cubic metres of water per second, which is almost 5000 times the amount that flows over Niagara Falls in North America.

Concerns about the breakdown of the Gulf Stream

There has been a great deal of discussion about the extent to which climate change could influence thermohaline circulation and its turnover processes in the Atlantic. After all, convection at high latitudes could be weakened by anthropogenic (caused by humans) warming of the atmosphere and the accompanying decrease in surface-



1.8 > The worldwide ocean currents of the thermohaline circulation system are extremely complex. The flow of cold, saline surface water (blue) downward and toward the equator can only be clearly recognized in the Atlantic. Warm surface water (red) flows in the opposite direction, toward the pole. In other areas the current relationships are not as clear-cut as they are in the Gulf Stream system (between North America and Europe). The Circumpolar Current flows around Antarctica, and does so throughout the total depth of the water column. The small yellow circles in the polar regions indicate convection areas. The dark areas are characterized by high salinity and the white areas by low salinity. Salty areas are mostly located in the warm subtropics because of the high evaporation rates here.

water density. Additionally the density will decrease as a result of lower salinity in the North Atlantic. Climate change will probably cause an increase in freshwater input through a number of pathways, which will affect convection and thermohaline circulation. One way would be by an increase in precipitation over both the continents and the ocean. Another would be the increase of freshwater run-off from the melting glaciers to the sea. Furthermore, because less ice forms when it is warmer, the salt concentration in the surface water would not be increased as much by this process.

Present-day climate models assume a weakening of the Atlantic turnover process by about 25 per cent by the end of this century. This would mean that less heat is transported northward from the tropics and subtropics. Ice-age scenarios such as those commonly proposed in the literature or films, however, are completely inappropriate, even if the circulation were to completely break down. The decreased influx of heat would be more than compensated by future global warming caused by the enhanced greenhouse effect. The Earth is warming up because of the insulating effect of carbon dioxide in the atmosphere. This temperature increase would offset the decreased northward heat transport from the tropics into the North Atlantic, and even exceed it on the adjacent land masses. When talking about the human impact on climate, scientists therefore tend to refer to a "warm age" rather than an "ice age".

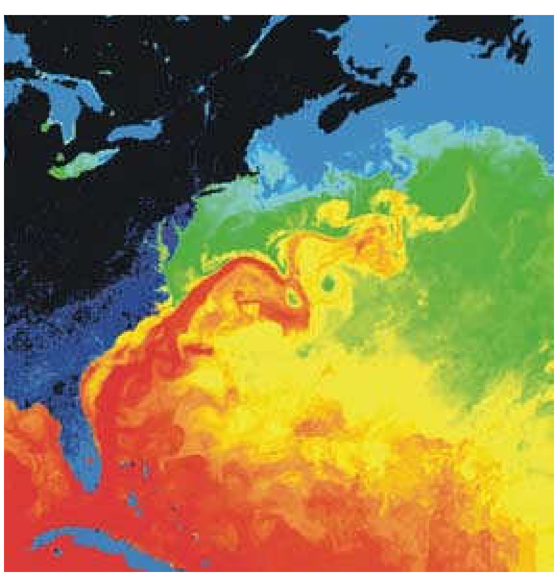
Eddies in the ocean – an important climate component

In addition to the large conveyor belt of thermohaline circulation, heat is also transported in the ocean by eddies, which are analogous to low-pressure systems in the atmosphere. But they are significantly smaller than the atmospheric low-pressure systems, which can often be several hundred kilometres wide. These mesoscale eddies form when water flows between regions with large density or temperature differences. They can be clearly recognized on satellite photographs. Investigations have shown that they not only occur at the ocean surface as, for example, in the North Atlantic area, but can also be located at great depths of thousands of metres, e.g. off the coast of Brazil. Because of their strong influence on the large-scale heat transport, these deep-sea eddies also play an important role in long-term climate processes.

The Coriolis force
The Earth's rotation causes all free linear motion on the Earth, such as air or water currents, to be diverted to one side. The diverting force is called the Coriolis force or Coriolis acceleration. It works in opposite directions in the northern and southern hemispheres. The Coriolis force is named after the French natural scientist Gaspare Gustave de Coriolis (1792 to 1843), who derived it mathematically.

Variable and dynamic – the influence of wind

Along with convection, winds also provide an important contribution in driving the ocean currents. In combination with the diverting force caused by the Earth's rotation (Coriolis force) and the shape of the ocean basins, winds determine the characteristic patterns of the worldwide system of surface currents. Especially striking are the large gyres that extend across entire ocean basins, for example between America and Europe. These surface currents include the Gulf Stream in the Atlantic Ocean, which is driven both by wind and the thermohaline force, as well as the Kuroshio in the Pacific Ocean, whose intensity just decreases with depth.



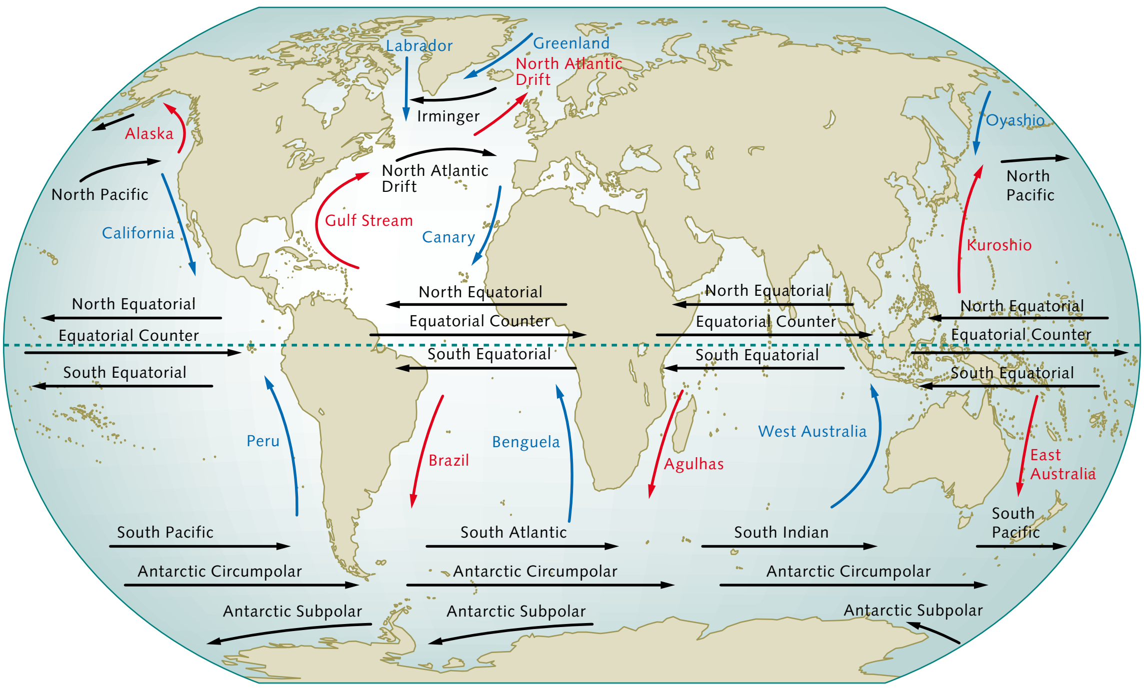
1.9 > Satellite photograph of the Gulf Stream and its eddies. Warm areas are red, cold areas are blue.

The Gulf Stream is a relatively fast current. Along the coast of North America it reaches a speed of around 3.6 kilometres per hour at the sea surface, which is a casual walking speed. It extends down to a depth of around 2000 metres, where the speed is around ten times slower because the influence of the wind is less and the density of the water is greater. Nevertheless, the wind can in fact have a direct influence down to great depths. Typical wind conditions can change for extended time periods. For example, the normally steady **trade winds** can blow from a different direction for months at a time, causing changes in the upwelling of water masses, and creating waves and currents in the ocean's interior that resonate at depth for decades. These waves can also change the ocean temperature and thus also the regional climate. From satellites these waves are perceived as slowly moving ups and downs of the ocean surface.

Furthermore, in certain regions the prevailing winds cause persistent upwelling and downwelling motion. In some areas the winds drive surface waters away from the land masses, allowing cold water from greater depths to rise in its place. The surface-water temperatures in these areas are therefore especially low. Important upwelling regions are often found on the western margins of continents where the winds blow parallel to the coast (Chile, California, Namibia). In the southern hemisphere, for example, because of the Coriolis force, the water is pushed to the left away from the coast when the wind is blowing from the south. This produces a rolling motion in the water, whereby the water on the surface moves away from the coast and water rises to replace it from below. This upwelling water is usually rich in nutrients, which is why many upwelling regions are also abundant with fish.

The ocean – a global storehouse for heat

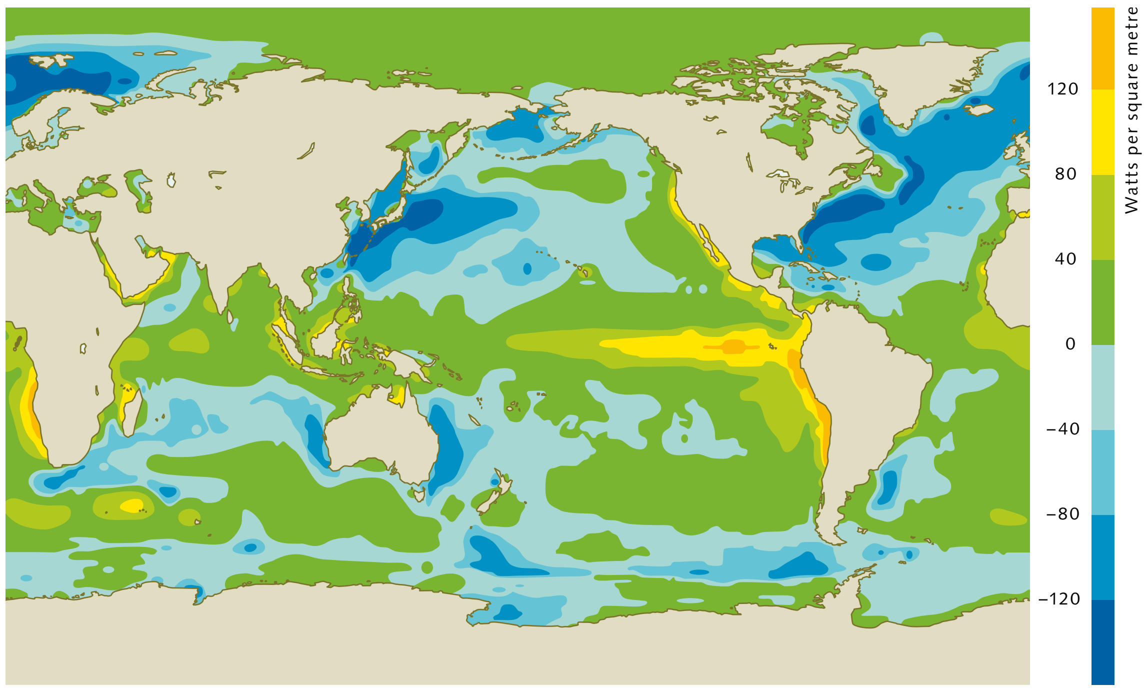
In addition to huge masses of water, large ocean currents also transport enormous amounts of heat around the globe. Similar to the way the water tank in a heating sys-



1.10 > The world's large ocean currents are also influenced by the prevailing winds. Warm ocean currents are red, and cold currents are shown in blue.

tem stores heat from the solar installation on the roof, the oceans are an immense heat reservoir that retains energy from the sun over a long time. The large ocean currents transport this heat for thousands of kilometres and, as illustrated by the example of the Gulf Stream, significantly influence the climate in many regions of the world. In the warm tropics and subtropics up to a latitude of around 30 degrees, more heat arrives at the Earth's surface on a yearly average than it releases. In the higher latitudes, and extending to the poles, the opposite relationship exists. As a result the atmosphere and the oceans transport energy northward and southward from the equator to compensate for the imbalance. In some tropical regions, such as the eastern Pacific, the ocean gains more than 100 watts of heat per square metre, which is about what a hot-water tank produces to keep an apartment comfortable. In the higher latitudes the ocean releases heat. The areas of greatest heat loss are off the eastern coasts of North America and Asia and in parts of the Arctic, with values of up to 200 watts per square metre. In the North Atlantic and North Pacific regions the oceans release heat on an immense scale.

The beneficiaries of this heat are those regions, including Europe, toward which the large current systems transport the warm water. The giant ocean currents transport a maximum amount of heat of just under three petawatts (quadrillion watts) to the north, which is around 600 times that produced by all the power stations worldwide. But the atmosphere also contributes to the energy balance between the tropics and the colder, higher latitudes. It transports an additional 2.5 to three petawatts of heat, resulting in a total northward transport of 5.5 to six petawatts. At European latitudes, heat transport in the atmosphere takes place through propagating low-pressure systems. In the Atlantic Ocean, however, the currents are more controlled and transport heat directly to the north. Here, warm water from the tropics flows northward far into the Arctic Ocean, where the water cools and releases heat into the environment. When it cools, the density increases. It sinks to greater depths and flows southward. The Atlantic current system transports enormous amounts of heat to the north through this thermohaline process and greatly exceeds the share transported by the wind-driven ocean circulation.



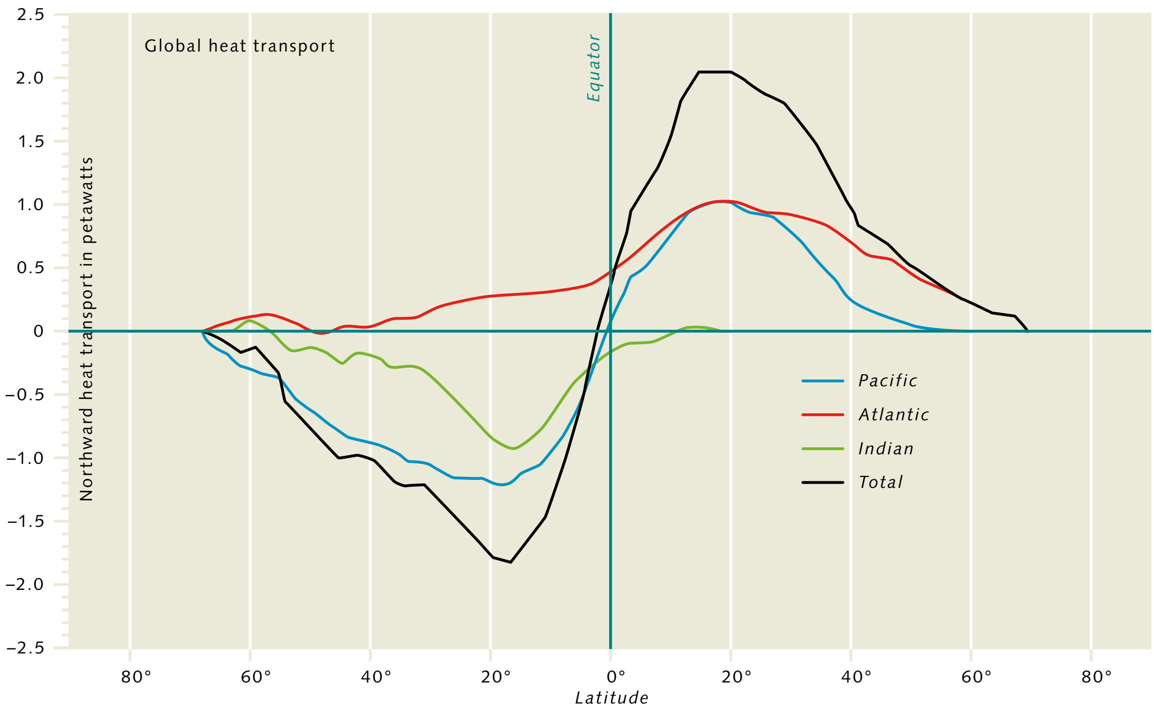
1.11 > Heat exchange between the atmosphere and the sea surface (in watts per square metre) is very variable depending on the ocean region. Positive values indicate absorption of heat by the ocean, which is characteristic of the tropics, and negative values indicate a heat loss, which is typical for the northern latitudes. In the high arctic regions, however, heat loss is relatively low because the sea ice acts as an insulating layer and prevents heat escaping from the water.

The Atlantic and Pacific Oceans each carry around one petawatt of heat northward from the tropics and subtropics. By comparison, the share moved by the Indian Ocean is negligible.

In this system the Atlantic has a unique function among the world's oceans. It is the only ocean basin that transports heat northward throughout its length, even in the southern hemisphere. Europeans all benefit from the northward trend, thanks to the Gulf Stream and the North Atlantic Current. The climate in the region of the North Atlantic is comparatively mild, especially in northwest Europe, including Germany. The winters in other regions at the same latitude are notably colder. In Canada, for example, the winter temperatures are around ten degrees Celsius lower than in Western Europe. But it is not the ocean circulation alone that causes the mild climate. Air currents also contribute significantly to this phenomenon. The distribution of mountain ranges, particularly the Rocky Mountains, which run from north to south along the west coast of North America, together with the influence of the Coriolis force, causes the formation of very stable, large-scale vortices in the atmosphere called standing planetary waves. Such a vortex lies above the USA because the Rocky Mountains act as an obstacle to divert large air masses. As a consequence the winds are predominantly westerly over the Atlantic carrying relatively mild air to northwest Europe, and fend off the cold from the east.

The uncertain future of sea ice

Sea ice in the Arctic regions has a significant impact on heat exchange between the atmosphere and ocean, because it acts as an insulating layer to prevent heat from



1.12 > Oceans contribute to the global transport of heat with different intensities. In the southern hemisphere, only the Atlantic transports heat to the north (positive values). The equator lies at zero degrees. The Atlantic and Pacific each carry around one petawatt of heat as far as 20 degrees north latitude. Further to the north, the Atlantic carries more than the Pacific. The Indian Ocean, on the other hand, makes a negligible contribution to northward heat transport.

escaping from the water. Considering how large the area of ice is, it is clear that it must have an impact on the global climate.

In the Arctic Ocean the sea ice, which is commonly called pack ice, has an average thickness of three metres. In the Southern Ocean it averages around one metre. The total area of sea ice expands and recedes with the seasons. On a yearly average around seven per cent of the oceans (about 23 million square kilometres) is covered with ice, which is equal to about three times the size of Australia. By comparison, the ice masses on land are relatively stable. They permanently cover around ten per cent of the land surface (14.8 million square kilometres). Scientists call the ice-covered areas of the Earth the cryosphere. In addition to land and sea ice, this also includes the shelf ice, the parts of continental ice sheets that extend into the ocean. Changes in the sea ice, including its extent, areal coverage, thickness, and movement, are caused by dynamic processes such as ocean currents and by **thermodynamic processes** such as freezing and melting. These, in turn, are influenced by solar radiation as well as the heat flux at the sea surface.

One of the most conspicuous and important characteristics of climate fluctuations is the change in sea-ice extent in the polar regions. During some winters the Arctic sea ice extends much further to the south than in others. Geophysicists consider the sea ice to be simply a thin, discontinuous layer on the polar oceans that is driven by winds and ocean currents, and is variable in thickness and extent. Sea ice forms a boundary between the two large components of the Earth system, the atmosphere and the ocean, and very significantly influences their interaction. Sea ice has a strong reflective property, called albedo, and it reflects a considerable amount of the

1.13 > As a rule, icebergs consist of freshwater or contain only small amounts of salt. Because of their slightly lower density compared to seawater, a small fraction extends above the water. The largest part is below the surface.

incoming sunlight. This effect is enhanced when the ice is covered with snow. The sea ice therefore influences the radiation balance of the Earth and thus plays an important role in the climate system.

The impact of sea ice on climate is further amplified by its insulating effect between the atmosphere and ocean. It inhibits the exchange of heat and wind energy between the atmosphere and ocean considerably. The atmosphere is therefore much colder above the sea-ice surface than above the open ocean. This has the effect of increasing the air-temperature difference between the tropics, subtropics, and the polar regions. In warmer regions the air has a greater tendency to rise, which lowers the air pressure significantly. By contrast, in very cold regions the air is heavier, and high pressure zones are created. Accordingly, the compensating air flow between high and low pressure areas is strong and, in concert with the Coriolis force, creates stronger westly winds in the middle latitudes. Of course, sea ice also influences convection processes in the ocean, and thus the formation of deep and bottom water. Sea ice therefore plays an important role in the large-scale ocean circulation, especially with regard to thermohaline circulation.

It is not yet known how global warming affects the formation of sea ice and the related processes. Ice melts when it becomes warmer. But it is difficult to predict what effect this has on the currents. In any case, all climate models predict an acceleration of warming in the Arctic with a continuing rise in trace-gas concentrations.

In addition, observations indicate a clear decrease in Arctic sea-ice cover in recent decades. This is partly related to a positive feedback mechanism called the ice-albedo feedback. Light surfaces have a very high albedo. When the sea ice retreats as a result of global warming, albedo decreases and more solar energy is available, which leads to additional warming, and melts more ice. This process primarily occurs at the margins of the sea ice. Similar to a spot of grass on the edge of a patchy snow cover, the seawater at the margins of the ice warms more rapidly, and the ice thaws faster there. The further the ice retreats, the larger the area of the open, relatively dark sea surface becomes. The melting is thus amplified. The shrinking of sea ice could therefore amplify climate change in the future. Ironically, this would provide people with something that they have been wanting for a long time: the opening of a northern seaway from Europe across the Arctic to Asia – the Northern Sea Route. In recent years the ice has retreated at such a rate that Arctic waters along the north coast of Russia could be navigable year-round by commercial ships in the future. The route is several thousand kilometres shorter than the trip through the Suez Canal. In the early autumn of 2009 a Bremen shipping company became one of the first private companies in the world to navigate the Northern Sea Route with a merchant vessel. But the negative consequences of climate change will presumably outweigh the advantages of a navigable northern route. There is, for instance, a substantial negative impact on Arctic animals such as the polar bear, whose habitat is melting away.

The large ocean currents and their driving forces have already been intensively investigated, but there are still many unanswered questions in the fine details. For example, thermohaline circulation, with the interplay of its driving factors, has not yet been completely explained. Different mathematical models have produced different conclusions. All models use the same equations, variables, and input parameters. But it is difficult to accurately estimate climate influences at scales of a few kilometers or even smaller and to apply them correctly within the large, global models.

Conclusion

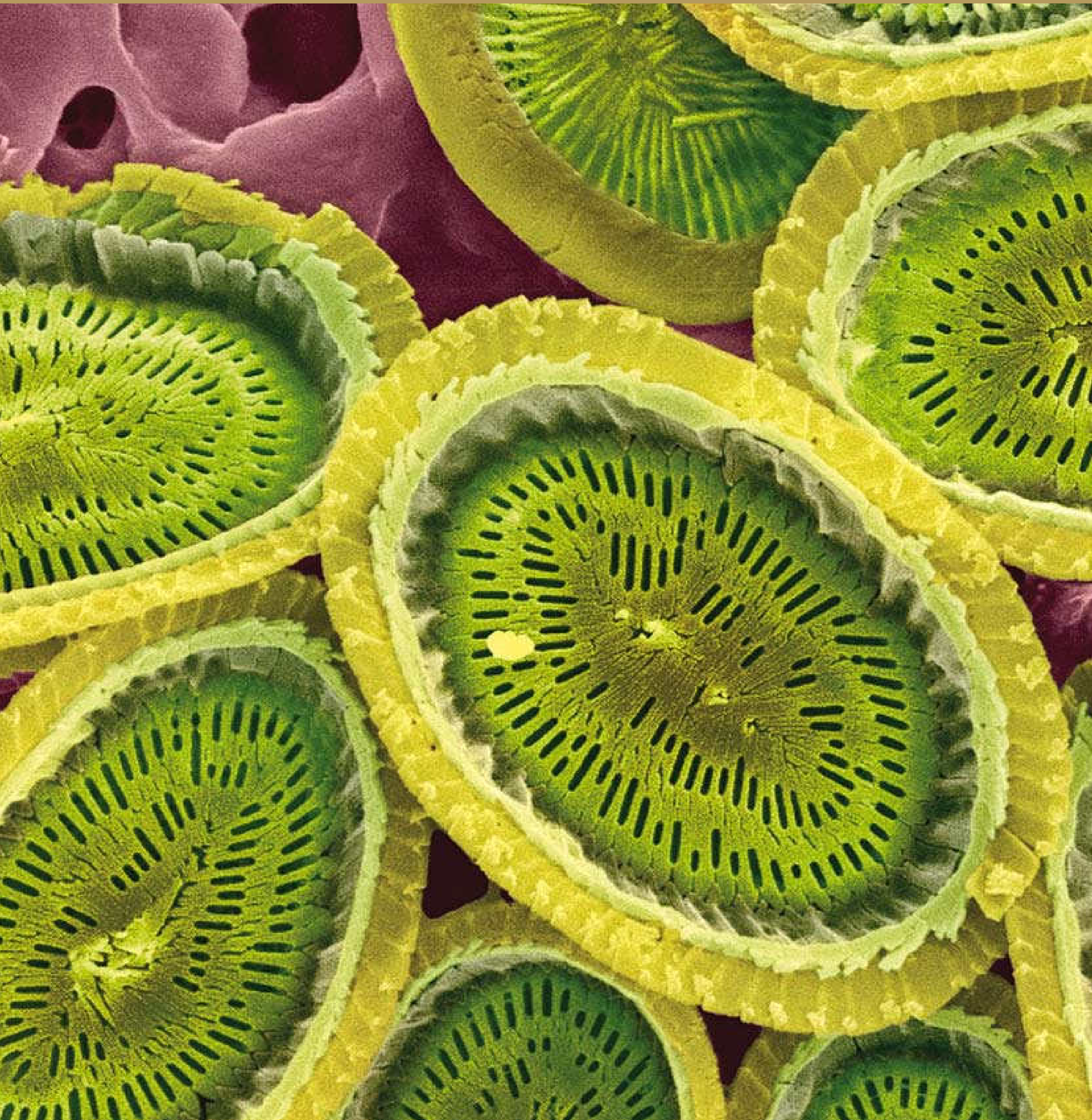
Time to act

Climate change will affect the oceans in many ways, and these will not be limited to just altering the currents or heat budget. Increasing carbon dioxide concentrations in the atmosphere are accompanied by higher concentrations in the oceans. This leads to increased carbonic acid levels, which acidifies the water. At present the consequences for marine animals cannot be predicted.

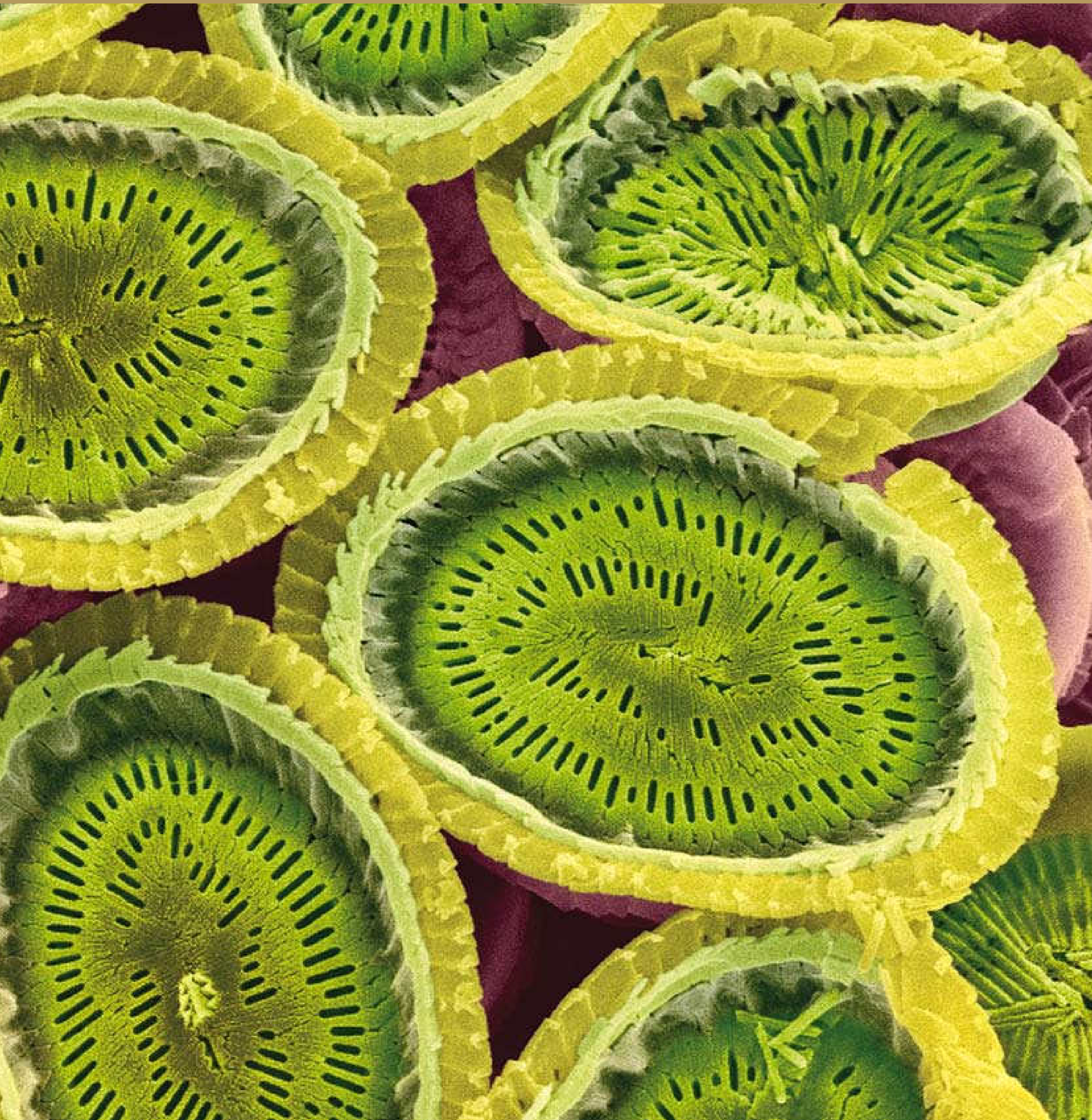
Similarly, very little is known about how the weakening of thermohaline circulation or the Gulf Stream will affect biological communities, such as crab or fish larvae which are normally transported by currents through the oceans. The dangers associated with rising sea level were again stressed during the climate conference in Copenhagen in 2009. Specialists today largely agree that sea level will rise by around one metre by the end of this century if the worldwide emission of greenhouse gases by humans continues to increase as rapidly as it has in recent decades. This will be fatal for island nations like the Maldives, which inundation could render uninhabitable within a few decades. The fact that scientists cannot yet predict with complete certainty what the future effects of climate change will be is not a valid argument for inaction. The danger is real.

Human society needs to do everything in its power to bring the climate-change experiment to an end as soon as possible. The climate system reacts slowly to changes caused by human intervention, so there is a strong possibility that some changes are already irreversible. This risk should provide sufficient motivation for forward-looking action to significantly reduce the emission of climate-relevant gases. There is no time to lose in implementing climate protection measures. There are many indications that the most severe consequences of climate change can still be avoided if investment is made today in low-carbon technology. It is time to act.

2 How climate change alters ocean chemistry



> Massive emissions of carbon dioxide into the atmosphere have an impact on the chemical and biological processes in the ocean. The warming of ocean water could lead to a destabilization of solid methane deposits on the sea floor. Because of the excess CO_2, the oceans are becoming more acidic. Scientists are making extensive measurements to determine how much of the humanmade CO_2 is being absorbed by the oceans. Important clues are provided by looking at oxygen.



The oceans – the largest CO_2-reservoir

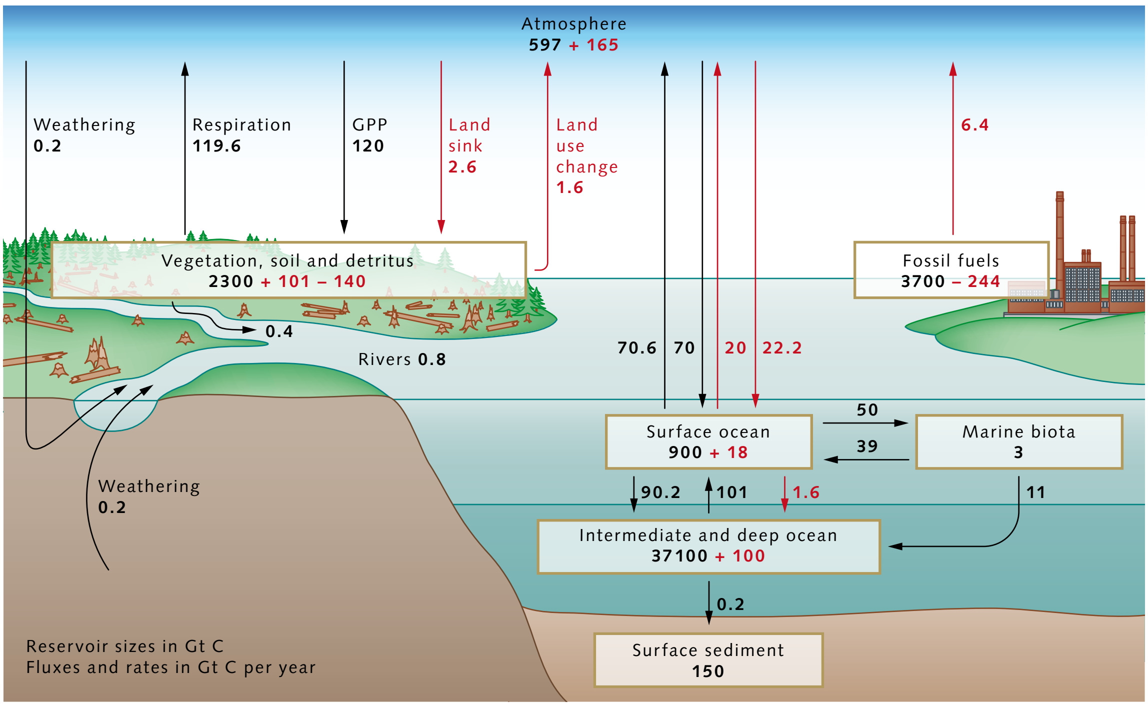
> The oceans absorb substantial amounts of carbon dioxide, and thereby consume a large portion of this greenhouse gas, which is released by human activity. This does not mean, however, that the problem can be ignored, because this process takes centuries and cannot prevent the consequences of climate change. Furthermore, it cannot be predicted how the marine biosphere will react to the uptake of additional CO_2.

The mutability of carbon

Carbon is the element of life. The human body structure is based on it, and other animal and plant biomass such as leaves and wood consist predominantly of carbon (C). Plants on land and algae in the ocean assimilate it in the form of carbon dioxide (CO_2) from the atmosphere or water, and transform it through photosynthesis into energy-rich molecules such as sugars and starches. Carbon constantly changes its state through the metabolism of organisms and by natural chemical processes. Carbon can be stored in and exchanges between particulate and dissolved inorganic and organic forms and exchanged with the the atmosphere as CO_2. The oceans store much more carbon than the atmosphere and the terrestrial biosphere (plants and animals). Even more carbon, however, is stored in the lithosphere, i.e. the rocks on the planet, including limestones (calcium carbonate, $CaCO_3$).

The three most important repositories within the context of anthropogenic climate change – atmosphere, terrestrial biosphere and ocean – are constantly exchanging carbon. This process can occur over time spans of up to centuries, which at first glance appears quite slow. But considering that carbon remains bound up in the rocks of the Earth's crust for millions of years, then the exchange between the atmosphere, terrestrial biosphere and ocean carbon reservoirs could actually be described as relatively rapid. Today scientists can estimate fairly accurately how much carbon is stored in the individual reservoirs. The ocean, with around 38,000 gigatons (Gt) of carbon (1 gigaton = 1 billion tons), contains 16 times as much carbon as the terrestrial biosphere, that is all plant and the underlying soils on our planet, and around 60 times as much as the pre-industrial atmosphere, i.e., at a time before people began to drastically alter the atmospheric CO_2 content by the increased burning of coal, oil and gas. At that time the carbon content of the atmosphere was only around 600 gigatons of carbon. The ocean is therefore the greatest of the carbon reservoirs, and essentially determines the atmospheric CO_2 content. The carbon, however, requires centuries to penetrate into the deep ocean, because the mixing of the oceans is a rather slow (Chapter 1). Consequently, changes in atmospheric carbon content that are induced by the oceans also occur over a time frame of centuries. In geological time that is quite fast, but from a human perspective it is too slow to extensively buffer climate change.

With respect to climate change, the greenhouse gas CO_2 is of primary interest in the global carbon cycle. Today, we know that the CO_2 concentration in the atmosphere changed only slightly during the 12,000 years between the last ice age and the onset of the industrial revolution at the beginning of the 19th century. This relatively stable CO_2 concentration suggests that the pre-industrial carbon cycle was largely in equilibrium with the atmosphere. It is assumed that, in this pre-industrial equilibrium state, the ocean released around 0.6 gigatons of carbon per year to the atmosphere. This is a result of the input of carbon from land plants carried by rivers to the ocean and, after decomposition by bacteria, released into the atmosphere as CO_2, as well as from inorganic carbon from the weathering of continental rocks such as limestones. This transport presumably still occurs today at rates essentially unchanged. Since the beginning of



2.1 > The carbon cycle in the 1990s with the sizes of the various reservoirs (in gigatons of carbon, Gt C), as well as the annual fluxes between these. Pre-industrial natural fluxes are shown in black, anthropogenic changes in red. The loss of 140 Gt C in the terrestrial biosphere reflects the cumulative CO_2 emissions from land-use change (primarily slash and burn agriculture in the tropical rainforests), and is added to the 244 Gt C emitted by the burning of fossil fuels. The terrestrial sink for anthropogenic CO_2 of 101 Gt C is not directly verifiable, but is derived from the difference between cumulative emissions (244 + 140 = 384 Gt C) and the combination of atmospheric increase (165 Gt C) and oceanic sinks (100 + 18 = 118 Gt C).

the industrial age, increasing amounts of additional carbon have entered the atmosphere annually in the form of carbon dioxide. The causes for this, in addition to the burning of fossil fuels (about 6.4 Gt C per year in the 1990s and more than 8 Gt C since 2006), include changes in land-use practices such as intensive slash and burn agriculture in the tropical rainforests (1.6 Gt C annually). From the early 19th to the end of the 20th century, humankind released around 400 Gt C in the form of carbon dioxide. This has created a serious imbalance in today's carbon cycle. The additional input of carbon produces offsets between the carbon reservoirs, which lead to differences in the flux between reservoirs when compared to pre-industrial times. In addition to the atmosphere, the oceans and presumably also land plants permanently absorb a portion of this anthropogenic CO_2 (produced by human activity).

The ocean as a sink for anthropogenic CO_2

As soon as CO_2 migrates from the atmosphere into the water, it can react chemically with water molecules to form carbonic acid, which causes a shift in the concentrations of the hydrogen carbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, which are derived from the carbonic acid. Because carbon dioxide is thus immediately processed in the sea, the CO_2 capacity of the oceans is ten times higher than that of freshwater, and they therefore can absorb large quantities of it. Scientists refer to this kind of assimilation of CO_2 as a sink. The ocean absorbs

Fertilizing the ocean with iron

Iron is a crucial nutrient for plants and the second most abundant chemical element on Earth, although the greatest portion by far is locked in the Earth's core. Many regions have sufficient iron for plants. In large regions of the ocean, however, iron is so scarce that the growth of single-celled algae is limited by its absence. Iron-limitation regions include the tropical eastern Pacific and parts of the North Pacific, as well as the entire Southern Ocean. These ocean regions are rich in the primary nutrients (macronutrients) nitrate and phosphate. The iron, however, which plants require only in very small amounts (micronutrients), is missing. Scientists refer to these marine regions as HNLC regions (high nutrient, low chlorophyll) because algal growth here is restricted and the amount of the plant pigment chlorophyll is reduced accordingly. Research using fertilization experiments has shown that plant growth in all of these regions can be stimulated by fertilizing the water with iron. Because plants assimilate carbon, carbon dioxide from the atmosphere is thus converted to biomass, at least for the short term.

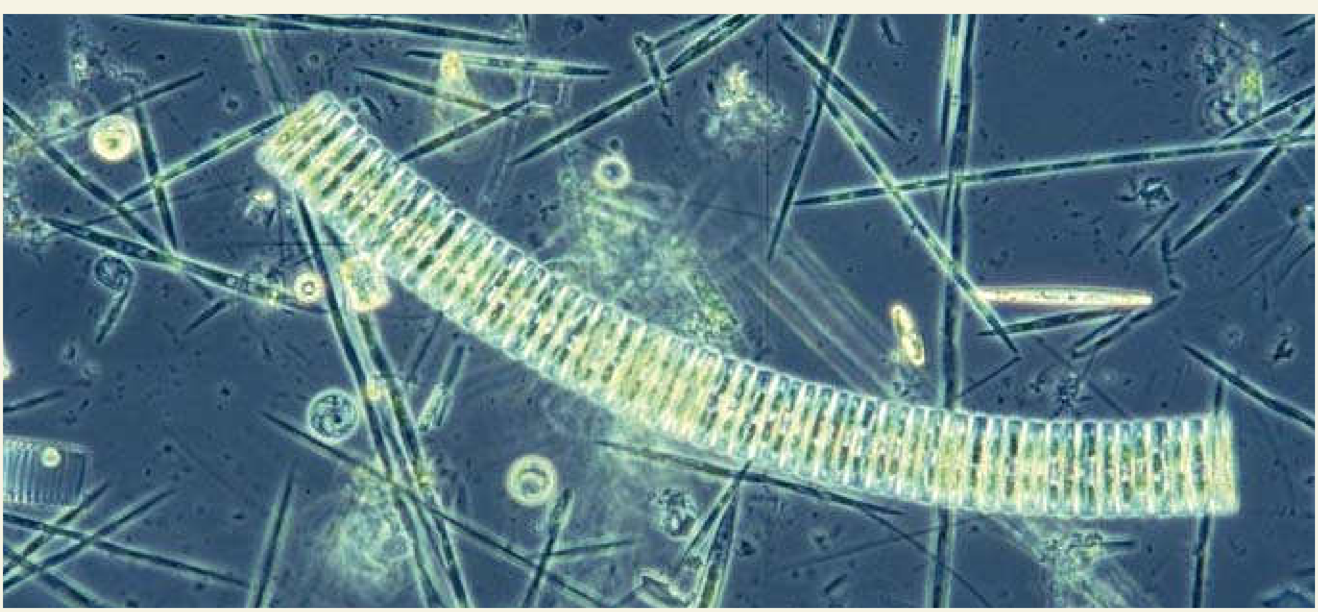
Iron fertilization is a completely natural phenomenon. For example, iron-rich dust from deserts is blown to the sea by the wind. Iron also enters the oceans with the meltwater of icebergs or by contact of the water with iron-rich sediments on the sea floor. It is presumed that different wind patterns and a dryer atmosphere during the last ice age led to a significantly higher input of iron into the Southern Ocean. This could, at least in part, explain the considerably lower atmospheric CO_2 levels during the last ice age. Accordingly, modern modelling simulations indicate that large-scale iron fertilization of the oceans could decrease the present atmospheric CO_2 levels by around 30 ppm (parts per million). By comparison, human activities have increased the atmospheric CO_2 levels from around 280 ppm to a present-day value of 390 ppm.

Marine algae assimilate between a thousand and a million times less iron than carbon. Thus even very low quantities of iron are sufficient to stimulate the uptake of large amounts of carbon dioxide in plants. Under favourable conditions large amounts of CO_2 can be converted with relatively little iron. This raises the obvious idea of fertilizing the oceans on a large scale and reducing the CO_2 concentrations in the atmosphere by storage in marine organisms (sequestration). When the algae die, however, and sink to the bottom and are digested by animals or broken down by microorganisms, the carbon dioxide is released again. In order to evaluate whether the fixed

2.2 > Iron is a crucial nutrient for algae, and it is scarce in many ocean regions, which inhibits algal growth. If the water is fertilized with iron there is a rapid increase in algae. Microscopic investigations of water samples taken by the research vessel "Polarstern" clearly show that algae in this iron-poor region proliferate quickly after iron fertilization. Around three weeks after fertilization the marine algal community was dominated by elongate, hard-shelled diatoms.

carbon dioxide actually remains in the ocean, the depth at which the biomass produced by iron fertilization is broken down and carbon dioxide is released must be known, because this determines its spatial and temporal distance from the atmosphere. Normally, 60 to 90 per cent of the biomass gets broken down in the surface water, which is in contact with the atmosphere. So this portion of the biomass does not represent a contribution to sequestration. Even if the breakdown occurs at great depths, the CO_2 will be released into the atmosphere within a few hundred to thousand years because of the global ocean circulation.

There are other reasons why iron fertilization is so controversial. Some scientists are concerned that iron input will disturb the nutrient budget in other regions. Because the macronutrients in the surface water are consumed by increased algal growth, it is possible that nutrient supply to other downstream ocean regions will be deficient. Algal production in those areas would decrease, counteracting the CO_2 sequestration in the fertilized areas. Such an effect would be expected, for example, in the tropical Pacific, but not in the Southern Ocean where the surface water, as a rule, only remains at the sea surface for a relatively short time, and quickly sinks again before the macronutrients are depleted. Because these water masses then remain below the surface for hundreds of years, the Southern Ocean appears to be the most suitable for CO_2 sequestration. Scientists are concerned that iron fertilization could have undesirable side effects. It is possible that iron fertilization could contribute to local ocean acidification due to the increased decay of organic material and thus greater carbon dioxide input into the deeper water layers. Furthermore, the decay of additional biomass created by fertilization would consume more oxygen, which is required by fish and other animals. The direct effects of reduced oxygen levels on organisms in the relatively well-oxygenated Southern Ocean would presumably be very minor. But the possibility that reduced oxygen levels could have long-range effects and exacerbate the situation in the existing low-oxygen zones in other areas of the world ocean cannot be ruled out. The possible consequences of iron fertilization on species diversity and the marine food chain have not yet been studied over time frames beyond the few weeks of the iron fertilization experiments. Before iron fertilization can be established as a possible procedure for CO_2 sequestration, a clear plan for observing and recording the possible side effects must first be formulated.

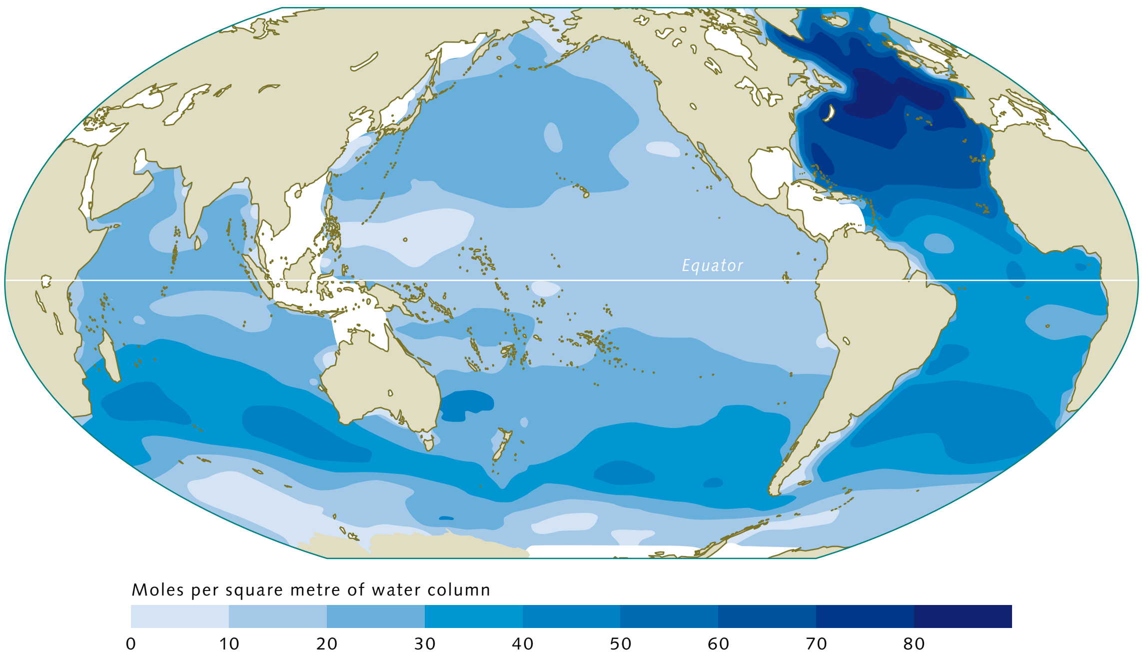


human-made atmospheric CO_2, and this special property of seawater is primarily attributable to carbonation, which, at 10 per cent, represents a significant proportion of the dissolved inorganic carbon in the ocean. In the ocean, the carbon dissolved in the form of CO_2, bicarbonate and carbonate is referred to as inorganic carbon. When a new carbon equilibrium between the atmosphere and the world ocean is re-established in the future, then the oceanic reservoir will have assimilated around 80 per cent of the anthropogenic CO_2 from the atmosphere, primarily due to the reaction with carbonate. The buffering effect of deep-sea calcium carbonate sediments is also important. These ancient carbonates neutralize large amounts of CO_2 by reacting with it, and dissolving to some extent. Thanks to these processes, the oceans could ultimately absorb around 95 per cent of the anthropogenic emissions. Because of the slow mixing of the ocean, however, it would take centuries before equilibrium is established. The very gradual buffering of CO_2 by the reaction with carbonate sediments might even take millennia. For today's situation this means that a marked carbon disequilibrium between the ocean and atmosphere will continue to exist for the decades and centuries to come. The world ocean cannot absorb the greenhouse gas as rapidly as it is emitted into the atmosphere by humans. The absorptive capacity of the oceans through chemical processes in the water is directly dependent on the rate of mixing in the world ocean. The current oceanic uptake of CO_2 thus lags significantly behind its chemical capacity as the present-day CO_2 emissions occur much faster than they can be processed by the ocean.

Measuring exchange between the atmosphere and ocean

For dependable climate predictions it is extremely important to determine exactly how much CO_2 is absorbed by the ocean sink. Researchers have therefore developed a

2.3 > Cement plants like this one in Amsterdam are, second to the burning of fossil fuels, among the most significant global sources of anthropogenic carbon dioxide. The potential for reducing CO_2 output is accordingly large in these industrial areas.



2.4 > The world ocean takes up anthropogenic CO_2 everywhere across its surface. The transport into the interior ocean, however, primarily takes place in the North Atlantic and in a belt between 30 and 50 degrees south latitude. The values indicate the total uptake from the beginning of the industrial revolution until the year 1994.

variety of independent methods to quantify the present role of the ocean in the anthropogenically impacted carbon cycle. These have greatly contributed to the present-day understanding of the interrelationships. Two procedures in particular have played an important role:

The first method (atmosphere-ocean flux) is based on the measurement of CO_2 partial-pressure differences between the ocean surface and the atmosphere. Partial pressure is the amount of pressure that a particular gas such as CO_2 within a gas mixture (the atmosphere) contributes to the total pressure. Partial pressure is thus also one possibility for quantitatively describing the composition of the atmosphere. If more of this gas is present, its partial pressure is higher. If two bodies, such as the atmosphere and the near-surface layers of the ocean, are in contact with each other, then a gas exchange between them can occur. In the case of a partial-pressure difference between the two media, there is a net exchange of CO_2. The gas flows from the body with the higher partial pressure into that of lower pressure. This net gas exchange can be calculated when the global distribution of the CO_2 partial-pressure difference is known. Considering the size of the world ocean this requires an enormous measurement effort. The worldwide fleet of research vessels is not nearly large enough for this task. A significant number of merchant vessels were therefore outfitted with measurement instruments that automatically carry out CO_2 measurements and store the data during their voyages or even transmit them daily via satellite. This "Voluntary Observing Ship" project (VOS) has been developed and expanded over the last two decades and employs dozens of ships worldwide. It is fundamentally very difficult to adequately record the CO_2 exchange in the world ocean, because it is constantly changing through space and time. Thanks to the existing VOS network, however, it has been possible to obtain measurements to provide an initial important basis. The database, covering over three decades, is sufficient to calculate the average annual gas exchange over the total surface of the oceans with some confidence. It is given as average annual CO_2 flux density (expressed in mol $C/m^2/year$), that is the net flux of CO_2 per square meter of ocean surface per year, which can be integrated to yield the total annual CO_2 uptake of the world ocean.

Our present picture is based on around three million measurements that were collected and calculated for the CO_2 net flux. The data were recorded between 1970 and 2007, and most of the values from the past decade were obtained through the VOS programme. Regions that are important for world climate such as the subpolar North Atlantic and the subpolar Pacific have been reasonably well covered. For other ocean regions, on the other hand, there are still only limited numbers of measurements. For these undersampled regions, the database is presently insufficient for a precise calculation. Still, scientists have been able to use the available data to fairly well quantify the oceanic CO_2 sink. For the reference year 2000 the sink accounts for 1.4 Gt C.

This value represents the net balance of the natural carbon flux out of the ocean into the atmosphere and, conversely, the transport of anthropogenic carbon from the atmosphere into the ocean. Now, as before, the annual natural pre-industrial amount of 0.6 Gt C is flowing out of the ocean. Conversely, around 2.0 Gt C of anthropogenic carbon is entering the ocean every year, leading to the observed balance uptake of 1.4 Gt C per year. Because of the still rather limited amount of data, this method has had to be restricted so far to the climatological CO_2 flux, i.e., a long-term average over the entire observation period. Only now are studies beginning to approach the possibility of looking at interannual variability for this CO_2 sink in especially well-covered regions. The North Atlantic is a first prominent example. Surprisingly, the data shows significant variations between individual years. Presumably, this is attributable to natural climate cycles such as the North Atlantic Oscillation, which have a considerable impact on the natural carbon cycle. Understanding such natural variability of the ocean is a prerequisite for reliable projections of future development and change of the oceanic sink for CO_2.

The second method attempts, with the application of rather elaborate geochemical or statistical procedures, to calculate how much of the CO_2 in the ocean is derived from natural sources and how much is from anthropogenic sources, although from a chemical aspect the two are basically identical, and cannot be clearly distinguished. Actually, several procedures are available today that allow this difficult differentiation, and they generally provide very consistent results. These methods differ, however, in detail, depending on the assumptions and approximations associated with a particular method. The most profound basis for estimating anthropogenic CO_2 in the ocean is the global hydrographic GLODAP dataset (Global Ocean Data Analysis Project), which was obtained from 1990 to 1998 through large international research projects. This dataset:

- includes quality-controlled data on a suite of carbon and other relevant parameters;
- is based on analyses of more than 300,000 water samples;
- contains data that were collected on nearly 100 expeditions and almost 10,000 hydrographic stations in the ocean.

All of these data were corrected and subjected to multilevel quality control measures in an elaborate process. This provided for the greatest possible consistency and comparability of data from a number of different laboratories. Even today, the GLODAP dataset still provides the most exact and comprehensive view of the marine carbon cycle. For the first time, based on this dataset, reliable estimateshave been made of how much anthropogenic carbon dioxide has been taken up from the atmosphere by the ocean sink. From the beginning of industrialization to the year 1994, the oceanic uptake of anthropogenic carbon dioxide amounts to 118 ± 19 Gt C. The results indicate that anthropogenic CO_2, which is taken up everywhere across the ocean's surface flows into the ocean's interior from the atmosphere primarily in two regions. One of these is the subpolar North Atlantic, where the CO_2 submerges with deep-water formation to the ocean depths. The other area of CO_2 flux into the ocean is a belt between around 30 and 50 degrees of southern latitude. Here the surface water sinks because of the formation of water that spreads to intermediate depths in the ocean.

The CO_2 input derived from the GLODAP dataset to some extent represents a snapshot of a long-term transition to a new equilibrium. Although the anthropogenic carbon dioxide continuously enters the ocean from the surface, the gas has not penetrated the entire ocean by any means. The GLODAP data show that the world ocean has so far only absorbed around 40 per cent of the carbon dioxide discharged by humans into the atmosphere between 1800 and 1995. The maximum capacity of the world ocean of more than 80 per cent is therefore far from being achieved.

How climate change impacts the marine carbon cycle

The natural carbon cycle transports many billions of tons of carbon annually. In a physical sense, the carbon is spatially transported by ocean currents. Chemically, it changes from one state to another, for example, from inorganic to organic chemical compounds or vice versa. The foundation for this continuous transport and conversion is made up of a great number of biological, chemical and physical processes that constitute what is also known as carbon pumps. These processes are driven by climatic factors, or at least strongly influenced by them. One example is the metabolism of living organisms, which is stimulated by rising ambient temperatures. This temperature effect, however, is presumably less significant for the biomass producers (mostly single-celled algae) than for the biomass consumers (primarily the bacteria), which could cause a shift in the local organic carbon balance in some regions. Because many climatic interactions are still not well understood, it is difficult to predict how the carbon cycle and the carbon pumps will react to climate change. The first trends indicating change that have been detected throughout the world ocean are those of water temperature and salinity. In addition, a general decrease in the oxygen content of seawater has been observed, which can be attributed to biological and physical causes such as changes in current flow and higher temperatures. It is also possible that changes in the production and breakdown of biomass in the ocean play a role here.

Changes in the carbon cycle are also becoming apparent in another way: The increasing accumulation of carbon dioxide in the sea leads to acidification of the oceans or, in chemical terms, a decline in the pH value. This could have a detrimental impact on marine organisms and ecosystems. Carbonate-secreting organisms are particularly susceptible to this because an acidifying environment is less favorable for carbonate production. Laboratory experiments have shown that acidification has a negative effect on the growth of corals and other organisms. The topic of ocean acidification is presently being studied in large research programmes worldwide. Conclusive results relating to the feedback effects between climate and acidification are thus not yet available. This is also the case for the impact of ocean warming. There are many indications for significant feedback effects here, but too little solid knowledge to draw any robust quantitative conclusions.

We will have to carry out focussed scientific studies to see what impact global change will have on the natural carbon cycle in the ocean. It would be naïve to assume that this is insignificant and irrelevant for the future climate of our planet. To the contrary, our limited knowledge of the relationships should motivate us to study the ocean even more intensely and to develop new methods of observation.

2.5 > In order to determine the effect of increasing atmospheric CO_2 concentrations on the ocean, an international research team enriched seawater with CO_2 in floating tanks off Spitsbergen, and studied the effects on organisms.

The consequences of ocean acidification

> Climate change not only leads to warming of the atmosphere and water, but also to an acidification of the oceans. It is not yet clear what the ultimate consequences of this will be for marine organisms and communities, as only a few species have been studied. Extensive long-term studies on a large variety of organisms and communities are needed to understand potential consequences of ocean acidification.

How climate change acidifies the oceans

Carbon dioxide is a determining factor for our climate and, as a greenhouse gas, it contributes considerably to the warming of the Earth's atmosphere and thus also of the ocean. The global climate has changed drastically many times through the course of Earth history. These changes, in part, were associated with natural fluctuations in the atmospheric CO_2 content, for example, during the transitions from ice ages to interglacial periods (the warmer phases within longer glacial epochs). The drastic increase in atmospheric CO_2 concentrations by more than 30 per cent since the beginning of industrialization, by contrast, is of anthropogenic origin, i.e. caused by humans.

The largest CO_2 sources are the burning of fossil fuels, including natural gas, oil, and coal, and changes in land usage: clearing of forests, draining of swamps, and expansion of agricultural areas. CO_2 concentrations in the atmosphere have now reached levels near 390 ppm (parts per million). In pre-industrial times this value was only around 280 ppm. Now climate researchers estimate that the level will reach twice its present value by the end of this century. This increase will not only cause additional warming of the Earth. There is another effect associated with it that has only recently come to the attention of the public – acidification of the world ocean.

There is a permanent exchange of gas between the air and the ocean. If the CO_2 levels in the atmosphere increase, then the concentrations in the near-surface layers of the ocean increase accordingly. The dissolved carbon dioxide reacts to some extent to form carbonic acid. This reaction releases protons, which leads to acidification of the seawater. The pH values drop. It has been demonstrated that the pH value of seawater has in fact already fallen, parallel to the carbon dioxide increase in the atmosphere, by an average of 0.1 units. Depending on the future trend of carbon dioxide emissions, this value could fall by another 0.3 to 0.4 units by the end of this century. This may appear to be negligible, but in fact it is equivalent to an increased proton concentration of 100 to 150 per cent.

The pH value
The pH value is a measure of the strength of acids and bases in a solution. It indicates how acidic or basic a liquid is. The pH scale ranges from 0 (very acidic) to 14 (very basic). The stronger an acid is the more easily it loses protons (H^+), which determines the pH value. Practically expressed, the higher the proton concentration is, the more acidic a liquid is, and the lower its pH value is.

The effect of pH on the metabolism of marine organisms

The currently observed increase of CO_2 concentrations in the oceans is, in terms of its magnitude and rate, unparalleled in the evolutionary history of the past 20 million years. It is therefore very uncertain to what extent the marine fauna can adapt to it over extended time periods. After all, the low pH values in seawater have an adverse effect on the formation of carbonate minerals, which is critical for many invertebrate marine animals with carbonate skeletons, such as mussels, corals or sea urchins.

Processes similar to the dissolution of CO_2 in seawater also occur within the organic tissue of the affected organisms. CO_2, as a gas, diffuses through cell membranes into the blood, or in some animals into the hemolymph, which is analogous to blood. The organism has to compensate for this disturbance of its natural acid-base balance, and some animals are better at this than others. Ultimately this ability depends on the genetically determined efficiency of various mechanisms of pH and ion regulation,

2.6 > By studying ice cores scientists want to discover which organisms live in the ice. Air bubbles in Antarctic ice cores also provide clues to the presence of trace gases in the former atmosphere, and to past climate. The ice cores are drilled using powerful tools. For more detailed study they are analysed in the laboratory. When ice crystals are observed under a special polarized light, their fine structure reveals shimmering colours.

which depends on the animal group and lifestyle. In spite of enhanced regulatory efforts by the organism to regulate them, acid-base parameters undergo permanent adjustment within tissues and body fluids. This, in turn, can have an adverse effect on the growth rate or reproductive capacity and, in the worst case, can even threaten the survival of a species in its habitat.

The pH value of body fluids affects biochemical reactions within an organism. All living organisms therefore strive to maintain pH fluctuations within a tolerable range. In order to compensate for an increase in acidity due to CO_2, an organism has two possibilities: It must either increase its expulsion of excessive protons or take up additional buffering substances, such as bicarbonate ions, which bind protons. For the necessary ion regulation processes, most marine animals employ specially developed epithelia that line body cavities, blood vessels, or the gills and intestine.

The ion transport systems used to regulate acid-base balance are not equally effective in all marine animal groups. Marine organisms are apparently highly tolerant of CO_2 when they can accumulate large amounts of bicarbonate ions, which stabilize the pH value. These organisms are usually also able to very effectively excrete protons. Mobile and active species such as fish, certain crustaceans, and cephalopods – cuttlefish, for instance – are therefore especially CO_2-tolerant. The metabolic rates of these animals can strongly fluctuate and reach

When carbonate formation loses equilibrium

The atmospheric gas carbon dioxide (CO_2) dissolves very easily in water. This is well known in mineral water, which often has carbon dioxide added. In the dissolution process, carbon dioxide reacts with the water molecules according to the equation below. When carbon dioxide mixes with the water it is partially converted into carbonic acid, hydrogen ions (H^+), bicarbonate (HCO_3^-), and carbonate ions (CO_3^{2-}). Seawater can assimilate much more CO_2 than fresh water. The reason for this is that bicarbonate and carbonate ions have been perpetually discharged into the sea over aeons. The carbonate reacts with CO_2 to form bicarbonate, which leads to a further uptake of CO_2 and a decline of the CO_3^{2-} concentration in the ocean. All of the CO_2-derived chemical species in the water together, i.e. carbon dioxide, carbonic acid, bicarbonate and carbonate ions, are referred to as dissolved inorganic carbon (DIC). This carbonic acid-carbonate equilibrium determines the amount of free protons in the seawater and thus the pH value.

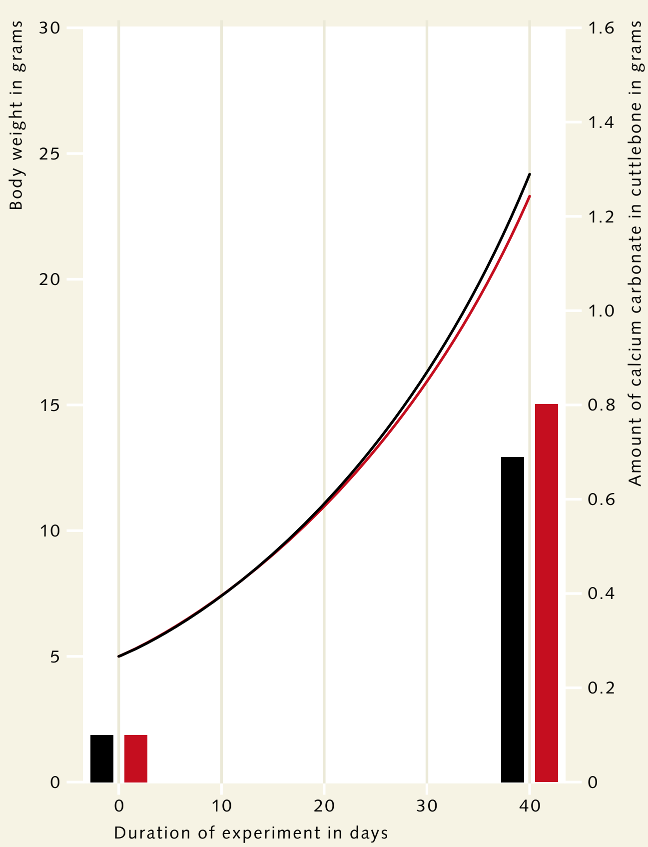
$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2\,H^+ + CO_3^{2-}$$

In summary, the reaction of carbon dioxide in seawater proceeds as follows: First the carbon dioxide reacts with water to form carbonic acid. This then reacts with carbonate ions and forms bicarbonate. Over the long term, ocean acidification leads to a decrease in the concentration of carbonate ions in seawater. A 50 per cent decline

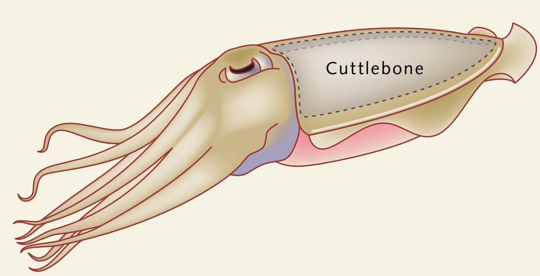
2.7 > Studies of the coral *Oculina patagonia* show that organisms with carbonate shells react sensitively to acidification of the water. Picture a shows a coral colony in its normal state. The animals live retracted within their carbonate exoskeleton (yellowish). In acidic water (b) the carbonate skeleton degenerates. The animals take on an elongated polyp form. Their small tentacles, which they use to grab nutrient particles in the water, are clearly visible. Only when the animals are transferred to water with natural pH values do they start to build their protective skeletons again (c).

of the levels is predicted, for example, if there is a drop in pH levels of 0.4 units. This would be fatal. Because carbonate ions together with calcium ions (als $CaCO_3$) form the basic building blocks of carbonate skeletons and shells, this decline would have a direct effect on the ability of many marine organisms to produce **biogenic** carbonate. In extreme cases this can even lead to the dissolution of existing carbonate shells, skeletons and other structures.

Many marine organisms have already been studied to find out how acidification affects carbonate formation. The best-known examples are the warm-water corals, whose skeletons are particularly threatened by the drop in pH values. Scientific studies suggest that carbon dioxide levels could be reached by the middle of this century at which a net growth (i.e. the organisms form more carbonate than is dissolved in the water), and thus the successful formation of reefs, will hardly be possible. In other invertebrates species, such as mussels, sea urchins and starfish, a decrease in calcification rates due to CO_2 has also been observed. For many of these invertebrates not only carbonate production, but also the growth rate of the animal was affected. In contrast, for more active animal groups such as fish, salmon, and the cephalopod mollusc *Sepia officinalis,* no evidence could be found as to know that the carbon dioxide content in the seawater had an impact on growth rates. In order to draw accurate conclusions about how the carbon dioxide increase in the water affects marine organisms, further studies are therefore necessary.



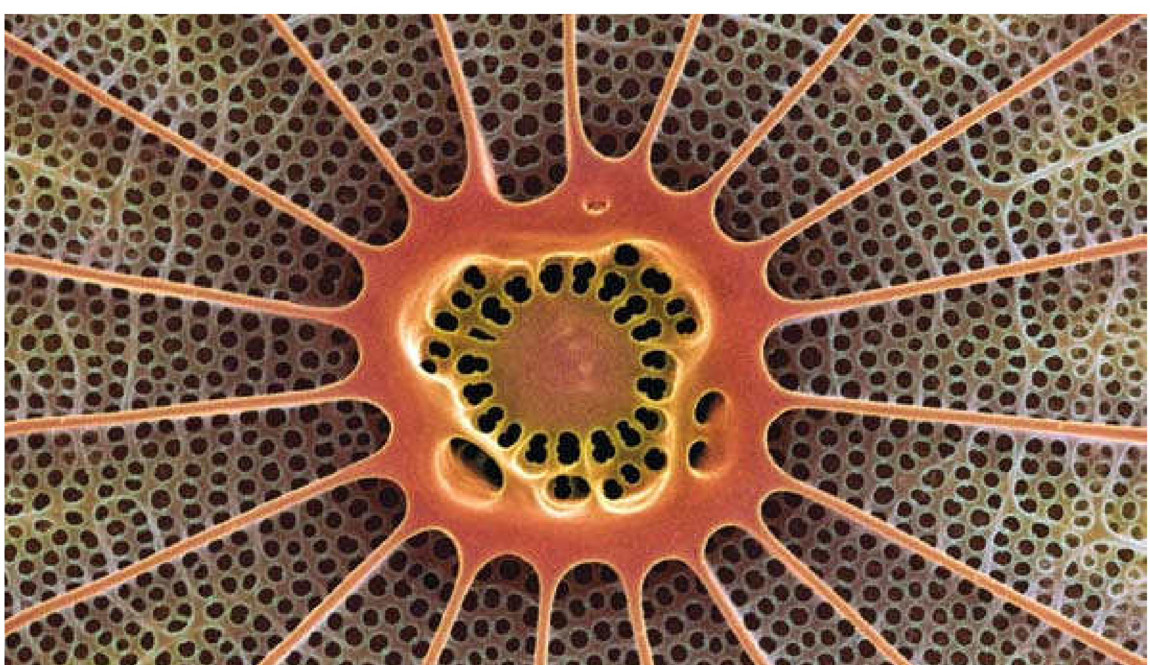
2.8 > Active and rapidly moving animals like the cephalopod mollusc (cuttlefish) *Sepia officinalis* are apparently less affected by acidification of the water. The total weight of young animals increased over a period of 40 days in acidic seawater (red line) just as robustly as in water with a normal pH and CO_2 content (black line). The growth rate of the calcareous shield, the cuttlebone, also proceeded at very high rates (see the red and black bars in the diagram). The amount of calcium carbonate ($CaCO_3$) incorporated in the cuttlebone is used as a measure here. The schematic illustration of the cephalopod shows the position of the cuttlebone on the animal.



very high levels during exercise (hunting & escape behaviour). The oxygen-consumption rate (a measure of metabolic rate) of these active animal groups can reach levels that are orders of magnitude above those of sea urchins, starfish or mussels. Because large amounts of CO_2 and protons accumulate during excessive muscle activity, active animals often possess an efficient system for proton excretion and acid-base regulation. Consequently, these animals can better compensate for disruptions in their acid-base budgets caused by acidification of the water.

Benthic invertebrates (bottom-dwelling animals without a vertebral column) with limited ability to move great distances, such as mussels, starfish or sea urchins, often cannot accumulate large amounts of bicarbonate in their body fluids to compensate for acidification and the excess protons. Long-term experiments show that some of these species grow more slowly under acidic conditions. One reason for the reduced growth could be a natural protective mechanism of invertebrate animal species: In stress situations such as falling dry during low tide, these organisms reduce their metabolic rates. Under normal conditions this is a very effective protection strategy that insures survival during short-term stress situations. But when they are exposed to long-term CO_2 stress, this protective mechanism could become a disadvantage for the sessile animals. With the long-term increase in carbon dioxide levels in seawater, the energy-saving behaviour and the suppression of metabolism inevitably leads to limited growth, lower levels of activity, and thus a reduced ability to compete within the ecosystem.

However, the sensitivity of a species' reaction to CO_2 stressor and acidification cannot be defined alone by the simple formula: good acid-base regulation = high CO_2 tolerance. There are scientific studies that suggest this is not the case. For example, one study investigated the ability of a species of brittlestar (echinodermata), an invertebrate that mainly lives in the sediment, to regenerate severed arms. Surprisingly, animals from more acidic seawater not only re-grew longer arms, but their calcareous skeletons also contained a greater amount of calcium carbonate. The price for this, however, was reduced muscle growth. So in spite of the apparent positive indications at first glance, this species is obviously adversely affected by ocean acidification because they

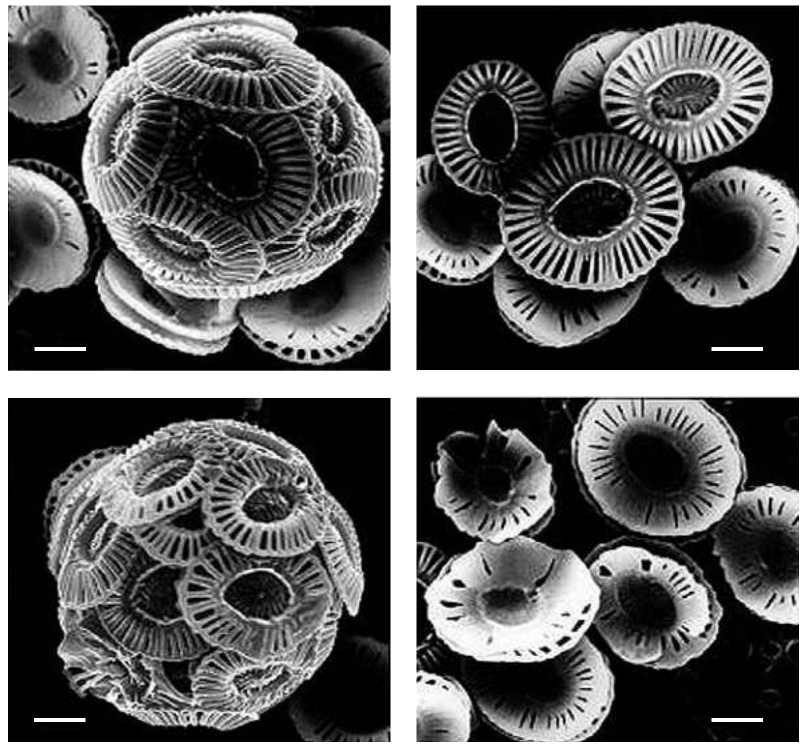


2.9 > Diatoms like this Arachnoidiscus are an important nutrient basis for higher organisms. It is still uncertain how severely they will be affected by acidification of the oceans.

can only efficiently feed and supply their burrows in the sediment with oxygenated seawater if they have fully functioning arms.

Even fish can be impaired. Many adult animals are relatively CO_2 tolerant. Early developmental stages, however, obviously react very sensitively to the CO_2 stressor. A strong impairment of the sense of smell in seawater with low pH values was observed in the larval clownfish. These animals are normally able to orientate themselves by a specific odour signal and, after their larval phase, which they spend free-swimming in the water column, to find their final permanent habitat on coral reefs. In the experiment, fish larvae that were raised in seawater with a pH value lowered by about 0.3 units, reacted significantly less to the otherwise very stimulating odour of sea anemones with which they live in symbiosis on reefs. If behavioural changes caused by CO_2 occur during a critical phase of the life cycle, they can, of course, have a strong impact on the reproductive success of a species.

It is not yet known to what extent other marine organisms are impacted by these kinds of effects of ocean acidification. Other studies on embryonic and juvenile stages of various species have shown, however, that the early developmental stages of an organism generally respond more sensitively to CO_2 stress than the adult animals do.



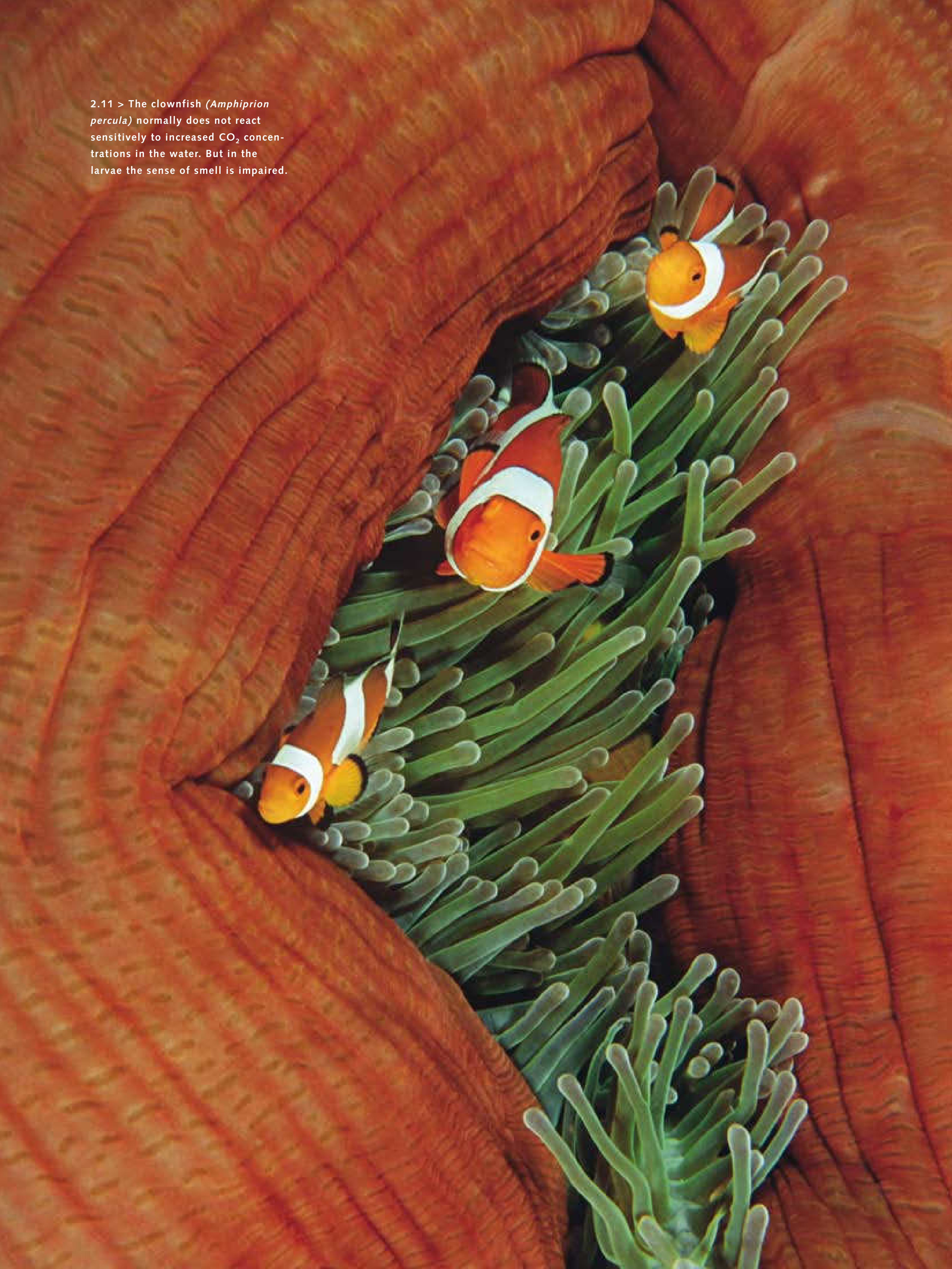
2.10 > These electron micrographs clearly illustrate that increased CO_2 concentrations in the water can disturb and lead to malformation in calcareous marine organisms, such as the coccolithophorid *Emiliana huxleyi* shown here. The upper pictures reflect CO_2 concentrations in the water of 300 ppm, which is slightly above the pre-industrial average CO_2 level for seawater. The bottom photographs reflect a CO_2 content of 780 to 850 ppm. For size comparison, the bars represent a length of one micrometre.

Threat to the nutrition base in the oceans – phytoplankton and acidification

The the entire food chain in the ocean is represented by the microscopic organisms of the marine phytoplankton. These include diatoms (siliceous algae), coccolithophores (calcareous algae), and the cyanobacteria (formerly called blue algae), which, because of their photosynthetic activity, are responsible for around half of the global primary productivity.

Because phytoplankton requires light for these processes, it lives exclusively in surface ocean waters. It is therefore directly affected by ocean acidification. In the future, however, due to global warming, other influencing variables such as temperature, light or nutrient availability will also change due to global warming. These changes will also determine the productivity of autotrophic organisms, primarily bacteria or algae, which produce biomass purely by photosynthesis or the incorporation of chemical compounds. It is therefore very difficult to predict which groups of organisms will profit from the changing environmental conditions and which will turn out to be the losers.

Ocean acidification is of course not the only consequence of increased CO_2. This gas is, above all, the elixir of life for plants, which take up CO_2 from the air or seawater and produce biomass. Except for the acidification problem, increasing CO_2 levels in seawater should



2.11 > The clownfish *(Amphiprion percula)* normally does not react sensitively to increased CO_2 concentrations in the water. But in the larvae the sense of smell is impaired.

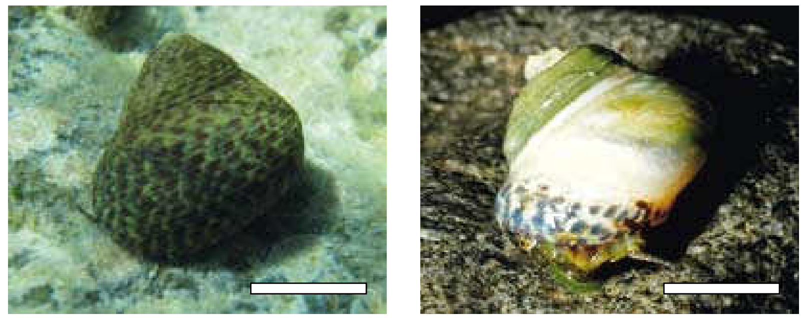
therefore favour the growth of those species whose photosynthetic processes were formerly limited by carbon dioxide. For example, a strong increase in photosynthesis rates was reported for cyanobacteria under higher CO_2 concentrations. This is also true for certain coccolithophores such as *Emiliania huxleyi.* But even for *Emiliania* the initially beneficial rising CO_2 levels could become fatal. *Emiliania* species possess a calcareous shell comprised of numerous individual plates. There is now evidence that the formation of these plates is impaired by lower pH values. In contrast, shell formation by diatoms, as well as their photosynthetic activity, seems to be hardly affected by carbon dioxide. For diatoms also, however, shifts in species composition have been reported under conditions of increased CO_2 concentration.

Challenge for the future: Understanding acidification

In order to develop a comprehensive understanding of the impacts of ocean acidification on life in the sea, we have to learn how and why CO_2 affects various physiological processes in marine organisms. The ultimate critical challenge is how the combination of individual processes determines the overall CO_2 tolerance of the organisms. So far, investigations have mostly been limited to short-term studies. To find out how and whether an organism can grow, remain active and reproduce successfully in a more acidified ocean, long term (months) and multiple-generation studies are neccessary.

The final, and most difficult step, thus is to integrate the knowledge gained from species or groups at the ecosystem level. Because of the diverse interactions among species within ecosystems, it is infinitely more difficult to predict the behaviour of such a complex system under ocean acidification.

In addition, investigations are increasingly being focused on marine habitats that are naturally characterized by higher CO_2 concentrations in the seawater. Close to the Italian coast around the island of Ischia, for instance, CO_2 is released from the sea floor due to volcanic activity, leading to acidification of the water. This means that there are coastal areas directly adjacent to one another with normal (8.1 to 8.2) and significantly lowered pH values (minimum 7.4). If we compare the animal and plant communities of these respective areas, clear differences can be observed: In the acidic areas rock corals are completely absent, the number of specimens of various sea urchin and snail species is low, as is the number of calcareous red algae. These acidic areas of the sea are mainly dominated by seagrass meadows and various non-calcareous algal species.



2.12 > Low pH values in the waters around Ischia cause corrosion of the shells of calcareous animals such as the snail *Osilinus turbinata*. The left picture shows an intact spotted shell at normal pH values of 8.2. The shell on the right, exposed to pH values of 7.3, shows clear signs of corrosion. The scale bars are equal to one centimetre.

The further development of such ecosystem-based studies is a great challenge for the future. Such investigations are prerequisite to a broader understanding of future trends in the ocean. In addition, deep-sea ecosystems, which could be directly affected by the possible impacts of future CO_2 disposal under the sea floor, also have to be considered.

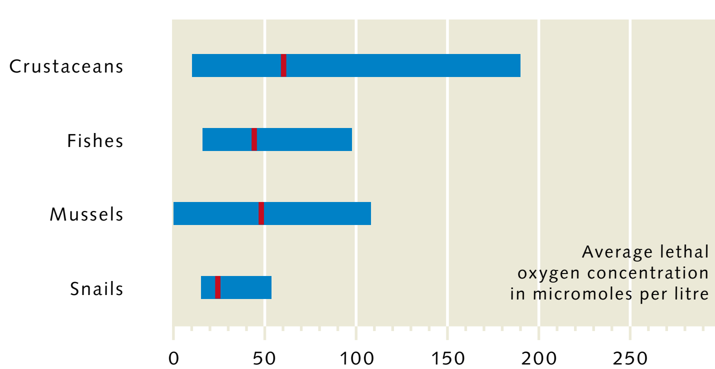
In addition, answers have to be found to the question of how climate change affects reproduction in various organisms in the marine environment. Up to now there have been only a few exemplary studies carried out and current science is still far from a complete understanding. Whether and how different species react to chemical changes in the ocean, whether they suffer from stress or not is, for the most part, still unknown. There is an enormous need for further research in this area.

Oxygen in the ocean

> Scientists have been routinely measuring oxygen concentrations in the ocean for more than a hundred years. With growing concerns about climate change, however, this parameter has suddenly become a hot topic. Dissolved oxygen in the ocean provides a sensitive early warning system for the trends that climate change is causing. A massive deployment of oxygen sensors is projected for the coming years, which will represent a renaissance of this parameter.

Oxygen – product and elixir of life

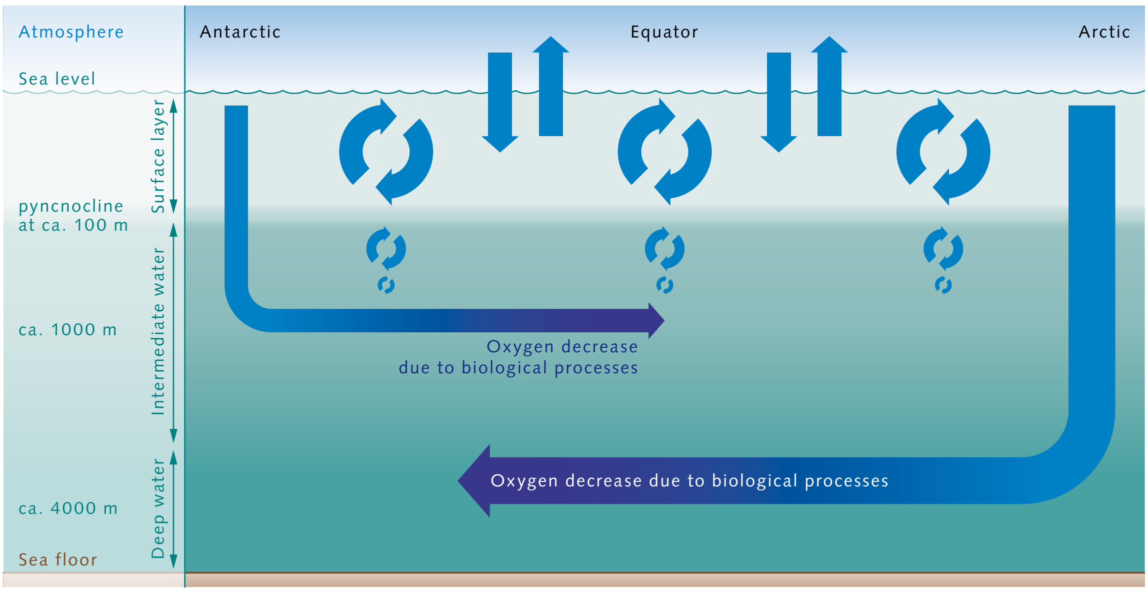
Carbon dioxide, which occurs in relatively small amounts in the atmosphere, is both a crucial substance for plants, and a climate-threatening gas. Oxygen, on the other hand, is not only a major component of the atmosphere, it is also the most abundant chemical element on Earth. The emergence of oxygen in the atmosphere is the result of a biological success model, photosynthesis, which helps plants and bacteria to convert inorganic materials such as carbon dioxide and water to biomass. Oxygen was, and continues to be generated by this process. The biomass produced is, for its part, the nutritional foundation for consumers, either bacteria, animals or humans. These consumers cannot draw their required energy from sunlight as the plants do, rather they have to obtain it by burning biomass, a process that consumes oxygen. Atmospheric oxygen on our planet is thus a product, as well as the elixir of life.



2.13 > Marine animals react in different ways to oxygen deficiency. Many species of snails, for instance, can tolerate lower O_2 levels than fish or crabs. The diagram shows the concentration at which half of the animals die under experimental conditions. The average value is shown as a red line for each animal group. The bars show the full spectrum: some crustaceans can tolerate much lower O_2 concentrations than others.

Oxygen budget for the world ocean

Just like on the land, there are also photosynthetically active plants and bacteria in the ocean, the **primary producers.** Annually, they generate about the same amount of oxygen and fix as much carbon as all the land plants together. This is quite amazing. After all, the total living biomass in the ocean is only about one two-hundredth of that in the land plants. This means that primary producers in the ocean are around two hundred times more productive than land plants with respect to their mass. This reflects the high productivity of single-celled algae, which contain very little inactive biomass such as, for example, the heartwood in tree trunks. Photosynthetic production of oxygen is limited, however, to the uppermost, sunlit layer of the ocean. This only extends to a depth of around 100 metres and, because of the stable density layering of the ocean, it is largely separated from the enormous underlying volume of the deeper ocean. Moreover, most of the oxygen generated by the primary producers escapes into the atmosphere within a short time, and thus does not contribute to oxygen enrichment in the deep water column. This is because the near-surface water, which extends down to around 100 metres, is typically saturated with oxygen by the supply from the atmosphere, and thus cannot store additional oxygen from biological production. In the inner ocean, on the



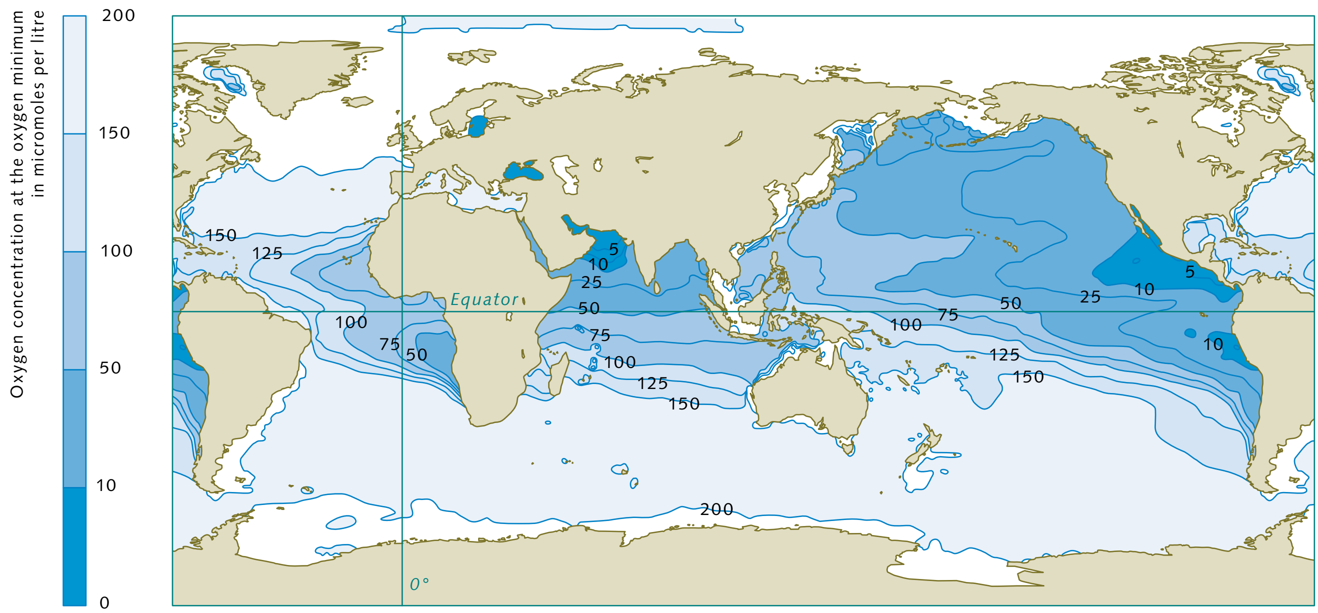
2.14 > Oxygen from the atmosphere enters the near-surface waters of the ocean. This upper layer is well mixed, and is thus in chemical equilibrium with the atmosphere and rich in O_2. It ends abruptly at the pyncnocline, which acts like a barrier. The oxygen-rich water in the surface zone does not mix readily with deeper water layers. Oxygen essentially only enters the deeper ocean by the motion of water currents, especially with the formation of deep and intermediate waters in the polar regions. In the inner ocean, marine organisms consume oxygen. This creates a very sensitive equilibrium.

other hand, there is no source of oxygen. Oxygen enters the ocean in the surface water through contact with the atmosphere. From there the oxygen is then brought to greater depths through the sinking and circulation of water masses. These, in turn, are dynamic processes that are strongly affected by climatic conditions. Three factors ultimately determine how high the concentration of dissolved oxygen is at any given point within the ocean:

1. The initial oxygen concentration that this water possessed at its last contact with the atmosphere.
2. The amount of time that has passed since the last contact with the atmosphere. This can, in fact, be decades or centuries.
3. Biological oxygen consumption that results during this time due to the respiration of all the consumers. These range from miniscule bacteria to the zooplankton, and up to the higher organisms such as fish.

The present-day distribution of oxygen in the internal deep ocean is thus determined by a complicated and not fully understood interplay of water circulation and biological productivity, which leads to oxygen consumption in the ocean's interior. Extensive measurements have shown that the highest oxygen concentrations are found at high latitudes, where the ocean is cold, especially well-mixed and ventilated. The mid-latitudes, by contrast, especially on the western coasts of the continents, are characterized by marked oxygen-deficient zones. The oxygen supply here is very weak due to the sluggish water circulation, and this is further compounded by elevated oxygen consumption due to high biological productivity. This leads to a situation where the oxygen is almost completely depleted in the depth range between 100 and 1000 metres. This situation is also observed in the northern Indian Ocean in the area of the Arabian Sea and the Bay of Bengal.

Different groups of marine organisms react to the oxygen deficiency in completely different ways, because of the wide range of tolerance levels of different marine



2.15 > Marine regions with oxygen deficiencies are completely natural. These zones are mainly located in the mid-latitudes on the west sides of the continents. There is very little mixing here of the warm surface waters with the cold deep waters, so not much oxygen penetrates to greater depths. In addition, high bioproductivity and the resulting large amounts of sinking biomass here lead to strong oxygen consumption at depth, especially between 100 and 1000 metres.

animals to oxygen-poor conditions. For instance, crustaceans and fish generally require higher oxygen concentrations than mussels or snails. The largest oceanic oxygen minimum zones, however, because of their extremely low concentrations, should be viewed primarily as natural dead zones for the higher organisms, and by no means as caused by humans.

Oxygen – the renaissance of a hydrographic parameter

Oxygen distribution in the ocean depends on both biological processes, like the respiration of organisms, and on physical processes such as current flow. Changes in either of these processes should therefore lead to changes in the oxygen distribution. In fact, dissolved oxygen can be viewed as a kind of sensitive early warning system for global (climate) change in the ocean. Scientific studies show that this early warning system can detect the expected decrease in oxygen transport from the atmosphere into the ocean that is driven by global current and mixing processes, as well as possible changes in the marine biotic communities. In recent years, this knowledge has led to a renaissance of oxygen in the field of global marine research.

In oceanography, dissolved oxygen has been an important measurement parameter for over a hundred years. A method for determining dissolved oxygen was developed as early as the end of the 19th century, and it is still applied in an only slightly modified form today as a precise method. This allowed for the development of an early fundamental understanding of the oxygen distribution in the world ocean, with the help of the famous German Atlantic Expedition of the "Meteor" in the 1920s.

Research efforts in recent years have recorded decreasing oxygen concentrations for almost all the ocean basins. These trends are, in part, fairly weak and mainly limited to water masses in the upper 2000 metres of the ocean.

Therefore, no fully consistent picture can yet be drawn from the individual studies. Most of the studies do, however, show a trend of decreasing oxygen concentrations. This trend agrees well with an already verified expansion and intensification of the natural oxygen minimum zones, those areas that are deadly for higher organisms. If the oxygen falls below certain (low) threshold values, the water becomes unsuitable for higher organisms. Sessile, attached organisms die. Furthermore, the oxygen deficiency leads to major changes in biogeochemical reactions and elemental cycles in the ocean – for instance, of the plant nutrients nitrate and phosphate.

Oxygen levels affect geochemical processes in the sediment but also, above all, bacterial metabolism processes, which, under altered oxygen conditions, can be changed dramatically. It is not fully possible today to predict what consequences these changes will ultimately have. In some cases it is not even possible to say with certainty whether climate change will cause continued warming, or perhaps even local cooling. But it is probable that the resulting noticeable effects will continue over a long time period of hundreds or thousands of years.

Even today, however, climate change is starting to cause alterations in the oxygen content of the ocean that can have negative effects. For the first time in recent years, an extreme low-oxygen situation developed off the coast of Oregon in the United States that led to mass mortality in crabs and fish. This new death zone off Oregon originated in the open ocean and presumably can be attributed to changes in climate. The prevailing winds off the west coast of the USA apparently changed direction and intensity and, as a result, probably altered the ocean currents. Researchers believe that the change caused oxygen-poor water from greater depths to flow to surface waters above the shelf.

The death zone off Oregon is therefore different than the more than 400 near-coastal death zones known worldwide, which are mainly attributed to eutrophication, the excessive input of plant nutrients. Eutrophication normally occurs in coastal waters near densely populated regions with intensive agricultural activity.

Oxygen – challenge to marine research

The fact that model calculations examining the effects of climate change almost all predict an oxygen decline in major parts of the ocean, which agrees with the available observations of decreasing oxygen, gives the subject additional weight. Even though the final verdict is not yet in, there are already indications that the gradual loss of oxygen in the world ocean is an issue of great relevance which possibly also has socio-economic repercussions, and which ocean research must urgently address.

Intensified research can provide more robust conclusions about the magnitude of the oxygen decrease. In addition it will contribute significantly to a better understanding of the effects of global climate change on the ocean. In recent years marine research has addressed this topic with increased vigour, and has already established appropriate research programmes and projects. It is difficult, however, to completely measure the temporally and spatially highly variable oceans in their totality. In order to draw reliable conclusions, therefore, the classic instruments of marine research like ships and taking water samples will not suffice. Researchers must begin to apply new observational concepts.

"Deep drifters" are an especially promising tool: these are submersible measuring robots that drift completely autonomously in the ocean for 3 to 4 years, and typically measure the upper 2000 metres of the water column every 10 days. After surfacing, the data are transferred to a data centre by satellite. There are presently around 3200 of these measuring robots deployed for the international research programme ARGO, named after a ship from Greek mythology. Together they form a worldwide autonomous observatory that is operated by almost 30 countries.

So far this observatory is only used on a small scale for oxygen measurements. But there has been developed a new sensor technology for oxygen measurements in the recent past that can be deployed on these drifters. This new technology would give fresh impetus to the collection of data on the variability of the oceanic oxygen distribution.

The Atlantic Expedition
For the first time, during the German Atlantic Expedition (1925 to 1927) with the research vessel "Meteor", an entire ocean was systematically sampled, both in the atmosphere and in the water column. Using an echosounder system that was highly modern for its time, depth profiles were taken across 13 transits of the entire ocean basin.

Climate change impacts on methane hydrates

> Huge amounts of methane are stored around the world in the sea floor in the form of solid methane hydrates. These hydrates represent a large energy reserve for humanity. Climate warming, however, could cause the hydrates to destabilize. The methane, a potent greenhouse gas, would escape unused into the atmosphere and could even accelerate climate change.

How methane ends up in the ocean

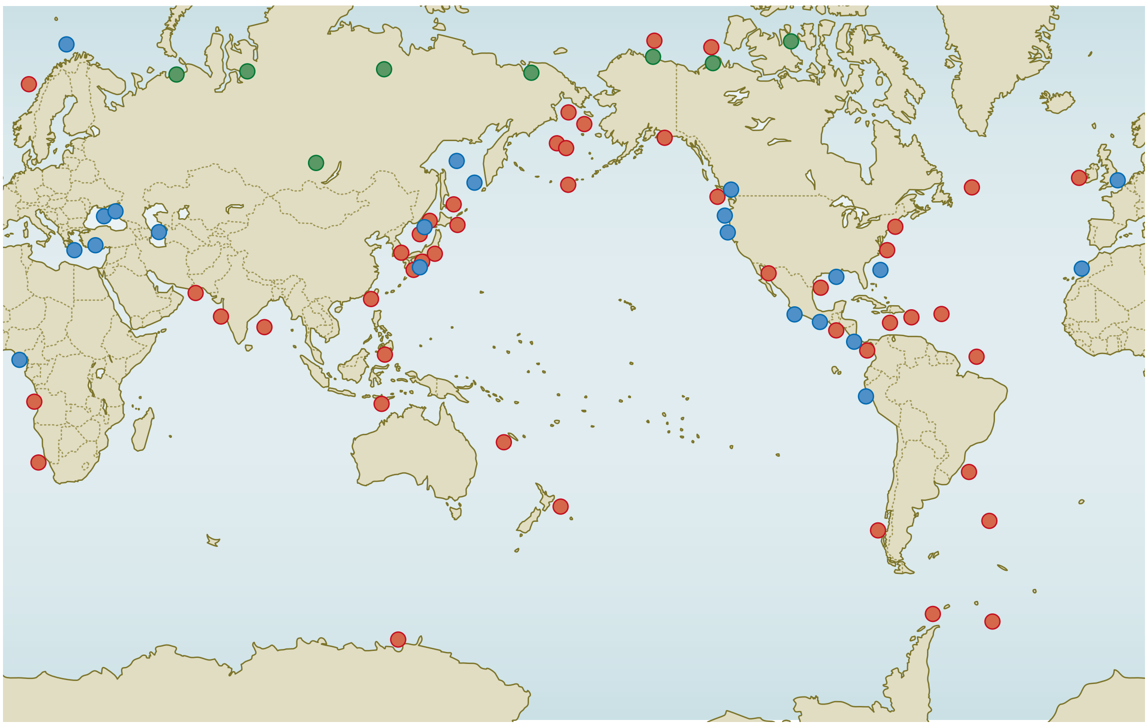
People have been burning coal, oil and natural gas for more than a hundred years. Methane hydrates, on the other hand, have only recently come under controversial discussion as a potential future energy source from the ocean. They represent a new and completely untapped reservoir of fossil fuel, because they contain, as their name suggests, immense amounts of methane, which is the main component of natural gas. Methane hydrates belong to a group of substances called clathrates – substances in which one molecule type forms a crystal-like cage structure and encloses another type of molecule. If the cage-forming molecule is water, it is called a hydrate. If the molecule trapped in the water cage is a gas, it is a gas hydrate, in this case methane hydrate.

2.16 > Methane hydrate looks like a piece of ice when it is brought up from the sea floor. This lump was retrieved during an expedition to the "hydrate ridge" off the coast of Oregon in the US.

Methane hydrates can only form under very specific physical, chemical and geological conditions. High water pressures and low temperatures provide the best conditions for methane hydrate formation. If the water is warm, however, the water pressure must be very high in order to press the water molecule into a clathrate cage. In this case, the hydrate only forms at great depths. If the water is very cold, the methane hydrates could conceivably form in shallower water depths, or even at atmospheric pressure. In the open ocean, where the average bottom-water temperatures are around 2 to 4 degrees Celsius, methane hydrates occur starting at depths of around 500 metres.

Surprisingly, there is no methane hydrate in the deepest ocean regions, the areas with the highest pressures, because there is very little methane available here. The reason for this is because methane in the ocean is produced by microbes within the sea floor that break down organic matter that sinks down from the sunlit zone near the surface.

Organic matter is composed, for example, of the remains of dead algae and animals, as well as their excrements. In the deepest areas of the ocean, below around 2000 to 3000 metres, only a very small amount of organic remains reach the bottom because most of them are broken down by other organisms on their way down through the water column. As a rule of thumb, it can be said that only around 1 per cent of the organic material produced at the surface actually ends up in the deep sea. The deeper the sea floor is, the less organic matter settles on the bottom. Methane hydrates therefore primarily occur on the continental slopes, those areas where the



2.17 > Methane hydrate occurs in all of the oceans as well as on land. The green dots show occurrences in the northern permafrost regions. Occurrences identified by geophysical methods are indicated by red. The occurrences shown by blue dots were verified by direct sampling.

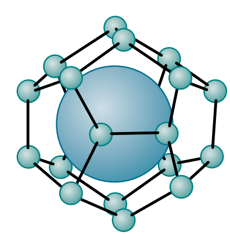
continental plates meet the deep-sea regions. Here there is sufficient organic matter accumulating on the bottom and the combination of temperature and pressure is favourable. In very cold regions like the Arctic, methane hydrates even occur on the shallow continental shelf (less than 200 metres of water depth) or on the land in permafrost, the deep-frozen Arctic soil that does not even thaw in the summer.

It is estimated that there could be more potential fossil fuel contained in the methane hydrates than in the classic coal, oil and natural gas reserves. Depending on the mathematical model employed, present calculations of their abundance range between 100 and 530,000 gigatons of carbon. Values between 1000 and 5000 gigatons are most likely. That is around 100 to 500 times as much carbon as is released into the atmosphere annually by the burning of coal, oil and gas. Their possible future excavation would presumably only produce a portion of this as actual usable fuel, because many deposits are inaccessible, or the production would be too expensive or require too much effort. Even so, India, Japan, Korea and other countries are presently engaged in the development of mining techniques in order to be able to use methane hydrates as a source of energy in the future (Chapter 7).

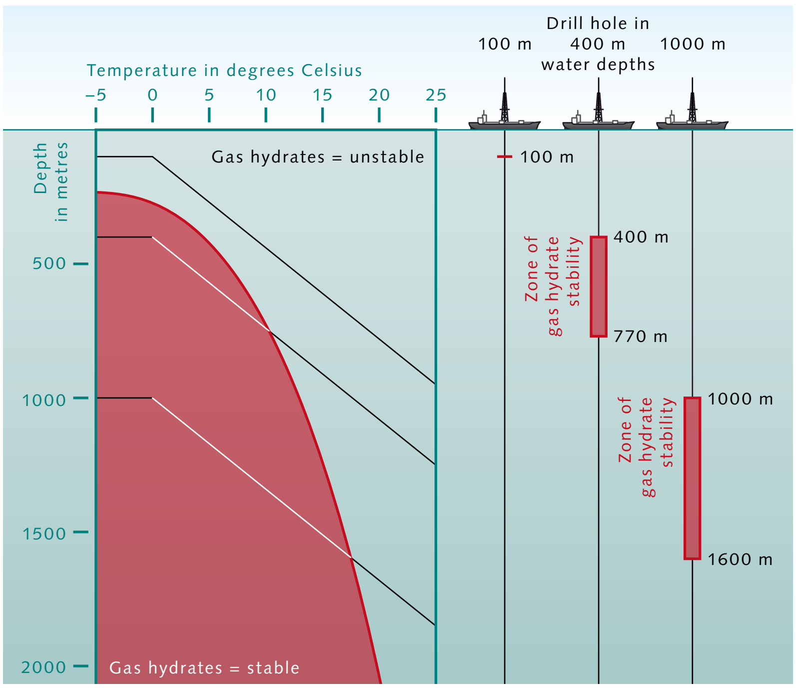
Methane hydrates and global warming

Considering that methane hydrates only form under very specific conditions, it is conceivable that global warming, which as a matter of fact includes warming of the oceans, could affect the stability of gas hydrates.

There are indications in the history of the Earth suggesting that climatic changes in the past could have led to the destabilization of methane hydrates and thus to the release of methane. These indications – including measurements of the methane content in ice cores, for instance – are still controversial. Yet be this as it may, the issue is highly topical and is of particular interest to scientists concerned with predicting the possible impacts



2.18 > In hydrates, the gas (large ball) is enclosed in a cage formed by water molecules. Scientists call this kind of molecular arrangement a clathrate.



2.19 > Gas hydrates occur when sufficient methane is produced by organic matter degradation in the sea floor under low temperature and high pressure conditions. These conditions occur predominantly on the continental margins. The warmer the water, the larger the water depths must be to form the hydrate. Deep inside he sea floor, however, the temperature is too high for the formation of methane hydrates because of the Earth's internal heat.

Oxidation
Many bacteria use methane to provide energy for their metabolism. They take up methane and transform it chemically. In this process the methane releases electrons and is thus oxidized. Some bacteria break the methane down with the help of oxygen. This is called aerobic oxidation. Other bacteria do not need oxygen. This kind of oxidation is called anaerobic.

of a temperature increase on the present deposits of methane hydrate.

Methane is a potent greenhouse gas, around 20 times more effective per molecule than carbon dioxide. An increased release from the ocean into the atmosphere could further intensify the greenhouse effect. Investigations of methane hydrates stability in dependance of temperature fluctuations, as well as of methane behaviour after it is released, are therefore urgently needed.

Various methods are employed to predict the future development. These include, in particular, mathematic modelling. Computer models first calculate the hypothetical amount of methane hydrates in the sea floor using background data (organic content, pressure, temperature). Then the computer simulates the warming of the seawater, for instance, by 3 or 5 degrees Celsius per 100 years. In this way it is possible to determine how the methane hydrate will behave in different regions. Calculations of methane hydrate deposits can than be coupled with complex mathematical climate and ocean models. With these computer models we get a broad idea of how strongly the methane hydrates would break down under the various scenarios of temperature increase. Today it is assumed that in the worst case, with a steady warming of the ocean of 3 degrees Celsius, around 85 per cent of the methane trapped in the sea floor could be released into the water column.

Other, more sensitive models predict that methane hydrates at great water depths are not threatened by warming. According to these models, only the methane hydrates that are located directly at the boundaries of the stability zones would be primarily affected. At these locations, a temperature increase of only 1 degree Celsius would be sufficient to release large amounts of methane from the hydrates. The methane hydrates in the open ocean at around 500 metres of water depth, and deposits in the shallow regions of the Arctic would mainly be affected.

In the course of the Earth's warming, it is also expected that sea level will rise due to melting of the polar ice caps and glacial ice. This inevitably results in greater pressure at the sea floor. The increase in pressure, however, would not be sufficient to counteract the effect of increasing temperature to dissolve the methane hydrates. According to the latest calculations, a sea-level rise of ten metres could slow down the methane-hydrate dissolution caused by a warming of one degree Celsius only by a few decades.

A wide variety of mathematical models are used to predict the consequences of global warming. The results of the simulations are likewise very variable. It is therefore difficult to precisely evaluate the consequences of global warming for the gas hydrate deposits, not least of all because of the large differences in the calculations of the size of the present-day gas hydrate deposits. One major goal of the current gas hydrate research is to optimize these models by using ever more precise input parameters. In order to achieve this, further measurements, expeditions, drilling and analyses are essential.

What happens when methane hydrate melts?

Not all the methane that is released from unstable methane hydrates ends up in the atmosphere. The greatest portion is likely to be broken down during its rise through the sediments and in the water column. This decomposition is mediated by two biological processes:

- anaerobic oxidation of methane by bacteria and archaea (formerly called archaebacteria) within the sea floor;
- aerobic oxidation of methane by bacteria in the water column.

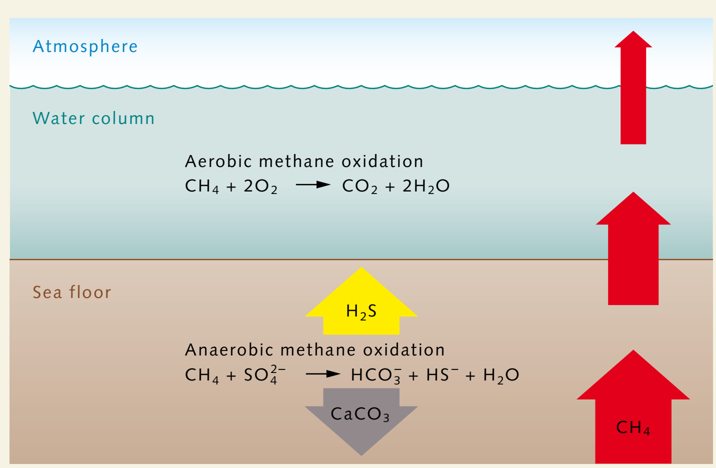
During anaerobic oxidation of methane in the sediment the microbes use sulphate (SO_4^{2-}), the salt of sulphuric acid that is present in large quantities in sea water, for the methane decomposition. In this process methane is converted to bicarbonate (HCO_3^-). If the bicarbonate reacts further with calcium ions (Ca^{2+}) in the seawater, calcium carbonate ($CaCO_3$) precipitates, which remains stored in the sea floor over long periods of time. That would be the ideal situation, because it would make the potent greenhouse gas methane (CH_4) harmless. At the same time, hydrogen sulphide (H_2S) is produced from the sulphate, which provides energy to chemosynthetic communities, including symbiotic clams and tubeworms. During aerobic oxidation in the water column, however, bacteria break down methane with the help of oxygen (O_2). In this process, carbon dioxide is produced, which dissolves in the water. Carbon dioxide contributes to ocean acidification. Furthermore, aerobic oxidation of methane consumes oxygen. The depletion of oxygen in the water column could create or expand oxygen minimum zones in the ocean, which are a threat for fishes and other sensitive organisms. Rough estimates suggest that anaerobic and aerobic oxidation of methane together currently convert around 90 per cent of the methane produced in the sea floor before it can reach the atmosphere. The more slowly methane migrates through the sea floor or through the water column, the more effective the microbes are in converting it.

A prerequisite for this kind of degradation is that the methane molecules are dissolved in water. Methane can only be degraded by the bacteria in this form. If the methane is released rapidly from the hydrates, it could rise in the form of gas bubbles that are not accessible by microorganisms. The microbial methane filter would thus fail, at least in part, if the methane hydrates break down very rapidly and large quantities of methane are released at once.

There is also a problem at shallow water depths, where the methane bubbles cannot completely dissolve in the water over the short distance from the sea floor to the atmosphere. In order to better understand such processes and to be able to make predictions about the functions of the microbial filters, researchers are currently investigating natural methane sources on the sea floor, so-called

Bacteria convert methane

Methane (CH_4) in the ocean is to a large extend consumed by microorganisms. During anaerobic decay within the sea floor, microbes convert methane with the help of sulphate (SO_4^{2-}). This process produces hydrogen sulphide anions (HS^-) and hydrogen sulphide (H_2S), which are closely related chemically and occur naturally together, as well as bicarbonate ($CaCO_3$). Bicarbonate can react with calcium ions (Ca^{2+}) to precipitate as calcium carbonate ($CaCO_3$). During aerobic decay (in the water column) oxygen (O_2) from the water is consumed. Carbon dioxide (CO_2) and water (H_2O) are produced. If large amounts of methane are released in the future from the gas hydrates in the sea floor, aerobic decay could result in the creation of oxygen minimum zones. The carbon dioxide produced could also contribute to ocean acidification.



2.20 > Large quantities of methane hydrate are stored not only in the sea floor, but also on land, especially in the perpetually frozen permafrost ground of the Russian tundra, such as here in the Russian republic of Komi. Scientists are concerned that the permafrost soils could melt due to global warming and thus release the methane hydrates.

cold seeps, which constantly release larger quantities of methane. These include near-surface gas hydrate deposits, mud volcanoes, and natural-gas seeps in shallow marine regions. These seeps are a kind of natural model where the behaviour of methane in the ocean can be studied. If we understand how nature reacts to these methane seeps at the sea floor, it will help us to estimate the consequences of larger methane releases from gas hydrates. The data obtained at the methane seeps should also help to improve the precision of mathematical methane hydrate simulations.

The disappearance of methane hydrates could have fatal consequences. Gas hydrates act like a cement that fills the pores between the fine sediment particles and stabilizes the sea floor. If the methane hydrates decompose, the stability of the sea floor is reduced due to the missing cement and the possible generation of excess pore pressure. In the worst case, large parts of continental margins fail. The resulting submarine landslides might cause severe tsunamis.

Massive mass movements occurred during the last ice age and the following deglaciation. The trigger was probably not always warming of the atmosphere, but also the opposite. Because large quantities of water were stored in the ice during the last ice age, sea level was around 120 metres lower than it is today. Especially in the shallow ocean regions, the water pressure was so low that massive amounts of methane hydrate could have been destabilized. Direct evidences for such slope failures caused by decomposing gas hydrates have not yet been found. There are, however, some indications suggesting a process in the past. Signs of seeping fluids are almost always found in the vicinity of slope failures. These slopes were possibly destabilized by gases released by decomposing gas hydrates and liquids. Researchers also, however, definitely see the possibility of a reverse relationship: it is conceivable that slope failures and the resulting reduction in pressure on underlying sediments caused the dissociation of methane hydrates at the continental margins, thereby releasing large amounts of free gas. The slumps would have been the cause rather than the result of gas escape. These uncertainties highlight the need for further research. It is, however, fairly certain that the disappearance of methane hydrates could lead to serious problems.

Methane emissions from the Arctic – a prime focus of future gas hydrate research

In the field of methane emission research today, the Arctic is one of the most important regions worldwide. It is believed that methane occurs there both in the form of gas hydrate in the sea and as free gas trapped in the deep-frozen permafrost. Methane deposits in permafrost and hydrates are considered to be very sensitive in the expansive shallow-shelf regions, because with the relatively low pressures it would only take a small temperature change to release large amounts of methane. In addition, new methane is continuously being produced because the Arctic regions are rich in organic material that is decomposed by microbes in the sediment. The activity of these microbes and thus the biological release rates of methane are also stimulated by increases in temperature. Hence methane emissions in the Arctic have multiple sources. International scientific consortia are now being established involving researchers from various disciplines – chemists, biologists, geologists, geophysicists, meteorologists – which are intensively addressing this problem. No one can yet say with certainty how the methane release in the Arctic will develop with global warming, either in the ocean or on the land. This research is still in its infancy.

Conclusion

Material fluxes – getting the full picture

The chemical and geochemical processes in the ocean are complex. Explaining them in their entirety will be a challenge for decades. There is clear evidence of global changes, such as the decrease in oxygen levels and acidification in the oceans. So far, however, our knowledge is not sufficient to say with certainty or in detail what impact climate change will have and how it will affect various parameters in the future.

It is certain that disturbances caused by climate change can have very serious consequences, because the chemical and geochemical material fluxes amount to many billions of tons. The amount of methane hydrate bound up in the sea floor alone is gigantic. If it is released and the methane rises into the atmosphere, it will have a significant impact on the development of future climate. Investigations of the chemical and geochemical processes are therefore of enormous importance if we want to learn what to expect and how humanity can respond to it.

Analyses of the CO_2 cycle reveal how the CO_2 reservoirs of the atmosphere, land biomass and ocean interact. The oceans are buffering increasing concentrations of atmospheric trace gases. But these processes and reaching a new CO_2 equilibrium will take millennia. Natural processes therefore cannot keep up with the speed at which humans continue to discharge CO_2 and other climate-relevant trace gases into the air. The only solution is to save energy and significantly reduce greenhouse gas emissions.

3 The uncertain future of the coasts

> It is now accepted that global warming will result in a significant sea-level rise in future, with many low-lying coastal areas around the world being lost to the sea over the coming centuries. The wealthy industrialized countries will be able to defend themselves from the encroaching waters for a time, albeit with massive technological effort. In the long term, however, they too will have to withdraw back from the areas under threat or, alternatively, adapt to rising water levels.

Sea-level rise – an unavoidable threat

> Since the end of the last ice age to the present day, sea level has risen by around 125 metres. This has natural as well as man-made causes. However, the human-induced greenhouse effect is intensifying this process. Its main effects are thermal expansion of water and melting of glaciers. This could result in the sea level rising by a further 5 metres within just 300 years.

Loss of habitats and cultural treasures

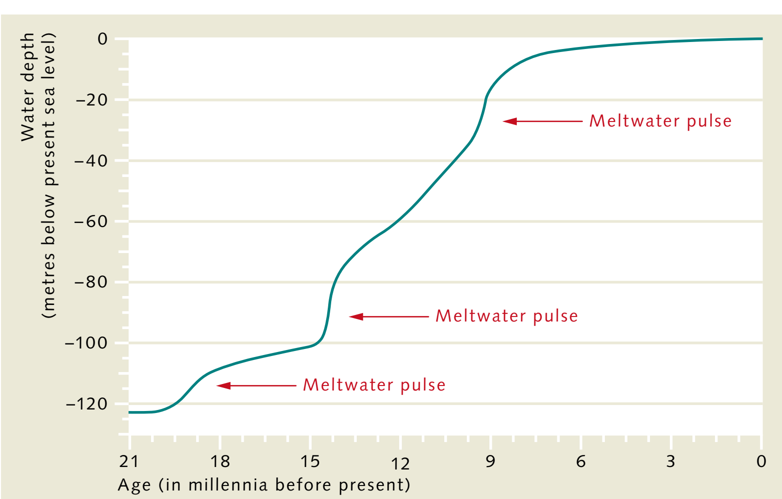
Sea-level rise is one of the most serious consequences of global warming. No one can really imagine how the coasts will look if the waters rise by several metres over the course of a few centuries. Coastal areas are among the most densely populated regions of the world and are therefore particularly vulnerable to the impacts of climate change. They include major agricultural zones, conurbations and heritage sites. How will climate change affect their appearance?

Researchers around the world are seeking answers to the question of how rapidly, and to what extent, sea level will rise as a consequence of climate change. In doing so, they must take account of the fact that sea level is affected not only by the human-induced greenhouse effect but also by natural processes. Experts make a distinction between:

- eustatic causes: this refers to climate-related global changes due to water mass being added to the oceans. The sea-level rise following the melting of large glaciers at the end of ice ages is an example of eustatic sea-level rise;
- isostatic (generally tectonic) causes: these mainly have regional effects. The ice sheets formed during the ice ages are one example. Due to their great weight, they cause the Earth's crust in certain regions to sink, so sea level rises relative to the land. If the ice melts, the land mass rises once more. This phenomenon can still be observed on the Scandinavian land mass today.

Sea level can change by 10 metres or so within the course of a few centuries and can certainly fluctuate by more than 200 metres over millions of years. Over the last 3 million years, the frequency and intensity of these fluctuations increased due to the ice ages: during the colder (glacial) periods, large continental ice sheets formed at higher latitudes, withdrawing water from the oceans, and sea level decreased dramatically all over the world. During the warmer (interglacial) periods, the continental ice caps melted and sea level rose substantially again.

The last warmer (interglacial) period comparable with the current climatic period occurred between 130,000 and 118,000 years ago. At that time, sea level was 4 to 6 metres higher than it is today. This was followed by an irregular transition into the last colder (glacial) period,



3.1 > Until 6000 years ago, sea level rose at an average rate of approximately 80 cm per century, with occasional sharp increases. There were at least two periods, each lasting around 300 years, when sea level rose by 5 metres per century. This was caused by meltwater pulses.

3.2 > Every time there is a storm, the North Sea continues its relentless erosion of the coast near the small English town of Happisburgh. The old coastal defences are largely ineffective. Here, a Second World War bunker has fallen from the eroded cliffs, while elsewhere along the coast, homes have already been lost to the sea.

with the Earth experiencing its Last Glacial Maximum (LGM) 26,000 to 20,000 years ago. At that time, sea level was 121 to 125 metres lower than it is today. Then the next warmer period began and sea level rose at a relatively even rate. There were, however, intermittent periods of more rapid rise triggered by meltwater pulses. These were caused by calving of large ice masses in the Antarctic and in the glacial regions of the Northern hemisphere, or, in some cases, by overflow from massive natural reservoirs which had been formed by meltwater from retreating inland glaciers. This relatively strong sea-level rise continued until around 6000 years ago. Since then, sea level has remained largely unchanged, apart from minor fluctuations amounting to a few centimetres per century.

Measured against the minor changes occurring over the last 6000 years, the global sea-level rise of 18 cm over the course of the last century is considerable. Over the past decade alone, sea level rose by 3.2 cm, according to measurements taken along the coast in the last century and, since 1993, satellite monitoring of the elevation of land and water surfaces worldwide (satellite altimetry). Admittedly, these are only short periods of time, but the measurements nonetheless point to a substantial increase in the rate of sea-level rise. Experts differ in their opinions about the extent to which specific factors play a role here:

- Between 15 and 50 per cent of sea-level rise is attributed to the temperature-related expansion of seawater;
- Between 25 and 45 per cent is thought to be caused by the melting of mountain glaciers outside the polar regions;
- Between 15 and 40 per cent is ascribed to the melting of the Greenland and Antarctic ice caps.

Based on the monitoring data and using computer modelling, predictions can be made about future sea-level rise, such as those contained in the latest Report by the Intergovernmental Panel on Climate Change (IPCC, 2007). This is the most up-to-date global climate report currently available, and it forecasts a global sea-

Sea-level rise
Sea-level rise has various causes. Eustatic rise results from the melting of glaciers and the discharge of these water masses into the sea. Isostatic rise, on the other hand, is caused by tectonic shifts such as the rise and fall of the Earth's crustal plates. Thermal expansion, in turn, is caused by the expansion of seawater due to global warming.

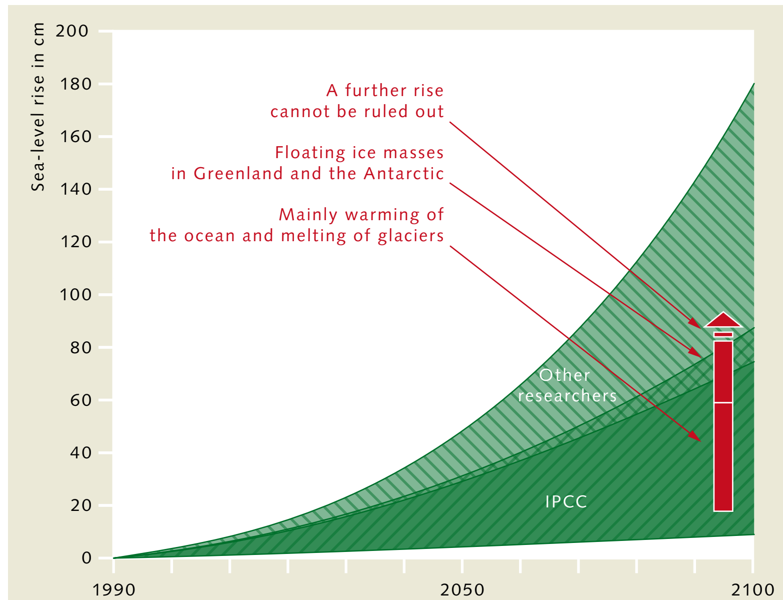
3.3 > Tourists preparing to abseil off the edge of the Ross Ice Shelf in Antarctica. Greater melting of the mass of floating ice that forms ice shelves could result in an increase in the calving rate of glaciers if the ice shelf is no longer there to act as a barrier.

level rise of up to 59 cm by 2100. This does not take into account that the large continental ice masses (i.e. primarily the Greenland and Antarctic ice sheets) could melt more rapidly as a result of global warming. In fact, current satellite monitoring around the edges of the Greenland ice sheet, West Antarctica and the mountain glaciers outside the polar regions shows that the height of the glaciers and hence the volume of ice are decreasing faster than experts had previously assumed. These data and computer modelling suggest that sea level could actually rise by more than 80 cm, and perhaps even by as much as 180 cm by the end of this century. The melting of the Antarctic and Greenland glaciers is likely to intensify well into the next century and beyond. The other mountain glaciers will already have melted away by then and will no longer contribute to sea-level rise.

The German Advisory Council on Global Change (WBGU) expects a sea-level rise of 2.5 to 5.1 metres by 2300. The reason for the considerable divergence in these figures is that the climate system is sluggish and does not change at an even or linear rate, so forecasts are beset with uncertainties. What is certain is that the sea-level rise will accelerate slowly at first. Based on the current rate of increase, sea level would rise by just under 1 metre by 2300.

The present rise is a reaction to the average global warming of just 0.7 degrees Celsius over the past 30 years. However, the IPCC Report forecasts a far greater temperature increase of 2 to 3 degrees Celsius in future. This could produce a sea-level rise at some point in the future that matches the level predicted by the German Advisory Council on Global Change.

As with all climate fluctuations that have occurred in the Earth's recent history, the global warming now taking place will increase temperatures in the polar regions more strongly than the global mean and will therefore significantly influence sea-level rise. The stronger warming at higher latitudes is caused by the decrease in albedo, i.e. the surface reflectivity of the sun's radiation: as the light-coloured, highly reflective areas of sea ice and glaciers shrink, more dark-coloured soil and sea surfaces are revealed, which absorb sunlight to a far greater extent. If most of the continental ice sheets in Greenland and West Antarctica melt, sea level could increase by as much as 20 metres over the course of 1000 years in a worst-case scenario.



3.4 > Sea level will rise significantly by the end of this century, although the precise extent to which it will rise is unclear. The Intergovernmental Panel on Climate Change (IPCC) forecasts a rise of up to 1 metre during this century (dark green shading above). Other researchers consider that a rise of as much as 180 cm is possible (light green shading above). As there are numerous studies and scenarios to back up both these projections, the findings and figures cover a broad range. There will certainly be feedback effects between the melting of the glaciers and the expansion of water due to global warming. Record rates of sea-level rise are predicted in the event of more rapid melting of the Antarctic and Greenland ice sheets.

In West Antarctica in particular, the marginal glaciers are becoming unstable as a result of flow effects, and are exerting pressure on the ice shelves floating on the sea. This could result in the ice shelf breaking away from the grounded ice to which it is attached, which rests on bedrock and feeds the ice shelf. This would ultimately result in the glaciers calving, as the ice shelf would no longer be there to act as a barrier. Furthermore, even with only a slight sea-level rise, marginal grounded ice masses could break away in significant amounts due to constant underwashing by the rising water.

How nature and humankind alter the coasts

> Coastlines are shaped by natural forces, often changing greatly in response to changing environmental conditions. On the other hand, humans also influence the coastal realm. They colonize and cultivate the coastal zones and excavate raw materials. Such interventions mesh with geological and biological processes, precipitating the most varied changes.

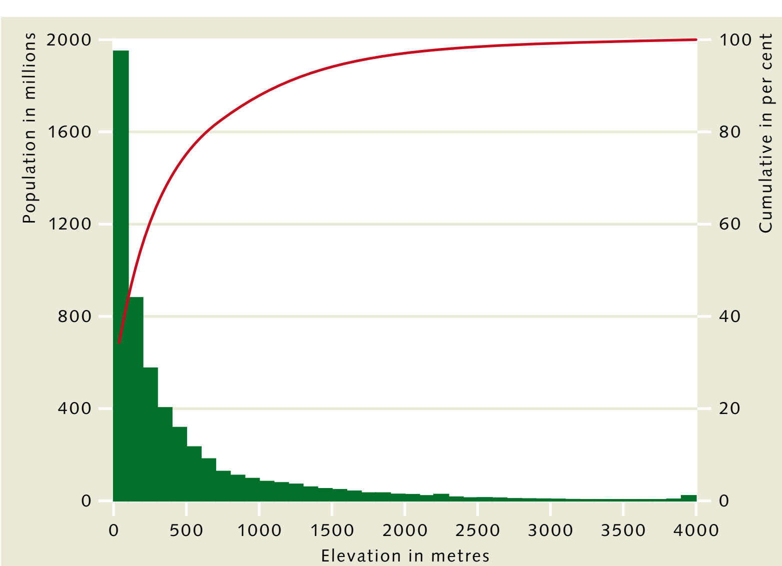
Importance and characteristics of coastal zones

The coast is the interface between the land, ocean and atmosphere. There is no standard definition of what constitutes "the coast" because it depends largely on one's perspective or the scientific question – the coastal zone can be considered more the sea, or more the land. Simply stated, the coastal zone encompasses that area where the land is significantly influenced by the sea, and the sea is notably influenced by the land. This is a complex space that is also strongly impacted by human activity. The coastal zones of the Earth are extremely diverse and tremendously important, not only for humankind.

- They cover around 20 per cent of the Earth's surface;
- They are the site of vital transport routes and industrial facilities;
- They are prime recreation and tourist areas;
- They are a resource for minerals and geological products;
- They contain important ecosystems with large species diversity;
- They function as an important sediment trap that consolidates sediments from the rivers;
- They influence many global parameters in their role as a buffer between the land and sea;
- 75 per cent of the mega-cities with populations over ten million are located in coastal zones;
- 90 per cent of the global fishery activity occurs in coastal waters;
- They are the place where more than 45 per cent of the world's population lives and works.

A large portion of the world population lives in flat coastal areas that can drastically change their shape within a short time. The populations in coastal zones are growing faster than in any other region on Earth. Coastal cities are expanding accordingly. People are claiming more and more land. At the same time they are making more intensive use of the coasts, for example by developing large wind-energy farms in the sea.

3.5 > Population distribution by elevation



Sediments shape the coasts

The shape of a coast is influenced by many factors. One important factor is the shifting of sediments, such as mud, sand and gravel. The sediments are primarily transported by wind-induced waves and water currents – either tidal currents, or rivers that flow into the sea. Depending on the currents, sediments are either eroded,

3.6 > Tidal currents on the coast of the Isle of Lewis, off the west coast of Scotland, have carried away the sand and left the stony ground exposed.

redistributed or deposited (accumulation). If sediments are carried away instead of being redeposited, the shape of the coast will change over time. One example of this is the East Frisian island Memmert, where currents caused so much erosion on the southwest side that the old lighthouse was standing in water until it was finally demolished. Another example is seen on the western beach of the Danish North Sea island Rømø. It is continually growing wider due to sediment input.

In principle, there are two main directions of sediment transport. One of these is parallel to, or along the coast. The other direction is either toward or away from the coast. The more sediment that is eroded or deposited, the more strongly the coastal form changes. The rate at which sediment can be eroded depends on its composition, as well as on the intensity and persistence of the wind and water currents. A strong storm tide can wash away immense amounts of sediment within a few hours. On hard, rocky coasts, which are more resistant to erosion than loosely deposited sand, the shape of the coastline changes comparatively slowly. A coast usually recedes as a result of erosion: More sediment is lost than is replaced by the currents. The developmental status of a coast, however, is not defined by its sediment balance alone. There are coastal areas that are stable over the long term because sediment is simply transported along them. In many coastal regions today, the natural input of sediments is hampered by construction projects such as dams. Only 20 per cent of the coastal regions worldwide are made up of loose materials such as sand, mud or gravel, but more than half of these coasts are suffering from erosion today. Of course, the loose-material coasts generally adapt quickly to changes because the sediments are redistributed relatively easily – material deficits at one place are balanced again by new sediment input. Yet whether the character of such a coast is preserved in individual cases is essentially dependent on the rate of sea-level rise, stability of the sediment, and sediment

3.7 > The old lighthouse on the East Frisian island of Memmert once stood in the dunes, but was washed out by erosion over the course of decades.

input. Even coastal protection measures do not only contribute to the preservation of the coasts. They can also alter the coasts. It is even very possible that by attempting to protect one segment of a coastline, another area is damaged. When one area is protected from erosion by construction of a breakwater, an adjacent, non-protected area may be deprived of its essential sediment input. Compared to sandy coasts, sea-level rise will have a less severe impact on steep and especially rocky coasts. Worldwide, steep and rocky coastlines make up about 80 per cent of all coasts.

Sediments cause the Earth's crust to sink

It is clear that coastal areas subside under the weight of the glacial masses placed there in ice ages. But sediments can also accumulate in such thick layers that they press down on the lithosphere, the Earth's crust. This subsides initially and then rises again later when the load is removed. In the case of glaciers, this happens when the ice melts at the end of an ice age. The rebound movement can last for several tens of thousands of years. An example of this can be seen on the Scandinavian land mass, which is still rising today by up to 9 millimetres a year. Sometimes the Earth's crust rebounds unevenly, so that one part is still sinking while another is rising.

Thick sediment packages are often deposited in delta regions where the rivers transport enormous quantities of sediment to the sea. Because of the stacking of sediments, the lithosphere gradually yields to the pressure. The subsiding bedrock thus produces a rise in sea level relative to the land. In some cases this isostatic subsidence is compensated by the gradual upward increase in sediment thickness. In other cases, however, the sediment itself is compressed by the increasing load so that the land mass still sinks.

Humans can also accelerate the subsidence, for instance by extracting groundwater, oil or natural gas, as in the Niger Delta. There are regions where the land surface is falling by up to 5 cm per year due to the combined effects of these factors. Relative sea level rises there accordingly.

Humans mould the face of the coasts

Over the past 8000 years, during the final phase of sea-level rise after the last ice age, sedimentation has contributed enormously to the development of the coasts. Coastal land areas grew by the deposition of transported material, and in some regions large river deltas were formed. Rivers are very important transport paths for carrying sediments to the coasts. The volume that they carry depends on several factors:

- The size of the catchment basin from the source to the estuary;
- The relief in the catchment basin (rivers in high-relief mountainous areas transport more sediment than rivers that flow through flatlands);
- The rock and sediment characteristics (for example, grain size) or the amount of available sediments from weathering and mechanical erosion;
- The climate in the catchment area and its impact on weathering;

- The amount of surface water flowing downstream and the storage capacity of the soil (how much water flows also depends on the amount of precipitation, which is, in turn, dependent on climate).

Forest clearing, overgrazing and imprudent farming practices lead to severe soil erosion, especially in tropical regions. If the sediments are not blocked by dams, they are mostly deposited in coastal regions. This can have consequences. For one, the sediments can cloud the water, change the water quality, and thus severely impact living organisms in the water. Turbidity also decreases light penetration and thus lowers the **primary productivity.**

On the other hand, high erosion could also lead to algal blooms because large amounts of nutrients in the rivers flow into the coastal waters with the sediments. When these algae die, they are broken down by microorganisms that consume oxygen. This can create lethal low-oxygen zones and consequently species diversity drops in these areas.

By contrast, many regions are plagued by a paucity of sediments because the water is held back by dams. Worldwide over 41,000 large dams are in operation. There are also many smaller dams and water reservoirs. Together, they block 14 per cent of the total global river flow, as well as enormous volumes of sediment. This is a severe loss for the replenishment of the coasts. Erosion increases. This sediment deficit is fatal in places where the basement is subsiding beneath the old, heavy sediment packages. New sediment is lacking that would normally be deposited to compensate for the subsidence. If the land sinks, saltwater gradually intrudes into the estuary and adds salt to the groundwater. The Nile is a good example of this. Before construction of the Aswan Dam, recurrent annual floods washed fertile sediments from the interior of the continent into the Nile Delta on the Mediterranean Sea. Not only were the sediments essential for the farmers on the banks of the Nile, they were also crucial to compensating for subsidence in the heavy delta region. After the dam was built in the 1960s,

3.8 > With the beginning of operations in 1968, the Aswan Dam was celebrated as a masterpiece of technology. At that time nothing was known about environmental impacts such as land salination on the coasts. The dam was officially opened in 1971. Its construction took around eleven years.

the flooding and transport of sediments came to a halt. This resulted in sustained harvest reduction and massive coastal erosion. Similar problems can be expected in China's Yangtze Delta because of the recently completed Three Gorges Dam.

Recent investigations on the North American Atlantic coast, based on interpretations of satellite photos and topographical maps covering a period of over 100 years, suggest that rising sea level also disturbs important sedimentation processes and will lead to changes on the coasts. It is believed that a sea-level rise of 1 metre will result in an average retreat of the coastline by about 150 metres. This presumes, according to the researchers, that the sediment balance (erosion and deposition) is in a state of equilibrium. The examples cited here, however, clearly show that that is not the case. For the calculations, therefore, one would at least have to consider the sediment transport along the coasts and changes in the sedimentation balance that sea-level rise would cause. So far that has not been done. The coastal retreat could therefore be even more drastic.

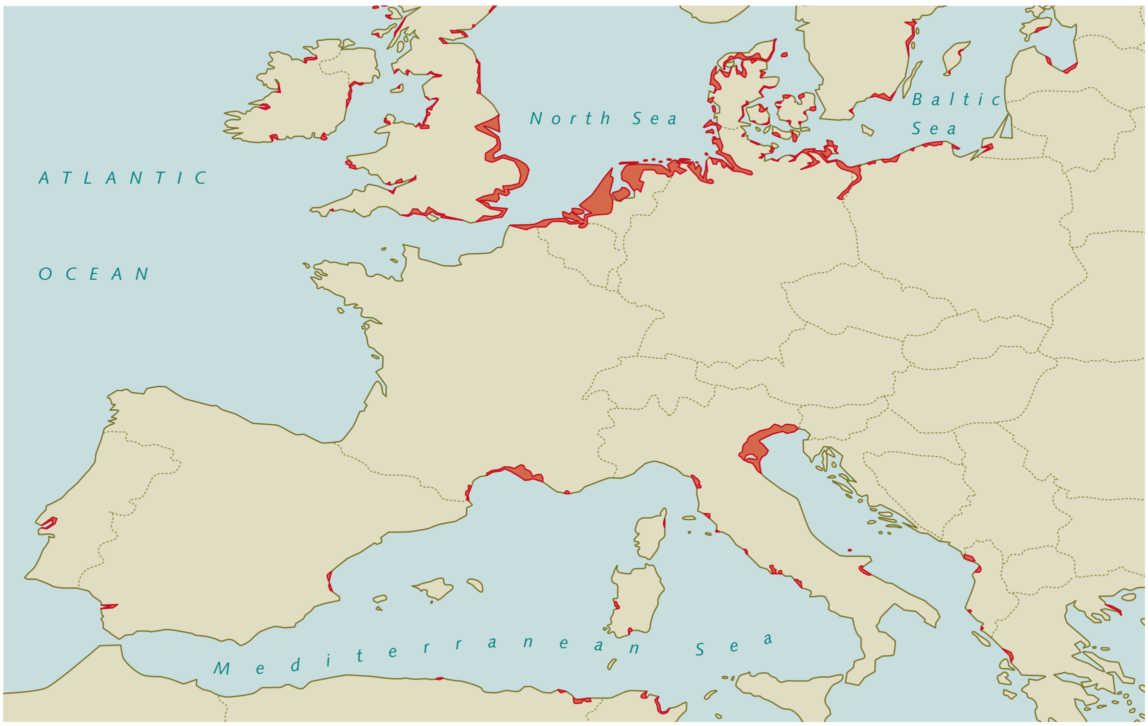
3.9 > At times of especially high water levels in the Lagoon of Venice some areas of the city, like the Piazza San Marco, are repeatedly flooded. Italians call the high water acqua alta.

Hydrologic engineering impacts

In many estuarine regions there is an alternating in- and outflow of seawater in phase with the tides, and thus a mixing of saline water with the fresh water continuously flowing out from the rivers. Suspended sediment from the land and sea can be deposited when the current-energy level drops. The sediment budget is subject to a very sensitive balance. The building of dams, deepening of channels, or other construction can severely disturb this balance. The impacts are often very serious.

Among other activities, the deepening of channels is highly controversial today. 95 per cent of global commerce depends on shipping. For logistical reasons most of the world's large harbours are located on river estuaries. The ever-increasing sizes of the ships used, with their corresponding deep draughts, require deeper channels. Additionally, the shipping routes are stabilized by structures on the banks, and current flow is optimized by control structures. The deepening of channels can release pollutants trapped in the sediments. In addition, the flow rates can increase, which also increases sediment redistribution.

Due to the larger volume of water flowing in and out, the tidal range can also increase. This further affects the sediment budget, because more rapidly flowing water has more energy for moving sediments. Sea-level rise and high-water events amplify these effects. There is already concern about how this impacts the structural integrity of the river dams. The high volume of ship traffic exacerbates the situation because the ships' wakes often erode the river banks. The removal of sediment or sand, which is a common procedure on the island of Sylt for beach restoration, changes the shape of the sea floor. In the



3.10 > If the coasts were not protected by dikes, sea-level rise of 2 metres would produce this picture. The red-coloured areas would be permanently inundated. According to current predictions sea level could rise by as much as 180 cm by the end of this century.

long term this can definitely have an impact on the protection of the coasts. It is possible that deepening the seafloor could shift the wave-break zone to a position closer to shore.

The removal of large quantities of sand would also change the habitats of marine organisms. This is similarly the case in the reverse situation when sand is discharged into the sea, for instance when dredged material is dumped onto the sea floor. 80 to 90 per cent of these sediments originate from operations related to channel deepening. Hundreds of millions of cubic metres of sediment are dumped annually worldwide. If they are not able to escape, marine organisms living in the dumping areas are covered up.

Coastal city growth

Human societies also damage the biotic environment through the tremendous growth rates of coastal cities. New land areas are often created in the sea to make room for the overflowing development. Many large projects worldwide, including the airport in Hong Kong, have been built in this way. For that project an area of over 9 square kilometres was filled. The harbour at Tianjin in China was even larger, appropriating around 30 square kilometres of marine area. These encroachments have significant impacts on the directly adjacent coastal zones. For example, fill material covering 180 hectares used in construction of the Nice airport triggered a disastrous landslide in 1979. This then caused a tsunami that took the lives of 23 people.

Climate change alters the coasts

In order to accurately predict the future fate of coastal regions, researchers must first determine whether the present measurable changes are actually a consequence of climate change or an expression of natural climate variability. We can only speak of climate change if climate-related changes are statistically discernable from natural fluctuations. Climate change is thus not equivalent to climate variability. Scientists hence need to have measurements and observations covering representative time intervals.

We already know that global warming will not lead to uniform increases of air and water temperatures everywhere, and the change is not restricted to temperature changes. The consequences of climate change can be highly variable. This is clearly illustrated in the following examples.

Melting of sea ice and thawing of permafrost grounds

Sea ice in the sub-polar and polar coastal waters acts as a buffer between the atmosphere and seawater. It prevents storms from creating waves that would roll into the coasts and remove sediments. If the ice masses shrink by thawing, this buffering effect is lost. Sediments that were previously protected by the ice cover are also more strongly eroded. Permanently hard-frozen soils, called **permafrost grounds,** thaw out. These are also more easily eroded by wind and waves on the coasts than the frozen land masses. On the other hand, erosion typically caused by icebergs and glaciers no longer occurs.

High tide and spring tides
Mean high tide refers to the average high-water level at a particular location on the coast. Flood tides that reach especially high above the mean high tide are referred to as spring tides. These occur regularly, corresponding to certain alignments of the sun and moon. It is particularly dangerous for the German North Sea coast when heavy storms from the west coincide with the spring tides.

Changes in freshwater balance, precipitation and sediment input

Climate change will presumably lead to the melting of continental glaciers, while at the same time the amount of new snow required for maintaining the glaciers will probably decrease. Over time this will also lead to a decline in the amount of freshwater flowing from the mountains. Water shortages could result. People could respond by increasing the amount of water held in reservoirs. This, however, would result in less fresh water and sediments being transported to the ocean. At the same time, in other areas, increased precipitation is expected as a consequence of global warming, for example, in the **monsoon regions** of the world. The strong monsoon rains and water discharge will lead to increased flooding and the transport of large amounts of sediments and nutrients by rivers into the coastal seas.

Island and coastal flooding

The rise in sea level caused by climate change will lead to flooding in many coastal areas and island groups. It is expected that these regions will not be just temporarily, but permanently submerged. These floods thus cannot be equated with the short-term, episodic flooding of land areas that will occur more frequently in the near future. Sea-level rise could reach the two-metre mark as early as the next century or soon thereafter.

This scenario, however, is based on topographic data alone. It does not take account of dikes and other protective structures. Simulations simply allow the water to flow over the coastal contours. This model also does not consider the increased removal of land by coastal erosion, which will probably accompany rising sea level. Complete coastlines, along with their surf zones, will likely shift landward due to the erosion. The destructive power of the water will then be unleashed on areas that were previously protected. Today, storm floods are already tearing out protective vegetation. These negative effects will only intensify in the future. The very gently rising coastal slopes, where the surf can gradually roll up to the land, are becoming steeper. The steeper coastal foreland presents a greater surface area of vulnerability for future storms to assault. Erosion gains dynamic momentum. The buffering capacity of the coastal foreland decreases.

Threatened regions also include many areas that are presently protected by dikes. For dike structures on the North and Baltic Seas the crown height is designed to be 30 to 90 cm above the maximum storm event height, as a safety factor in consideration of future sea-level rise. This will not be sufficient, however, for a sea-level rise of 2 metres. Many densely settled areas in the North Sea area today already lie below the mean high-tide level, and in the Baltic Sea area at around the present-day sea level.

Other coastal areas are characterized by complex and important ecosystems. These produce biomass that sometimes has a direct impact on the shape of the coast. For example, the growth of corals can create new islands. Coral banks are also important bulwarks that break the surf. In some cases the growth of corals can even compensate for the rise of sea level. Whether the formation of new corals will be able to keep up with the rise of sea level in the future depends on the rate of the rise as well as on water temperature. Researchers are concerned that living conditions for the adaptable but sensitive corals will become worse; firstly, because the water temperature in some areas is already too high today and, secondly, because the corals will not be able to keep up with the projected sea-level rise or possible subsidence of the coasts.

Other shallow coastal segments, such as estuarine areas, mangroves and marshes, which themselves provide natural protection against storm floods, are also threatened by flooding. In case the mangroves and marshes sink, waves can encroach onto the land and cause considerable damage. Only in very rare and uncommon cases could such changes be compensated by sediment input from inland.

Extreme water levels

It is now believed that extreme weather events such as tropical storms and storm surges will occur more frequently due to global warming. These will likely intensify the impacts of sea-level rise because when sea level is higher the destructive capacity of a storm on the coast is much greater. Scientists expect to see increased storm activity particularly in the temperate and tropical regions. There is still no consensus as to whether the frequency of storm activity will increase worldwide, because different scientific computer models and measurement data have yielded different results.

Storm floods originate through the interplay of storm systems and tides. When storm winds push the water toward the coasts during flood tide, especially during spring flood, the risk of flooding for large land areas is greatly increased. Such storms can last for several days and cause the water to rise so high that it does not abate even during the ebb tide.

Storms can also have severe effects in marginal seas such as the Baltic Sea, where the tidal ranges are minimal. Just like in a bathtub, the wind piles water masses up in one part of the basin, and when the wind abates or changes direction they slosh back. If the wind then blows in the opposite direction, the two factors can amplify the effect. As a consequence the water level on the German Baltic Sea coast can rise by more than 3 metres. Heavy precipitation can even intensify this situation because the rainwater or high water from the rivers cannot flow off due to the already high water level on the coast.

Increasing incidence of high water

There are other factors related to sea-level rise besides just increased water levels. It is of critical importance that unusually high storm-surge levels are occurring more often, as the example of the threat for Germany illustrates. With a sea-level rise of 1 metre, dangerous storm surges will occur more often because the base level is then a metre higher. In this case, a 100-year high-water level, like the storm flood of 1976 on the German North Sea coast, could take place every ten years. The probability of recurring severe storm surges would increase significantly. On the German Baltic Sea coast with its lower storm-flood levels, this effect would be even more pronounced. A 100-year high-water level with an elevation of 2.5 metres above **mean sea level** (German: Normalnull, NN) would occur every 2 to 5 years there.

3.11 > The storm surge of 1976 is notable as the most severe storm flood ever recorded on the German North Sea coast, and failure of the dike, as seen here on the Haseldorfer Marsh on the Elbe River, caused extremely severe damage. The water level in Cuxhaven reached a record high of 5.1 metres above normal. Nonetheless, the consequences were less severe than those of the flood of 1962 because many segments of the dike had been reinforced in the meantime.

The battle for the coast

> More than a billion people – most of them in Asia – live in low-lying coastal regions. During the course of this century some of these areas could be inundated by rising sea levels. The inhabitants will be forced to find ways of coping with the water or to abandon some areas altogether. For some time now experts have been trying to establish which regions will be the hardest hit.

The million dollar question: how bad will it be?

Climate change is placing increasing pressure on coastal regions which are already seriously affected by intensive human activity. This raises the question of whether – or to what extent – these areas will retain their residential and economic value in the decades and centuries to come, or whether they may instead pose a threat to the human race. Also, we do not know what changes will occur to the coastal ecosystems and habitats such as mangroves, coral reefs, seagrass meadows and salt marshes that provide the livelihood of coastal communities in many places.

Scientists have tried in various studies over recent years to assess the extent of the threat posed by sea-level rise. To appreciate the coastal area at greatest risk of flooding, it is necessary to first analyse current heights above sea level. This is not easy because no reliable topographical maps yet exist for many coastal areas. At a rough estimate more than 200 million people worldwide live along coastlines less than 5 metres above sea level. By the end of the 21st century this figure is estimated to increase to 400 to 500 million.

3.12 > Bangladesh experienced the full force of Cyclone Aila in 2009. Thousands of people lost their homes. This woman saved herself and her family of five in a makeshift shelter after the gushing waters burst a mud embankment.

During the same timeframe the coastal megacities will continue to grow. New cities will be built, particularly in Asia. In Europe an estimated 13 million people would be threatened by a sea-level rise of 1 metre. One of the implications would be high costs for coastal protection measures. In extreme cases relocation may be the only solution. A total of a billion people worldwide now live within 20 metres of mean sea level on land measuring about 8 million square kilometres. This is roughly equivalent to the area of Brazil. These figures alone illustrate how disastrous the loss of the coastal areas would be. The Coastal Zone Management Subgroup of the IPCC bases its evaluation of the vulnerability of coastal regions, and its comparison of the threat to individual nations on other features too:

- the economic value (gross domestic product, GDP) of the flood-prone area;
- the extent of urban settlements;
- the extent of agricultural land;
- the number of jobs;
- the area/extent of coastal wetlands which could act as a flood buffer.

A quite accurate estimate has now been made of which nations would suffer the most because a large percentage of the population lives in coastal regions. Bangladesh and

Climate change threats to the coastline of northern Germany

Northern Germany's coastline extends over about 3700 kilometres. The North Sea coast and islands account for about 1580 kilometres, and the Baltic Sea coast including the Bodden waters (a local term for shallow coastal waters) and islands about 2100 kilometres. The low-lying North Sea areas less than 5 metres above sea level are considered to be under threat, as are the areas along the Baltic Sea coast less than 3 metres above sea level. This equates to a total area of 13,900 square kilometres, a large proportion of which is currently protected by dykes. About 3.2 million people live in these flood-prone areas. The economic value of these regions currently amounts to more than 900 billion euros. There are also more than a million jobs here. Most vulnerable to storm floods and storm tides are the major cities, which include Hamburg and Bremen in particular in the North Sea region, and Kiel, Lübeck, Rostock and Greifswald along the Baltic Sea. Coastal erosion is threatening many tourist centres on both coastlines. Furthermore large sections of the ecologically-valuable saltmarshes and intertidal mudflats could be lost in the long term. It is safe to say that the cost of coastal protection measures will rise, particularly dyke construction and beach nourishment.

3.13 > On the North Sea island of Sylt, huge four-legged concrete "tetrapods" are designed to protect the coast near Hörnum from violent storm tides. Such defence measures are extremely costly.

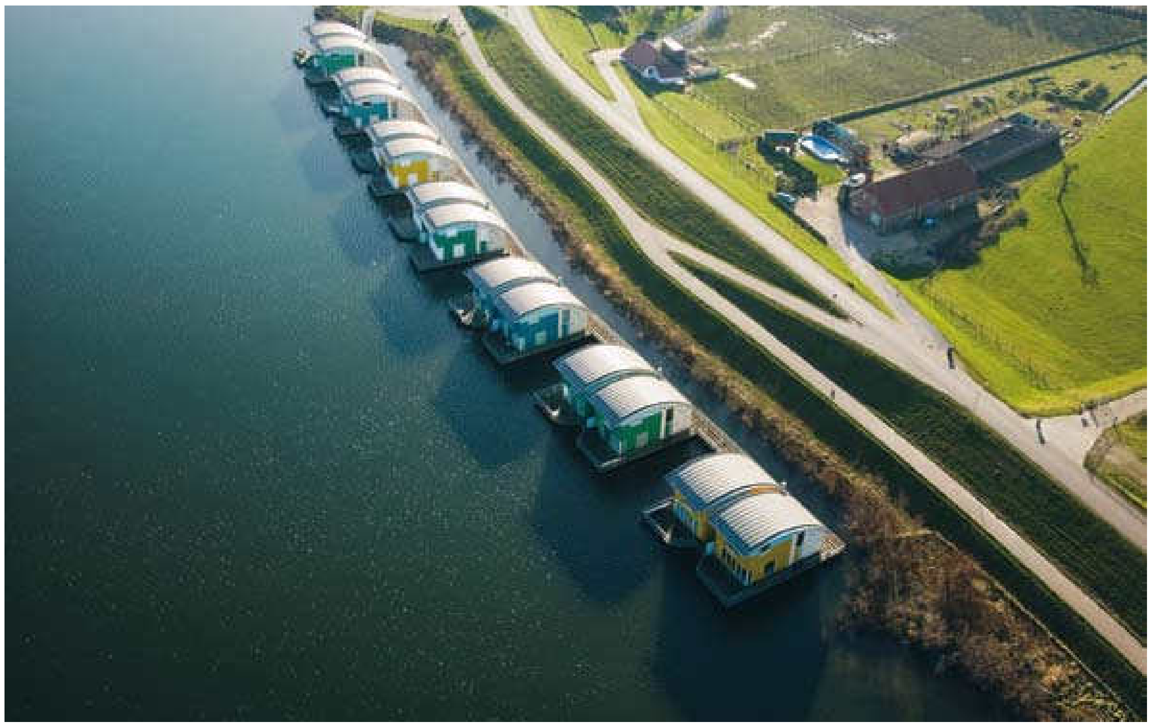
Vietnam are extremely vulnerable. Nearly all the population and therefore most of the national economy of the low-lying archipelagos of the Maldives and the Bahamas are now under threat. In absolute numbers China is at the top of the list.

The most vulnerable regions in Europe are the east of England, the coastal strip extending from Belgium through the Netherlands and Germany to Denmark, and the southern Baltic Sea coast with the deltas of Oder and Vistula rivers. There are also heavily-populated, flood-prone areas along the Mediterranean and the Black Sea, such as the Po delta of northern Italy and the lagoon of Venice as well as the deltas of the Rhône, Ebro and Danube rivers.

Some densely-populated areas in the Netherlands, England, Germany and Italy already lie below the mean high-water mark. Without coastal defence mechanisms these would already be flooded today. For all these regions, therefore, the question of how fast the sea level will rise is extremely important and of vital interest. We need to resolve how we can intensify coastal protection right away, how society can adapt itself to the new situation, and whether it might even be necessary to abandon some settlements in the future. Without appropriate coastal protection, even a moderate sea-level rise of a few decimetres is likely to drive countless inhabitants of coastal areas in Asia, Africa and Latin America from their homes, making them "sea-level refugees". The economic damage is likely to be enormous. The infrastructure of major harbour cities and especially regional trading and transportation networks – which often involve coastal shipping or river transport – would also be affected. Experts have prepared a detailed estimate of the implications of rising sea levels on Germany's coastlines.

An old saying for tomorrow: Build a dyke or move away

Ever since first settling along the coast, human societies have had to come to terms with changing conditions and the threat of storms and floods. Over time they developed ways of protecting themselves against the forces of nature. Today four distinct strategies are used, none of them are successful in the long term:



3.14 > The Netherlands is readying itself for future flooding. Engineers have constructed floating settlements along the waterfront at Maasbommel. Vertical piles keep the amphibious houses anchored to the land as the structures rise with the water levels.

1. Adaptation of buildings and settlements (artificial dwelling hills, farms built on earth mounds, pile houses and other measures);
2. Protection/defence by building dykes, flood barriers or sea walls;
3. Retreat by abandoning or relocating threatened settlements (migration);
4. "Wait and see", in the hope that the threat abates or shifts.

A culture of risk developed early on in Europe and parts of East Asia (Japan, China). Phases of retreat and adaptation until the Middle Ages were followed in more modern times by a strategy of defence; a strategy adopted in North America and other areas which were settled later. The effective protection of low-lying regions and coastal cities from flooding, land loss, water-logging and groundwater salinity is a both costly and technologically complex process. However, the example of the Netherlands shows that a small and affluent industrialized nation, when faced with a serious potential threat, is certainly capable of following the strategy of defence over the long term – after all, virtually two thirds of its country lies below the mean high-water mark. Germany also invests heavily in maintaining and protecting its much longer coastline with dykes and other structures. Each year the Netherlands and Germany together spend about 250 million euros on coastal defence. Although this amounts to only 0.01 per cent of the German and 0.05 per cent of the Netherlands' gross national income, it should not be forgotten that these amounts are utilized for the maintenance and/or fortification of existing defence works. Much poorer coastal and small island states are not in a position to protect their coastlines on a similar scale. Confronted with rising sea levels they have the choice of either adapting or retreating. But even resettlement projects like that of the Carteret Islands, part of Papua New Guinea, which began in 2007, are costly. It is not yet possible to accurately assess the exact cost of evacuating 1700 people, but this will certainly amount to several million US dollars.

Effects of sea-level rise on natural coastal systems		Possible protective/adaptive measures	Relative costs
1. Flooding of low-lying areas and resultant damage	a) Storm tides b) Backwater in estuaries	1. Dykes and flood barriers [P] 2. Artificial dwelling mounds, flood-proof building (standards) [A] 3. Identification of risk zones [A/R] 4. Adapted land-use and landscape planning [A/R]	1. Very high (construction, maintenance) 2. Medium to high 3. Very low (one-off) 4. Medium (recurrent)
2. Loss of or changes to coastal wetlands		5. Adapted land development planning [A/R] 6. Dyke relocation [A/R] 7. Foreshore reclamation [P/A] 8. Beach nourishment, sediment protection [P]	5. Low to medium (ongoing) 6. Very high (one-off) 7. High (recurrent) 8. Medium/low (ongoing)
3. Direct and indirect morphological changes, particularly erosion of beaches and bluffs		9. Construction of groynes, bank protection, sea walls [P] 10. Beach nourishment, dune protection [P] 11. Underwater reefs, breakwaters [P] 12. Development-free zones [R]	9. Medium to high (construction) 10. Medium/low (ongoing) 11. Medium to high (construction) 12. Low to high (one-off)
4. Intrusion of saltwater	a) into surface water b) into ground water	13. Dams and tide gates to prevent influx of saltwater [P] 14. Adapted/reduced withdrawal of water [A/R] 15. Pumping in of freshwater [P] 16. Adapted withdrawal of water [A/R]	13. High (construction, maintenance) 14. Low (ongoing) 15. Medium (recurrent) 16. Low (permanent)
5. Higher (ground)water levels and limited soil drainage		17. Soil/land drainage improvement [P] 18. Construction of pumping stations [P] 19. Altered land use [A] 20. Designation of flood areas/ high risk areas [A/R]	17. High (ongoing) 18. Very high (construction, maintenance) 19. Low (permanent) 20. Very low (recurrent)

3.15 > Rising sea levels impact differently on coastal areas and their inhabitants. Societies may take steps to protect themselves, but the costs can be substantial and ultimately exceed the benefits. The measures are classified as: [P] – Protective, [A] – Adaptive, and [R] – Retreat measures

3.16 > Nations with the largest populations and the highest proportions of population living in low-lying coastal areas. Countries with fewer than 100,000 inhabitants are not included. Also excluded are 15 small island states with a total of 423,000 inhabitants.

Top ten nations classified by population in low-lying coastal regions			Top ten nations classified by proportion of population in low-lying coastal areas		
Nation	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions	**Nation**	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions
1. China	127,038	10 %	**1. Maldives**	291	100 %
2. India	63,341	6 %	**2. Bahamas**	267	88 %
3. Bangladesh	53,111	39 %	**3. Bahrain**	501	78 %
4. Indonesia	41,807	20 %	**4. Suriname**	325	78 %
5. Vietnam	41,439	53 %	**5. Netherlands**	9590	60 %
6. Japan	30,827	24 %	**6. Macao**	264	59 %
7. Egypt	24,411	36 %	**7. Guyana**	419	55 %
8. USA	23,279	8 %	**8. Vietnam**	41,439	53 %
9. Thailand	15,689	25 %	**9. Djibouti**	250	40 %
10. Philippines	15,122	20 %	**10. Bangladesh**	53,111	39 %

There are different strategies for combating and coping with the effects of rising sea levels. Whether a measure is used at a regional or local level depends mainly on the cost and the geological features of the area. In the Ganges-Brahmaputra delta region of Bangladesh for instance, heavy sea dykes would sink into the soft subsoil. Also, there is no money available to erect hundreds of kilo-metres of dykes. Such a project is likely to cost more than 20 billion euros – at least a hundred times more than the annual coastal defence costs of the Netherlands and Germany combined. The national economy of Bangladesh could not support anything like this amount. In other areas there are simply not enough building materials to protect the coast. Many coral islands do not have the sediment they need to hydraulically fill the coastline, or the space and building materials for dykes and sea walls. Even if enough cash were available, these islands would still be largely defenceless against the sea. The threat from rising sea levels is worsened by the fact that coralline limestone is being removed from the reefs and used to build hotel complexes.

It is impossible to foresee with any accuracy what the rising sea levels will mean for coastal and island nations and their defence in the 21st century, as this largely depends on the extent and speed of developments. If they rise by much more than 1 metre by 2100, then the dykes and protective structures in many places will no longer be high enough or stable enough to cope. New flood control systems will have to be built and inland drainage systems extensively upgraded. Experts anticipate that the annual costs of coastal protection in Germany could escalate to a billion euros – to protect assets behind the dykes worth 800 to 1000 billion euros. On a global scale the cost could be a thousand times greater. Although the costs of defence and adaptation would appear worthwhile to some nations in view of the substantial economic assets protected by the dykes, the poorer coastal areas will probably be lost or become inhabitable. The inhabitants will become climate refugees.

Presumably the industrialized countries are capable of holding back the sea for some time using expensive, complex coastal protection technology. But even there, this strategy will ultimately have to give way to adaptation or even retreat. Extremely complex defensive fortifications such as the flood barriers of London, Rotterdam and Venice are likely to remain isolated projects. For most other areas the development of modern risk management concepts would be more logical.

Conclusion

The future of the coast – defence or orderly retreat?

The shape of coastal zones is governed by a balance of different factors such as erosion stability, sedimentation, tides, storm frequency and ocean currents. Climate change, rising sea levels and human activity can disturb or intensify these factors and influence the equilibrium of the coasts. Such imbalances can usually be compensated for, to a certain crucial tipping point. Once this point is reached any changes are irreversible, and a return to the natural equilibrium is no longer possible. The combined effect of human activity and climate change are pushing many coastal areas towards their tipping point. In future, therefore, all building activity and the moving of substances such as dredged material must be planned very carefully with a thought to sustainability. This calls for an integrated coastal zone management system. Without doubt sea levels will rise slowly at first, speeding up and continuing well beyond the 21st century. Gradually, many coastal areas will become uninhabitable. People will lose their homes and a part of their culture. Affluent coastal nations will be able to slow down this process for some time, but will have to invest enormous financial and technical capital on measures of protection and adaptation. For the present time Germany will not depart from its strategy of defence along the coastlines of the North and Baltic Seas. The cost-benefit ratio of coastal protection (for people and material assets) is favourable. However, here too the population will in the long term be forced to decide whether to retreat from these coastal areas or to adapt to the advancing sea. Architects in the Netherlands are already building the first floating settlements which, firmly anchored to the land, can float at high tide. This is a good example of the strategy of adaptation – people are learning to live with the water. In future people in many places will have to adopt similar sustainable land-use and development planning strategies. This applies particularly to the severely threatened shorelines below 5 metres. It is also conceivable that buffer zones will be established in settlement areas, where building will be allowed only in accordance with certain low-risk specifications. In some flood-prone areas no high-quality homes or businesses may be located on the ground floor even today. In the medium term, however, there is one main objective: to limit climate change and sea-level rise as much as possible by taking action to mitigate climate change.

4 Last stop: The ocean – polluting the seas

> Human society inevitably generates immense amounts of waste arising from the production and utilization of food as well as industrial and consumer goods. A considerable amount of this waste eventually ends up in the oceans. Fortunately, the pollution from oil has been decreasing in recent years. But the increasing load of nutrients and pollutants and general littering of the oceans are a growing cause for concern.

Over-fertilization of the seas

> Rivers convey agricultural nutrients and untreated wastewater to the oceans. In many areas this causes a massive proliferation of algae. In some regions entire habitats are altered. Efforts to curtail the flood of nutrients have been successful in some parts of Europe, but worldwide the situation is growing worse.

Rivers – the lifeblood of coastal waters

Coastal waters are among the most productive regions of the oceans. The greatest numbers of fish, shellfish and seafood in general are caught here. The high productivity is a result of nutrients that are transported by rivers from the land into the sea. These mainly comprise phosphate and nitrogen compounds, which plants require for growth. Phytoplankton in the ocean, microscopically small algae in particular, also utilizes these substances. Because of the high availability of nutrients, phytoplankton grows exceptionally well in coastal regions. It is consumed by zooplankton, small crustaceans, fish larvae, and other creatures, and thus forms the base of the food web in the ocean.

The high productivity of coastal waters also makes them increasingly attractive areas for aquaculture. The output of the aquaculture industry increased worldwide by a factor of fifteen between 1970 and 2005. But rivers are not the only source of nutrients for coastal areas. On the west coast of Africa, for instance, ocean currents from greater depths bring nutrient-rich water up to the surface, where light can penetrate. In these **upwelling regions,** the nutrients also promote a rich growth of algae, increase productivity through the entire food web, and ultimately produce a greater yield for fisheries. A natural level of nutrients is therefore a positive factor and is essential for marine organisms in the coastal waters.

4.1 > Eutrophication stimulates the growth of algae, which are sometimes pounded to foam in the surf, as seen here on the German North Sea coast.

Too much of a good thing

In many densely populated regions of the Earth, however, excessive amounts of nutrients are finding their way into the coastal waters. A large proportion of these nutrients come from the intensive agricultural application of chemical fertilizers, which are washed by rain into the rivers.

Between 1970 and 2005 the amount of nitrogen fertilizer alone, applied globally, increased by almost a factor of three. Nitrogen and phosphate compounds are also transported to the sea by untreated wastewater, and via the atmosphere from the burning of fossil fuels. The production and decay of organic material are unnaturally intensified by the huge amounts of nutrients in coastal waters. Scientists call this process eutrophication. The availability of nutrients is so great that the phytoplankton population grows beyond normal levels, producing a classic algal bloom. In the North Sea and in the Wadden Sea, massive algal occurrences are occasionally whipped into a foam by the surf. These sometimes form piles up to a metre high, resembling giant meringues. A serious

4.2 > Over-fertilization of the seas usually first becomes apparent with the appearance of copious amounts of green algae. Prior to the start of the Olympic sailing competition in Qingdao in 2008, the algae had to be removed from the water surface by hand.

threat is presented by the propagation of toxic algae. These are poisonous to various organisms in the sea, such as fish and clams and if they enter the food chain, they may also be ingested by humans. Numerous cases have been reported of people dying after eating poisoned shellfish. Scientists have also verified the deaths of marine mammals from algal toxins that they ingested with their food. These toxic algal blooms occur along the coast of Texas, for example. Because they discolour the water they are commonly called "red tides" or "brown tides".

The blooms of non-toxic algae can also create problems when the algae die. The dead algae sink to the bottom where they are broken down by microorganisms through a process that depletes oxygen in the seawater. Low oxygen concentrations in the water can lead to large-scale mortality of fish and crustaceans. When the oxygen levels begin to drop, the animals that can actively move, such as fish and crabs, leave the area first. Within the sea floor, the population of animals that require a healthy oxygen supply diminishes at the same time. If the oxygen concentration continues to drop, then most of the other species living in the sea floor also disappear. Only a few species that can tolerate low oxygen levels remain. If the bottom water finally becomes completely depleted of oxygen, even these organisms will die off.

But eutrophication also causes blooms of other organisms besides phytoplankton. It has a significant effect on larger plants, and can often change entire coastal ecosystems. One example of this was the formation of a vast carpet of green algae on the Chinese coast at Qingdao in 2008, which disrupted the Olympic sailing competition. In other cases, eutrophication leads to the disappearance of seagrass beds (Chapter 5) or to changes in the species composition in certain habitats. In short, eutrophication is an illustration of how changes onshore can impact the ocean, because the oceans are connected to the land masses by rivers and the atmosphere. To counteract the negative effects of eutrophication, serious efforts are being made to reduce the input of phosphate and nitrogen compounds into coastal waters.

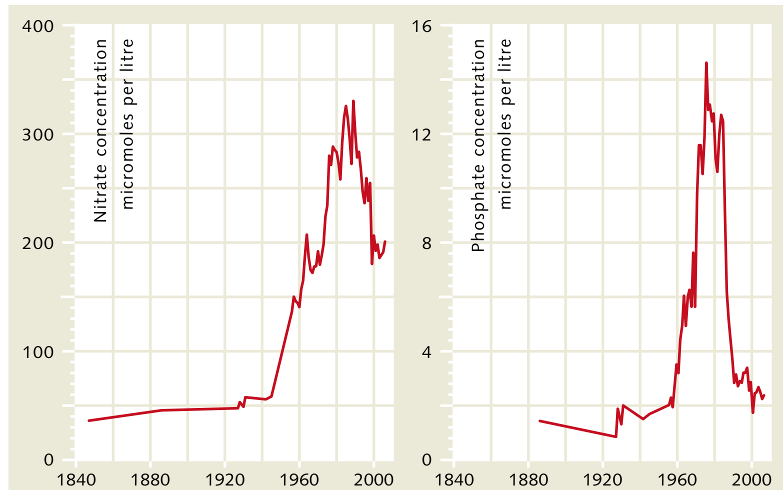
4.3 > When conditions are favourable for phytoplankton growth, algal blooms occur in the oceans, as here in the Baltic Sea. Through the massive reproduction of cyanobacteria, formerly called blue-green algae, the water in these areas turns green. Such phenomena are completely natural, but because of over-fertilization these blooms are occurring with unusually high frequency today.

Reversing the trend

The Rhine River and North Sea present a good example illustrating how the input of nutrients by rivers into the ocean has evolved through time in European regions, because extensive data are available for both of these water bodies. The first observations were made as early as the mid 19th century. Water samples from the Rhine near the border of Germany and Holland were taken and analysed over several decades. Near the border town of Lobith, researchers documented a strong increase in phosphate and nitrate concentrations from the mid-20th century. Appropriate measures were taken that have succeeded in consistently reducing the concentrations since the mid-1980s.

The causes of the increase included a growing input from agriculture and industry as well as the discharge of untreated urban sewage. Laundry detergent with phosphate additives to decalcify the wash water was a significant source of phosphates. As early as the 1970s, a ban on this type of detergent had already begun to reduce the phosphate concentrations in the Rhine. Then, in the 1980s, the nitrogen levels in the river also began to drop. This can be attributed in part to improved fertilizing methods in agriculture that resulted in lesser amounts of nutrients being washed from the fields. Another reason is the improved treatment of industrial and domestic wastewater. In 1987, environmental ministers from the North Sea countries finally agreed to a goal of halving the amounts of phosphate and nitrogen transported by rivers. For phosphates this goal was reached quickly. For the nitrogen compounds it took almost 25 years. Despite decreasing phosphate and nitrogen concentrations in the water, however, the Rhine River still carries large amounts of nutrients to the North Sea, because it flows through a highly developed and intensively used agrarian region. The present nitrate loads are still higher than in the pre-industrial age 150 years ago. Similar situations exist in other European river regions and in the USA.

In some parts of Europe, political decisions have thus led to a reversal of the trends and a reduction of nutrient input into the oceans. But the opposite trend can be observed globally. Computer models indicate that the use of fertilizer is increasing in many regions due to population growth and the intensification of agriculture. Accordingly, in many coastal regions, the amounts of phosphate and nitrogen being washed into the sea by the rivers are increasing. Particularly in Southeast Asia, rivers are carrying more and more nutrients to the sea, and experts expect this trend to continue.



4.4 > Eutrophication in coastal waters is primarily caused by an abundance of nitrates (nitrogen compounds) and phosphates that are washed into the ocean by large rivers. For example, since the middle of last century the concentration of nutrients in the Rhine River near the border town of Lobith has increased enormously. This is largely due to the intensive use of chemical fertilizers in agriculture and inadequate wastewater treatment. Counteractive measures such as a ban on phosphate detergents and improved fertilizing techniques have been successful in significantly reducing the input since the 1980s. But in many other coastal regions of the world the nutrient concentrations continue to increase.

A global problem

The effects of eutrophication have been coming to light since the 1960s. Researchers have noted more abundant algal blooms, oxygen-poor zones in coastal regions, and changes in coastal ecosystems. The causes of eutrophication have been thoroughly analysed in numerous studies, and there is certainly a direct connection between environmental changes and nutrient input. But for a long time researchers were in disagreement as to how the phos-

The Mississippi River and the Gulf of Mexico dead zone

No other North American river has a drainage basin as large as that of the Mississippi. The amount of nutrients it discharges into the Gulf of Mexico is correspondingly large. Because freshwater from the river is lighter than the salty seawater, it settles as a distinct layer above the seawater. This phenomenon is called stratification. The freshwater layer acts like a blanket to prevent the exchange of gases, oxygen for example, between the seawater and the atmosphere. This kind of stratification is also observed in other coastal areas, such as in the Baltic Sea between Denmark and Sweden, and in the Norwegian fjords. In the case of the Mississippi River, however, the situation is exacerbated by the especially high levels of nutrients it contains. The presence of the nutrients leads to profuse algal growth. When the algae die their remains sink into the lower water layer. There they are broken down by bacterial activity, a process that consumes oxygen. This causes the oxygen levels in the deep-lying saltwater layer to drop drastically. Free-swimming organisms flee the area due to the oxygen deficiency. Less mobile animals such as mussels die. For this reason, the low-oxygen areas off the coasts of Louisiana and Texas are called "dead zones". In 2002 an oxygen-deprived area of more than 20,000 square kilometres was observed. This is equal to half the area of Germany. There is considerable evidence that the oxygen problem associated with stratification has only begun to occur more frequently since the middle of last century. The increase is probably due to the rising nutrient concentrations, especially nitrogen, which has trebled since the 1950s. Stratification in the northern Gulf of Mexico is, in fact, a natural phenomenon that is especially pronounced during years with high rainfall. Storm events like hurricanes can cause effective mixing of the water, and even counteract the effects of stratification. But the nutrient transport of the Mississippi River is still too great. A management plan has now been adopted to attempt to reduce the nutrient input, with an aim of limiting the maximum area of the dead zone to around 5000 square kilometres. The measures being applied include improved wastewater treatment, optimized fertilization practices, and the creation of flood-plain areas along the rivers, which would absorb significant amounts of the nutrients.

4.5 > The Mississippi River carries vast amounts of sediments (yellow-brown) and nutrients into the Gulf of Mexico, which are then transported westward along the coast by the wind. The nutrients cause a strong growth of algae (green). Oxygen is consumed in the deep water as bacteria break down the algae. This results in a completely oxygen-depleted dead zone along a broad strip of the US coast.

phates and nitrates interact as nutrients. Some experts accepted that the "law of the minimum", formulated by the agronomist Carl Sprengel in 1828, was valid for algal growth. According to this theory, a plant requires several nutrients in order to thrive. If one nutrient is missing, then it cannot grow. This means that the growth of plants would always be limited by the one substance that is not available in sufficient quantity. This would suggest that it is sufficient to remove one nutrient, either phosphate or nitrogen, from the wastewater and rivers in order to stop the growth of algae. This would also significantly reduce the costs of water treatment.

This assumption, however, now appears to be too simplistic. Continuing experiments and observations show that multiple factors acting in concert are often responsible for limiting plant growth. Experts call this phenomenon co-limitation. Eutrophication can only be combated successfully if both phosphate and nitrogen are reduced. However, this is fraught with difficulty, primarily because nitrogen released by agricultural activity is not easily contained. This is also true of nitrogen released into the atmosphere by the burning of natural gas, oil or coal. Eutrophication is therefore likely to continue to occur in coastal waters in the future.

One example of a strongly eutrophic area is the German Bight. In the 1980s the oxygen concentration in its deep waters dropped to alarming levels. At the same time an increase in primary productivity in the form of enhanced algal growth was observed in the Wadden Sea. Seagrass, a plant that is the foundation for a unique habitat in the North Sea and Wadden Sea, disappeared. It was displaced by an excessive proliferation of green algae. All over the world, bays with limited water exchange are affected by eutrophication because nutrients are not effectively dispersed. These include Tokyo Bay, Long Island Sound in the USA, the Baltic Sea, and several of the fjords in Norway.

Eutrophication with an excessive growth of phytoplankton has also been observed in some areas in the Mediterranean Sea, such as the north-eastern Adriatic Sea or the bay at Athens. The Gulf of Mexico is a special case: here the Mississippi River discharges such a large volume of nutrients that an extensive low-oxygen area has formed along the coast.

Any chance of recovery?

Through systematic measures such as the Water Framework Directive of 2000, or the Marine Strategy Framework Directive adopted in 2008, the European Union is striving to improve water quality in the European coastal waters. Key parameters for evaluating water quality are sufficient oxygen content, low nutrient levels, and the presence of certain algal species and bottom dwellers. Wherever possible the previously eutrophic waters should be restored to their natural condition, or at least to an only slightly impacted state. Improved monitoring for ongoing assessment should also be carried out in order to identify changes and their causes.

Due to world population growth, eutrophication will continue to be a problem for decades to come. There is presently little hope of a worldwide reduction in the amounts of nutrients being discharged into coastal waters. A true dilemma exists: humankind has a vital need for agriculture and the production of grain, but this results in vast amounts of fertilizers ending up in the rivers and oceans. Often costly abatement measures are therefore required to achieve a balance between the nutrient input from agriculture and the negative impact on the ecosystem. One particular problem is that it is impossible to completely restore a coastal ecosystem affected by eutrophication to its original state. Eutrophication is not fully reversible. Studies in several European coastal systems indicate that a long period of eutrophication produces lasting changes in the ecosystem that cannot simply be reversed by reducing the nutrient input. Nonetheless, the example of the Wadden Sea clearly illustrates that practical measures can be effective in decreasing the amount of nutrients and creating a general improvement in the marine environment. In the northern Wadden Sea, for instance, there are indications that the seagrass beds have recovered and are expanding again as a result of the reduction of nutrients and algal blooms.

Organic pollutants in the marine environment

> It has long been known that specific toxins accumulate in the natural environment and in living organisms, causing damage to health. As a result, the use of many of these chemicals is now prohibited. However, new toxic substances that were not initially recognized as a threat are frequently detected in the environment. Polyfluorinated compounds (PFCs) are one current example. There is still no solution to this problem.

The downside of consumption

Chemical-based products are found in plastic casing for computers, in athletic-hall flooring, in rubber soles for jogging shoes – the applications are endless. In consequence, a very wide range of chemicals is used in industry today. According to the Organisation for Economic Co-operation and Development (OECD), approximately 100,000 different chemical substances are currently on the market worldwide. In Europe alone, approximately 10,000 chemicals are produced and marketed annually in amounts of greater than 10 tonnes. It is estimated that between 1 and 3 per cent of these chemicals are problematical. These environmentally relevant pollutants include heavy metals such as lead and mercury, which are released into the environment by the burning of oil, mining activities, and industrial emissions and effluents. Persistent organic pollutants, known as POPs, are another problematical substance category.

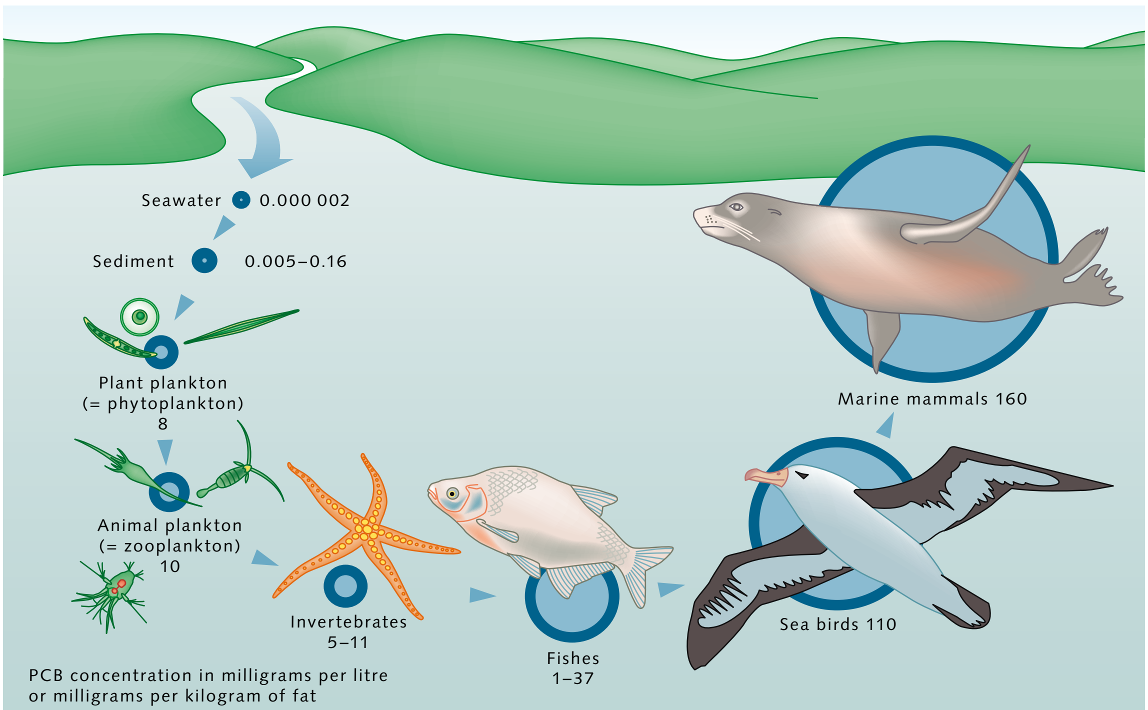
4.6 > During the phocine distemper virus (PDV) epidemics in 1988 and 2002, thousands of dead seals were washed up on German beaches and had to be collected and destroyed.

Poisonous and persistent – POPs

The Stockholm Convention on Persistent Organic Pollutants adopted in 2001 deals with persistent organic pollutants (POPs), i.e. substances that possess toxic properties and resist degradation. They include pesticides such as DDT and lindane, industrial chemicals such as polychlorinated biphenyls (PCBs), and substances such as dioxins, which are the unwanted by-products of manufacturing and combustion processes. As these substances are highly stable and therefore non-degradable to a large extent, they can be transported over long distances and accumulate in the environment.

POPs cause problems because they are stored in the fatty tissue or organs of animals, where they can have toxic effects. For example, they can disrupt the endocrine system, cause cancer or genetic defects, and weaken the immune system.

Various effects of POPs on marine mammals have been investigated. Studies of Baltic ringed seals *(Phoca hispida)* and grey seals *(Halichoerus grypus)* found uterine occlusions, stenoses and tumours, resulting in reduced reproductive ability. Other observed effects included colonic ulcers, as well as reduced bone density, which led to changes in the skeletal system. In seals and porpoises, researchers found indications that POPs depress the immune and endocrine systems. A further topic of discussion in this context is whether these pollutants and the weakening of the immune system affect the spread of epidemics, such as the disease that killed thousands of seals in the North Sea in 1988 and again in 2002 – probably an epidemic of the phocine distemper virus.



4.7 > Bioaccumulation of toxins in the marine food chain has long been recognized as a problem. The process illustrated here relates to polychlorinated biphenyls (PCBs), a typical environmental toxin.

Humans mainly ingest POPs from food and drinking water, but also from the air (mainly by breathing in dust particles) and through the skin (through direct contact with the chemicals). The highest concentrations of POPs are generally found in marine mammals and humans, both of which are at the top of the food chain.

Polyfluorinated compounds: a fresh cause for concern

Besides the "classic" POPs, mentioned above, new types of persistent toxic compounds of non-natural origin were identified in the environment at the end of the 1990s, which could not be detected before as the appropriate technology and analytical methods had not yet been developed. These include polyfluorinated compounds (PFCs), which have been used in a wide variety of everyday applications for more than 50 years. PFCs are mainly used as fluoropolymers in the textile industry, for example, in the manufacture of breathable membranes for outdoor clothing, and in the paper industry in the production of water-, stain- and grease-proof paper (e.g. fast-food packaging). They are also used for surface treatment of furniture, carpets and clothing textiles and in non-stick coatings for cookware (such as Teflon frying pans).

It is believed that a total of six manufacturers have produced around 4500 tonnes of PFCs every year over the past decade: a relatively small amount compared with other chemicals. This group of substances is significant nonetheless, due to its environmentally relevant properties, as some PFCs are highly bio-accumulative in organisms.

At present, more than 350 different PFCs are known to exist. The best-known is perfluorooctanesulfonic acid, more commonly known as PFOS. Based on animal experiments with PFOS, researchers conclude that repeated exposure can have an extremely adverse effect on human health; among other possible effects, it may cause damage to the liver. PFOS may also be carcinogenic, and it is also thought to impair the development of progeny. PFOS therefore recently became the first PFC to be listed as a persistent organic compound (POP) under the Stockholm Convention, which means that it is now on the list of particularly hazardous chemicals for which a worldwide ban is to be imposed.

Occurrence of polyfluorinated compounds

Polyfluorinated compounds (PFCs) have been industrially manufactured for around half a century, but it has only recently been possible to detect their presence in the environment due to new chemical and analytical techniques. Natural origins of these chemicals are not known to exist, and yet today PFCs can be detected in water, soil, air and living organisms worldwide – including humans. High levels of PFCs have been found in numerous foods as well as in human blood and breast milk.

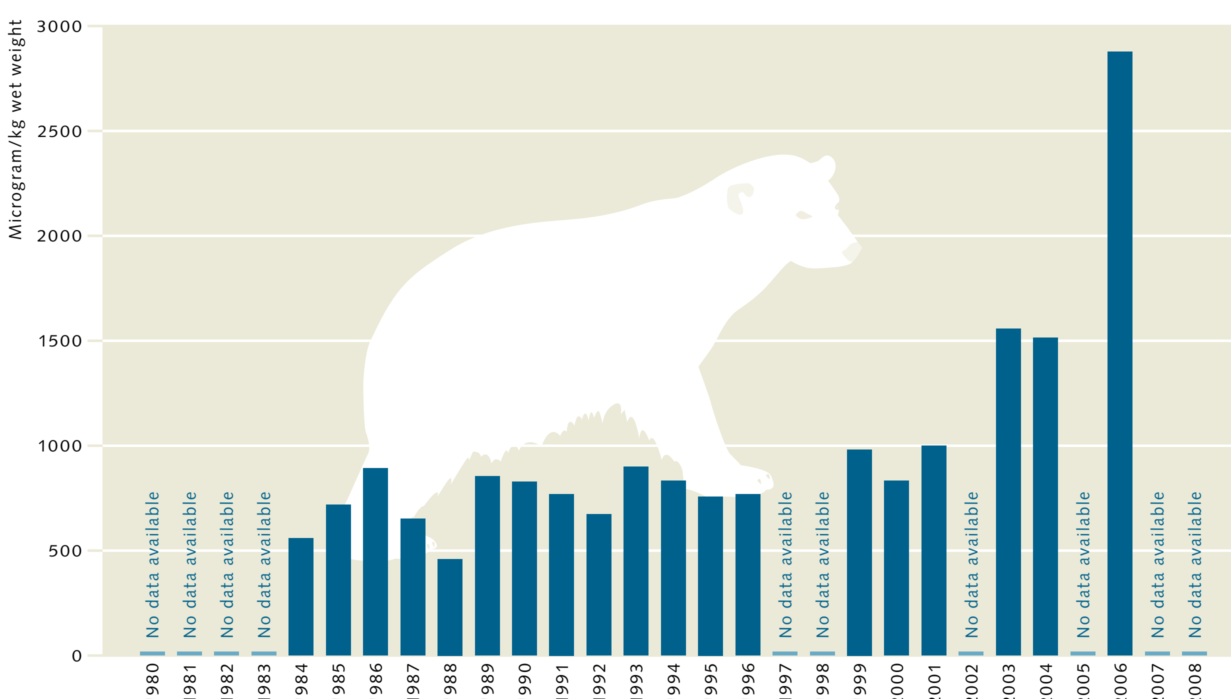
The distribution of PFOS in the environment is particularly well-researched. High concentrations of these substances have been detected in fish, seals and sea birds worldwide and, above all, in Arctic polar bears, which are at the top of the food chain. Researchers from Canada and Denmark have reported a sharp rise in PFOS concentrations in liver samples taken from polar bears in Canada, Alaska and Greenland in recent decades.

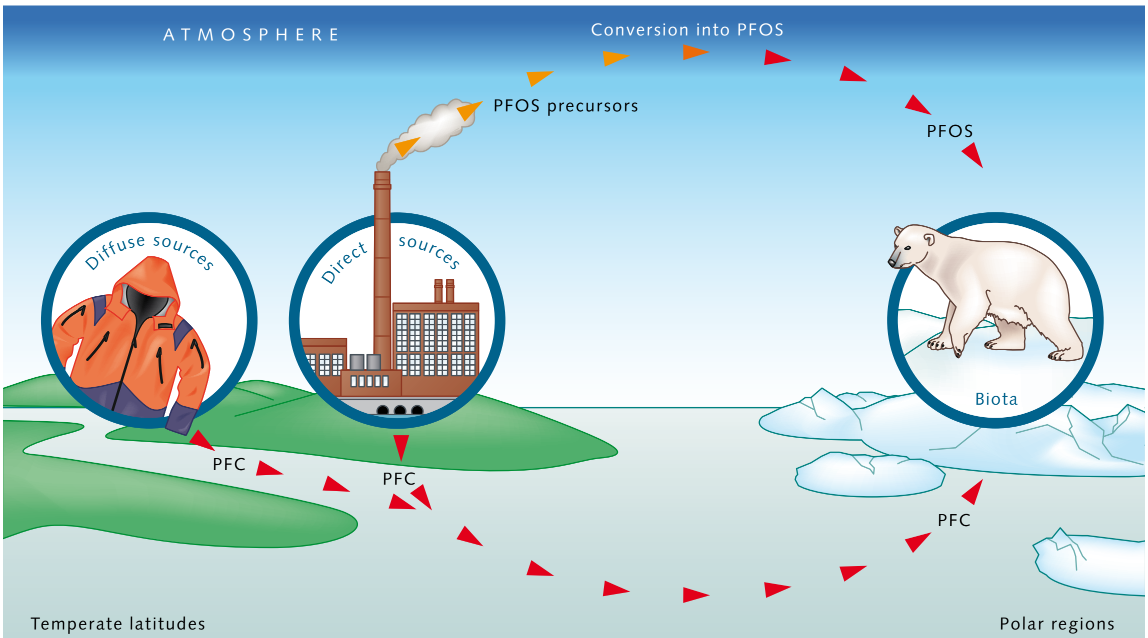
Compared to other environmentally relevant POPs, such as polychlorinated biphenyls, PFCs are found in much higher concentrations. In Swedish studies of human blood from 1994 to 2000, the mean PFC concentration was 20 to 50 times higher than the concentration of the polychlorinated biphenyls and about 300 to 450 times higher than that of hexachlorobenzene, two "classic" organic pollutants that have been recognised as hazardous for decades.

Transport of PFCs

The detection of PFCs and especially PFOS in marine mammals such as Arctic seals and polar bears, and even in the blood of the Arctic's human inhabitants, the Inuit, raises the question of transportation: How did these substances end up in the sea and even in the Arctic? There are numerous different sources of PFCs. They are released, for example, during the use of the every-day con-

4.8 > PFOS concentrations in the livers of East Greenland polar bears have increased significantly in recent years. The measurements were obtained from deep-frozen liver samples.





4.9 > PFCs can travel great distances in water or air. Through a direct pathway, they enter the rivers in wastewater and are carried down to the sea. They can also be transported indirectly through the atmosphere. For example, volatile PFOS precursors are released into the atmosphere, where they are converted into PFOS, which is then deposited back on the Earth's surface at the place of origin or elsewhere in rainfall or in dust particles.

sumer durables mentioned above – from carpeting, outdoor clothing, cookware and fast-food packaging. However, in Germany, relatively large concentrations of PFCs also enter the rivers from municipal and industrial wastewater treatment plants, which cannot capture these substances. The rivers then wash these substances into the North Sea. From here, they are carried by the main North Sea and Atlantic Ocean currents to the Arctic, where they are ingested by microorganisms in the water and thus enter the food chain, bioaccumulating in larger organisms and finally in the organs of polar bears and humans.

PFCs are also transported long distances through the atmosphere by the movement of air masses. Compounds such as PFOS are not volatile, but volatile precursor compounds escape into the atmosphere during the manufacturing process. Physical and chemical processes that take place in the atmosphere then convert these chemical precursors into stable end products such as PFOS. These are removed from the air by precipitation and enter the seawater in soluble form or bound to dust particles, or are deposited on land or ice surfaces. PFCs can thus travel great distances and can be detected in the environment a long way from their place of origin or use.

Protection from new pollutants

Today PFCs are distributed all over the world. They are found in water, in the air, in living organisms and even in our own bodies. They are likely to persist for generations. This group of substances clearly shows that it is impossible to predict all the environmental impacts, or the delayed effects, of new chemical substances. In the future too, it is likely that some substances that were initially regarded as harmless, but whose undesirable effects can only be discerned after some time has elapsed, will be detected in the marine environment. Nowadays, however, intensive efforts are being made to limit the further global spread of pollutants. For example, risk assessments are carried out before chemicals are licensed for use, in order to determine to what extent they could constitute a hazard. There are also various voluntary renunciation schemes for producers, as well as relevant legislation. In other words, a start has been made.

Litter – pervading the ocean

> Every year, large amounts of litter enter the sea. As plastics are particularly durable, the mass of plastic debris in the world's oceans is steadily increasing – often with fatal consequences for countless sea creatures. Microscopic breakdown products from plastics, which scientists have only recently started to study in detail, may also pose a threat. Although the problem has existed for some time, there is still no effective strategy in place to turn the tide on marine litter.

Top ten marine debris items:

1. Cigarettes/ cigarette filters
2. Bags (plastic)
3. Food wrappers/ containers
4. Caps/lids
5. Beverage bottles (plastic)
6. Cups, plates, forks, knives, spoons (plastic)
7. Beverage bottles (glass)
8. Beverage cans
9. Straws, stirrers (plastic)
10. Bags (paper)

Litter: Where does it come from?

Take a stroll along any beach after a storm and you will get an idea of just how much litter is floating around in the world's oceans: the sand is strewn with plastic bottles, fish boxes, light bulbs, flip-flops, scraps of fishing net and timber. The scene is the same the world over, for the seas are full of garbage. The statistics are alarming: the National Academy of Sciences in the USA estimated in 1997 that around 6.4 million tonnes of litter enter the world's oceans each year. However, it is difficult to arrive at an accurate estimate of the amount of garbage in the oceans because it is constantly moving, making it almost impossible to quantify.

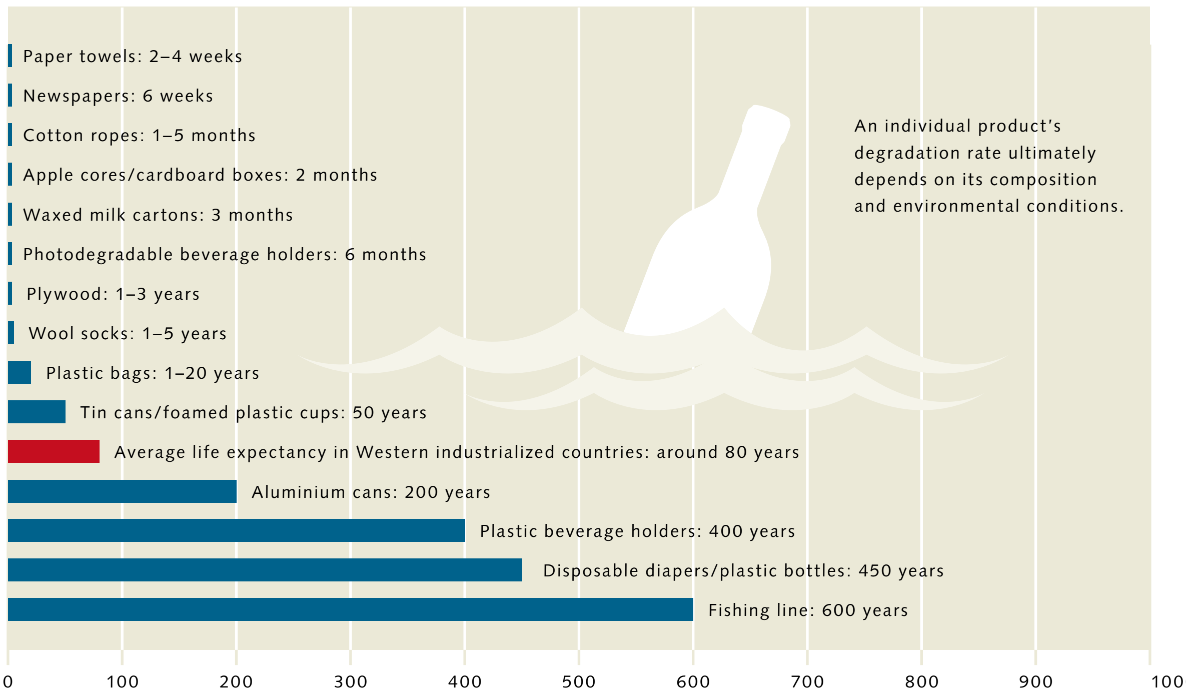
A further complicating factor is that the litter enters the marine environment by many different pathways. By far the majority originates from land-based sources. Some of it is sewage-related debris that is washed down rivers into the sea, or wind-blown waste from refuse dumps located on the coast, but some of it comes from careless beach visitors who leave their litter lying on the sand.

Shipping also contributes to the littering of the oceans: this includes waste from commercial vessels and leisures that is deliberately dumped or accidentally lost overboard and, above all, torn fishing nets. As most of the litter is plastic, which breaks down very slowly in water and may persist for decades or even centuries, the amount of debris in the marine environment is constantly increasing.

Scientific studies have revealed regional variations in the amount of litter in the sea. In many regions, researchers have reported quantities of floating plastic debris in the range of 0 to 10 items of debris per square kilometre. Higher values were reported in the English Channel (10 to 100 items/square kilometre), but in Indonesia's coastal waters, 4 items of debris in every square metre were reported – many orders of magnitude above the average.

The problem does not only affect the coastal areas, however. Propelled by the wind and ocean currents, the litter – which is highly persistent in the environment – travels very long distances and has become widely dispersed throughout the oceans. It can now even be found on remote beaches and uninhabited islands.

In 1997, researchers discovered that the floating debris accumulates in the middle of the oceans – in the North Pacific, for example, where massive quantities of water constantly circulate in a swirling vortex of ocean currents known as gyres, which extend for many hundreds of kilometres and are driven by light winds. The plastic debris ends its journey here. The litter circulates constantly, with new debris being added all the time. Environmental researchers call it the Great Pacific Garbage Patch. The concentration of litter is extremely high, which is particularly worrying if we consider that it is located in the open sea thousands of miles from the coast. Scientists have detected up to 1 million plastic particles per square kilometre here. Much of the debris consists of small fragments of plastic that were fished out of the water using fine-mesh nets. By contrast, studies in the English Channel, and many other surveys carried out elsewhere, are based on the visual method of quantification, which means that scientists simply count the pieces of debris that are visible as they pass by in their research vessels.



4.10 > The amount of litter in the oceans is constantly increasing. Much of it degrades very slowly. Plastic bottles and nylon fishing line are particularly durable. Although many plastics break down into smaller fragments, it will take decades or even centuries (estimated timescales) for them to disappear completely.

The amount of floating oceanic debris is immense. However, it is thought that around 70 per cent of the litter eventually sinks to the sea floor. The worst-affected areas are the coastal waters of densely populated regions or regions with a high level of tourism, such as Europe, the US, the Caribbean and Indonesia. In European waters, up to 100,000 pieces of litter visible to the naked eye were counted per square kilometre on the sea floor. In Indonesia, the figure was even higher – up to 690,000 pieces per square kilometre. Much of the litter is harmless, but some of it is responsible for marine mammal deaths. Seals and otters, for example, which feed on fish, crabs and sea urchins on the sea floor, are frequent casualties.

Tiny but still a threat – microplastics

For some years now, scientists have increasingly turned their attention to what remains of the plastic debris after prolonged exposure to wave action, saltwater and solar radiation. Over time, plastics break down into very tiny fragments, known as "microplastics". Microplastics are now being detected in ocean waters, sand and sea-floor sediments all over the world. These tiny particles, just 20 to 50 microns in diameter, are thinner than a human hair. Marine organisms such as mussels filter these particles out of the water. Experimental analyses have shown that the microplastics accumulate not only in the stomachs but also in the tissue and even the body fluids of shellfish. The implications are still unclear, but as many plastics contain toxic substances such as softeners, solvents and other chemicals, there is concern that microplastics could poison marine organisms and, if they enter the food chain, possibly humans as well.

The silent killers – ghost nets

Derelict fishing gear – known as "ghost nets" – poses a particular threat to marine wildlife. These are nets which have torn away and been lost during fishing activities, or old and damaged nets that have been deliberately discarded overboard. The nets can remain adrift in the sea and continue to function for years. They pose a threat to fish, turtles, dolphins and other creatures, which can become trapped in the nets and die. The tangled mass then snags other nets, fishing lines and debris, so that over time, the ghost nets become “rafts”, which can grow to hundreds of metres in diameter. Some of these nets sink to the sea floor, where they can cause considerable environmental damage. Propelled by currents, they can tear up corals and damage other habitats such as sponge reefs.

Impacts on people

For a long time, marine litter was regarded as a purely aesthetic problem. Only coastal resorts attempted to tackle the problem by regularly clearing debris from the beaches. However, as the amount of litter has increased, so too have the problems. It is difficult to put a precise figure on the economic costs of oceanic debris, just as it is difficult to quantify exactly how much litter there is in the sea. In one study, however, British researchers showed that marine litter has very serious implications for humans, particularly for coastal communities. The main impacts include:

- risks to human health, including the threat of injury from broken glass, syringes from stranded medical waste, etc., or from exposure to chemicals;
- rising costs of clearing stranded debris from beaches, harbours and stretches of sea, together with the ongoing costs of operating adequate disposal facilities;
- deterrent effect on tourists, especially if sections of coastline are notoriously polluted. This results in loss of revenue from tourism;
- damage to ships, such as dented hulls and broken anchors and propellers from fouling by floating netting or fishing line;
- fishery losses: torn nets, polluted traps and contaminated catches; if nets become choked with debris, the catch may be reduced;
- adverse effects on near-coastal farming: numerous items of plastic waste and other forms of wind-borne marine debris may be strewn across fields and caught on fences; livestock may be poisoned if they ingest scraps of plastic or plastic bags.

Impacts on animals

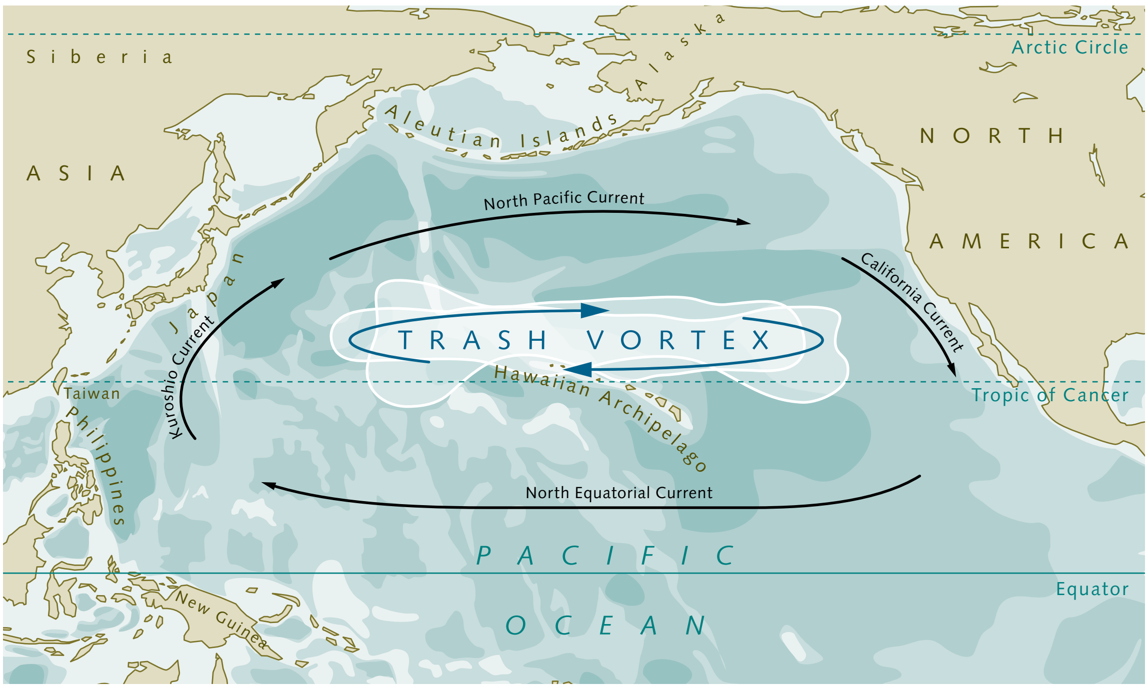
The presence of such large quantities of debris has a catastrophic effect on marine fauna. Seabirds such as the various species of albatross *(Diomedeidae)* or the Northern fulmar *(Fulmarus glacialis)* pick up fragments of plastic from the sea surface, ingest them and then often pass them to their chicks in regurgitated food. It is by no means uncommon for birds to starve to death as their stomachs fill with debris rather than food. Analyses of the stomach contents of seabirds found that 111 out of 312 species have ingested plastic debris. In some cases, up to 80 per cent of a population were found to have ingested debris.

In another study, the stomach contents of 47 harbour porpoises *(Phocoena phocoena)* from the North Sea were investigated. Nylon thread and plastic material were found in the stomachs of two of these individuals. In other cases, the debris itself can become a death trap. Dolphins, turtles, seals and manatees can become entangled in netting or fishing line. Some of them drown; others suffer physical deformities when plastic netting, fishing line or rubber rings entwine the animal’s limbs or body, inhibiting growth or development.

There is another threat associated with plastic debris as well: almost indestructible and persistent in the environment for many years, plastic items drift for thousands of miles and therefore make ideal “rafts” for many marine species. By “hitch-hiking” on floating debris, alien species can cross entire oceans and cover otherwise impossibly long distances. Plastic debris thus contributes to the spread of invasive species to new habitats, and can even destabilize habitat equilibrium in some cases (Chapter 5).

Raising awareness: The first step forward

The fact that marine litter is a problem that must be taken seriously is only gradually being recognized. The United Nations Environment Programme (UNEP) has therefore launched an intensive publicity campaign in an effort to raise awareness of this critical situation. Its main focus is



4.11 > In the Great Pacific Garbage Patch between Hawaii and North America, vast quantities of litter are constantly circulating. Many plastic items are transported thousands of kilometres across the sea before they are caught up in the gyre.

on working with non-governmental organizations and government agencies to improve the situation at the regional level. This includes promoting the introduction of regulations and practices that in many cases are already the norm in Western Europe, such as waste separation systems, recycling, and bottle deposit-refund schemes. Various litter surveys have shown that much of the debris found in the North Sea, for example, comes from shipping rather than from land-based sources. However, the situation is reversed in many countries of the world, where waste is often dumped into the natural environment without a thought for the consequences and, sooner or later, is washed into the sea. In these cases, shipping plays a less significant role. UNEP is therefore emphasizing the importance of efficient waste management systems.

UNEP also supports high-profile, media-friendly clean-up campaigns such as the annual International Coastal Cleanup (ICC). Every year, volunteers, especially including children and young people, clear litter from beaches and riverbanks. The main aim is to raise young people's awareness of the problem of global marine litter. In 2009 alone, around 500,000 people from some 100 countries took part in the ICC. Before all the litter is disposed of onshore, each item is recorded. Although the data collection is carried out by laypersons and may therefore contain errors, the International Coastal Cleanup nonetheless provides a very detailed insight every year into the worldwide litter situation.

Indeed, surveying marine litter – i.e., regular monitoring – is an important tool in assessing how the situation is developing. In various regions of the world, professionals have been recording the debris found along the coasts for many years. In the north-east Atlantic region, for example, a standard methodology for monitoring marine litter was agreed to by the Contracting Parties to the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), and this has been in effect for around 10 years. Using a common, standardized survey protocol, 100-metre stretches of around 50 regular reference beaches in the north-east Atlantic region are surveyed three to four

4.12 > The Laysan albatross *(Phoebastria immutabilis)* is also affected by the litter in the Pacific Ocean, as the birds mistake the brightly coloured plastic for food and ingest it. Here, the photographer has laid out stranded items of debris neatly on the beach. These types of objects are typically found among the stomach contents of albatross, and can cause the death of many of the affected birds.

times a year. It was this monitoring activity that found that the debris in the North Sea mainly comes from shipping.

International agreements lack teeth

For some years, efforts have been made to stem the tide of litter with international agreements. These include the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78). Since 1988, Annex V to the Convention has specified which types of waste must be collected on board and may not be discharged into the sea. For example, under the MARPOL Convention, disposal of food wastes into the sea is prohibited if the distance from the nearest land is less than 12 nautical miles. Disposal of all plastics into the sea is prohibited. For the EU, on the other hand, Directive 2000/59/EC of the European Parliament and of the Council of 27 November 2000 on port reception facilities for ship-generated waste and cargo residues requires ships to dispose of their waste before leaving port and obliges ports to ensure the provision of adequate reception facilities for such waste. Ships must contribute to the costs of the reception facilities through a system of fees.

If a ship has proceeded to sea without having disposed of its waste, the competent authority of the next port of call is informed and a more detailed assessment of factors relating to the ship's compliance with the Directive may be carried out. Critics point out that both the assessment itself and the communication between ports are inadequate. The fact that there has been no decrease in the amount of debris along the North Sea coast as yet also suggests that the international agreements lack teeth. Annex V of the MARPOL Convention is therefore being revised at present.

In any case, the agreements have no impact on the amount of waste entering the sea from land-based sources. It is hoped that the Marine Strategy Framework Directive (MSFD) – the European Union's tool to protect the marine environment and achieve good environmental status of the EU's marine waters by 2020 – will improve the situation. Besides addressing topics such as marine pollution from contaminants and the effects of underwater noise on marine mammals, the MSFD in addition deals with the issue of waste. An initial assessment of the current environmental status of the waters concerned and the environmental impact of human activities is to be completed by 2012, and a programme of measures is to be developed by 2015. The necessary measures must then be taken by the year 2020 at the latest.

Turning the tide against litter: The future

Experts agree that the littering of the seas will only stop if the entry of waste from land-based sources can be controlled. According to UNEP, this means that numerous countries will have to develop effective waste avoidance and management plans. At present, the prospect of this happening seems somewhat bleak, especially given the vast quantities of waste involved. Environmental awareness-raising and education would therefore appear to be a more promising approach. The popularity of the International Coastal Cleanup programme is an encouraging sign that there is growing recognition, around the world, of the need to prevent littering of the seas.

To address the problem of ghost nets, UNEP is calling for stronger controls, which would involve fishermen being monitored and having to log the whereabouts of their nets. Work is also under way to develop acoustic deterrent devices for fishing gear that can, for example, alert dolphins to the presence of nets. The Fishing for Litter scheme being set up in Scotland and Scandinavia is another positive example of action being taken. Fishermen and port authorities have joined forces so that debris caught in fishing nets can be disposed off correctly onshore. Instead of throwing the litter back into the sea, the fishermen collect the debris on board and bring it back into port. Recycling schemes for old fishing nets are also being developed. In all probability, the global problem of marine litter can only be solved through numerous individual schemes such as these. However, without a concerted effort by the international community as a whole, the problem is likely to continue.

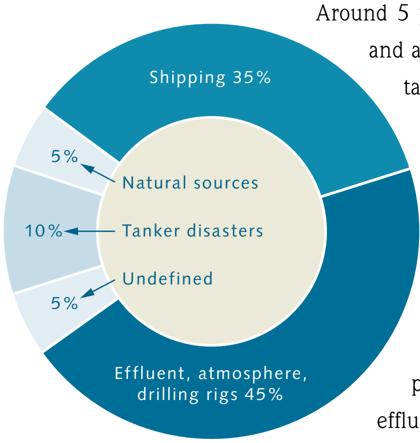
Oil pollution of marine habitats

> Oil pollution is one of the most conspicuous forms of damage to the marine environment. Oil enters the seas not only as a result of spectacular oil tanker or oil rig disasters, but also – and primarily – from diffuse sources, such as leaks during oil extraction, illegal tank-cleaning operations at sea, or discharges into the rivers which are then carried into the sea. The designation of marine protected areas, increased controls and the use of double hull tankers are just some of the measures now being deployed in an effort to curb marine oil pollution.

How oil enters the sea

The public generally takes notice of the problem of marine oil pollution when an oil tanker breaks up in heavy seas or a disaster occurs at an oil platform, one example being the Deepwater Horizon incident in the Gulf of Mexico in spring 2010. In such cases, oil slicks often drift towards the coasts and kill seabirds and marine mammals such as seals. Yet in reality, spectacular oil tanker disasters account for only around 10 per cent of global marine oil pollution.

4.13 > Oil enters the sea along various pathways. Around one third comes from regular accident-free shipping operations.

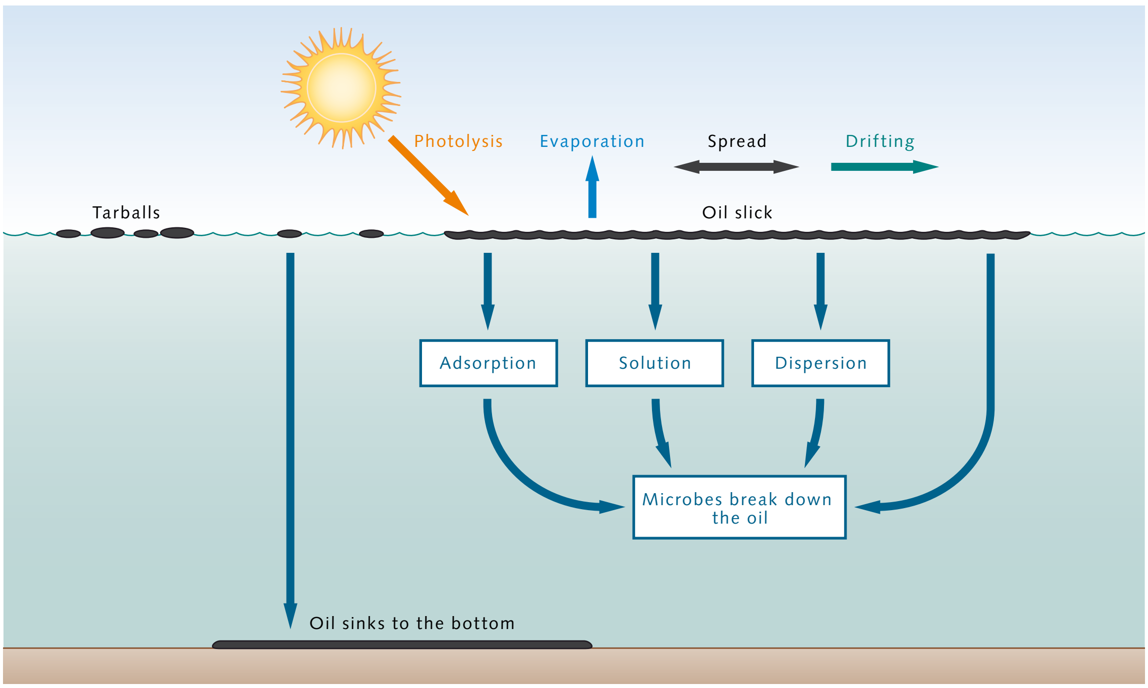


Most of the oil enters the seas along less obvious pathways, making it correspondingly difficult to precisely estimate global oil inputs into the marine environment. Around 5 per cent comes from natural sources, and approximately 35 per cent comes from tanker traffic and other shipping operations, including illegal discharges and tank cleaning. Oil inputs also include volatile oil constituents which are emitted into the atmosphere during various types of burning processes and then enter the water. This atmospheric share, together with inputs from municipal and industrial effluents and from oil rigs, accounts for 45 per cent. A further 5 per cent comes from undefined sources.

Although vegetable oils such as palm oil are now being produced in increasing quantities and are therefore also entering the atmosphere, oil pollution still mainly consists of various types of oil from fossil sources, created over millions of years from deposits of microscopically small marine organisms, mainly diatoms (Chapter 7). This crude oil consists of around 10,000 individual substances, with hydrocarbons being the main component (more than 95 per cent). However, the precise composition can vary considerably according to the place of origin. Crude oil also contains heavy metals and nitrogen compounds.

The extent to which mineral oils and their components adversely affect the various marine habitats and their flora and fauna varies considerably from case to case. Major oil spills have the greatest and most disruptive impact, although their effects are in most cases regionally limited. Since the *Torrey Canyon* tanker disaster in 1967, when around 115,000 tonnes of crude oil were spilled on a reef off the southern English coast, resulting in the largest oil pollution incident ever recorded up to that time, numerous field studies have been carried out which now provide a very clear overview of the impacts of various types of oil on organisms and habitats. However, one oil disaster is quite never the same as another, and the precise effects of an accidental oil spill depend on a variety of conditions.

A crucial factor, for example, is how quickly the oil breaks down or sinks from the surface of the sea to the lower depths, where the damage it causes is likely to be relatively limited. This breakdown is influenced by various physical, chemical and biological processes. Depending on a variety of different environmental conditions such as temperature, nutrient content in the water, wave action etc., the breakdown of the petroleum hydrocarbons may take shorter or longer periods of time. During



4.14 > In the sea, oil is modified and broken down in a variety of ways. Generally, when an oil spill occurs, the oil immediately forms large slicks which float on the water's surface. A proportion of the oil evaporates or sinks, but other oil constituents are broken down by bacteria or destroyed by solar radiation. Finally, the oil solidifies into clumps (tarballs), which are more resistant to bacterial breakdown.

the first few hours or even during the first few weeks, the oil is modified by the following chemical and physical processes:

- evaporation of volatile constituents;
- spreading of the spilled oil in large oil slicks drifting on the surface waters;
- formation of dispersions (small oil droplets in the water column) and emulsions (larger droplets of oil-in-water or water-in-oil);
- photooxidation (molecular changes to the oil constituents caused by natural sunlight) and solution.

Processes such as sedimentation and breakdown by bacteria, on the other hand, may continue for months or even years, although in some cases, under favourable conditions, they may be completed within a matter of days.

The reason for this discrepancy is that, firstly, the various substance groups contained in the oil undergo biological breakdown at different rates. The speed of breakdown depends primarily on the molecular structure of the oil constituents. The more complex the hydrocarbon molecules, the longer it takes for the oil to be broken down by microorganisms. Secondly, the rate at which the various hydrocarbons are broken down is increased by the following factors:

- high temperatures, promoting bacterial activity;
- a large surface area (if necessary, the surface area of the slick can be increased through the use of dispersants, i.e. surface-active agents [surfactants] which promote the formation of dispersions);
- good oxygen supply for the bacteria;
- good nutrient supply for the bacteria;
- low number of predator organisms which would reduce the number of bacteria.

Some of the above-mentioned processes have a very considerable influence on the extent of oil damage. Water-in-oil emulsions, for example, are a contributory factor in the formation of "chocolate mousse". This viscous emulsification can increase the original volume of the oil as much as fourfold, rendering the use of chemical dispersants impossible and making it far more difficult to pump the oil off the water surface.

How oil damages habitats

It is generally not possible to protect an entire coastline from the effects of a major oil spill, so the authorities have to set priorities for their oil spill response. It goes without saying that designated conservation areas, such as national parks, or sensitive marine areas are particularly worth protecting and are given high priority in clean-up efforts. As a rule, however, these areas are too large to be protected in their entirety. Here, sensitivity rankings can facilitate the oil spill response: these describe the general sensitivity of the various shoreline types to oil pollution. In exceptional cases, it may even be possible to define "sacrificial areas" which are less important from a nature conservation perspective and where no protective measures are taken.

When defining these sensitivity rankings, one factor which is taken into account is whether the section of coastline is a "high-energy" area, e.g. with rocky or sandy shores that are subjected to direct wave action, or whether they are relatively calm, "low-energy" areas such as the Wadden Sea, which are protected by sandbanks or offshore islands. Of course, within the major habitats described here, other more detailed sensitivity rankings can be defined for a targeted oil spill response.

EXPOSED ROCKY AND SANDY SHORES: Exposed rocky and sandy shores are classed as areas of relatively low sensitivity because the oil deposited by the sea is cleared very swiftly by wave action. Nonetheless, major oil spills can change the composition of biological communities in these habitats over the longer term. In such cases, populations of former dominant species such as crustaceans and molluscs may decline. In rocky crevices, rough gravel and on mussel beds, the oil pollution may persist for many years.

SANDY BEACHES: Here, a different situation applies. The extent to which the oil penetrates the ground and how long it remains there depend primarily on the structure of the beach. An extensive beach with little surf and with branching channels, for example, is far more vulnerable than a steep beach with a less diverse structure. Coarse-grained sediment facilitates oil penetration, makes the clean-up process more difficult, and increases the risk of follow-up damage from re-surfacing oil. Beach areas used as habitats or breeding sites by endangered species, such as turtles, are classed as particularly sensitive.

CORAL REEFS: Corals are also highly sensitive to oil pollution. Various studies show that damaged coral reefs are very slow to regenerate. Oil pollution can also affect entire communities. For example, less sensitive species of algae can colonize oil-contaminated areas which were previously coral habitats. Very little research has so far been undertaken to investigate how oil spills affect the relationship between corals and the many species associated with them. The linkage between numerous specialized species and the great significance of symbioses within these ecosystems indicate that far-reaching and long-term impacts can be anticipated after major oil spills.

MANGROVES: Mangrove habitats react with particular sensitivity to oil pollution. Here, an oil spill can inflict severe damage on trees and the sensitive organisms living in them and in sediment. This damage is caused by toxic hydrocarbons, but can also occur as a result of oil cover, which shuts off the oxygen and freshwater supply. The regeneration of damaged populations of flora and fauna is a lengthy process. As the harmful hydrocarbons are removed from sediment very slowly in mangroves, habitat recovery is further delayed.

SOFT SUBSTRATES AND SANDBANKS: Sections of coastline with soft substrates and sandbanks, such as the Wadden Sea on the North Sea coast, are classed as particularly or highly sensitive. The organisms living at great density in and on the sediment provide the basic food supply for fish and birds. Although in most cases, very little oil penetrates the often water-saturated fine pores of muddy sediment, these areas are generally densely populated by burrowing organisms whose activities cause the oil to sink deeper into the ground. On the other hand, the stirring and mixing of sediment by these organisms – known as bioturbation – also help to break down the oil by churning up the sediment, exposing deeper layers to the air and bringing oily sediment to the surface. As this activity promotes a healthy oxygen supply, the oil is then

4.15 > A specially equipped ship deploys a boom, consisting of inflatable floats, in an attempt to contain the crude oil spilled at sea by the oil tanker *Sea Empress* after it went aground off the coast of Wales in 1996. In rough seas, however, the use of these skimmers has little effect.

Oiled and poisoned – the effects on flora and fauna

The damage caused to seabirds' plumage is probably the most notorious effect of oil pollution. As a result of oil contamination, the plumage can no longer perform its vital functions of repelling water and providing thermal insulation. If much of the plumage is covered in oil, the bird will lose body heat and die. A similar effect can be observed when marine mammals' fur is coated with oil. The fur can no longer insulate the mammal from cold air and water, which weakens it and may even cause death in extreme cases.

In plants, oil contamination of shoots interrupts gas transport from the leaves to the roots, which causes the plant to die. Filter-feeders such as mussels and organisms such as sea snails and worms which take up nutrients from the sea floor often ingest oil along with their food. The toxic hydrocarbons can then be passed along the food chain when the contaminated mussels are eaten by other animals. Birds and mammals often ingest oil when they attempt to clean their oil-coated feathers or fur. Soft-skinned creatures such as fish and many invertebrates mainly absorb petroleum hydrocarbons through the skin and especially through the gills, which process large quantities of water.

Petroleum hydrocarbons have many different effects according to the species. In many fauna, they mainly impair growth and metabolic activity. Studies show that lobsters and lug worms react by reducing their nutrient intake. In mussels and fish, studies show that growth is impaired by oil pollution. Researchers have repeatedly observed behavioural changes in response to exposure to oil. Seals are reported to be extremely lethargic, which scientists attribute to nerve damage caused by the intake of volatile petroleum hydrocarbons during respiration in the immediate aftermath of oil spills.

Reproduction of numerous marine organisms is also adversely affected. Poisoning by oil can cause genetic damage: in salmon, for example, increased ovum mortality was observed after an oil spill. In herring, numerous freshly hatched progeny were malformed. Scientists have also reported that the concentration of specific hydrocarbons in sediment increases the number of genetic mutations in mangrove trees. Often, toxic oil constituents can also damage the reproductive organs of marine organisms: an increase in the number of sterile shellfish, for example, was observed during the year following an oil spill. In the case of corals, scientists reported that the number of progeny decreases in chronically oil-polluted areas.

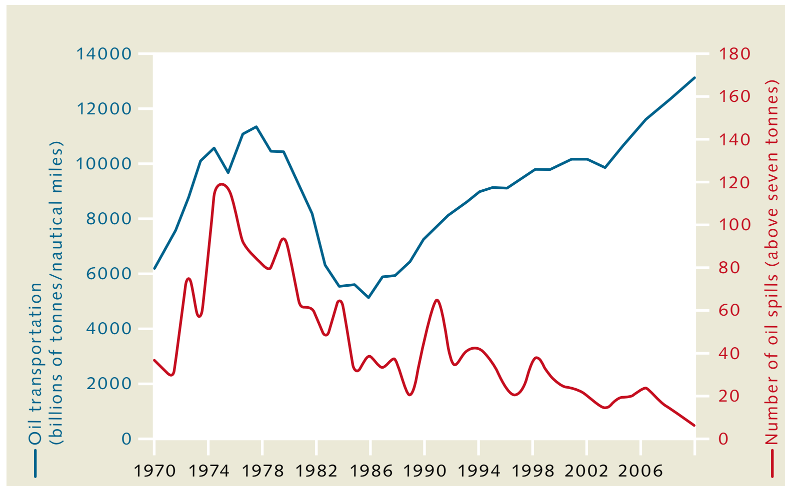
Furthermore, many marine fauna lose their sense of direction, as many of them use very fine concentrations of certain substances as a means of finding their way around their environment and identifying prey, predators or partners for reproduction. These natural substances are **biogenic** hydrocarbons whose molecular structure is similar to some hydrocarbons contained in crude oil. If large quantities of the alien hydrocarbons enter the water during an oil spill, the animals find it impossible to detect the natural substances, making it far more difficult for them to find food or identify a breeding partner.

4.16 > In San Francisco Bay, a stricken seabird attempts to clean oil from its plumage following an oil spill from the *Cosco Busan* container ship after it collided with a tower of a bridge in November 2007. Accidents such as this contribute to the chronic oil pollution of the seas.

broken down more quickly by bacteria. If the organisms in the sediment have been killed by the oil, however, bioturbation ceases and the oil remains in the ground for longer, causing long-term habitat damage.

SALT MARSHES: Very few studies have been carried out to investigate how oil affects invertebrate organisms found in salt marshes, such as insects and worms. The vegetation, however, can suffer long-term damage from oil pollution, with major implications for breeding and resting birds in the salt marshes, whose plumage may be covered in oil or which could lose their basic food supply. To sum up, the following regeneration periods can be assumed:

- Exposed rocky and sandy shores: between a few months and 5 years;
- Protected rocky shores and coral reefs: between 2 and more than 10 years;
- Protected soft substrates, salt marshes, mangroves: between 2 and more than 20 years.



4.17 > Although the quantities of oil being transported across the oceans have increased considerably since the 1970s, the amount of marine oil pollution caused by oil tanker disasters, technical defects or negligence has fallen dramatically. The sharp decrease in tanker traffic in the late 1970s was caused by the economic crisis which occurred during that period. The statistics cover oil spills above 7 tonnes; records of smaller spills are somewhat patchy.

Responses to oil spills and pollution

In scenarios other than disasters that occur in deep waters, such as the explosion at the oil drilling rig in the Gulf of Mexico in spring 2010, an oil spill disaster response is most effective while the slick is still drifting on the water surface. From a technical perspective, some countries prefer to use exclusively mechanical methods to contain oil spills, such as oil skimmers or booms that form floating barriers on the water, while others opt for chemical methods, mainly involving the use of dispersants, which are usually dropped on the slick in large quantities from aircraft. The effectiveness of these chemicals is heavily dependent on the type and condition of the oil, however. A further limiting factor is that these dispersants can generally only be used for a short time after the spill has occurred, as the chemical and physical processes described above begin to impair their effectiveness after only a few hours. If the oil slicks are drifting towards sensitive sections of shoreline, using these agents may be a sensible option, however. The dispersants drive the oil from the surface down into deeper waters, reducing the risk that seabirds or sensitive flora will become coated with oil. Following the explosion at the Deepwater Horizon drilling rig in 2010, however, the oil flowed out of the borehole at great depth and entered the entire water column, partly as a massive cloud of oil. Very little experience has been gained in responding to disasters of this type and on this scale. As an initial response, massive quantities of dispersants were deployed, with currently unforeseeable ecological consequences. Bioremediation can also be successfully deployed in suitable – i.e. nutrient-poor – marine areas. This involves seeding the water with nutrients to promote the growth of bacteria that break down oil.

No matter which strategy is deployed, it can only be successful and effective as part of a broader national contingency plan in which well-trained emergency teams implement a coherent and well-thought-out response. In the US, Germany, other North Sea states and certain other countries, such contingency plans have been in place for a number of years. In these countries, the days

4.18 > Workers on a beach at the popular Gulf Shores resort in the US remove sacks of oil-covered algae. The resort, along the coast of Alabama, is one of the communities in the Gulf of Mexico which have been polluted by oil from the Deepwater Horizon disaster in June 2010.

when the authorities often failed to adopt a prompt, effective or appropriate response to oil spills due to a lack of clear responsibilities, equipment and personnel are over. On their own, however, technical management strategies are not enough. Global and regional agreements are required to protect the sea from oil pollution, and mechanisms need to be in place to monitor compliance with them. A positive example is the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78), which from 1983 formed the basis for the designation of marine protected areas where tanker traffic is wholly or partly restricted. As a result of the Convention, there was a reduction in the number of oil tanker disasters during the 1980s. In addition to other provisions on operational discharges of oil, MARPOL 73/78 also paved the way for the introduction of double hull tankers. The United States' 1990 Oil Pollution Act and the International Management Code for the Safe Operation of Ships and for Pollution Prevention (ISM Code) adopted by the **International Maritime Organization (IMO)** in 1998 also contributed to the further decrease in oil pollution over subsequent decades.

The outlook for the future – cautious optimism

Marine oil pollution has undoubtedly decreased in recent decades. International conventions, the designation of protected areas and the mandatory introduction of double hull tankers have all made a contribution here. At the same time, as the Deepwater Horizon disaster clearly demonstrates, the situation for the marine environment continues to give cause for concern. Furthermore, the illegal discharge of oil during tank-cleaning operations, which still accounts for one third of oil pollution, cannot be tackled effectively without more stringent controls and tough penalties. Combating oil pollution in shallow waters such as the Wadden Sea will also continue to be a problem in future as response vessels generally cannot operate in waters of less than 2 metres depth.

Conclusion

Much to be done ...

Humankind is still discharging millions of tonnes of problematical substances into the sea. Some enter the marine environment during the production or use of specific products, while others can be classed as litter, or contaminate the sea with oil. However, the present situation differs from the past in one crucial respect. Whereas humankind, until only a few decades ago, deliberately disposed of waste in the sea, by far the major share of litter and pollutants now enters the sea indirectly along many different pathways. This is exactly what makes it so difficult to combat pollution – for in order to improve the situation, a whole package of measures is required. For example, in order to curb nutrient overfertilization of the seas, treatment plants need to be built onshore and the amount of fertilizer used in agriculture must be reduced. The success achieved in improving water quality in Western European rivers shows that the nutrient load can indeed be decreased in this way. Ultimately, every individual nation has a responsibility to adopt appropriate measures to keep its marine environment clean. Substances which are dispersed into the environment from the atmosphere, however, are far more difficult to control. This applies to nitrogens from the burning of oil, gas and coal, and to industrial chemicals such as polyfluorinated compounds or other persistent molecules. Here, the pollutants need to be captured at source. In some cases, however, the origin of the substances is not yet properly understood. Robust risk assessments offer a promising solution here: these evaluate the potential hazards associated with a given substance before it is brought to market. In contrast to substances such as polyfluorinated compounds, which are difficult to monitor because they are released not only during the production but also during the use of certain products, the solution to the littering of the oceans is obvious, and starts with correct disposal. In countries such as the Netherlands and Germany, recycling and bottle-deposit systems are well-established as a means of effectively managing the flow of disposable packaging. Many other countries, however, lack well-functioning waste recovery systems. However, waste management can only really work if the general public is sensitized to the problem of waste. There are now good examples of effective environmental awareness-raising all over the world.

In contrast to the marine litter situation, a more positive trend can be observed with regard to oil pollution. The amount of oil in the sea has been decreasing for years. It is difficult to say whether this is due to more stringent controls on commercial shipping, monitoring overflights or better ship safety. It is also unclear, at present, which measures would be effective in significantly reducing oil pollution in future. One thing is certain: the threat posed by major tanker disasters is taken far more seriously today than just a few years ago. Disasters such as the Deepwater Horizon drilling rig explosion in the Gulf of Mexico nonetheless demonstrate that humankind is often helpless in the face of the problems caused by oil. It is still unclear whether the trend towards oil extraction at ever greater depths will increase oil pollution in the oceans. However, as the most recent example shows, there are currently very few strategies in place to combat oil pollution in the deep seas. Oil clean-up technologies for use when emergencies occur in deep-sea oil extraction and drilling therefore need to be developed as a matter of urgency. The oil industry has announced that it plans to set up a voluntary rapid response force; however, such measures must be monitored by impartial agencies.

5 Climate change impacts on marine ecosystems

> There can be no doubt that climate change will alter marine life. Changes in ecosystems usually have multiple natural causes, but increasing carbon dioxide levels in the atmosphere and global warming are now playing a critical role. The extent of the coming disruption to biotic communities is unknown.

Biological systems under stress

> Marine life forms are fundamentally well adapted to natural variations in environmental conditions. They can even tolerate extreme situations for a limited time. But climate change is altering some habitats so severely that the stress becomes too great for many species. Where several unfavourable factors combine, the cumulative effect can cause the extinction of species.

Changing habitats

Stress is a common phenomenon nowadays. Not only people suffer from stress. Marine plants and animals are also subject to stressors – pressures brought on by changes in their habitat conditions. Stress has been around forever. But it has clearly been intensifying in recent years as a result of climate change. Sometimes stress is triggered by just one stressor. In the ocean, for example, it could be due to increased sedimentation from a storm burying bottom dwellers, or an algal bloom causing light deficiency in deep water layers. Unfortunately, however, climate change often introduces several stressors at the same time, leading to "multiple stress". At a particular location and time, the temperature, light availability and pH can all drift outside the range optimal for an organism. Sometimes introduced species can also act as stressors – as predators, pathogenic agents, or feeding competitors.

As an additional complicating factor, the various stressors do not always act independently. In some cases the effects can be additive, or even amplified. This amplification does not lead inevitably to immediate death. In many cases the stressors initially only impair the productivity of an organism in some way. Interactions of the weakened organism with its environment, with predators, parasites, competitors, pathogens or reproductive partners are thus altered. These effects can significantly exceed the primary effects of the stressors such as the stress caused by light deficiency. The various linkages are further illuminated in the example of the bladderwrack seaweed described below.

Too many environmental changes at once

The most common stressors on marine ecosystems amplified by climate change include:

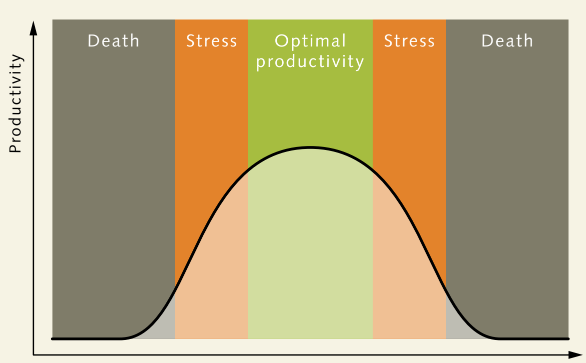
- gradual acidification of seawater, accompanied by inhibition of the calcification process, which is the formation of calcium carbonate by marine organisms (Chapter 2);
- warming of seawater and associated secondary effects, including more pronounced stratification of the water column, increased metabolic rates of the organisms, or changes in the solubility constants, which affect the amounts of certain dissolved substances in the water such as gases or carbonates;
- an increase or decrease in salinity in marginal seas, and the accompanying adverse effects on the ion budgets of living cells (Chapter 2);
- eutrophication, which is an excessive accumulation of nutrients, and other kinds of chemical pollution of seawater. Climate researchers predict increased precipitation rates for wide areas of the Baltic Sea region in the future. Increased rainfall washes more fertilizer from farmland into the sea (Chapter 4);
- changes in near-coastal current and sedimentation processes caused by human construction projects, which, in part, may be carried out as a response to climate change and rising sea levels. These include harbours, breakwaters and dykes (Chapter 3);
- the spread of exotic species into new habitats. The compositions of communities will doubtless be changed as a result of multiple stress. In addition, geographic distribution zones could shift so that species

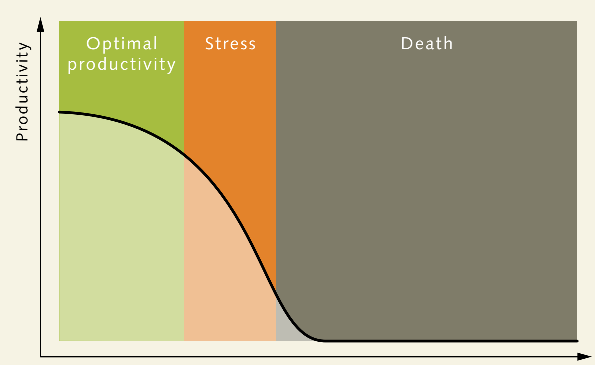
The origins and impacts of stress

Within its habitat an organism is influenced by various environmental factors to which, as a rule, it is quite well adapted, even under significant fluctuations. This adaptation of the organism to the abiotic conditions in its range, that is, the chemical and physical conditions, has taken place over thousands or even millions of years, over evolutionary time scales. Stress is produced when these environmental variables lie, either temporarily or continuously, outside the range to which the biological system (a cell or species) is adapted. These kinds of stress situations can be generated in various ways:

- when temporary fluctuations in the abiotic conditions occur (for example, seasonal or weather anomalies);
- when pelagic organisms (i.e. free-swimming in the water column), such as planktonic larvae, drift away from the centre of their habitat and colonize the margins of the distribution area where the environmental conditions are not ideal;
- when climate zones shift more rapidly than species can evolutionarily adapt to the new conditions.

Organisms are not always defenceless or at the mercy of change. They are quite capable of adapting to new conditions and responding to stress. Adaptation is possible in three ways. The quickest of these, phenotypic plasticity, can be observed within days or weeks: individuals adjust to new conditions in their habitat by changing their growth form, metabolism, or diet. Of course this is only possible to a limited extent. Relatively rapid adaptations over a few generations are also possible through selective processes. When genotypes exist within a population, i.e. individuals have certain traits that are not immediately apparent but are contained in their genetic makeup, and these individuals are better able to cope with the new conditions than others of their species, then they will assert themselves fairly quickly. The productivity and survival of the population is thereby assured. Evolutionary processes in the classical sense, such as the random occurrence of a mutation that allows survival in the changing environment, are generally too slow in most species with long-lived generations to keep up with the habitat changes caused by climate change.





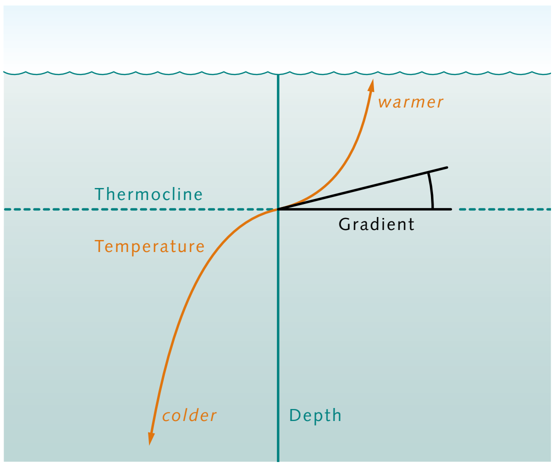
5.1 > Different environmental variables have different effects on organisms. Many plants or animals thrive best at moderate temperatures – the intermediate optimum (left). If it becomes warmer or colder the situation deteriorates. The productivity of the organism declines. The "extreme optimum" follows a different pattern: in a clean environment the organism functions optimally. If toxins spread in the habitat, productivity declines. In both cases the animal or plant experiences stress that can lead to death. If the stress persists for an extended period, then species in the affected area can even become completely extinct.

die out in their native habitats. It is also conceivable that exotic species could become newly established in regions outside their former range.

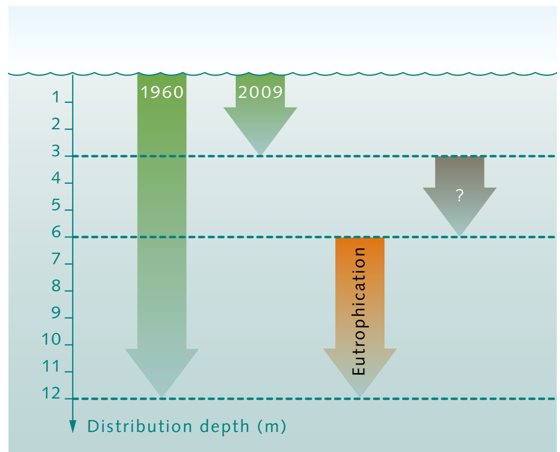
Bladderwrack – a species under constant stress

The bladderwrack, *Fucus vesiculosus,* is a seaweed of temperate latitudes commonly found in the North and Baltic Seas. It primarily colonizes the **intertidal zone**, but can occasionally occur in water depths of up to 12 or even 15 metres. The bladderwrack serves a number of important functions in the ecosystem. It is both a food source for various organisms and an important provider of oxygen. It offers protection for juvenile animals and serves as a **substrate** upon which diverse species can colonize. Its population in the western Baltic Sea has decreased by more than 90 per cent over the past four decades – in many areas it is no longer observed at depths of 12 metres, but only down to 3 metres. Its decline at greater depths has long been attributed to eutrophication – an environmental stressor (Chapter 4). It was presumed that an overabundance of nutrients in the water led to an increased density of plankton blooms, which restricts the amount of light penetration reaching the sea floor. Furthermore, it was assumed that a light deficiency on the sea floor during a plankton bloom would limit the bladderwrack's ability to defend itself against predators. In addition, it appears that under decreasing light conditions the bladderwrack is less able to defend itself against bacteria. But this explanation is inadequate, first because the bladderwrack can store energy and therefore survive darker periods, and second because it can still thrive under very low light conditions. Even considering that increased numbers of organisms such as microalgae grow directly on the bladderwrack's surface under eutrophic conditions, leading to added competition

5.2 > The bladderwrack *Fucus vesiculosus* is widely distributed throughout Europe. It could die out in some areas as a result of climate change.



5.3 > The boundary zone between warm, near-surface waters and the deeper cold waters is called thermocline. The gradient is a measure of how rapidly the temperature changes in the thermocline. A high gradient means rapid changes over short depth intervals.



5.4 > In 1960 the bladderwrack could be found to a depth of 12 metres in the western Baltic Sea; in 2009 only down to 3 metres. The light deficiency caused by eutrophication contributed significantly to its disappearance between 6 and 12 metres – yet it cannot explain its absence between 3 and 6 metres.

for light and food between the algae and the seaweed, it still should be able to survive down to 6 metres. Only below this depth would the energy deficit caused by light deficiency and feeding competition be severe enough to be fatal. So this alone cannot explain why the plant is becoming scarce at depths below 3 metres.

Now it is believed that the decrease in bladderwrack abundance at the relatively shallow depths of between 3 and 6 metres has other causes: For one, the warming of seawater, which can be clearly detected today, leads to a general increase in metabolic rates, so that predators become hungrier and bacterial attacks more intense. In addition, abrupt temperature differences at changing water depths impair the capability to defend against aggressors. In the summer a thermocline is often present, precisely at depths of around 4 to 5 metres. The distinctive temperature change here within a few centimetres of water depth becomes even more pronounced as the water temperature rises. If the depth of the thermocline oscillates up and down, a bladderwrack living at these depths experiences rapid and large temperature fluctuations – which diminishes its defensive capability. Furthermore, a new biotic stressor has appeared in recent years: the red algae *Gracilaria vermiculophylla,* which was introduced from South-East Asia. The habitat requirements of this species are very similar to those of the bladderwrack. The problem is that, unlike the bladderwrack, the red algae can reproduce asexually, which makes it especially prolific. Furthermore, it is more tolerant of fluctuations in local abiotic conditions and also less attractive to predators. And still further, predators of the bladderwrack even use the red algae as a protective cover to hide from their own enemies. Another problem is that chemical secretions from *Gracilaria* diminish the germination potential of *Fucus* eggs.

So *Fucus* is clearly exposed to a number of stressors along with their direct and indirect effects: light reduction, colonization and predator pressure, and competition with algae for nutrition. All of these together hinder its growth and germination processes. The *Fucus* population is thus experiencing an ever decreasing ability to offset its losses from predation and competition. The example of *Fucus* clearly illustrates that, although the direct effects of climate change alone may be minor, they are nevertheless devastating because of changes in the interactions among various organisms.

Disruption to the plankton cycle

> Recent experiments and studies show that climate change – and global warming in particular – is pushing established biological systems off balance. This can have a devastating effect on some organisms. What is most disturbing is that the natural rhythm of the ocean's most important food source, the phytoplankton, is changing.

The copepods
Copepods belong to the crustaceans. They are found in both saltwater and freshwater. Although most of these animals are only a few 100 micrometres to a few millimetres in size, they are the most species-rich group of the crustaceans (around 14,000 species), and make up the largest share of marine zooplankton. Copepods therefore represent an important food source for fish and other pelagic animals.

Essential single-celled organisms

Plankton is a vital food source for life in the ocean. Phytoplankton, algae and cyanobacteria, take up nutrients dissolved in the water, grows, and undergoes cell division. Biomass is thus produced, on which zooplankton such as copepods feed. The zooplankton, in turn, is eaten by fish and their larvae. Plankton therefore plays a key role in the **biogeochemical** cycle of the ocean. Disruptions to plankton development caused by climate change will thus have a critical impact on the functioning of the entire **pelagic system**.

Faltering plankton growth

Plankton predominantly comprises short-lived organisms. As a rule, these reproduce so rapidly that several generations may be produced within a single year. The development of planktonic organisms generally follows a regular annual cycle that begins with a spring bloom of the phytoplankton. At this time the increasing light availability promotes a rapid increase in the abundance of phytoplankton. Only a few weeks after the winter minimum the biomass reaches its annual peak value, following which it undergoes a continuous decrease. This is, for one, because of the zooplankton feeding on the phytoplankton, but also because of large amounts of the dissolved plant nutrients being consumed during the bloom and sinking to greater depths. So the phytoplankton finds ever decreasing amounts of nutrients in the water.

In nutrient-poor and cold marine regions the spring bloom represents the only influx of nutrition for the zooplankton during the year, while in other regions it represents the greatest such influx. So the spring bloom is also very important for the nourishment of fish that feed primarily on zooplankton. The benthic organisms, in turn, also benefit from the large amounts of organic material sinking to the sea floor, the dead remains of both phytoplanktonic and zooplanktonic organisms.

Because the plankton consists of short-lived organisms, it reacts rapidly to physical and chemical changes in the ocean and to fluctuations in nutrient availability. The size of populations can sometimes vary greatly within a few days or weeks. Depending on conditions the actual composition of the plankton assemblage can change, with certain species suddenly becoming predominant. Variations due to climate change have definitely already been observed. Some of these are consistent with expectations. Just like the earlier fruit tree blossom on land, the spring bloom of plankton begins earlier in many marine regions. In addition, the ranges of some planktonic species are shifting toward the poles in response to ocean warming.

One example is the northward expansion of a characteristically temperate-zone copepod, *Calanus helgolandicus*, a small crustacean that is displacing *Calanus finnmarchicus*, a species native to Scandinavian latitudes. Since both species are important sources of food for fish and have similar food requirements, this will probably not have grave impacts on the functioning of the ecosystem. But not all changes in plankton communities are so benign. In some cases warming of the water causes zooplankton offspring to hatch too early and starve. This has been demonstrated in water-tank experiments.

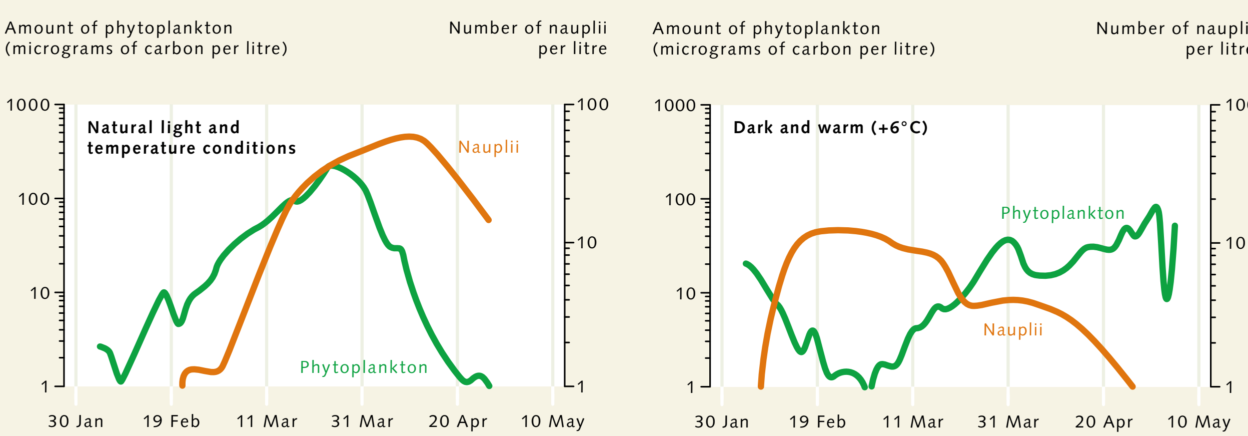
Plankton experiment: Climate change in a tank

Researchers have experimentally investigated the impacts of climate change on the spring bloom of phytoplankton. Tanks measuring 1.4 cubic metres were filled with planktonic organisms corresponding to the developmental stage of the phytoplankton in late winter. The tanks were then exposed to different amounts of light and different patterns of spring temperature development in climate chambers. The experiments simulated the present-day average spring temperature sequence, as well as patterns reflecting warming of 2, 4, and 6 degrees Celsius. The results were impressive. The spring bloom occurred 1 to 1.5 days earlier per degree of temperature increase. An increased light supply amplified this effect.

The zooplankton reacted even more strongly to warming: the copepod larvae, called nauplii, hatched up to 9 days earlier per degree of temperature increase. The consequences of this were disastrous because most of the nauplii hatched before the spring bloom of phytoplankton. There was no food available for them so they starved, and an entire generation was lost.

Not only did the warming cause a shift in the timing of the spring bloom. The total biomass of phytoplankton as well as its composition was also altered – to the detriment of the zooplankton. Under normal conditions large-celled **diatoms** dominated, which are a good food base for copepods. Under warmer conditions the smaller **flagellates** dominated. These, however, are not an optimal food source for copepods. The implications are obvious: the animals grow more slowly; they produce fewer eggs and therefore fewer offspring.

But the warming of seawater can have further negative consequences beyond those for the food chain "phytoplankton – zooplankton – fish". It also impacts on the storage capacity of the greenhouse gas CO_2 in the ocean, the "biological CO_2 pump" (see text box on the following page). Under warmer conditions the respiration of zooplankton and bacteria is enhanced, which produces CO_2. This means that the CO_2 initially taken up by phytoplankton is released back into the surface water. The proportion of CO_2 that remains fixed in the biomass and sinks to the sea floor as organic material, to finally be incorporated as carbon in the sediments, is therefore reduced. This is a serious problem because it represents a fatal feedback mechanism for climate change: Due to climate change a natural process is weakened that has until now been able to extract a portion of the anthropogenic CO_2 that is so harmful to the climate.



5.5 > Phytoplankton reproduction (green line) normally begins with the increase in light availability around the end of winter, before the hatching of the zooplankton larvae (nauplii, red line). This ensures that there is enough food available for the zooplankton. But if less light is available and the water is 6 degrees warmer, the zooplankton hatch before the phytoplankton bloom, and the larvae starve. This is an especially disturbing scenario because it is exactly what researchers are predicting for the Baltic Sea: less light due to increased cloud cover with an accompanying rise in water temperatures due to climate change.

The CO_2 pump in the ocean

In oceanic biogeochemistry, the transport of organic carbon via sedimentation down to the deep water and finally to the sediments of the ocean is referred to as the biological carbon dioxide pump. Initially, carbon dioxide is taken up by phytoplankton during photosynthesis and converted into organic carbon. However, most of this carbon is released again during respiration, either by the phytoplankton itself or by zooplankton and bacteria, which feed on phytoplankton or its dead remains.

Near-surface respiration cycles carbon dioxide back into the water, from where it can return to the atmosphere. Only a minute fraction of the organic matter produced in the surface ocean sinks down to waters below the permanent thermocline. These waters of great oceanic depth do not get into contact with the atmosphere on a seasonal basis. Only this fraction of the primary production of organic carbon acts as a drain on atmospheric carbon dioxide and can be termed the CO_2 pump.

5.6 > The mauve stinger, *Pelagia noctiluca* whose painful sting is normally not deadly to humans, has become increasingly abundant in the Mediterranean Sea in recent years.

Mounting threat of harmful algal blooms

Harmful algal blooms (HABs) are massive growths of toxic or otherwise harmful phytoplankton. HABs are becoming ever more frequent worldwide. It is not yet known, however, why this is. Eutrophication, the increased concentration of nutrients in the water, is considered to be the main cause, but climate change also appears to play a role. Harmful algal blooms normally occur in the summer months when the water column is thermally stratified. A warm, light surface layer overlies a colder, heavier deep layer. The warmer the surface water, the more pronounced the temperature gradient is at the thermocline between the layers.

A strong temperature gradient prevents water masses from mixing at the thermocline, because the density difference between the cold and heavy water, and the warm and light water, acts as a barrier. Nutrients from greater depths are therefore prevented from circulating to the surface. So when the nutrients near the surface have been consumed by phytoplankton growth, there is no source of replenishment. The vertical barrier between a zone with enough light and insufficient nutrients, and a zone with insufficient light and abundant nutrients, which is characteristic of the summer, is thus reinforced.

Relatively large mobile phytoplankton species have an advantage here. With vertical migration they can move back and forth from the deeper nutrient-rich water to the shallower layer penetrated by light where photosynthesis is carried out. Such species include numerous dinoflagellates and, especially in the Baltic Sea, cyanobacteria, which can regulate their specific gravity to rise and descend like a diver. One problem with this is that both groups include numerous toxic species. If mussels consume these organisms, then the mussels become dangerous or even lethal to humans.

The planktonic organisms may also release some of the toxins directly into the water. In some cases these are even detectable in aerosols, small droplets wafting in the air that are produced by breaking waves in the surf. An especially notorious culprit is the dinoflagellate *Karenia brevis*, whose periodic blooms off the coast of Florida cause mortality of fish, poisoning of mussels, inflammation in swimmers and, in extreme cases, asthma attacks in visitors to the beach. Experts attribute the increased incidence of these blooms to general climate warming.

5.7 > The dinoflagellate *Karenia brevis* occurs primarily in the Gulf of Mexico. Its nerve poison, Brevetoxin A, can lead to inflammation and asthma attacks in humans.

5.8 > Small crustaceans like this Calanus-species are widely distributed in the oceans and one of the most important food sources for fish.

As mentioned, there are also numerous toxic groups of cyanobacteria. Investigations so far have focused on cyanobacteria that live in freshwater – especially in waters that are used as sources for drinking water or where bathers are in danger from cyanobacteria. But toxic strains of various cyanobacteria such as *Nodularia spumigena* have also been verified in the Baltic Sea.

Trouble with jellyfish

Beside more frequent HABs scientists are also observing explosive growth of jellyfish populations. The impacts of such proliferation are quite well known: injured swimmers, clogged fish nets, feeding competition for fishes, and predation of fish eggs and larvae. The possible causes of these burgeoning populations are somewhat controversial. One significant problem, presumably, is overfishing. Fish that feed on zooplankton are in feeding competition with the jellyfish. If the fish are absent, then the jellyfish have an abundance of available food. It is also known that jellyfish are more robust than many species of fish, especially in the sense that they can tolerate much lower oxygen concentrations. Oxygen deficiencies in the oceans, in turn, occur increasingly as a result of eutrophication. More biomass is created because of eutrophication. As a result, more organic material sinks into the deep water where it is decomposed by oxygen-consuming microorganisms. The result is a general decrease in oxygen. Climate change, which causes warming of the ocean surface, can exacerbate this situation. The warming slows down exchange processes because the oxygen-rich surface water mixes less with the colder deep water. Only small amounts of the oxygen consumed by microorganisms at greater depths are replaced. Increasing jellyfish scourges could therefore be a result of combined stressors. Climate change will therefore lead to a restructuring of the pelagic biocoenoses, which will disadvantage the classical food chain “phytoplankton – zooplankton – fish”. Jellyfish, on the other hand, will benefit from that. Presumably overfishing and eutrophication of coastal waters will have additional synergistic effects that will worsen the situation.

Species encroaching on alien territories

> For a long time now people have been transporting organisms from one part of the world to another – sometimes unintentionally, but in some cases deliberately. Entire ecosystems have been transformed as a result. Climate change could exacerbate this problem because warmer waters may favour the establishment of immigrating species.

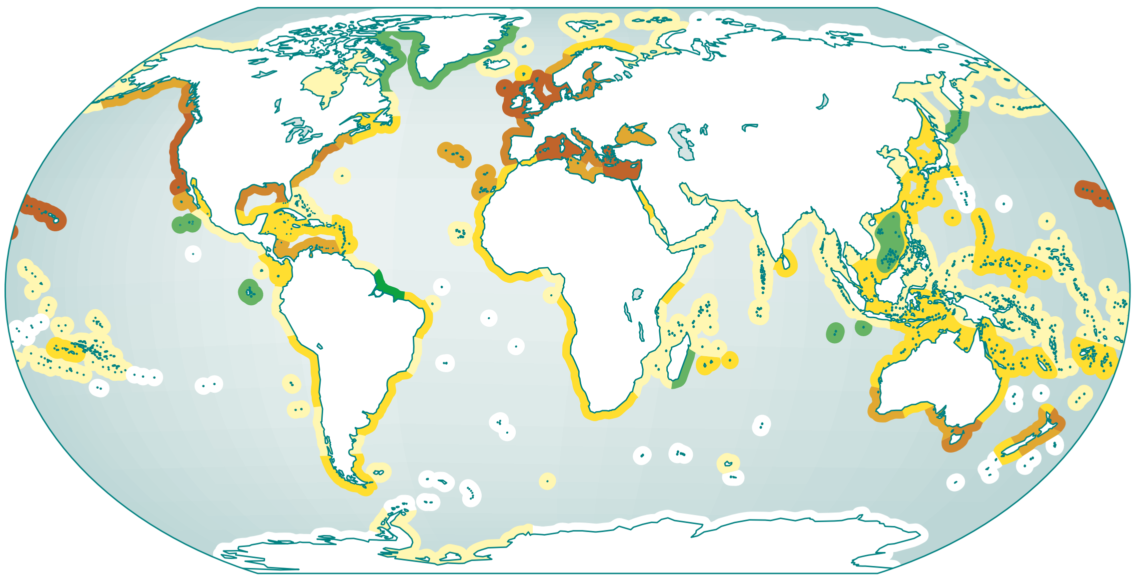
Causes of the dispersal of marine organisms

Since humans began to sail the seas, other species have been travelling around the globe with them. These are not limited to useful plants and animals, nor to pests such as pathogenic agents or rats, but also include significant numbers of marine organisms. Historical records and archaeological finds show that the sailing ships of the early explorers were colonized by up to 150 different marine organisms that lived on or in the wooden hulls, or used the metal parts such as anchor chains as a **substrate.** If the growth became a nuisance, the organisms were scraped off while at sea. In other cases the organisms remained on the rotting hull of a ship when it was scrapped and could no longer be repaired. It is hardly surprising then that many wood-boring species such as the shipworm *Teredo navalis* are found around the world today. However, it is no longer possible to determine whether these species were already cosmopolitan before the European voyages of discovery. It is common knowledge, however, that humans have contributed to the dissemination of many species. Increasing numbers of marine organisms are now transported over the oceans as a result of globalization, trade and tourism. It is estimated that the water in ballast tanks used to stabilize freighters is alone responsible for transporting tens of thousands of different species between geographically-distant regions. Most of these exotics die during the trip or at the destination, while only a small fraction are able to successfully reproduce and form a new **population**. But a study of six harbours in North America, Australia and New Zealand has shown that, in spite of all obstacles, one to two species were able to successfully establish themselves per year at each of the sites investigated.

Geographical barriers can also be overcome by canals. Over 300 species have already migrated through the Suez Canal from the Indian Ocean into the Mediterranean Sea. In addition, rivers and other waterways are responsible for species exchange, such as between the Baltic Sea and the Black Sea. Another important cause for the dispersal of marine organisms is the trade of living marine organisms for aquaculture, aquaria and the food industry.

Specialists divide the coastal waters of the world into a total of 232 ecoregions which are either separated from each other by geographical barriers such as land bridges, or are clearly different from each other with respect to certain environmental characteristics such as salinity. According to a report issued in 2008, new species have already been introduced by humans to at least 84 per cent of these 232 ecoregions.

Investigations in the North and Baltic Seas show that at least 80 to 100 exotic species have been able to establish themselves in each of these areas. In San Francisco Bay, 212 foreign species have already been identified, and for the Hawaiian Islands it is assumed that about a quarter of the marine organisms that can be seen without a microscope have been imported. Relatively little is known about the distribution of microorganisms or other plants and animals that are hard to identify. Species records are also sketchy for many marine regions where access is difficult. Experts assume that in future exotic organisms will have better chances to establish themselves in some regions due to climate warming. Organ-



5.9 > Invasive species thrive particularly well in certain coastal ecoregions of the Earth. Most affected are the temperate latitudes. Regions where immigrants do not encroach on or displace native species are shown in green.

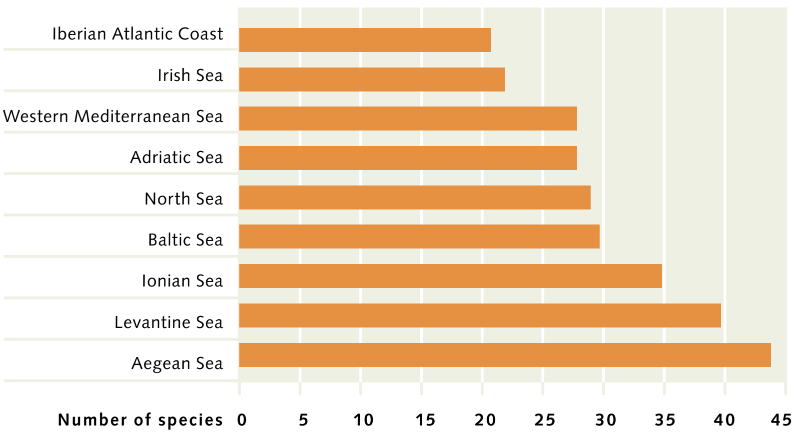
isms from South-East Asia, for example, which prefer a warm climate, could take root in regions that were previously too cold for them.

New species alter biodiversity

Many exotic species infiltrate the native flora and fauna without dominating them, thus increasing the diversity of the species association. Natural catastrophes can completely destroy habitats and be fatal to entire species communities. In these cases a completely different species assemblage develops in the affected regions through the influx of new species. An example of this is the Baltic Sea which was formed after the last Ice Age – that is, in the relatively recent geological past – and is only around 7000 years old in its present form as a brackish sea. One indigenous species alone evolved there, the alga *Fucus radicans.* All other species native to this area today migrated from habitats such as the North Sea or the White Sea. The immigration of species from other regions is thus not always problematic nor caused by human activity.

Since Christopher Columbus travelled to America in 1492, exchange between distant parts of the Earth has steadily increased. It has thus become more likely that species will encroach on ecoregions that are far removed from their natural areas of origin. Sometimes the new species create problems. They may displace a number of native species and thereby lead to a decrease in biodiversity. This is especially likely to occur if they have no natural enemies in the new location. For example, within only 15 years of its initial discovery in Monaco the Australian green alga *Caulerpa taxifolia* had overgrown 97 per cent of all the suitable ground between Toulon and Genoa, and had spread into the northern Adriatic and as far as Sicily. The alga produces a repellent substance that makes it unpalatable to most herbivores. There are organisms that feed on *Caulerpa* and have adapted to the repellent, but these species are not present in the Mediterranean Sea.

The Asian algae *Sargassum muticum* and *Gracilaria vermiculophylla* also formed practically monospecific stands in some coastal areas after their introduction to



5.10 > The number of ecologically or economically problematic imported species in the most affected marine regions of Europe.

Europe. The northern Pacific seastar *Asterias amurensis,* on the other hand, established itself in south-eastern Australian waters in the mid-1980s. Only 2 years after it was first detected in Port Philipp Bay, a large bay off Melbourne, more than 100 million specimens were estimated. This starfish too found practically no natural enemies in its new habitat, enabling it to decimate stocks of native starfish, mussels, crabs and snails. The biomass of the starfish eventually exceeded the total amount of all commercially fished marine animals in the region.

Cases of newly imported species displacing native species have been documented in 78 per cent of the 232 coastal ecoregions of the world. Many cases have been reported from the temperate latitudes in particular, those regions of the Earth where it is neither extremely hot nor extremely cold. With the exception of Hawaii and Florida, the 20 coastal ecoregions most strongly afflicted by invasive marine organisms are located exclusively in the temperate North Atlantic and North Pacific or in southern Australia, and nine of these regions are in Europe. Some places, like San Francisco Bay, are now dominated by non-native species. There, the encroaching species are often considered to be a threat to marine biodiversity, although so far not a single case is known in which a species introduced from outside has caused the extinction of native organisms.

Economic impacts of alien species

Introduced marine organisms can inflict economic losses on fisheries. The warty comb jelly *Mnemiopsis leidyi*, native to America, brought about a collapse of the coastal fisheries in the Black Sea 25 years ago, an area already greatly weakened ecologically at that time due to overfishing and eutrophication. Specimens that were probably introduced with ballast water were first sighted there in 1982. The jellyfish spread rapidly and ravaged native species, especially fish, by feeding on their eggs and larvae. The commercial fishery harvest decreased by around 90 per cent. In 1989 counts of 240 specimens per cubic metre of water were made, the greatest concentration of *M. leidyi* in the world. Only the unintentional introduction of another comb jelly, *Beroe ovata* – a predator – was effective in repelling the population and allowing a comeback of the fish population. Invasive species are also causing problems on the eastern coast of North America. There the European common shore crab *Carcinus maenas* caused a decline in the clam fishery harvest. In some cases invasive marine organisms can even present a hazard to human health. One example of this is illustrated by microalgae of the genus *Alexandrium*, which produce a nerve toxin. Species of *Alexandrium* have recently been discovered in many coastal areas where they probably did not exist just a few decades ago. Such phenomena can obviously have extremely negative effects on tourism.

Introduced species are not only transported unintentionally in the ballast water of ships. Entrepreneurs often import marine organisms from other countries to non-indigenous habitats for aquaculture breeding. This may provide short-term commercial profits, but also poses the risk of imported species displacing native organisms, leading to intermediate- or long-term economic or ecological damage. Studies have shown that at least 34 per cent of the 269 introduced marine organisms investigated were deliberately imported for aquaculture breeding. One example is the Japanese giant oyster *Crassostrea gigas*, which has taken up residence and established itself in at least 45 ecoregions. Between 1964 and 1980 in particular, large amounts of young oysters, called spat, were imported into Europe. In many cases the ecological impact was devastating. In North America and Australia the giant oyster forms dense colonies that displace native species. Furthermore, they frequently cause eutrophication of the coastal waters because they excrete indigestible particles agglutinated with mucus, which cause the additional organic contamination of the water. The presence of giant oysters in France has also led to pollution of the waters. In addition, a decline in the zooplankton as well as larger animals has been observed. In the Netherlands and Germany the giant oysters tend to settle on blue mussel banks. This is threatening an important species of traditional fishery.

It is assumed that besides the giant oyster at least 32 additional species have been unintentionally introduced into the North Sea, including the common Atlantic slippersnail *Crepidula fornicata* and the alga *Gracilaria vermiculophylla*, both of which have proven to be ecologically problematic. In order to avoid this kind of hazard in the future, a standard assessment system would be helpful. This could be used to estimate the potential of a species displacing other organisms. In addition, it could be used to weigh up the advantages and disadvantages of introducing an external species to a certain habitat.

By comparing problematic and harmless imported species, experts have been trying for some time to identify characteristics that indicate a high potential for displacement of the native species. For example, some algal species float while others sink. Whether the species drifts and can thus easily disperse depends essentially on this factor. But so far it has proven difficult to draw conclusions about the displacement potential of a species based on individual traits. Perhaps it will never be possible to make confident predictions about the behaviour of a species in a new location, because numerous critical factors are at play. This prediction is further complicated as a species establishes itself in a new habitat over an extended time period, living through numerous phases. After an initial expansion phase, during which a species thrives, there usually follows a decline before the species has completely adapted to the new habitat. Before the displacement potential of a species can be confidently estimated, it has to be known which phase the species is in at a given time. But that is very difficult to determine.

Combating the introduction of species

In 2004 the IMO passed a convention to deal with ballast water treatment. The first countries to sign the agreement, together representing around a quarter of worldwide sea traffic, committed to installing ballast-water treatment systems in their seaports and to carrying out regular inspections of ballast water. From 2016 onwards such systems will also be mandatory on board ships. International cooperation is also strengthened through initiatives of the ICES, which agreed in the mid-1990s on a code of conduct for the handling of exotic species in aquaculture, and recommended quarantine procedures, among other measures. The existence of the European common market has made the exchange of species between member states easier. The commercial transport of oyster larvae, as an example, is now practically equal in significance to ballast water as a cause of species introduction within the EU. At the same time, the import of oysters from non-EU regions has largely been eliminated. International cooperation within the EU has, on the one hand, improved protections against the import of species from non-European bioregions, but on the other hand it has exacerbated the exchange of species between bioregions inside the EU.

Can future introductions be avoided?

Caution is necessary when dealing with foreign marine organisms because species introduction is largely irreversible. Any kind of mechanical removal of established species is virtually impossible. Many species go through microscopic dormant or larval stages during which they are free-floating. During such phases the organisms defy all efforts to control them. It may be possible to introduce natural enemies to the new habitat, but then these organisms could later become a threat themselves. Government policy and environmental management will therefore have to take a stronger stance to control the primary causes of species introduction. It is important that this includes uninterrupted monitoring of aquaculture and ballast water, for example. Unilateral efforts at the national or local levels, however, will hardly be effective. International strategies practiced by all states bordering an ecoregion have greater chances of success.

Marine biodiversity – a vital resource

> For a long time the significance of biological diversity in the world's oceans was unclear. It is now known to play a vital role in maintaining the functionality and productivity of ecosystems. It also makes habitats more resilient to environmental change. But the well-balanced species communities are becoming increasingly unstable.

The rapid disappearance of species

Biological diversity in the oceans has decreased dramatically since industrialization began in the 19th century. The primary causes for the losses include the destruction of habitats by trawler fishing, pollution and eutrophication of the seas, as well as the steady progress of climate change. Biological diversity is probably declining more rapidly than ever before in the history of the Earth. But at the same time, only a small fraction of the species in the deep sea and polar oceans have so far been identified, making the loss of species in the oceans much more difficult to record and evaluate than on land.

Why is marine biodiversity important?

Every ecosystem performs certain functions that are critically important for organisms. One of the most important functions of marine ecosystems is the production of plant biomass from sunlight and nutrients (primary productivity), which represents the basic food source for all life in the ocean, and ultimately also for humans. Around half of the worldwide primary productivity is achieved by microscopically small plants, the phytoplankton, which grow and divide in the ocean. Another function performed by ecosystems is the creation of habitats, or structures, in coastal ecosystems. For example, macroalgae, seagrass and corals form large undersea forests, meadows or reefs that provide habitats for many other species such as molluscs, crustaceans and fish. Kelp forests and seagrass meadows in the Baltic Sea are vital **habitats** for the fry and juvenile fish that grow up here before swimming into the open ocean as adults. Gastropods and small crustaceans likewise feed on microalgae growing on the kelp or seagrass. They thereby ensure that the structure-forming plants are not smothered, and are allowed to grow – that is their contribution to the ecosystem. The molluscs and crustaceans that feed on microalgae are the basic food source for larger predatory crustaceans and fish.

Seagrass and kelp itself have relatively long life spans because they are poor food sources for grazing crustaceans and molluscs. They store nutrients in their biomass for a long time, including nitrogen and phosphorous compounds transported by rivers from agricultural areas to the sea. Seagrass and macroalgae thus function as a kind of biological purification system in coastal ecosystems.

Scientists have addressed the question of whether the dramatic decline in biological diversity has consequences for the stable functioning of ecosystems. After 10 years of intensive study, the answer is clear – yes, it does. Experiments in coastal ecosystems, particularly seagrass meadows and kelp forests, have shown that biological diversity in the oceans is essential for maintaining the ecosystem functions described above. Species diversity was decreased in various ways during these experiments in order to compare the ecosystem functions of species-rich with species-poor areas. In one field experiment, for example, the number of seaweed species was artificially reduced by removing some at the beginning of the growth period. The total algal biomass in this species-poor area did, in fact, decrease, thereby resulting in a decline in the food for consumers as well as the number of available **habitats**. In another experiment, the number of grazing

5.11 > Hundreds of fish species live in kelp forests like this one off California. These include the yellowtail rockfish or "greenie" *Sebastes flavidus.*

species that feed on the microalgae growing on seagrass was reduced. It was found that the species-poor grazer communities consumed fewer microalgae than species-rich communities. The shortage of grazing species resulted in a slower growth of seagrass because the increased growth of microalgae repressed photosynthesis in the seagrass.

These two experiments indicate that a decrease in biological diversity has a negative impact on the structure of the habitat, regardless of whether the number of species of producers (macroalgae) or consumers (grazers) is reduced.

How does biological diversity work?

Different species have different physical and biological requirements. It is precisely these that explain the positive effects of biological diversity. There are some algal species that grow optimally in strong light while others prefer lower light conditions. This means that some species of algae grow toward the light and form a crown like that of a tree, while other forms grow better in the shadow beneath them. This has two ramifications: first, the two forms can live together without one depriving the other of its needs, and second, they make optimal use of the available light. Together they produce more food for other species than would one form alone. This complementary use of available resources, the so-called "complementarity effect", is an important positive characteristic of biological diversity.

On the other hand, a particular ecosystem function such as grazing on seagrass is often performed by individual, very efficient species. For example, isopods and gastropods, two invertebrates that feed on algae, each have different nutritional preferences. Grazing gastropods have a strong rasp-like tongue which they use to graze on thin layers of microalgae, while isopods prefer the larger forms of filamentous algae. If the algal flora on

Kelp forests
Dense forests of algae where kelp is predominant are called kelp forests. These are characterized by long, thin, brown and red algae that can grow up to several metres long. Kelp forests mainly occur off the west coast of America, the coast of Argentina, the west coast of Africa, and off Australia and New Zealand. Kelp forests are unique ecosystems with characteristic species associations.

blades of seagrass is dominated by thin growths of microalgae, then the seagrass is mostly grazed by the gastropods. If the water has a higher nutrient content, then fibrous algal forms predominate, and isopods work to keep the seagrass free of algae. Which of these two varieties of grazer performs this job depends on the ambient environmental conditions. If an ecosystem function is carried out primarily by a single species rather than several, it is referred to as the "selection effect". The particular environment selects, so to speak, the current optimally functioning species.

Not only is the number of species important. Also significant is how many individuals of each species are present, or which species is predominant. Because of the selection effect, natural communities are usually composed of a few predominant species and a larger number of species with fewer individuals. Under stable environmental conditions, ecosystem functions, such as the creation of plant biomass, are often sustained by predominant species with optimal traits. The numerous but less abundant species play a subordinate role in these functions. But if the environmental conditions change, they are often called to task. A previously unimportant species can suddenly become predominant.

In the oceans also, a location often has only a few predominant species. There are even extreme cases where a single species prevails over all others. These ecosystems include seagrass meadows and kelp forests. In these cases biological diversity is achieved not by the abundance of species, but through the genotypic diversity of seagrass plants within a single species. Although the plants all belong to the same species, there are hidden differences in their genetic makeup.

Where in other situations species diversity sustains the ecosystem, in the seagrass meadow the genotypic diversity fills this need – that is, the invisible genetic differences between individuals of the same species. In fact, in seagrass meadows where several different genotypes were experimentally planted, the result was a greater density of shoots and a greater total biomass. The number of grazers also increased. So because of increased genotypic diversity, the general ecosystem function of biomass production was enhanced. More seagrass was present and there was an increase in food availability for predatory fish due to the abundance of grazers. Even the ecosystem's ability to resist certain disturbances and environmental changes can be improved through genotypic diversity. In one case a seagrass area with high genotypic diversity recovered after an extreme heat wave more quickly than areas with lower diversity.

In a world experiencing climate change the diversity of less abundant species or genotypes will presumably become increasingly important. These represent a kind of potential "biological insurance" for the sustainability of ecosystem functions. They may possess as yet unknown traits or genetic information that would make them capable of adapting to the new environmental conditions, and therefore be more productive and resilient than the original predominant species or genotypes.

To what extent is biodiversity under threat?

Because of rapid changes in water temperature, salinity and nutrient concentrations, and due to overfishing, habitat destruction and the introduction of foreign species, global biological diversity in the oceans is rapidly declining. There is no doubt about this: the disruptive forces are cumulative and will cause further species to disappear. This will then cause a decrease in the stabilizing function of the formerly diverse communities, with potentially hazardous results – habitats that cannot perform their ecosystem functions, or that lose their resilience. Coral reefs, for example, with their great biological diversity, are being transformed by overfishing and nutrient inputs into species-poor habitats where only a few algal species dominate. Too few reef fish remain to keep the corals free of algal overgrowth, so that new coral larvae have difficulty establishing themselves.

The European bladderwrack forests, in turn, are being displaced by species-poor communities predominated by filamentous algae. Filamentous algae are a poor habitat for juvenile fish and many other organisms. For one thing, they produce less oxygen and for another, they only store nutrients for a short time because, in contrast to bladderwrack forests, they are relatively short-lived, and are a favourite food for gastropods and crustaceans. This is further exacerbated by the fact that the filamentous algae and massive phytoplankton blooms resulting from higher nutrient concentrations effectively block light from the new bladderwrack seedlings. As a result, their growth is severely hampered.

The disappearance of a species that provides an important ecosystem structure, in this case the bladderwrack, can alter the environmental conditions and thus also the habitat to the detriment of other species. One important eventual consequence is the further decline of biological diversity, so that in the future the ecosystem can no longer perform its function.

Conclusion

Impacts and repercussions

Global climate change will inevitably lead to more or less simultaneous changes in numerous environmental variables during the coming decades and centuries. How strongly individual species and communities are affected by these changes depends on a variety of factors. It is not yet possible to estimate to what extent the living conditions in various marine ecosystems will change regionally. Antarctic planktonic algae could actually benefit from the warming of seawater, just as freshwater species in the eastern Baltic Sea could benefit from a salinity decrease in their ecosystem. In some habitats, the introduction of foreign species could even increase the species diversity for a time. In most cases, however, a geographical shift of environmental parameters will lead to a stress situation that exceeds the tolerance of some organisms. For example, due to future warming, the bladderwrack, which is adapted to cold water, will be stressed beyond its tolerance limits at the southern margin of its distribution off Portugal.

This abiotic stress would also be intensified if the change occurred more rapidly than the species could adapt to it. Species that cannot adapt to the abiotic changes will have to retreat to more favourable habitats in order to survive. But if they cannot spread rapidly enough or far enough, or cannot assert themselves in their new communities, they will die out. In both cases a local displacement of species can be expected. Sensitive species will disappear while opportunistic, more adaptive species will become more abundant. These will also include many introduced, alien species.

A restructuring of the species makeup of a community can eventually change the functionality of the community. Which ecosystem functions the marine communities perform in the future, whether the existing communities perform them better or worse, whether functions performed in the past completely disappear or just shift seasonally or spatially, all of this depends on whether the ecological functions of a disappearing species can be taken over by the species present or those newly introduced. In individual cases ecosystems may be able to cope with the regional changes of the species community, for example through immigration. But from a global perspective, species will be lost and ecosystems will undergo fundamental change.

The potential consequences of the loss of a species are impressively illustrated by the classic example of the sea otters native to kelp forests. Sea otters feed, in part, on sea urchins, which eat kelp. Because in the past sea otters were extensively hunted in some areas, sea urchin populations burgeoned, leading to the widespread destruction of kelp forests. Consequently not only were habitats changed, but even the near-coastal currents were altered in some areas.

6 Exploiting a living resource: Fisheries

> For decades, the catch from the world's fisheries steadily increased – with the result that many fish stocks are now classified as overexploited or depleted. Failed fisheries policies and poor fisheries management are to blame for this situation. Short-term profits appear to take priority over the development of a low-impact, sustainable fisheries sector that will remain economically viable in the long term.

Marine fisheries – the state of affairs

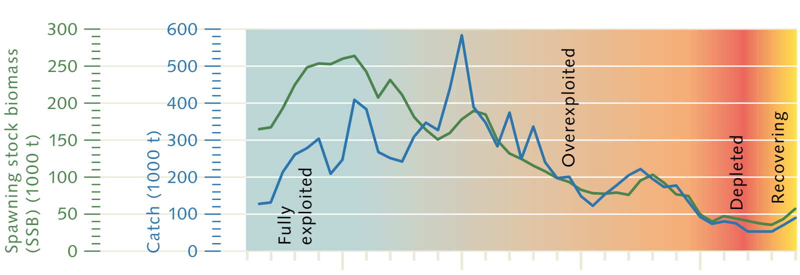
> Fish is an important source of food for people. It also represents an important sector of the economy: the estimated annual landed value of fish globally is around USD 90 billion. However, in many of the world's maritime regions, perpetual overfishing is putting stocks at risk.

Exploitation on a massive scale

Total global production of fish and fishery products from capture fisheries and aquaculture currently stands at around 140 million tonnes per annum. Until the early 1990s, the harvest from marine fishing followed an almost constant upward trajectory, with landings worldwide increasing fourfold from an annual figure below 20 million tonnes in 1950 to around 80 million tonnes in 1990. Since the 1990s, the total amount of fish, shellfish and crab caught in the sea has remained more or less constant.

Due to the great demand for fishery products, fish farming is also steadily expanding, especially in Asian countries. With an annual growth of around 7 per cent, aquaculture is one of the most rapidly expanding food industry sectors. Aquaculture already provides more than 40 per cent of the global consumption of fish and shellfish. However, many fish species raised in the aquaculture sector are predatory fish, which rely on a supply of other fish for food. Wild-caught fish are therefore used as feed. Although the amounts vary considerably according to species, it takes an average of around 5 kilograms of fish meal and fish oil to produce 1 kilogram of farmed fish.

6.1 > The example of North Sea cod shows how a fish stock collapses (i.e. becomes depleted) if there are no longer enough mature fish (spawning stock, green) available to produce offspring.



Wild-caught fish are also used as breeding stock. Switching to consumption of farmed fish alone, therefore, does not necessarily protect wild fish stocks.

The expansion of marine fishing has contributed significantly to the decline and in some cases the depletion of global fish stocks. Overexploitation particularly affects long-lived fish species such as redfish *(Sebastes marinus)* which take several years to reach maturity and begin spawning. In extreme cases, it may even lead to the depletion of the stock. For example, stocks of cod in the Northwest Atlantic off the United States coast have collapsed after years of overfishing.

Decline of spawning stock

North Sea cod stocks, too, have been greatly reduced by intensive fishing. This species is a particularly good example of the effects of the exploitation of the seas. Experts define a stock as a self-sustaining population of a fishspecies within a geographically defined area. The spawning stock – i.e. the mature individuals that are capable of reproduction – are particularly important in scientific terms. The Food and Agriculture Organization of the United Nations (FAO) does not provide any precise definitions of the various status categories of stocks. For example, the boundary between "fully exploited" and "overexploited" status is somewhat fuzzy. According to the FAO, the term "fully exploited" means that a fishery is operating at or close to an optimal yield level, with no expected room for further expansion. A stock is termed "overexploited" if it is being exploited above a level that is believed to be sustainable in the long term, evident

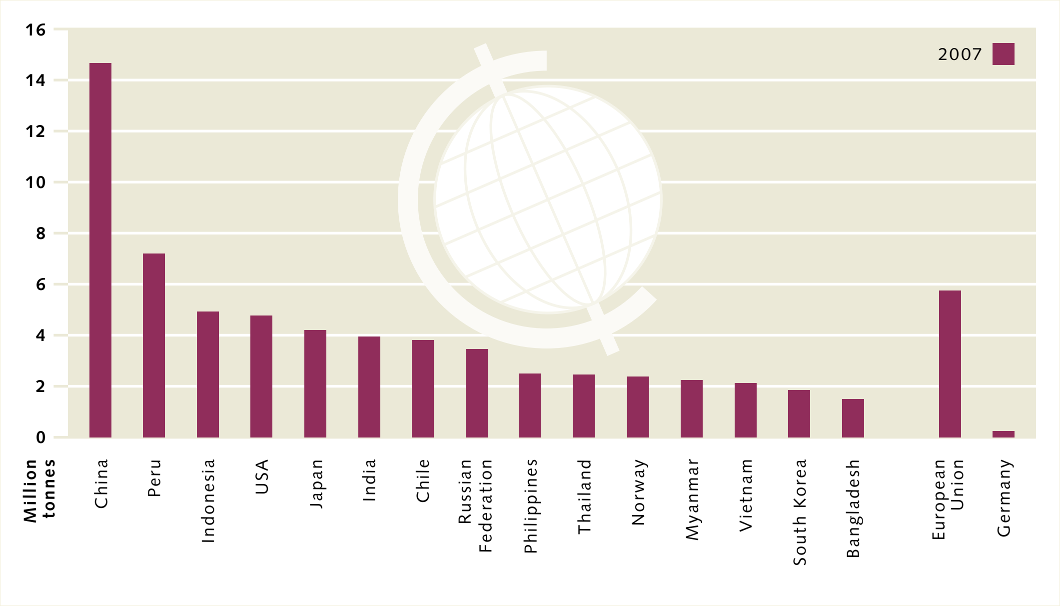
6.2 > Aquaculture is a booming industry today and fish are being farmed on a large scale, as seen here on the Chinese island of Hainan. However, fish farms do not necessarily help to conserve wild fish stocks as they require large quantities of fish meal or wild-caught forage fish for feed.

from the steady decline of the stock. A stock is said to be depleted if catches are well below historical levels, irrespective of the amount of fishing effort exerted. A stock is said to be recovering if catches are again increasing after having been depleted.

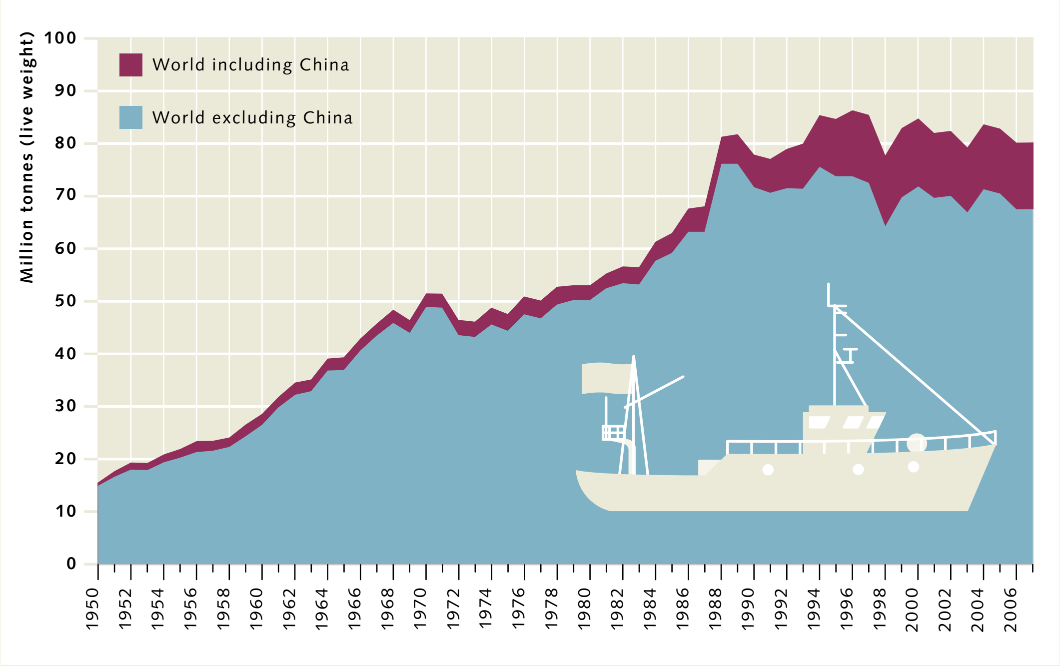
According to FAO estimates, there has been a steady increase in the proportion of overexploited and depleted stocks since the 1970s. By contrast, there has been a decrease of around 50 per cent in the proportion of underexploited stocks, which stood at an estimated 20 per cent in 2006. This trend may be due to the development of increasingly efficient fishing technology, including technically improved means to locate shoals of fish and ever more powerful fishing vessels. The construction of enormous factory ships means that large catches can be frozen while the vessel is still at sea, enabling ships to exploit fishing grounds at great distances from the port of landing. Continuing advances in fishing technology also allow fish to be caught at ever greater depths. Furthermore, due to a lack of alternatives, commercial fishing is increasingly turning to species that were previously regarded as unprofitable, of poor quality, or unfit for consumption.

Stock assessment – a difficult task

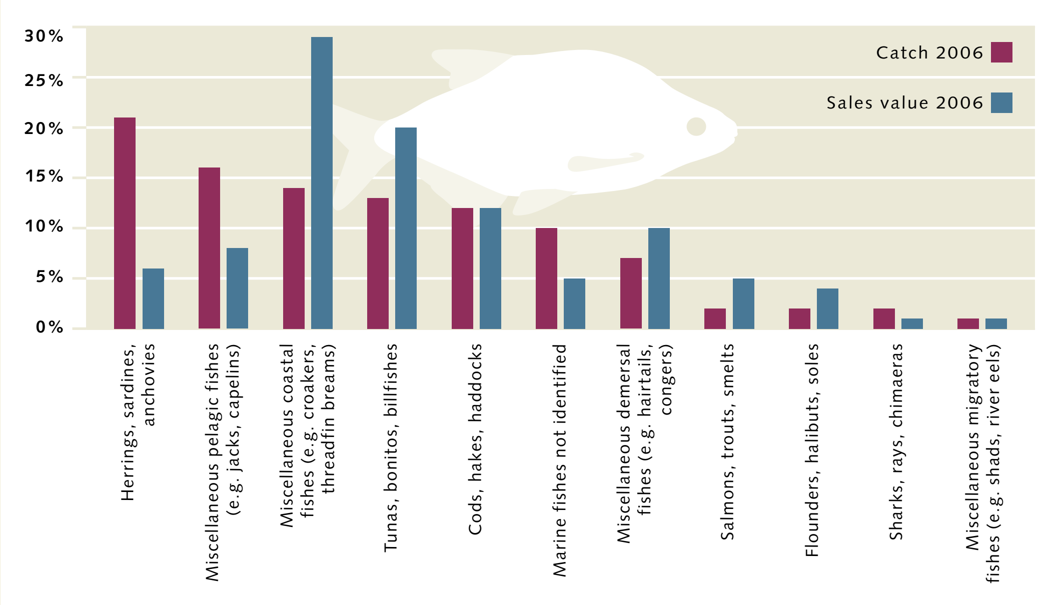
Correctly assessing fish stocks is a difficult task. As it is not possible to count fish individually, stock sizes are now estimated using mathematical models. Current catch figures from the fishing industry are an important source of data in this endeavor. The models also take account of the effort that must be employed in order to catch this quantity of fish, based, for example, on the number of fishing days or the fleet size – for the fewer the fish there are in the sea, the greater the effort needed to achieve a specific catch volume. However, even today not all catches are reported, so the available data may be incomplete. The mathematical models therefore also include information from scientific test catches, which are regularly carried out by fisheries biologists and include data



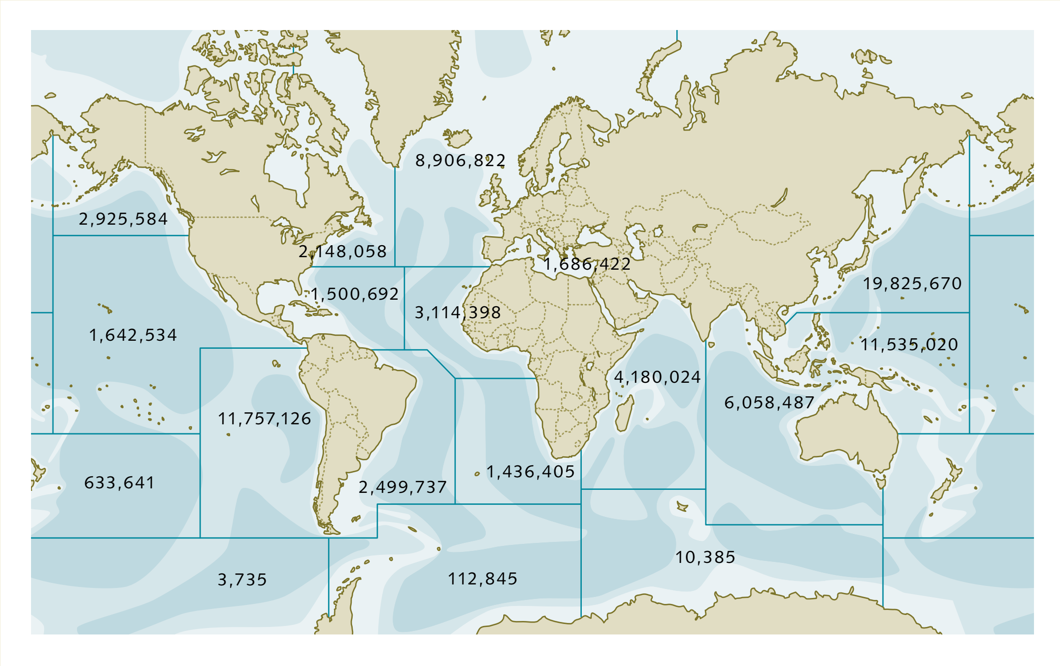
6.3 > Top producer countries, based on catch



6.4 > World marine capture fisheries production since 1950



6.5 > Catches and landing values by groups of species



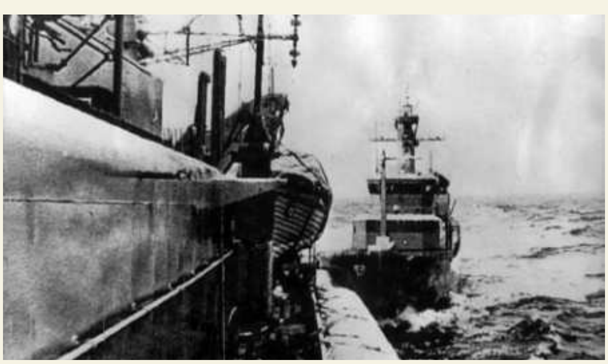
6.6 > Catches by region in tonnes (live weight) (2007)

The fate of the cod

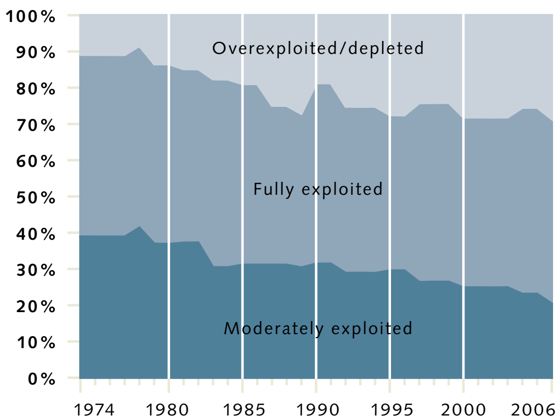
Atlantic cod *(Gadus morhua)* – commonly known simply as cod and also found in other maritime regions, including the Baltic Sea – was a popular staple food across much of northern Europe and the islands of the North Atlantic for a very long time. Cod stocks were abundant and the species was easy to catch. It was one of the main ingredients in Britain's national dish, fish and chips, while in Norway, air-dried cod (stockfish) was a popular traditional food. Cod – which can reach up to 1.5 metres in length – is a demersal fish, which means that it lives on or near the bottom of the sea. Its habitats are located in the coastal regions of the Atlantic Ocean. Cod can be found near the coast as well as at depths of up to 600 metres. Cod is a difficult species to farm, however.

The great dependence of the fishing nations on their cod stocks was demonstrated in the "Cod Wars" from 1958 until 1975. During this period, a series of political confrontations erupted after Iceland – concerned about the future of its traditional fishing grounds and more intensive competition from foreign deep-sea trawlers – progressively expanded its Exclusive Economic Zone (EEZ) (Chapter 10) from 3 to 200 nautical miles. In so doing, Iceland succeeded in protecting cod stocks in the Northeast Atlantic from overexploitation by other fishing nations. This is evident from the fact that around 1 million tonnes of cod are still being harvested annually in the Northeast Atlantic, whereas cod stocks in the Northwest Atlantic range off the east coast of North America are an outstanding example of failed fisheries management. Here, the once abundant cod stocks off Newfoundland, which in the past yielded some 600,000 tonnes of catch weight annually, have now collapsed after years of overfishing.

How could this have happened? After centuries of mainly coastal fishing using smaller fishing vessels, in 1950 the fishing industry switched to industrial bottom fishing using trawl nets and also began fishing in deeper waters. Catches increased considerably in the short term, leading to a decrease in population size. Attempts to regulate catches with international fishing quotas and Canada's efforts to tackle the problem by expanding its Exclusive Economic Zone could not curb the dramatic drop in yield. After the population had completely collapsed at the end of the 1980s, there was no option but to close the commercial cod fishery in 1992, followed by a ban on artisanal fishery in the coastal communities of Newfoundland in 2003. The social and economic consequences of this move have been severe. Biologists now believe that due to the massive disruption of the marine ecosystem, it has passed a tipping point and that even with a total ban on fishing, cod stocks will not recover.



6.7 > Fighting over fish: the economic significance of the fishing industry for some nations became apparent during the "Cod Wars" in the Northeast Atlantic. The United Kingdom and Iceland even deployed warships in the conflict over control of the fishing grounds. On 7 January 1976, the Icelandic patrol boat *Thor* (above left, background) collided with the British frigate *Andromeda* (foreground) some 35 nautical miles off the Icelandic coast. According to the British version of events, the collision occurred after *Thor* attempted to cut the nets of the British trawler *Portia* (above right, centre). During the manoeuvre, *Thor* abruptly changed course and rammed the frigate. The dispute between the two countries was so intense that Iceland even broke off diplomatic relations with the UK for a time.



6.8 > The use intensity of commercially relevant fish stocks has increased significantly worldwide.

on the age structure of the fish stocks and stock density. Measured in terms of total catch weight, the People's Republic of China tops the list of the world's leading fishing nations by a clear margin; China claims to land an estimated 14 million tonnes of fish or more annually. In second place is Peru, with an annual catch weight of around 7 million tonnes. In regional terms, the Northwest Pacific (19.8 million tonnes) and the Southeast Pacific (11.8 million tonnes) are the fishing areas yielding the largest catches.

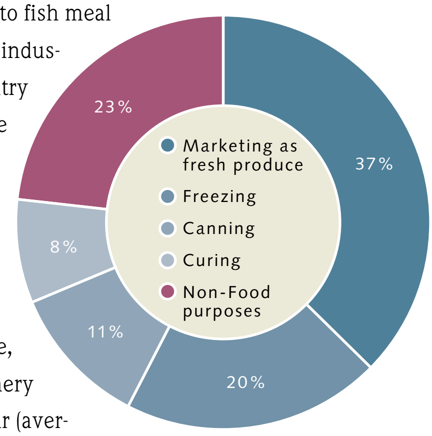
With annual production of 7 to 10 million tonnes, the Peruvian anchoveta is the most productive marine species. It is a mainstay of the Peruvian fishing industry and is also caught by other countries. Second in the ranking is Alaska pollock *(Theragra chalcogramma)* (2.9 million tonnes), followed by Atlantic herring *(Clupea harengus)* (2.4 million tonnes).

Generating billions in revenue – with fish meal and gourmet fillets

The estimated landed value of fish globally is around USD 90 billion. Even more added value is generated in the processing industry, which turns the fresh catch into a variety of fishery products. The commercial value of different fish species varies considerably, firstly due to the different amounts available on the world markets and, secondly, because various fish species enjoy different levels of popularity among consumers. Rare species of tuna can command prices in excess of 100 euros per kilogram on the Asian market, whereas fishermen are paid as little as 10 to 20 cent for a kilo of sprats.

The prices of fishery products also depend on how the catches are processed. Broken down by quantity, the various forms of utilization of world fisheries production have remained more or less constant over recent years. Around three-quarters of the catch is destined for direct human consumption, with approximately half of this reaching the final consumer in the form of fresh fish, a quarter being processed into frozen food products, and a further quarter being preserved by curing, pickling or canning before being brought to market. The remaining 23 per cent of the catch is processed into fish meal and fish oil, mainly for the feedstuffs industry, and is used in aquaculture and poultry farming, for example. The significance of fish in terms of its contribution to the human diet also varies from region to region. Consumption of fishery products is heavily dependent on the availability of other food sources and proximity to the sea. Worldwide, approximately 16.4 kilograms of fishery products (live weight) per capita per year (average for 2003 to 2005) are used for consumption. This figure includes products from inland fisheries and aquaculture. However, per capita consumption in the European Union countries (EU-15) is 25.7 kilograms – well above this average. Compared with countries such as Spain (42.6 kilograms) and Portugal (55.4 kilograms), where fish has traditionally formed a major part of the diet, per capita consumption of fishery products in Germany is 14.3 kilograms, and hence broadly in line with the global average.

6.9 > Utilization of fisheries production (breakdown by quantity), 2006. "Non-food purposes" largely consists of the production of fish meal and fish oil for use in fish or livestock farming.



Fishing and aquaculture provide employment for an estimated 43.5 million people worldwide, mostly in Asian and African countries. The People's Republic of China accounts for the major share, with more than 12 million people employed in fishing and aquaculture.

The causes of overfishing

> It is now generally understood when and why fish stocks become depleted. Global demand for fish and the intensity of fishing activity are known to be key factors in this context, but ecological aspects also play an important role. The influencing variables need to be studied in more detail, however, in order to provide a conclusive explanation of the causes of overfishing.

Dwindling fish stocks – too complex for simple explanations

Whether a fish stock survives over the long term or is fished to the point of depletion depends on how much of the fish is caught. This is determined primarily by the fishing effort deployed. The term "fishing effort" comprises the combination of the structure of the fleet within a given fishery, the fishing gear and fishing technology used, and the amount of time spent fishing. Another factor influencing catch volumes is consumer demand, e.g. for certain species of fish or for products that have been processed in a particular way. Ultimately, it is consumer demand that determines to what extent the fishing effort pays off for fishermen.

Fishing opportunities are also influenced by a variety of ecological factors. The marine ecosystem comprises not only the various fish stocks, each characterized by their individual stock density and age structure, but also the biotic (living) and abiotic (non-living) environment. The biotic environment includes predators such as marine mammals, birds and predatory fish, as well as prey such as plankton and other species of fish. It also includes species of flora and fauna that interact with the fish stocks in other ways – corals are one example, as they form habitats for fish. Key parameters of the abiotic environment include temperature, salinity and oxygen concentration, as well as water quality.

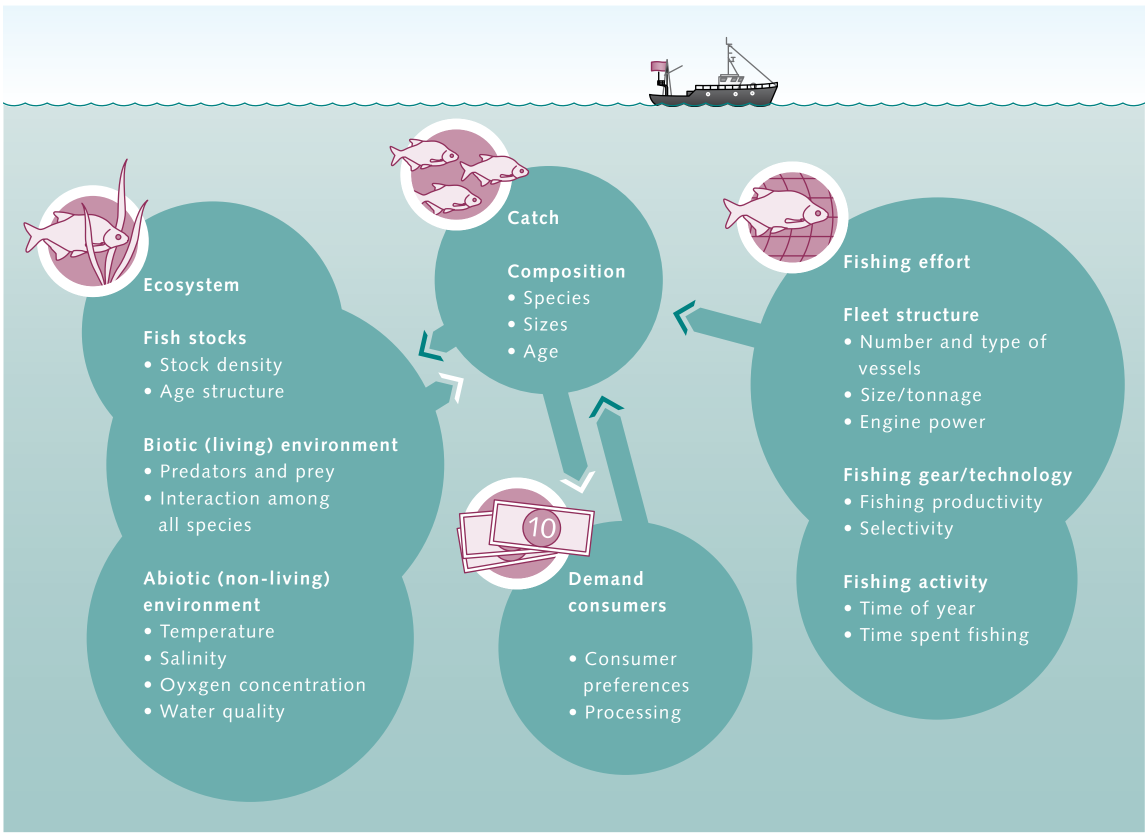
The interactions between the various influencing factors occurring throughout the ecosystem are highly complex and therefore difficult to determine. They may also change over time, for example, as a consequence of global warming (Chapters 1, 2 and 5). Consumer demand and fishing effort indirectly affect the marine ecosystem as well. Depending on the volume and composition of the catch, the age structure and density of the fish stocks may change, and this can affect the coexistence of the various species of marine flora and fauna.

Sustainable management – the Alaska pollock fishery

There are many stocks of Alaska pollock *(Theragra chalcogramma)* in the Pacific, five of which are managed in accordance with the US Groundfish Fishery Management Plans (FMPs). These plans contain expert groups' recommendations on the precise catch volumes that are sustainable for specific species, and are intended to ensure that fishing activity takes place in accordance with the maximum sustainable yield (MSY) principle. On the average, stocks have now already reached almost 80 per cent of the level required for harvesting at MSY. A moderate level of fishing activity takes place, which means that the quantities of fish being withdrawn from the sea are relatively small, and this level may even be less than is strictly necessary. Nonetheless, fishermen are currently still able to harvest approximately 1.1 million tonnes annually, mainly in the Bering Sea and around the Aleutian Islands. The fishermen use nets that are trawled through the water, not dragged along the sea floor. This does much to conserve bottom-dwelling species. Careful selection of nets with appropriate mesh sizes and other technical measures will also help to substantially reduce bycatch.

Ecological and economic objectives of fisheries policy

The implementation plan adopted at the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg established the maximum quantity of fish that



6.10 > Schematic overview of a marine fishery. The white arrows show the route taken by the fish from the sea to the consumer. The dark-green arrows show the impacts of consumer demand and fishing effort on catch volumes and the marine ecosystem.

can be harvested annually with a view to protecting the world's stocks. This is known as the maximum sustainable yield (MSY). The MSY is the maximum annual catch that can be taken from a species' stock over an indefinite period without jeopardizing that stock. The volume of the catch that can be sustained over an indefinite period depends on the size of the stock. For many stocks, the size of the stock that would permit MSY is equivalent to around half the natural equilibrium stock without fishing activity.

As fish species vary in terms of their commercial value, the economically relevant variable is not the weight of the catch in tonnes but the value of the fishing yield. Fishing costs are the second major economic variable in a given fishery. An increase in fishing effort leads to higher operating costs due to the costs of increasing inputs such as wages, fuel and fishing gear. As a consequence, fishing is particularly profitable if the difference between the fishing yield and the total costs is sufficiently large. Analogous to the MSY, the value of the largest positive difference between total revenues and total costs of fishing is known as the maximum economic yield (MEY).

Economic incentives for overfishing

From an economic perspective, the problem of overfishing arises because marine fish stocks are a "common" resource: a fish, once caught, belongs to the fisherman, whereas a fish that is still in the sea does not. Viewed in economic terms, a fish in the sea has value by virtue of the fact that it reproduces and continues to gain in weight, which means that the fishing yield will increase in the future if the fish stays in the sea. So there is a price asso-

6.11 > Even today, deep-sea fishing is back-breaking work. However, vessels are now equipped with state-of-the-art fishing technology, including aids to locate shoals of fish.

ciated with catching the fish because this value is lost. In the case of overexploited stocks, which are in particular need of recovery, this price may even exceed the market price obtained for the landed fish. As fish stocks are a common resource, however, in an open and completely unregulated open-access fishery no one ever pays the true economic price. For that reason, the economic costs of fishing are underestimated and far more fish are caught than is economically sensible.

If a fish stock is of a size that permits the maximum economic yield (MEY) to be achieved, there is a strong incentive for individual fishermen to deploy additional vessels or work additional shifts in order to increase their personal earnings. This means that in an open fishery, the fishing effort will be scaled up until it is virtually impossible for any fisherman to generate any profits at all.

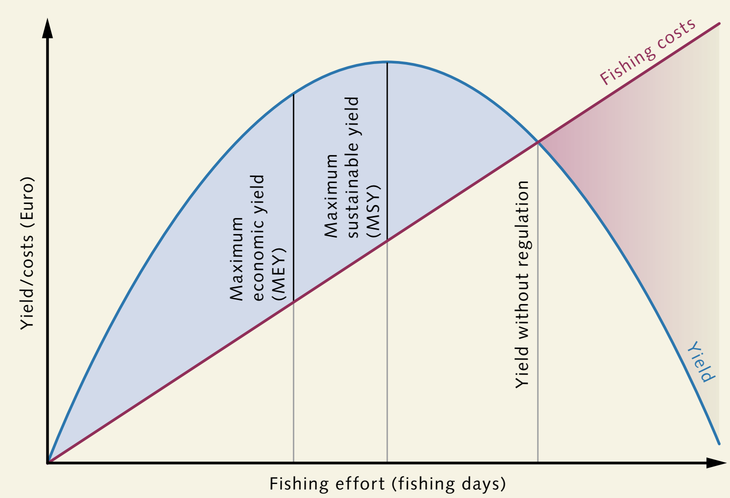
Furthermore, state subsidies allow the fishery to be maintained even when the direct costs of the fishing effort have already exceeded the value of the fishing yield. Fishermen's individual operating costs are reduced in many cases by direct or indirect subsidies. Every year worldwide, more than USD 10 billion is paid to fishermen in the form of fuel subsidies or through modernization programmes, with 80 per cent of this in the industrialized countries.

According to calculations by the World Bank, the global fishing effort should be reduced by 44 to 54 per cent in order to maximize total economic benefits from global fishery, i.e. in order to achieve maximum economic yield. The World Bank currently estimates the loss of future net benefits due to overfishing to be in the order of USD 50 billion annually – a substantial figure compared with the total annual landed value of fish globally, i.e. around USD 90 billion.

A further major difficulty for successful regulation of fishing, in terms of the maximum economic yield (MEY), is ongoing enforcement and monitoring. If a particular fishery is highly profitable, fishermen may be tempted to drive up their earnings by making illegal landings. Around one-third of all fishery products reaching the market are estimated to come from illegal fishing, or fishing activities that circumvent international agreements. Illegal, unreported and unregulated (IUU) fishing obstructs efforts to conserve and maintain fish stocks. IUU fishing is not just carried out by a few private entrepreneurs who deliberately violate the law and others' fishing rights. It also involves vessels registered in countries whose own standards do not meet those adopted by the international community or who lack the capacities to establish control mechanisms. Illegal, unreported and unregulated fishing therefore mainly harms artisanal fisheries in the coastal regions of developing countries. The annual global economic cost of IUU fishing is estimated to be at least USD 10 billion.

The profits of fishing

To what extend fishing is economically profitable in the long term by considering the yield, the operating costs and the fishing effort. A specific constant effort will result in the maximum sustainable yield (MSY) being achieved. This is the maximum annual catch that can be taken from a species' stock over an indefinite period without jeopardizing that stock. The maximum economic yield (MEY), by contrast, is a monetary variable. It is equivalent to the maximum annual earnings from fishing, and represents the largest difference between total revenues and total costs. The MEY is attained at a lower level of effort than the MSY. Without regulation, the fishing effort would increase for as long as fishing remained commercially viable, i.e. as long as the earnings obtained from fishing remain positive. In an unregulated fishery, the effort is therefore the point at which revenue and costs are equally high.



Classic approaches to fisheries management

> For many years, authorities have been attempting to control fishing with a variety of regulatory instruments in order to conserve stocks. These instruments include fishing quotas, limits on the number of fishing days, and restrictions on the engine power of fishing vessels. However, many of these measures fail because the quotas and restrictions introduced are not stringent enough, are not properly monitored, or because fishing practice simply ignores the regulations.

How can overfishing be avoided?

Overfishing means that the annual catch volumes are ecologically and economically unsustainable. Ultimately, excessively high catches are the result of too much fishing effort. As fish stocks decline, the effort required to catch a given quantity of fish continually increases. Fisheries policy or centralized fisheries management has responded to this situation by adopting direct measures that aim to limit catch volumes or indirect measures focussing on fishing effort.

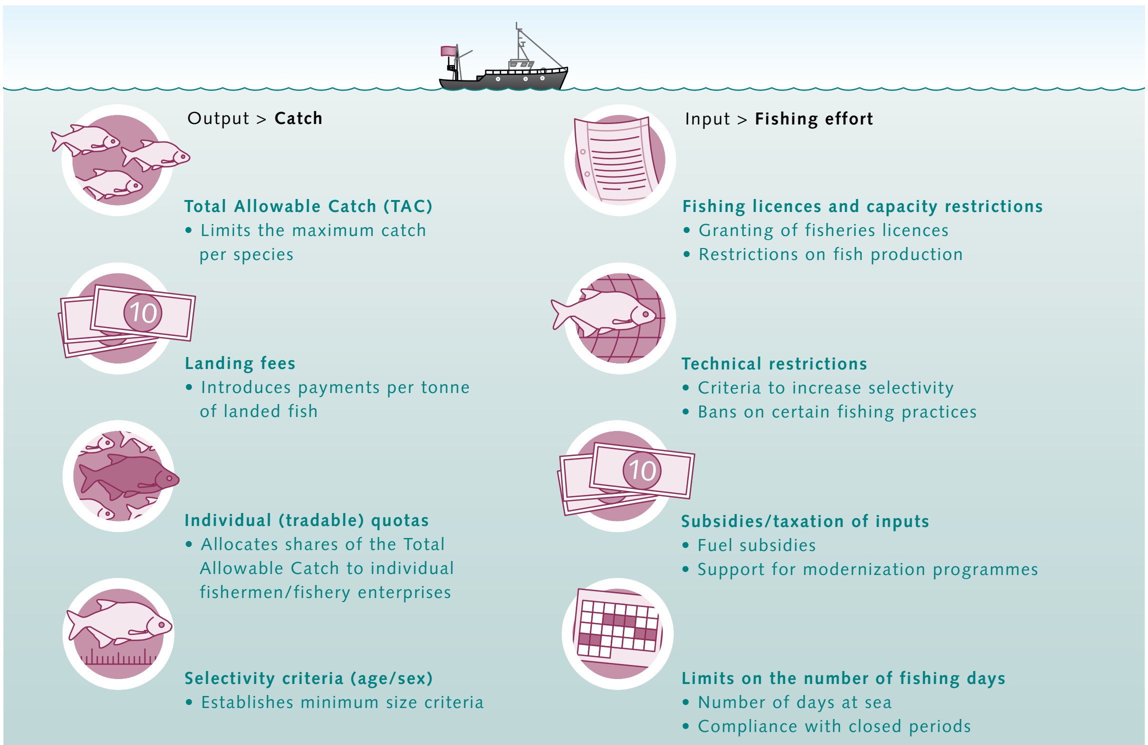
Reducing catches

In order to reduce total catch to a biologically and economically sustainable level, authorities frequently introduce Total Allowable Catches (TACs). Ideally, the TACs should be set at a level that allows the maximum economic yield (MEY) to be achieved in the long term. However, TACs alone are not enough to safeguard economic efficiency, for at the start of every new fishing season with a limited TAC, each fisherman would attempt to secure the largest possible share of the quota for himself by engaging in a very high fishing effort for a short period (also known as the “race to fish”). If the quota is thus exhausted within a relatively short time, fishing capacity then remains unused until the next fishing season. In order to give the individual fishermen a modicum of planning security throughout the entire fishing season, the TACs are therefore allocated to individual vessels, fishermen or cooperatives.

6.12 > Deep-frozen tuna for sale at a Tokyo fish market. Japan is the fifth-largest fishing nation in the world.

Fisheries policy strategies that grant fishermen the right, in one way or another, to determine the quantity of fish they will harvest over the long term are known as “rights-based management of fisheries”. Individual transferable quotas (ITQs) are the prime example. Here, fishermen are allocated individual quotas, which they can trade freely with other fishermen. Fishermen who operate relatively uneconomically are likely to sell some of their quotas, while more economically efficient companies can purchase additional ITQs. In the long term, the effect of this is to concentrate the quotas among a small number of fishery enterprises, thereby ensuring that the Total Allowable Catch is landed at lower total cost.

These concentration processes can be observed in practice. In New Zealand, for example, where a system of ITQs has been in place since 1986, the number of ITQ holders was around one-third lower in 2000 than in 1990. Obviously, not all social objectives can be achieved solely by means of the individual transferable



6.13 > Classic approaches to fisheries management either focus directly on restricting catches or attempt to limit fishing effort. However, monitoring these regimes is often fraught with difficulty.

quotas, especially if there is a desire to ensure the survival of small, less economically efficient fishery enterprises. As small fishery enterprises can opt to sell their quotas, however, they are clearly in a more favourable position than would be the case without the option of quota trading.

As a rule, quotas are specified in tonnes and are broken down by species. However, the actual catch consists of fish from different age groups and levels of quality, and therefore different values. This often encourages fishermen to engage in the practice of high grading, i.e. the selective landing of fish so that only the best-quality fish are brought ashore. Lower-quality fish are discarded back into the sea so that the quota is filled with high-grade fish.

This practice reduces fish stocks without benefiting the consumer. In some fisheries, bycatch amounts to 40 per cent or more of the catch. This bycatch is discarded overboard like waste. Despite these difficulties, rights-based management of fisheries has performed well overall. New studies based on large datasets show that this management approach promotes not only economic efficiency but also sustainability of fisheries. For example, the share of depleted stocks in fisheries subject to rights-based management is just 14 per cent – far less than the 28 per cent in fisheries without a similar type of regulation.

As an alternative to tradable quotas, there is also the possibility of regulating overfishing using landing fees. These fees operate in a similar manner to individual tradable quotas. The difference is that the fisherman does not buy additional quotas but pays a fee, based on the amount of fish actually caught, to a designated authority. The landing fee ensures that the true economic price is paid for the fish, thereby removing any incentive for overfishing.

Similar to the data requirements for setting a TAC, the fees can only be set at the optimal level if information is

A negative example – EU fisheries management

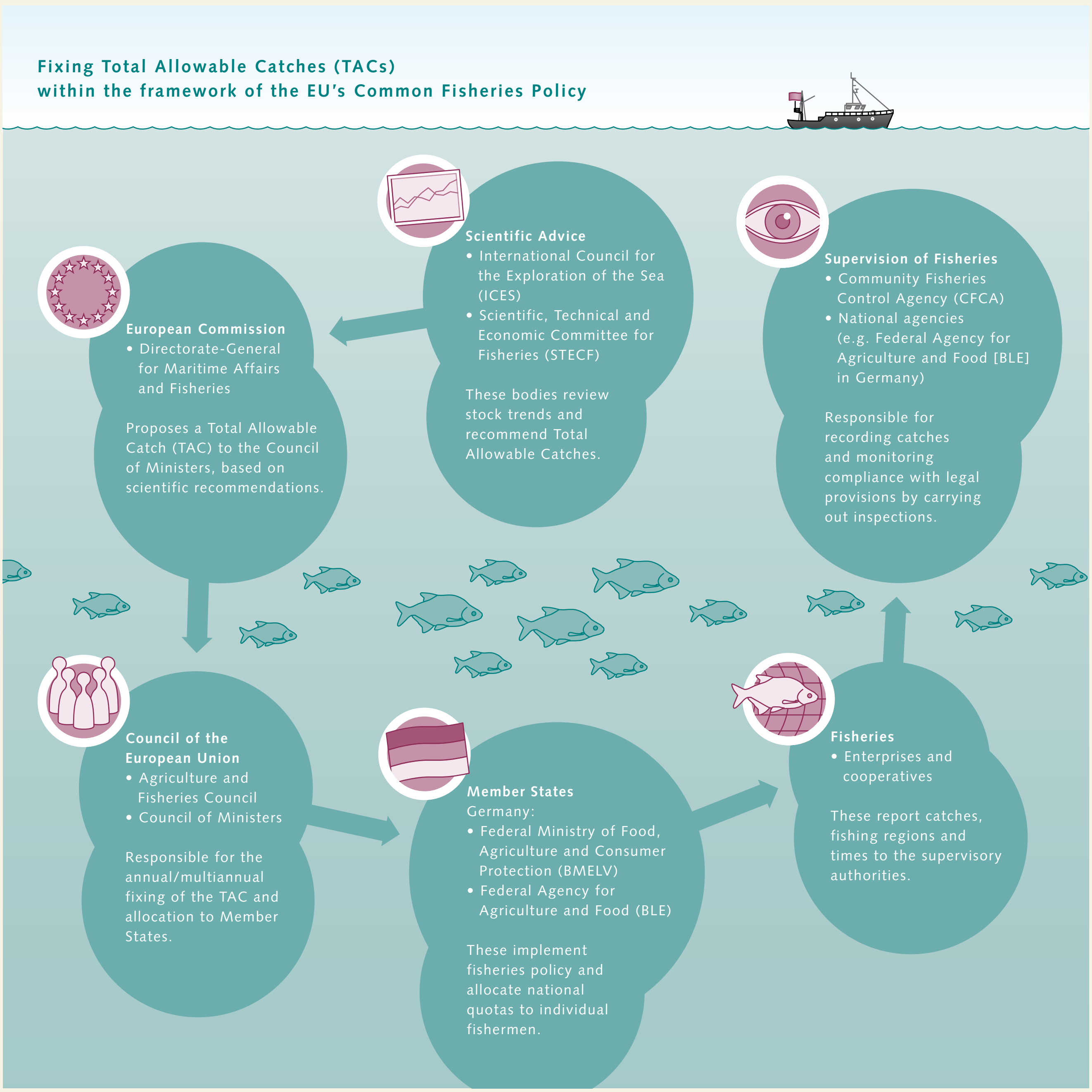
One example of a fisheries management regime which is widely regarded as a failure is the current Common Fisheries Policy (CFP) adopted by the European Union. The stated aim of the CFP is to help conserve fish stocks and to contribute to an economically viable and competitive fisheries and aquaculture industry. And yet, in recent years, there has been a dramatic decline in fish stocks in some cases, as well as a significant decrease in fishing industry profits.

There is one primary reason for this: every year, the European Commission makes recommendations on the Total Allowable Catch (TAC) to the Council of Ministers based on scientific evidence. The Council of Ministers, however, often disregards these recommendations because, as a rule, the priority for these ministers seems to protect jobs in the short term, not to maintain sustainability. As a consequence, the annual catch agreed to by the Council of Ministers is generally around 48 per cent more than the scientists' recommended figure. The fact that 88 per cent of European fish stocks, measured against maximum sustainable yield (MSY), are overexploited is due in part to these excessively high catch quotas.

Furthermore, the minimum sizes of fish that may be landed are often so small that 50 per cent of the fish have no chance of ever spawning before they are caught. The minimum legally permissible mesh sizes of fishing nets also allow fish smaller than the minimum landing size to be caught. These fish – amounting to as much as 40 per cent of the catch – die as a result of capture and are generally discarded overboard. The CFP has introduced a range of regulatory instruments, such as the annual Total Allowable Catch (TAC), restrictions on the permissible number of fishing days, fleet reductions, and limits on the size and engine power of fishing vessels. Besides numerous regulations relating to fishing technology, such as minimum mesh sizes, the CFP also allows some fishing grounds to be closed. Enforcement of the regime involves monitoring and sanctions. However, in a highly diverse community like the European Union, this is fraught with difficulty, for in practice every Member State applies the regime with varying levels of efficiency. There is very little incentive for a Member State to impose stringent controls on its fishing fleet if neighbour states fishing the same waters fail to do so. A further problem is that bycatch is not recorded or sanctioned. This means that fishermen can fish above their quota and simply discard the surplus by dumping it overboard. This common practice, which is known as high grading, consistently undermines the annual fishing quotas set by the Council of Ministers.

In response to this situation, the Community Fisheries Control Agency (CFCA) was established in 2005 to organize operational coordination of fisheries control and inspection activities by the Member States and to assist them to cooperate so as to comply with the rules of the Common EU Fisheries Policy. However, there is still a lack of reliable data about catches, violations of the regime, and illegal fishing. In fact, there is some evidence that even the European Commission is reluctant to impose sanctions on Member States which violate the CFP. For example, the Commission rarely makes use of its powers, conferred upon the Commission in respect of Member States by Articles 226 and 228 of the EC Treaty, to bring matters before the European Court of Justice (ECJ) if they fail to enforce the CFP in their own country.

Furthermore, the subsidies paid to the European fishing industry create the wrong incentives. Between 2000 and 2006, some 4 billion euros were paid out in subsidies for, among other things, fleet modernization and the fish processing industry. There are also numerous regulations governing how the individual subsidies are to be used. These regulations are intended to prevent further increases in overcapacity in the fishing fleets. In total, the European Union has an estimated 2000 rules and regulations relating to the fishing industry, many of them difficult to understand and in some cases even contradictory. From a legal perspective, a further factor in the failure of the CFP is thus the lack of transparency in the measures adopted by the European Union. Due to the different interests and priorities, as well as the different election schedules in the various Member States, it is very difficult to achieve a consensus among the national ministers responsible for fisheries, who decide the annual Total Allowable Catches (TACs) in the Council of Ministers. As a consequence, measures adopted within the CFP framework generally tend to be geared toward the lowest common denominator. Given the flawed state of fisheries in the European Union, the European Union is now planning a comprehensive reform of the CFP. At present, numerous proposals are being discussed for the framing of a new CFP to be adopted in 2012. In order to ensure that the new CFP has legitimacy, the existing regional advisory bodies that bring together various interest groups – fishermen, scientists, politicians and environmental organizations – should be expanded. Admittedly, it is still too early at this stage for a conclusive assessment, but hopefully this will promote more transparency and more broad-based practical support for the CFP's objectives.


Fixing Total Allowable Catches (TACs)
within the framework of the EU's Common Fisheries Policy
Scientific Advice
• International Council for the Exploration of the Sea (ICES)
• Scientific, Technical and Economic Committee for Fisheries (STECF)
These bodies review stock trends and recommend Total Allowable Catches.
Supervision of Fisheries
• Community Fisheries Control Agency (CFCA)
• National agencies (e.g. Federal Agency for Agriculture and Food [BLE] in Germany)
Responsible for recording catches and monitoring compliance with legal provisions by carrying out inspections.
European Commission
• Directorate-General for Maritime Affairs and Fisheries
Proposes a Total Allowable Catch (TAC) to the Council of Ministers, based on scientific recommendations.
Council of the European Union
• Agriculture and Fisheries Council
• Council of Ministers
Responsible for the annual/multiannual fixing of the TAC and allocation to Member States.
Member States
Germany:
• Federal Ministry of Food, Agriculture and Consumer Protection (BMELV)
• Federal Agency for Agriculture and Food (BLE)
These implement fisheries policy and allocate national quotas to individual fishermen.
Fisheries
• Enterprises and cooperatives
These report catches, fishing regions and times to the supervisory authorities.

6.14 > Different fishing techniques have various impacts on fish stocks and the marine environment.

Fishing gear	How it works	Bycatch (other fish species)	Bycatch (turtles, seabirds, mammals)	Adverse impacts on sea floor
Gillnet	The gillnet is anchored at a fixed position in the water. The fish are caught in the mesh.	Low level of bycatch of other species, not least due to the specific sites selected for the setting of gillnets.	High levels in some cases. The use of acoustic deterrent devices (pingers) is not particularly effective.	Minimal
Pound net	The net is anchored at a fixed position in the water. Fish are caught in the closed end of the net.	Not a problem as bycatch remains alive.	Nets should be covered to prevent birds from being caught. Very little data available about bycatches of mammals and turtles.	Minimal
Purse seine	The purse seine is a net that is used to encircle a school of fish. The net is then drawn together to retain the fish by using a line at the bottom, allowing the net to be closed like a purse.	Low, as purse seines target schools of one species.	High levels of dolphin bycatch. Mitigation techniques are now reducing dolphin bycatch in purse seine gear.	None
Pelagic trawl	This is a funnel-shaped net that is towed by one or two vessels. The fish are captured in the "cod end", i.e. the trailing end of the net.	Can be a problem in some areas, depending which species is being targeted for trawling.	Low	None
Bottom trawl	Works in a similar way to the pelagic trawl, but is dragged along the seabed.	Can be a problem in some areas, depending which species is being targeted for trawling.	Low	High, depending on the type of trawl gear used.
Beam trawl	The net is mounted on a heavy metal beam and is towed along the seabed.	Can be a problem in some areas, depending which species is being targeted for trawling.	Low	Very high: the beams and chains plough up the seabed to a depth of several centimetres.
Long-line	Consists of a long main line with a large number of short lines (called snoods) carrying numerous baited hooks.	Can be a problem in some areas, depending which species is being targeted. Sharks are the most common bycatch.	Problematical in some fisheries, posing a threat to seabirds and turtles.	None

available about the structure and size of fish stocks. Here, the main problem is that fishermen reject the concept of direct payments for, unlike quotas, which are allocated free of charge, these fees reduce their earnings. Landing fees therefore play only a minor role in practical fisheries policy at present.

Restricting fishing effort

In addition to the use of quotas, fishing can also be regulated by restricting the fishing effort. For example, fishing capacity can be limited by capping the number of licences available for allocation to fishing vessels or by restricting the engine power or size of vessels. It is also possible to limit the duration of fishing, e.g. by capping the number of days that may be spent at sea.

Effort-based regulation offers fishermen a number of loopholes, however. Fishermen frequently circumvent the restrictions on fishing time by increasing their fishing capacity. They can thus harvest the same quantity of fish in a reduced number of days spent at sea. A well-known example is the Pacific halibut fishery, where at the end of the 1980s, fishing was only permitted for three days a year. In practice, during this very short fishing season, a vast fishing fleet was deployed and caught the same quantity of fish as had previously been harvested in an entire year.

Moreover, an effort-based regime requires constant adaptation to bring it into line with the latest technological developments. Increasingly efficient technology to locate fish shoals, for example, makes it possible to track and harvest a given quantity of fish in ever shorter time periods. Increasingly detailed legal provisions are also required, ultimately leading to overregulation and generating high economic costs.

Nonetheless, experts agree that some regulation of fishing technology and practices is essential. For example, fishing methods that inflict particularly severe damage on the marine ecosystem are banned in many regions; these methods include blast fishing, which uses explosives and indiscriminately kills all the fish within a given area.

6.15 > Blast fishing – the practice of using explosives to kill fish – is banned in most places around the world as it kills a large number of marine organisms. In areas where there is very little control of fishing practices by the authorities, some fishermen continue to deploy this devastating technique, as seen here in Brazil.

Allocating fishing rights

Territorial use rights in fisheries (TURF) are an alternative to centralized approaches to fisheries management. Here, individual users or specific user groups, such as cooperatives, are allocated a long-term and exclusive right to fish a geographically limited area of the sea. Catches and fishing effort are decided upon by the individual fishermen or user groups.

This self-organization by the private sector can also help to achieve a substantial reduction in government expenditure on regulation and control. Users also have a vested interest in ensuring that they do not overexploit the stocks, as this is necessary to safeguard their own incomes in the long term. However, a use right for a stock of fish or other living resource in the ocean is exclusive only for non-migratory species such as crustacea and molluscs.

One example of successful management by means of territorial use rights is the artisanal coastal fishery in Chile, which mainly harvests bottom-living species, particularly sea urchins and oysters. Fishermen here have shown that they have a vested interest in pursuing sustainable fishing once they have the prospect of obtaining secure revenues from these fishing practices over the long term.

Toward more sustainable fisheries

> In order to improve the situation and ensure that fish stocks are managed sustainably, the current approach to fisheries management urgently needs to be reformed. To protect fish stocks in the future, greater account must also be taken of the ecological linkages between various fish species and their habitats, as so far, stocks have tended to be viewed in isolation.

Tangible scope for improvement

In view of the weaknesses described, a reform of the existing approach to fisheries management is urgently needed. It would be sensible to start by applying the classic instruments used to regulate catches far more consistently and enforce them more effectively. It must be borne in mind, in this context, that a quota can only be effective if it is set at a sufficiently stringent level. In addition to better quota regimes, instruments such as the establishment of marine protected areas and certification of sustainable fisheries can also contribute to sustainable fisheries management.

Marine protected areas – havens for endangered species

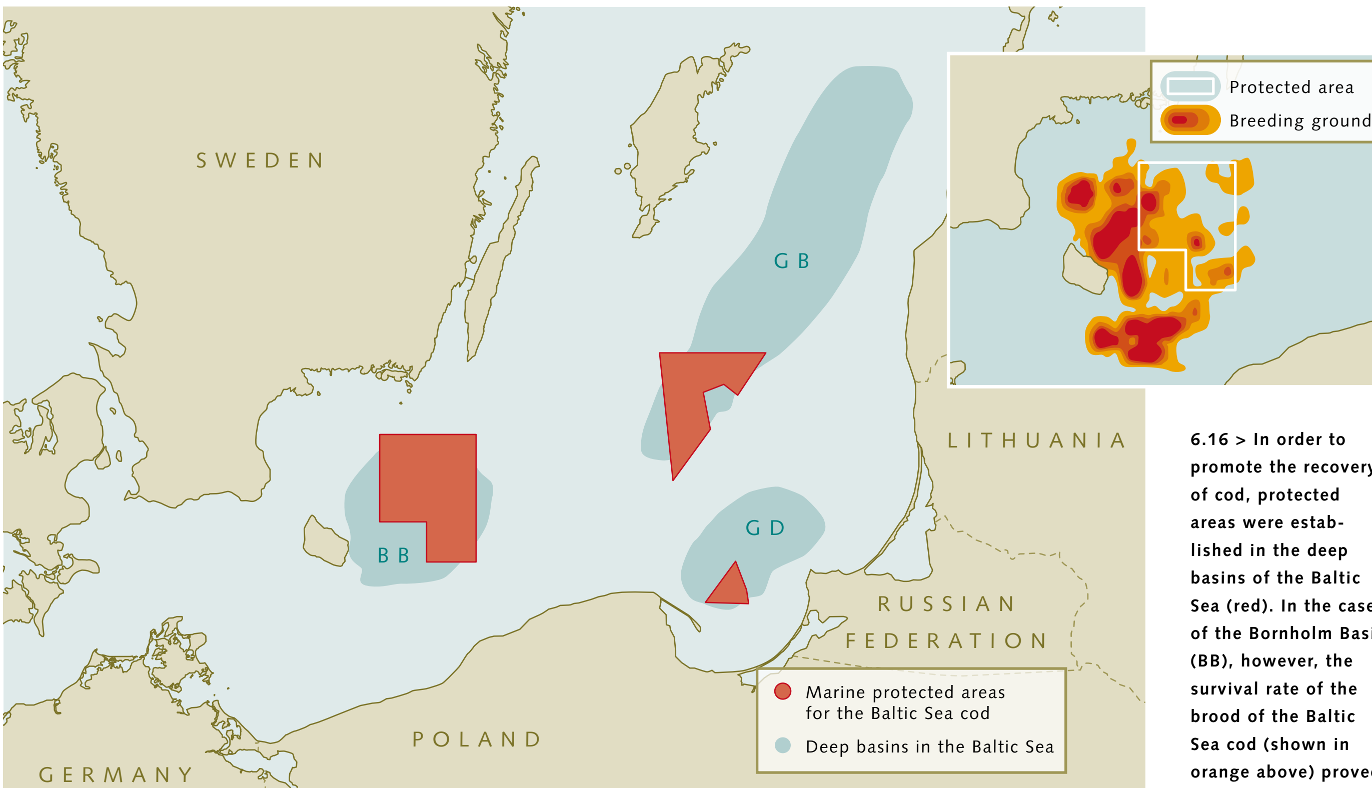
Marine protected areas are geographically defined areas of the sea in which all or some economic activities – especially fishing – are prohibited. Closing off these areas helps to conserve marine ecosystems, especially by protecting endangered species or unique habitats such as coral reefs. Since 2004, for example, the North East Atlantic Fisheries Commission (NEAFC) has banned the use of bottom trawls in some areas in order to protect cold-water corals.

Various studies have shown that marine protected areas can help to support the recovery of fish stocks. One advantage of protected areas is that they are relatively easy to establish and monitor. Satellite-based location and electronic logbook systems, known as Vessel Detection Systems (VDS) and Vessel Monitoring Systems (VMS), enable the routes taken by industrial fishing vessels to be tracked. However, one problem is defining the right size for the protected area. If the protected area is too small, its effect will be limited, as fish will migrate out of the protected area and will be caught elsewhere. And indeed, a higher level of fishing activity has been observed on the periphery of existing protected areas compared with elsewhere. If it is too large, however, the stock may recover within the protected area, but this does not benefit the fishery, which has no access to these increased fish stocks.

It would seem that areas providing refuge for juveniles are most suitable as protected areas for the purpose of fisheries management. Heavily overfished maritime regions, where very few fish can be caught in any case, may also be suitable for designation as marine protected areas. However, the refuge areas used by the juveniles of various species are often distributed across many different maritime regions, so a single protected area may not always help to protect several species at once.

The difficult quest for the right protected area – the case of the Baltic Sea cod

It is extremely difficult to determine exactly which region is the right one in which to establish a marine protected area, as the example of the Baltic Sea cod clearly illustrates. As a result of severe overfishing and unfavourable environmental conditions such as oxygen depletion in the deep water, stocks of Baltic Sea cod massively declined in the 1980s, falling to around one-seventh of their former levels within just a few years. Despite some



6.16 > In order to promote the recovery of cod, protected areas were established in the deep basins of the Baltic Sea (red). In the case of the Bornholm Basin (BB), however, the survival rate of the brood of the Baltic Sea cod (shown in orange above) proved to be highest outside the protected area.

recovery in recent years, stocks are still well below a level that would permit harvesting at maximum sustainable yield (MSY).

In order to constrain the fishing of spawning populations and stabilize the radically depleted stock, fishing bans were imposed in some areas of the Baltic Sea. The Bornholm Basin (BB) is particularly important for the continued existence of the Baltic Sea cod, as the survival rate of eggs and larvae in the more easterly spawning grounds such as the Gotland Basin (GB) and the Gdansk Basin (GD) is relatively low due to the often poor oxygen conditions here.

The fishing ban area in the Bornholm Basin was first established for the period from May to August 1995. Despite the progressive expansion of the protected area in subsequent years, however, no significant stock improvement was observed. The reason for this is that, although the protected area is located in an area of the sea with high spawning activity, current studies show that there are spatial differences in mortality. The highest survival rates of larvae and juveniles are, it seems, found on the margins of the Bornholm Basin, i.e. outside the current protected area.

This study suggests that the wrong location may possibly have been chosen for the protected area. As a consequence, the areas that are important for the survival of the species are inadequately protected, and there is even a risk that the protected area has a counterproductive effect, as fishing activity is now shifting to the major spawning grounds.

Despite these setbacks, however, protected areas are an important building block for the conservation or recovery of a stock. However, the example also shows that the establishment of protected areas is only really beneficial if it is based on adequate ecological and economic data.

6.17 > Cod is common throughout the North Atlantic. Its western stocks have been depleted by fishing, however. Protected areas for cod have been established in the Baltic Sea.

Certification of sustainable fisheries

The complex economic interactions between the various influencing factors, such as consumer demand for different species of fish, are often still not considered in conventional fisheries management. For this reason, non-governmental organizations and some initiatives supported by the private sector are opting for a different solution.

Their aim is to influence consumer demand by means of information campaigns and the certification of sustainable fishery products with a view toward reducing demand for overexploited species, and encouraging consumers to choose products from sustainable fisheries instead. The idea is to encourage producers, over the long term, to respond to this shift in consumer demand and switch to more sustainable methods of production.

Certification is therefore conditional upon fulfilment of specific production criteria, such as a commitment to refrain from fishing endangered stocks and from deploying destructive fishing techniques that have attracted particular criticism, such as the use of beam trawls, which destroy seabed habitats. Two of the best-known movements are the Marine Stewardship Council and the Friend of the Sea initiative.

The Marine Stewardship Council (MSC) was founded in 1997 by an environmental organization and an international food corporation, and has operated on an independent basis since 1999. The Friend of the Sea initiative was also established by an environmental organization and is notable for the fact that it certifies aquaculture products as well. Critics of these certification schemes complain about the often inadequate ecological criteria established for certified fishery products. A further point of contention is to what extent demand for certified fish is genuinely replacing the demand for conventionally caught fish, or whether it is in fact generating additional demand for fishery products.

Overall, then, demand-oriented approaches may be a good way of enhancing sound fisheries management, but are not an sufficient solution on their own to guarantee sustainable fisheries.

6.18 > The Marine Stewardship Council was established by the nature conservation organization WWF and the food corporation Unilever in 1997 in order to promote responsible fishing.

Conclusion

Is sustainable fishing feasible?

Fishing contributes significantly to our food supply and provides a source of income for millions of people. Most fish stocks worldwide, however, have been fished to the limits of their capacity or beyond. In the interest of sustainable fishing, it would be sensible to start by applying the classic instruments used to regulate catches far more consistently than hitherto, and to enforce them more effectively. It must be borne in mind, in this context, that a quota can only be effective if it is set at a sufficiently stringent level. The basic prerequisites for a sustainable and efficient fishing industry are effective national and international institutions to establish and monitor fisheries policy. One of the greatest challenges arising in the future will be to achieve a better understanding of the connections between human influence on the ecosystems and the development of natural resources, in order to establish a sustainable and economically viable marine fisheries sector. Furthermore, successful fisheries management must take account of the economic interactions between various fisheries.

Maintaining natural resources is, ultimately, the key prerequisite for achieving long-term and sustainable revenues. Successful fisheries management will increase the profitability and productivity of the fishing industry. If stocks are given the chance to recover, this will also benefit the industry. Much higher yields could then be achieved in the long run, at greatly reduced fishing costs.

7 Marine minerals and energy

> Our appetite for energy and mineral resources seems insatiable. As land-based resources become increasingly scarce, those in the oceans are attracting greater interest. The fuels and ores in the deep sea are particularly tempting. But wind and wave power could also meet a proportion of our energy needs.

Fossil fuels

> Oil and natural gas are the key resources powering industrial societies. But deposits are dwindling and prices are rising. For this reason oil companies are turning their attention to resources which were previously thought too difficult and expensive to tap: the oil and gas deposits deep in the oceans. Already, more than a third of the oil and gas extracted worldwide comes from offshore sources.

Reliance on oil and gas

Without natural gas, oil and coal, our world would stand still. Scarcely a car, a train or a ship would be seen. Computers would shut down and the lights would go out in most offices. Today's industrial nations are almost entirely dependent on fossil fuels, and energy consumption around the world has risen by about 70 per cent over the past three decades. The International Energy Agency (IEA) in Paris estimates that consumption will increase by at least another 50 per cent by 2030. The greatest consumers are the USA, China and Russia, but here too the demand for energy will continue to escalate.

The growing demand and increasing prices can be expected to fuel interest in the oil and gas deposits buried deep in the oceans, previously considered too expensive to extract.

Formation and exploration of fossil fuels

Gas and oil form in the sea over a period of millions of years, as the remains of animals and plants sink to the ocean floor. Combined with particles flushed from the land, they are buried and compressed into layers of sediment several kilometres thick on the ocean floor. Aided by the Earth's pressure and temperature conditions, bacteria convert the biomass into precursor substances from which hydrocarbons are ultimately formed. These hydrocarbons can permeate certain layers of rock and sediment as they move up towards the surface, in a process called migration. In some cases they become trapped in impermeable layers of rock, which is where the actual deposits are ultimately formed. Depending on the ambient conditions, oil or natural gas develops.

Today's sources of fossil fuels are between 15 and 600 million years old. During this period the continental plates shifted, transforming oceans into landmasses, with the result that mineral deposits can be found both on land and at sea. Oil and gas are usually found where vast layers of sediment cover the ocean floor.

These days seismic equipment is used to prospect for new reserves. This equipment generates sound waves which are reflected back from the layers of rock and sediment in the ground. From the sound waves geologists can estimate whether the layers could contain oil or natural gas. At sea the sound waves are generated by what is known as an airgun, which works with compressed air. The echoes reflected back are received via hydrophones on the ocean floor or the research vessel.

The future of oil lies in our oceans

Since industrial oil extraction began in the mid-19th century, 147 billion tonnes of oil have been pumped from reserves around the world – half of it during the past 20 years. In 2007 alone, oil consumption worldwide reached a total of about 3.9 billion tonnes. There is no doubt that extraction will soon be unable to keep pace with annually increasing needs. Experts anticipate that in the next 10 years so-called "peak oil" will be reached, the point at which the world's oil supplies go into irreversible decline.

Currently the conventional oil reserves – i.e. those which can be recovered easily and affordably using today's technology – are estimated to be a good 157 billion tonnes. Of this amount, 26 per cent (41 billion tonnes) are to be found in offshore areas. In 2007 1.4 billion tonnes of oil, the equivalent of about 37 per cent of annual oil production, was derived from the ocean. The proportion of offshore production is therefore already relatively high. The most productive areas are currently the North Sea and the Gulf of Mexico, the Atlantic Ocean off Brazil and West Africa, the Arabian Gulf and the seas off South East Asia.

For some years now the trend has been towards drilling in deeper and deeper water. In 2007 oil was extracted from 157 fields at depths of more than 500 metres. In 2000 there were only 44 such fields. Of these, 91 per cent are situated in the so-called Golden Triangle in the Atlantic between the Gulf of Mexico, Brazil and West Africa. While the output of the relatively shallow waters of the North Sea (average depth 40 metres) will reduce in the coming years, production is likely to increase elsewhere, particularly in the Golden Triangle, off India, in the South China Sea and the Caspian Sea off Kazakhstan.

The deeper marine areas therefore harbour additional potential for the future. Experts estimate that the offshore trend will accelerate as oil becomes increasingly scarce. The downside here is that extraction is complex and expensive. For instance, extraction from fields at great depths requires floating production and drilling vessels, or pumping stations permanently mounted on the ocean bed.

	IEA (2008) USD per barrel	Petrobras (2008) USD per barrel
Middle East	3–14	7–19
CIS States	n.s.	15–35
Deep sea	32–65	23–45
Enhanced Oil Recovery	30–82	25–63
Arctic	32–100	25–50
Other regions	10–40	12–30

7.1 > Extraction costs of conventional oil by type and region according to IEA and Petrobras estimates (enhanced oil recovery = improved oil production in mature oil fields).

Offshore gas prospects

The consumption of natural gas is also steadily growing. In 2007 global consumption was a good 3 trillion cubic metres, about 520 billion cubic metres more than in 2001. As a comparison, the average German house-hold uses about 3500 cubic metres of gas each year. The greatest consumers of natural gas are the USA, which accounts for about a quarter of world gas consumption, followed by Russia, Iran, Japan and Germany.

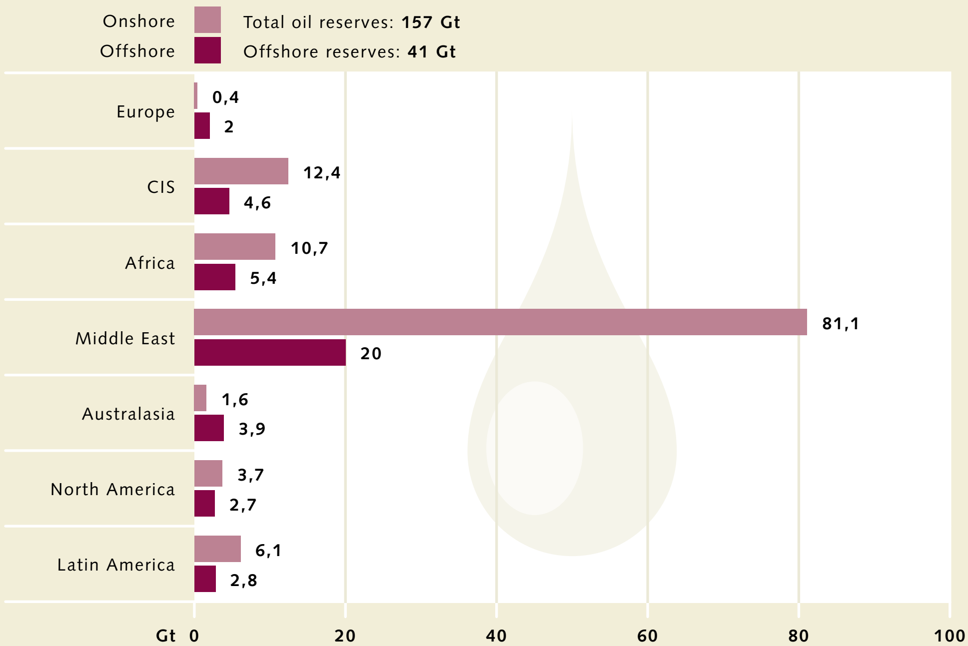
Occurrences of natural gas are very unevenly distributed around the globe. As far as onshore deposits are concerned, almost three quarters of the world's reserves are concentrated in the Commonwealth of Independent States (CIS) and the Middle East. Offshore it is a slightly different story. The frontrunner is the Middle East, which harbours considerably more gas in the ocean floor than in its land-based reserves.

The South Pars / North Dome field located on the Iranian border with Qatar in the Persian Gulf is considered the world's largest reserve of natural gas, with an estimated 38 trillion cubic metres. This amount is phenomenal considering that the total reserves of natural gas worldwide are thought to be 183 trillion. Other potentially important offshore regions are the North Sea, the Gulf of Mexico, Australasia, Africa and the CIS states, along with the Golden Triangle where gas is also produced as a by-product of the oil industry.

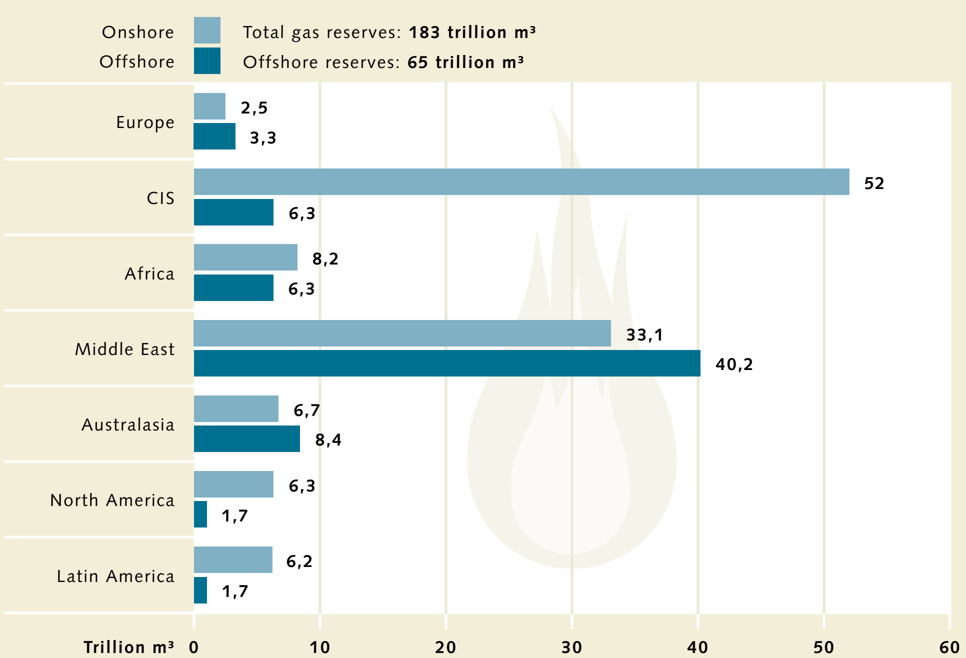
The North Sea is still the most important gas-producing area, but it will be overtaken by other regions in the years to come. Extraction will pick up in the Middle East in the near future, as well as off India and Bangladesh, Indonesia and Malaysia.

Offshore gas production of 65 trillion cubic metres currently accounts for a good third of the worldwide total, and this figure will continue to rise. Between 2001 and

Reserves and resources
"Reserves" are mineral deposits which have been accurately measured and which can be extracted economically using current technology. In contrast, "resources" are mineral deposits which are geologically proven, but which are not currently feasible for economic extraction, and also those deposits which have not yet been ascertained with certainty, but which can reasonably be expected to occur based on the geological characteristics of the area.



7.2 > Geographic distribution of conventional oil reserves 2007 onshore and offshore by region



7.3 > Geographic distribution of conventional natural gas reserves 2007 onshore and offshore by region

2007 it grew by just under 20 per cent, of which about a quarter each came from the North Sea and Australasia, and about 15 per cent from the Gulf of Mexico and the Middle East. As with oil, the trend is clear: offshore production is growing more strongly than onshore production. Drilling operations are also moving into greater water depths. The Cheyenne gas field in the Gulf of Mexico currently holds the record, producing from a depth of 2740 metres.

Getting gas across oceans: Liquefied natural gas

Liquefied natural gas (LNG) plays a crucial role in humankind's conquest of the sea. It is cheaper to ship cooled and liquefied natural gas across the oceans in huge tankers than through pipelines. LNG already accounts for a quarter of today's global trade in gas. In future, natural gas is more likely to be moved by ship than overland through pipelines. On land it is cheaper to use pipelines of up to about 3000 kilometres in length than to liquefy the gas and transport it by sea. On the seabed, however, pipelines are uneconomical from the first metre onwards. Shipping the liquefied natural gas from the offshore extraction plant to the land is much more cost-effective.

An LNG plant liquefies natural gas by cooling it to about minus 160 degrees Celsius. This process consumes large amounts of energy and contributes significantly to the cost of the LNG transport chain. Nonetheless, it is clear that the LNG proportion of the natural gas trade will substantially increase in future. The market is expected to grow by 8 per cent annually over the next 15 years, and to expand more strongly than the pipeline gas trade. Several liquefaction facilities are already in operation.

Recently an LNG plant began operations in Norway, liquefying gas from the Barents Sea. First the natural gas is pumped from the "Snø-hvit" ("Snow White") gas field to dry land at Hammerfest where it is processed. The first LNG facilities will also soon be built directly over the gas fields off the West African coast. Tankers will be able to berth on the spot.

The Arctic region, a special case

As the Arctic sea ice melts as a result of climate change (Chapter 1), hopes are growing among Arctic nations of tapping the oil and natural gas deposits in the northern polar regions. Current scientific studies suggest that the area harbours substantial resource deposits. It is estimated that about 30 per cent of undiscovered gas and 13 per cent of undiscovered oil can be found in the marine areas north of the Arctic Circle. According to scientists, the considerable gas deposits are located mainly in Russian waters. In contrast, the relatively small quantities of oil are hardly likely to impact greatly on world oil production.

As yet, nobody can say whether or when extraction will begin in the Arctic, especially as various legal questions have yet to be clarified (see Chapter 10). Also, production is not yet viable in these undeveloped areas as prospecting will require complex and expensive operations using icebreakers.

The finite nature of oil and natural gas

What is certain is that the extraction of oil and natural gas from the world's oceans will increase in future. The technology is already well-established, but the costs involved are still much higher than for onshore or shallow water production. As the world's reserves of oil and gas run short and prices increase, however, hitherto unprofitable sources will become more economic to exploit. Offshore fields will be able to contribute significantly to meeting the future energy needs of our industrial society.

Nobody knows for certain how long the global reserves and resources of oil and gas will last – particularly as it is difficult to predict future consumption trends. For example, from today's perspective, resources of natural gas will probably be adequate to ensure supply well into the second half of this century. But if natural gas is used to power motor vehicles or generate electricity in power stations, the reserves could be exhausted much more quickly.

Marine minerals

> Natural gas and oil have been extracted from the seas for decades, but the ores and mineral deposits on the sea floor have attracted little interest. Yet as resource prices rise, so too does the appeal of ocean mining. The excavation of massive sulphides and manganese nodules is expected to begin within the next few years.

The sea floor – humankind's resource repository

The oceans hold a veritable treasure trove of valuable resources. Sand and gravel, oil and gas have been extracted from the sea for many years. In addition, minerals transported by erosion from the continents to the coastal areas are mined from the shallow **shelf** and beach areas. These include diamonds off the coasts of South Africa and Namibia as well as deposits of tin, titanium and gold along the shores of Africa, Asia and South America.

Continental plates
The Earth's crust is made up of numerous continental plates that are in permanent motion. They move a few centimetres each year. This continental drift means that plates are veering away from each other in some places. At these plate boundaries the Earth's crust is splitting apart. Fresh magma is continuously being extruded from the fissures and, over time, it piles up on the ocean floor to form large undersea ridges.

Efforts to expand ocean mining into deep-sea waters have recently begun. The major focus is on manganese nodules, which are usually located at depths below 4000 metres, gas hydrates (located between 350 and 5000 metres), and cobalt crusts along the flanks of undersea mountain ranges (between 1000 and 3000 metres), as well as massive sulphides and the sulphide muds that form in areas of volcanic activity near the plate boundaries, at depths of 500 to 4000 metres.

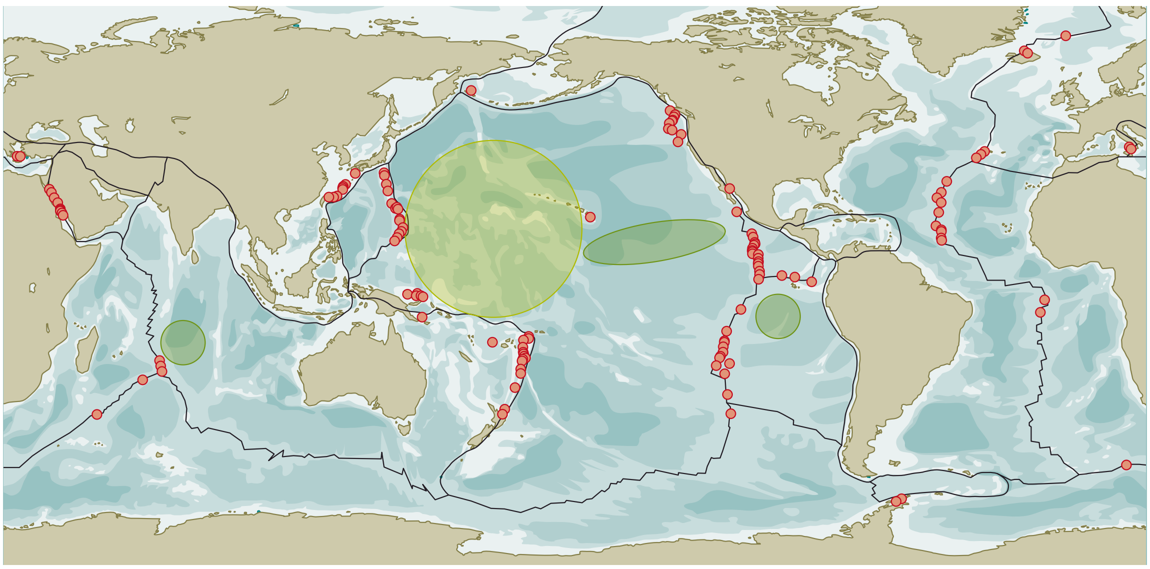
Back in the early 1980s there was great commercial interest in manganese nodules and cobalt crusts. This initial euphoria over marine mining led to the International Seabed Authority (ISA) being established in Jamaica, and the United Nations Convention on the Law of the Sea (UNCLOS) being signed in 1982 – the "constitution for the seas". Since entering into force in 1994, this major convention has formed the basis for signatories' legal rights to use the marine resources on the sea floor outside national territorial waters (Chapter 10).

After that, however, the industrial countries lost interest in resources. For one thing, prices dropped – making it no longer profitable to retrieve the accretions from the deep sea and utilize the metals they contained. Also, new onshore deposits were discovered, which were cheaper to exploit. The present resurgence of interest is due to the sharp increase in resource prices and attendant rise in profitability of the exploration business, and in particular to strong economic growth in countries like China and India which purchase large quantities of metal on world markets.

Even the latest economic crisis is not expected to slow this trend for long. The industrial and emerging countries' geopolitical interests in safeguarding their supplies of resources also play a role. In light of the increasing demand for resources, those countries which have no reserves of their own are seeking to assert extraterritorial claims in the oceans.

Manganese nodules

Covering huge areas of the deep sea with masses of up to 75 kilograms per square metre, manganese nodules are lumps of minerals ranging in size from a potato to a head of lettuce. They are composed mainly of manganese, iron, silicates and hydroxides, and they grow around a crystalline nucleus at a rate of only about one to 3 millimetres per million years. The chemical elements are precipitated from seawater or originate in the pore waters of the underlying sediments. The greatest densities of nodules occur off the west coast of Mexico (in the Clarion-Clipperton Zone), in the Peru Basin, and the Indian Ocean. In the Clarion-Clipperton Zone the manganese nodules lie on the deep-sea sediments covering an area



Continental plate margins
Distribution of cobalt crusts
Occurences of manganese nodules
Occurences of black smokers

Depth below sea level
– 2000 m
– 4000 m
– 6000 m
deeper than 6000 m

7.4 > The sea floor contains extensive resources. They are concentrated in certain regions depending on how they were formed.

of at least 9 million square kilometres – an area the size of Europe. Their concentration in this area can probably be attributed to an increased input of manganese-rich minerals through the sediments released from the interior of the Earth at the **East Pacific Rise** by hydrothermal activity – that is, released from within the Earth by warm-water seeps on the sea floor and distributed over a large area by deep ocean currents.

Manganese nodules are composed primarily of manganese and iron. The elements of economic interest, including cobalt, copper and nickel, are present in lower concentrations and make up a total of around 3.0 per cent by weight. In addition there are traces of other significant elements such as platinum or tellurium that are important in industry for various high-tech products.

The actual mining process does not present any major technological problems because the nodules can be collected fairly easily from the surface of the sea floor. Excavation tests as early as 1978 were successful in transporting manganese nodules up to the sea surface. But before large-scale mining of the nodules can be carried out there are still questions that need to be answered. For one, neither the density of nodule occurrence nor the variability of the metal content is accurately known. In addition, recent investigations show that the deep seabed is not as flat as it was thought to be 30 years ago. The presence of numerous volcanic elevations limits the size of the areas that can be mined.

Furthermore, the excavation of manganese nodules would considerably disturb parts of the seabed. The projected impact would affect about 120 square kilometres of ocean floor per year, an area the size of the city of Kiel. Huge amounts of sediment, water, and countless organisms would be dug up with the nodules, and the destruction of the deep-sea habitat would be substantial. It is not yet known how, or even whether, repopulation of the excavated areas would occur.

Since 2001 several permits have been issued to governmental institutions by the ISA to survey manganese fields. These are not for actual mining but for a detailed initial investigation of the potential mining areas. In

Cross-section view of a manganese nodule: Over millions of years, minerals are deposited around a nucleus.

2006 Germany also secured the rights to a 150,000 square kilometre area – twice the size of Bavaria – for a period of 15 years. Last year, for the first time, industrial companies also submitted applications for the exploration of manganese nodule fields in the open sea in cooperation with developing countries (Kingdom of Tonga, Republic of Nauru).

Cobalt crusts

Cobalt crusts form at depths of 1000 to 3000 metres on the flanks of submarine volcanoes, and therefore usually occur in regions with high volcanic activity such as the territorial waters around the island states of the South Pacific. The crusts accumulate when manganese, iron and a wide array of trace metals dissolved in the water (cobalt, copper, nickel, and platinum) are deposited on the volcanic substrates.

Their growth rates are comparable to those of manganese nodules. The cobalt crusts also contain relatively small amounts of the economically important resources. Literally tonnes of raw material have to be excavated in order to obtain significant amounts of the metals. However, the content of cobalt (up to 2 per cent) and platinum (up to 0.0001 per cent) is somewhat higher than in manganese nodules. Extracting cobalt from the ocean is of particular interest because it is found on land in only a few countries (Congo, Zaire, Russia, Australia and China), some of which are politically unstable. Alternative marine prospects could reduce our dependence on supplies from these countries.

Technologically, the mining of cobalt crusts is much more complex than manganese nodules. For one, it is critical that only the crust is removed, and not the underlying volcanic rocks. In addition, the slopes of the volcanoes are very ragged and steep, which makes the use of excavation equipment more difficult. It is therefore not surprising that cobalt crust mining is only at the conceptual stage at present. Cobalt crust mining would also have a significant impact on the benthic organisms. It is therefore vital that prior environmental impact studies are carried out. In most cases monitoring by the International Seabed Authority (ISA) is not possible because many cobalt occurrences are located within the territorial waters of various countries.

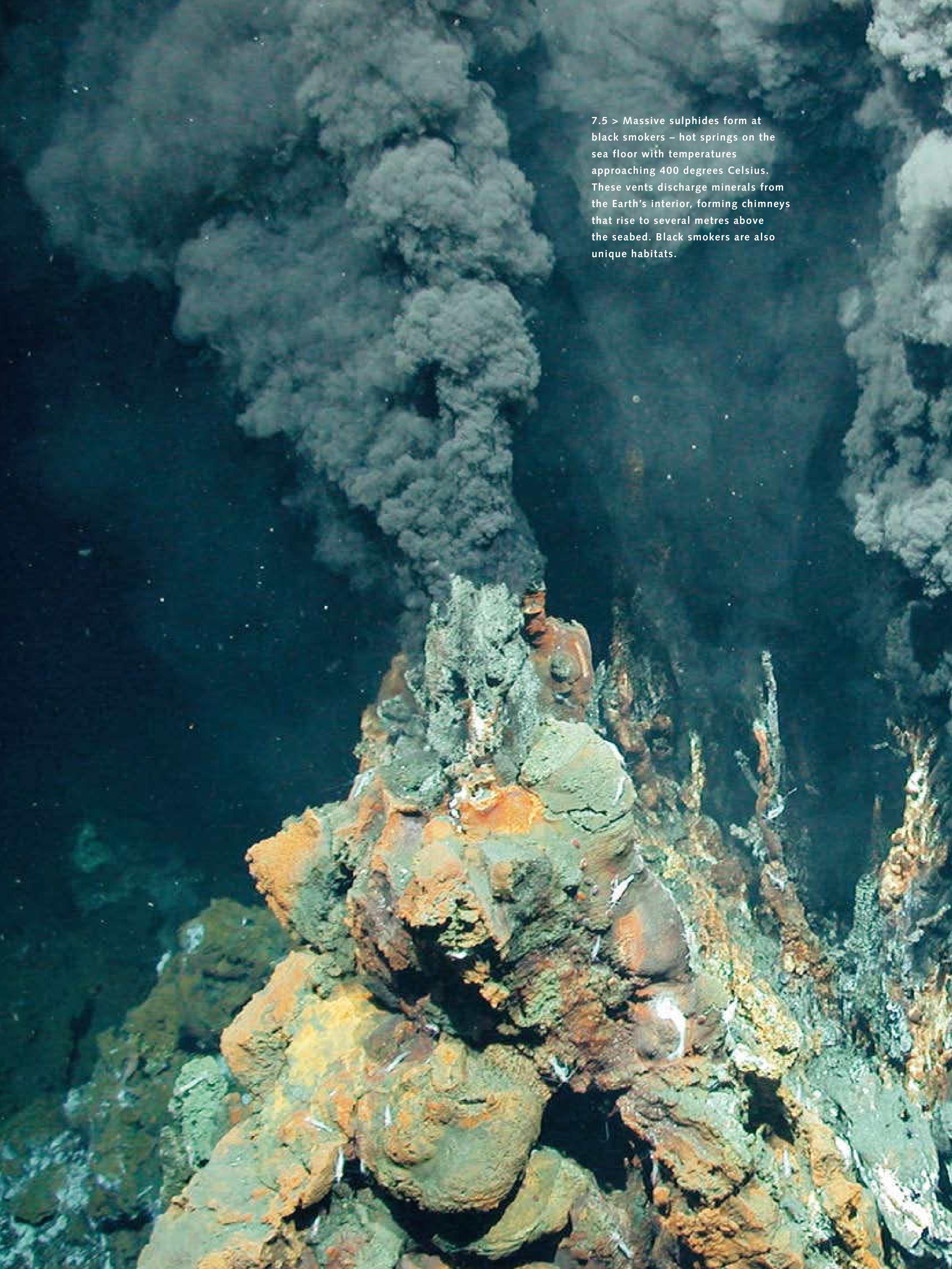
Massive sulphides

The third resource under discussion is a sulphur-rich ore that originates at "black smokers". These occurrences of massive sulphides form at submarine plate boundaries, where an exchange of heat and elements occurs between rocks in the Earth's crust and the ocean due to the interaction of volcanic activity with seawater.

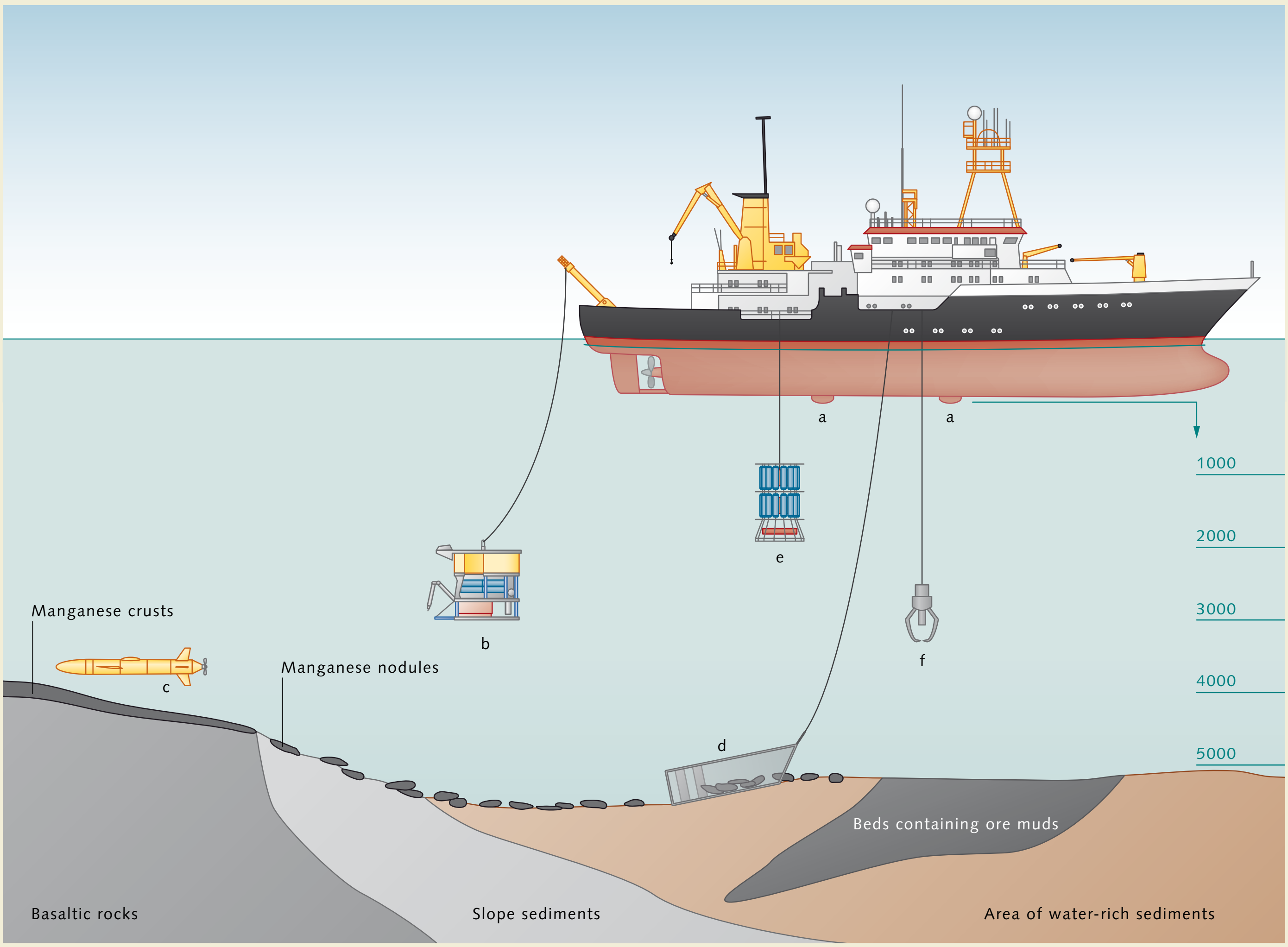
Cold seawater penetrates through cracks in the sea floor down to depths of several kilometres. Near heat sources such as magma chambers, the seawater is heated to temperatures exceeding 400 degrees Celsius. Upon warming, the water rises rapidly again and is extruded back into the sea. These hydrothermal solutions transport metals dissolved from the rocks and magma, which are then deposited on the sea floor and accumulate in layers. This is how the massive sulphides and the characteristic chimneys ("black smokers") are produced.

These were first discovered in 1978 at the East Pacific Rise. For a long time it was thought that massive sulphides with mining potential were only formed on **mid-ocean ridges**, because the volcanic activity and heat production here are especially intense. But since then more than 200 occurrences worldwide have been identified. Experts even estimate that 500 to 1000 large occurrences may exist on the sea floor. But there are also great differences in size. Most occurrences are only a few metres in diameter and the amount of material present is negligible.

So far only a few massive sulphide occurrences which are of economic interest due to their size and composition are known. While the black smokers along the East Pacific Rise and in the central Atlantic produce sulphides comprising predominantly iron-rich sulphur compounds – which are not worth considering for deep-sea mining – the occurrences in the southwest Pacific contain greater amounts of copper, zinc and gold. They are also located in comparatively shallow water (less than



7.5 > Massive sulphides form at black smokers – hot springs on the sea floor with temperatures approaching 400 degrees Celsius. These vents discharge minerals from the Earth's interior, forming chimneys that rise to several metres above the seabed. Black smokers are also unique habitats.



7.6 > A wide variety of instruments is used to explore the sea floor in the search for resources.

a. A depth profile of the sea floor is produced using an echo sounder.
b. Remotely-operated vehicles (ROVs) are equipped with cameras and grabbing arms. These are used to produce images of the sea floor and collect rock samples.
c. Autonomous underwater vehicles (AUVs) can dive down to the sea floor. They are equipped with echo sounders and various measurement sensors, and return to the ship after a deployment of about 20 hours.
d. Large samples are collected by a dredge towed behind the ship as it can hold more material than a grab sampler.
e. Multirosettes are used to take water samples at different depths and to measure physical and chemical parameters.
f. Individual bottom samples, including small boulders, can be collected by grab samplers deployed directly from the ship. These instruments are equipped with cameras to facilitate underwater orientation.

2000 metres) and lie within the exclusive economic zones of nations near them (Chapter 10), which makes the possible mining more technologically and politically feasible. This is because a country can decide for itself with respect to the mining of marine resources within its own exclusive economic zone. The deep sea floor outside these sovereignty limits, however, is overseen by the International Seabed Authority (ISA; Chapter 10).

Present mining scenarios primarily envision the exploitation of cooled, inactive massive sulphide occurrences that are only sparsely populated by living organisms. Active black smokers are rejected for the time being because most of them contain only comparatively minor amounts of resources. Furthermore, because of the nutrient rich waters rising from below, they provide an important habitat for numerous, and in part, endemic organisms.

The largest known sulphide occurrence is located in the Red Sea, where tectonic forces are pulling Africa and the Arabian Peninsula apart. Here, the sulphides are not associated with black smokers, but appear in the form of iron-rich ore muds with high contents of copper, zinc and gold. This occurrence, at a water depth of about 2000 metres, was discovered in the 1960s. Because of its muddy consistency, it appears that these deposits will not prove problematic to mine, and this was successfully tested in the 1980s.

Of the three sea floor resources discussed here, massive sulphides are the least abundant in terms of total volume, but they are of particular interest because of their high resource content. Some mining companies have already obtained exploration licences in national waters, and are advancing the technology for prospecting and extraction. In May 2010 the ISA even has granted one exploration licence in the Indian Ocean to China. So far only permits for research have been granted for the deep sea.

In the near future the mining of copper and gold from massive sulphides is likely to commence off the coasts of Papua New Guinea and New Zealand. Mining operations had been planned to start this year, but due to the present economic recession, major metal and mining companies have experienced a decline in turnover in spite of the relatively high prices of gold, and the projects were postponed at short notice. But a recovery of the metal market is expected for the future. The companies will therefore soon be able to proceed with their plans.

The future of marine mining

Of the three resource types waiting to be extracted from the deep sea, the mining of massive sulphides in the exclusive economic zones (200 nautical miles) of west Pacific nations (Papua New Guinea) seems to be most feasible at present. Despite the latest economic crisis, production could start in the next few years. Because of their relatively high content of valuable metals, the mining of massive sulphides may be profitable for some companies. But the metal content of the global massive sulphides is lower than that of the ore deposits on land. It is therefore unlikely that the marine mining of massive sulphides will have a significant impact on the global resource supply.

Manganese nodules and cobalt crusts present quite different prospects. The amounts of copper, cobalt and nickel they contain could without doubt rival the occurrences on land. In fact, the total cobalt is significantly more than in all the known deposits on land. About 70,000 tonnes of cobalt are presently mined on land each year and the worldwide supply is estimated at about 15 million tonnes. By comparison, a total of about 1000 million tonnes of cobalt is estimated to be contained in the marine manganese nodules and cobalt crusts.

In spite of these immense resources, sea floor mining will only be able to compete with the substantial deposits presently available on land if there is sufficient demand and metal prices are correspondingly high. Furthermore, the excavation technology has yet to be developed.

The serious technological difficulties in separating the crusts from the substrate, combined with the problems presented by the uneven sea floor surface, further reduce the economic potential of the cobalt crusts for the present. Therefore, it seems that marine mining of cobalt crusts should not be anticipated any time soon.

Methane hydrates

> Until 10 years ago, hardly anyone had heard of methane hydrates. But now these chemical compounds in the sea floor are mooted to be an energy source of the future. The amount of hydrate-bound u far exceeds the reserves in conventional deposits. However, methane hydrates are not only a potential energy source; they also pose a considerable climate risk.

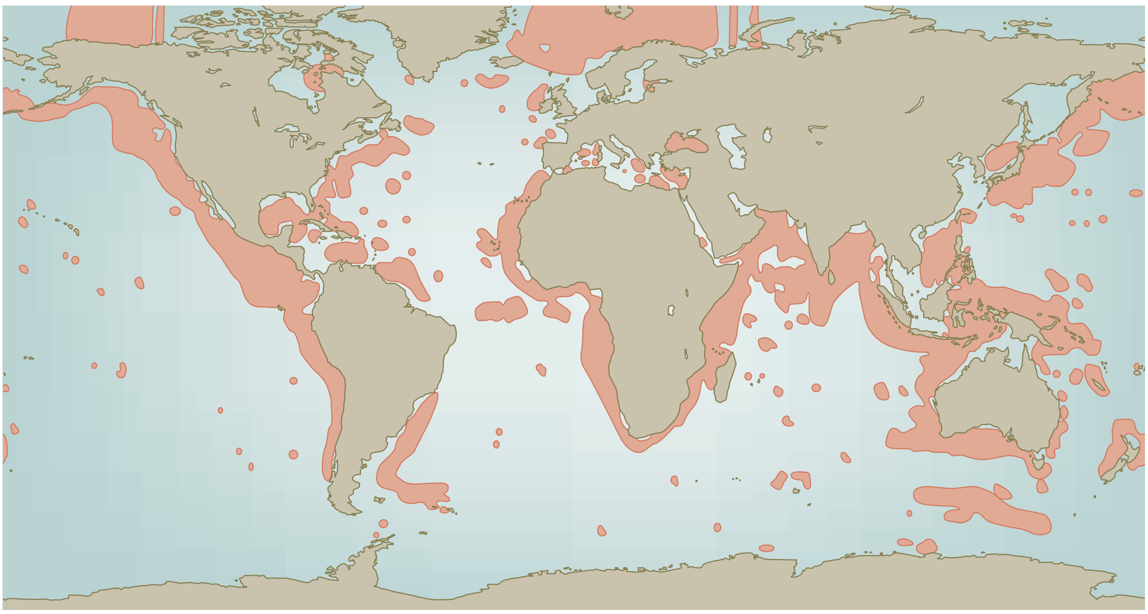
Breeding ground for methane hydrates: The sea floor

Methane hydrates are white, ice-like solids that consist of methane and water. The methane molecules are enclosed in microscopic cages composed of water molecules. Methane gas is primarily formed by microorganisms that live in the deep sediment layers and slowly convert organic substances to methane. These organic materials are the remains of **plankton** that lived in the ocean long ago, sank to the ocean floor, and were finally incorporated into the sediments.

Methane hydrates are only stable under pressures in excess of 35 bar and at low temperatures. The sea floor is thus an ideal location for their formation: the bottom waters of the oceans and the deep seabed are almost uniformly cold, with temperatures from 0 to 4 degrees Celsius. In addition, below a water depth of about 350 metres, the pressure is sufficient to stabilize the hydrates. But with increasing depth into the thick sediment layers on the sea floor the temperatures begin to rise again because of the proximity to the Earth's interior. In sediment depths greater than about 1 kilometre the temperatures rise to over 30 degrees Celsius, so that no methane hydrates can be deposited. This, however, is where the methane formation is especially vigorous. First, small methane gas bubbles are produced deep within the sediment. These then rise and are transformed to methane hydrates in the cooler pore waters near the sea floor. So the methane is formed in the deep warm sediment horizons and is converted and consolidated as methane hydrate in the cold upper sediment layers. No methane hydrates are found in marginal seas and shelf areas because the pressure at the sea floor is not sufficient to stabilize the hydrates. At the bottom of the expansive ocean basins, on the other hand, where the pressure is great enough, scarcely any hydrates are found because there is insufficient organic matter embedded in the deep-sea sediments. The reason for this is that in the open sea the water is comparatively nutrient poor, so that little biomass is produced to sink to the sea floor. Methane hydrates therefore occur mainly near the continental margins at water depths between 350 and 5000 metres. For one reason, enough organic material is deposited in the sediments there, and for another, the temperature and pressure conditions are favourable for methane to be converted to methane hydrates.

Greenhouse gas formation

Vast amounts of methane hydrate are buried in sediment deposits on the continental slopes. The total global amount of methane carbon bound up in these hydrate deposits is in the order of 1000 to 5000 gigatonnes – i.e. about 100 to 500 times more carbon than is released annually into the atmosphere by the burning of fossil fuels (coal, oil and gas). At low temperatures the methane hydrates on the sea floor are stable, but if the water and the sea floor become warmer, then the hydrates can break down. Because microorganisms then oxidize the resulting methane gas to form the greenhouse gas carbon dioxide (CO_2), methane hydrates have recently become a topic of intense discussion within the context of climate change. Methane, which itself acts as a strong green-



7.7 > It is known that methane hydrates are present throughout the world's oceans, primarily on the continental margins. Estimates of the total amounts of the deposits, however, are still very inexact.

house gas, does not escape directly out of the sea as methane because it is transformed into CO_2. But the formation and release of carbon dioxide are considerable. An additional problem is that the oxygen in seawater is consumed through the formation of carbon dioxide (Chapter 2).

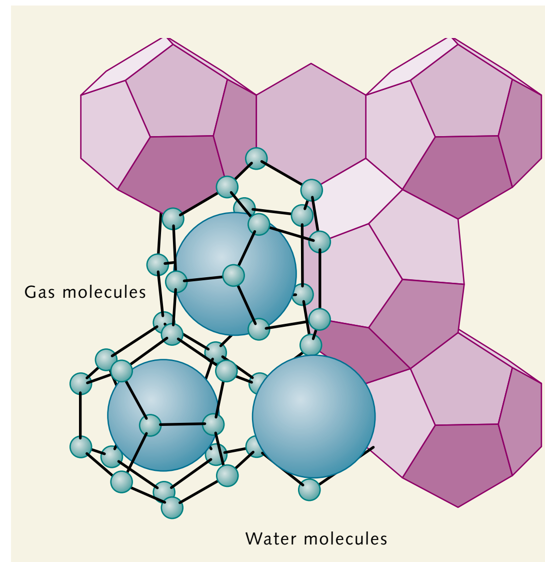
In 2008 British and German researchers discovered gas seeps at a depth of 350 metres on the continental slope off Spitsbergen that are probably fed by melting hydrates. Long-term measurements of the water temperatures off Spitsbergen indicate that the bottom-water masses and thus also the slope sediments have significantly warmed in recent decades. Models also predict that the sea floor in Arctic areas will continue to heat up in the coming decades and centuries due to climate change. Scientists therefore fear that large quantities of methane hydrate will melt there in the future, releasing increased amounts of CO_2 into the ocean and the atmosphere. The oxygen content of the seawater will decrease accordingly.

Furthermore, the CO_2 released not only contributes to further global warming, it also leads to acidification of the oceans (Chapter 2). Examples from the geological past support this scenario. Based on geological records it can be assumed that hydrates have broken down on a large scale numerous times in the Earth's history, leading to extreme global warming and massive extinctions of organisms on the sea floor. Further investigations are necessary to determine the scale at which changes in the climate and oceans will accelerate in the future due to the release of methane gas at the sea floor.

A future energy source?

Although the immense methane hydrate occurrences represent a risk to the climate, they are also a potential energy source. The amount of natural gas bound up in the hydrates far exceeds the natural gas reserves in conventional deposits. Natural gas fed into the supply lines from conventional sources already consists of more than 95 per cent methane. Until now, mining hydrates in the ocean has been considered an expensive process. As resource prices rise, however, these reserves are becoming more attractive to the offshore industry.

7.8 > Methane hydrates occur worldwide. This ice-like block with a honeycomb structure was obtained from the sea floor during a research expedition off the coast of Oregon.



7.9 > In methane hydrates, the methane gas molecules are tightly enclosed in cages composed of water molecules. Increasing temperatures render the cages unstable, the gas escapes.

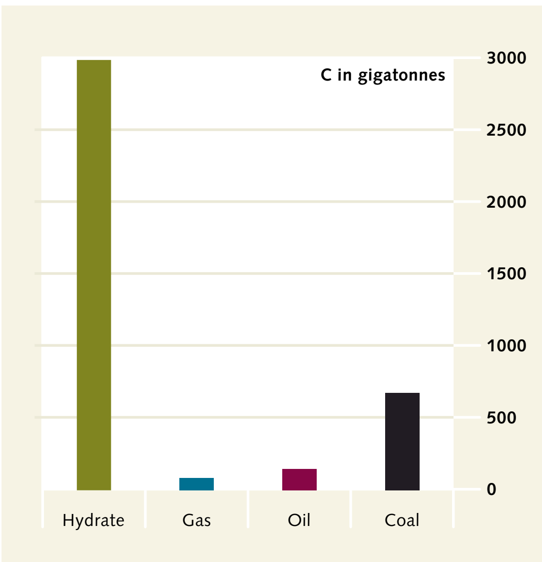
Many scientists estimate that mining the hydrates could be economically feasible at an oil price of about 50 to 60 US dollars per barrel. This implies that production would already be profitable today. Great efforts are presently being made to develop hydrate deposits, particularly in the territorial waters of Japan, China, India, South Korea and Taiwan.

Carbon dioxide storage in the ocean

At the same time, new technologies are being developed in Germany that may be useful for exploring and extracting the hydrates. The basic idea is very simple: the methane (CH_4) is harvested from the hydrates by replacing it with CO_2. Laboratory studies show that this is possible in theory because liquid carbon dioxide reacts spontaneously with methane hydrate. If this concept could become economically viable, it would be a win-win situation, because the gas exchange in the hydrates would be attractive both from a financial and a climate perspective.

Natural gas is a relatively clean fossil fuel. CO_2 emissions from gas-fired power plants are about 50 per cent lower than from conventional coal-fired plants. But even the emissions from modern gas-fired systems can be reduced considerably when CCS technology (carbon capture and storage) is installed. By this method the CO_2 is isolated directly at the power plant and is stored in underground geological formations.

Another option would be to inject the CO_2 into the marine methane hydrates; by this method, not only would methane gas be obtained, but the carbon dioxide would also be securely captured. Onshore, CO_2 is stored as a supercritical fluid that is mobile and chemically very aggressive. Some experts are concerned that underground storage reservoirs could therefore start to leak after a time. If, instead, carbon dioxide is stored as a hydrate within the cold deep sea floor, it would be much safer, because CO_2 hydrates are considerably more thermally stable than methane hydrates. Even warming of the sea floor would not destabilize them. But this approach also involves ecological risk. During hydrate



7.10 > The amount of carbon stored in methane hydrates at the sea floor (C in gigatonnes) far exceeds that stored in oil, gas and coal.

7.11 > A group of marine scientists on the deck of a research vessel ignite methane gas released from a degrading hydrate block.

excavation the methane could escape unchecked into the seawater. To eliminate this risk, only the very deep hydrate occurrences that are covered by fine-grained sediment layers at least 100 metres thick should be developed. This is the only way to enable the methane gas to be retrieved safely through a borehole without the possibility of its escaping into the environment.

In addition, care must be taken to ensure that the formation pressure is not increased by more than 10 bar during retrieval of the gas, as the sediment layers could otherwise break open and allow large amounts of methane to escape.

Is there a future for methane mining?

So far the necessary mining technology has only been tested under laboratory conditions. Many years of development work are still needed to be able to reliably evaluate the potentials and risks and to realize mining on an industrial scale. The extraction of natural gas from methane hydrates onshore was successfully tested for the first time in 2008 by Japanese and Canadian scientists. In northern regions, methane hydrates lie hundreds of metres beneath the permafrost sediments. It is cold enough and the pressure is sufficient for hydrates to form there too. In contrast to the deposits in the sea floor, however, these hydrate occurrences are easy to access and therefore suitable for production tests. The tests showed that it is possible to produce natural gas by breaking down methane hydrates through the introduction of heat or the release of pressure.

The retrieval of methane by replacement with carbon dioxide will now be tested onshore. A Norwegian-American consortium is set to carry out a production test in Alaska. The first offshore attempts are then planned for 2012 to 2014 on the continental slope off Japan. How and when methane hydrates are finally mined in the future depends on the results of these field investigations. And of course the development of world market prices for natural gas and **carbon dioxide emission rights** are also pivotal to any decisions to begin offshore mining on a major scale.

Renewable energies

> Until now, the expansion of renewable energies, such as wind and solar power, has mainly taken place onshore. The energy in the oceans has remained largely untapped. But things are changing. The production of environmentally friendly energy from the oceans is now being promoted worldwide. Expectations are high. It is hoped that wind, waves and ocean currents will meet a substantial share of the world's electricity needs.

An unretrieved treasure trove

The oceans are teeming with energy. Tidal forces move immense masses of water. Strong winds build up mighty waves. Almost 90 per cent of global wind energy is contained in the turbulence above the world's oceans. Wind, waves and currents together contain 300 times more energy than humans are currently consuming. For a long time, this abundance went untapped. In recent years, however, we have begun to harness this energy. The first offshore wind farms were built. Hundreds of power plants have been and are being built to convert ocean current and wave energy to electricity. The key renewable marine energies are:

- Wind energy;
- Wave energy;
- Tidal energy;
- Ocean current energy;
- Energy derived from temperature differences at various ocean depths (ocean thermal energy conversion – OTEC);
- Energy derived from the different salt content of freshwater and saltwater (osmotic power).

In theory, these energy resources could easily meet the energy needs of the entire human race. However, only a proportion of their potential can be utilized: many marine regions such as the deep sea are virtually impossible to develop, and the costs of cabling the power to the grid would be prohibitive.

Many of the potential locations in coastal areas can be ruled out because they are either reserved for the fishing industry, reserved for shipping, or they are protected areas. All the same, these renewable energies could still meet a significant share of the world's energy needs in future.

Offshore wind

Wind energy is currently at the most advanced stage of development, and the signs are extremely promising. Experts estimate that offshore wind power alone could in future supply about 5000 terawatt-hours (TWh) of electricity a year worldwide – approximately a third of the world's current annual electricity consumption of about 15,500 terawatt-hours (1 terawatt-hour = 1 trillion watts). It is anticipated that offshore wind energy plants (WEPs) alone in Europe will supply about 340 terawatt-hours a year by 2015.

About 40 offshore wind energy projects have so far been implemented worldwide, most of them in the United Kingdom, Denmark, the Netherlands and Sweden. Two trends are clear. One, that the facilities are getting bigger all the time, and two, that we are constantly venturing into deeper waters, which will allow the construction of wind farms over far greater areas. Whereas at the beginning of this century we were building in coastal areas at depths of 2 to 6 metres, wind turbine towers are now anchored to the ocean floor at depths of more than 40 metres.

Floating offshore concepts are also being developed for even deeper waters. The world's first floating wind energy plant was recently constructed off the coast of Norway by a Norwegian-German consortium. Backed by the experience of hundreds of thousands of onshore WEPs, wind energy has become a mature technology. The high wind speeds and harsh environmental conditions at sea, however, mean that some technological improvements are required, a fact borne out by the problems encountered by the first large-scale wind farm in Denmark. For this reason only twelve wind turbines from different manufacturers were initially built and tested at Germany's first offshore wind farm "Alpha Ventus". Located in the North Sea about 40 kilometres off the island of Borkum, the farm was sponsored by the German Federal Ministry of Economics.

Offshore plant is still considerably more expensive to construct than onshore due to the challenging foundation work and complicated connection to the power grid. Nonetheless, according to experts, offshore wind energy, supported by feed-in payments and support measures, will continue to grow substantially in the coming years.

Wave energy

The global technical potential of wave energy is estimated at 11,400 TWh per year. Its sustainable generating potential of 1,700 TWh per year equates to about 10 per cent of global energy needs. There are various different concepts for generating power from wave energy, most of which can be classified in three basic types:

- The "Oscillating Water Column" principle:
  Wave action causes water to move up and down in an air-filled chamber. The air is displaced and forced through a turbine which generates electricity. Pilot plants of this type were set up in recent years in Portugal, Scotland and Japan.
- The "Oscillating Bodies" principle:
  Facilities of this type use the motion of ocean waves to generate electricity. They include semi-submerged generators on which a float on a fixed counterbearing moves either sideways or up and down. Other systems consist of flexible mounted components that move against each other, putting hydraulic oil under pressure. The oil in turn drives a turbine. Recently, the British "Pelamis" system, a type of sea snake composed of several segments that float on the water's surface, created quite a stir. Pelamis, the world's first wave energy system, was established off the coast of Portugal in 2008 and is connected to the power grid by an undersea cable. Similar farms are planned in Spain and Portugal.
- The "Overtopping" principle:
  Similar to a dam, overtopping devices have a reservoir that is filled by incoming waves to levels above the surrounding ocean. The energy of the water falling back to the ocean is used to drive a turbine. Prototypes of both floating and fixed systems have already been installed in Denmark and Norway.

The right location for green power

In future, before energy systems can be built in the sea, environment impact assessments must be made to determine how the technology will affect the marine environment. Many suitable locations are likely to be ruled out on environmental grounds. Experts therefore differentiate between the technical potential of an energy technology and its sustainable potential. The technical potential includes all the plant locations which are theoretically feasible. The sustainable potential looks at environmental factors, such as the damage a tidal power plant may cause to stretches of river, thus eliminating some locations. The sustainable potential is accordingly lower than the technical potential. Experts are calling for marine spatial planning for ocean-based renewable technologies to be simplified. Until now, separate approval processes have applied to wind energy and wave energy facilities respectively. To shorten decision-making processes, it would make sense to incorporate several energy production technologies in spatial planning at the same time, rather than individual wind farms, thereby designating areas for renewable marine power generation as a whole. This would make it much easier to combine different technologies in a single marine area – for instance, wind turbine towers which also incorporate ocean current plants.

Tidal energy

Tidal power plants work in a similar way to power plants at a reservoir – except that the water masses do not flow downhill but are moved back and forth with tidal flows. Unlike other forms of ocean energy, tidal energy has been utilized commercially for some time. The La Rance tidal power station began operations in 1966 at St. Malo on the Atlantic coast in northern France, where the La

Rance River flows into the sea. At high tide the water flows upstream through the large turbines of the power station, and at low tide it flows downstream again. The 240 megawatt (MW) power station (1 megawatt = 1 million watts) has a similar output to a gas-fired power station. Similar facilities have been constructed in Canada, China and Russia over the past 20 years, although these are considerably smaller. A 260 MW tidal power station integrated in an existing dam is scheduled to come onstream in South Korea this year.

The United Kingdom has been planning to construct a major tidal power station at the estuary of the River Severn between England and Wales for some time. The location could supply enough energy to meet 7 per cent of the United Kingdom's entire power needs. However, critics fear that the construction of the dams could devastate vital nature reserves and bird sanctuaries. The environmental damage could be substantial. For this reason alternative concepts and locations are now being discussed.

Ocean current energy

Ocean current energy can also be harnessed using submerged rotors which are driven by the motion of the water. It has been estimated that ocean current power stations and tidal power plants together could harness several 100 terawatt-hours of electricity per year worldwide.

For some time now tests have been carried out on some rotor concepts, such as the Seaflow system, the prototype of which commenced operations off the English coast in 2003. Its successor, SeaGen, is now rotating in the Strangford Narrows off the Irish coast. Under this concept two rotors are mounted on the tower of the plant. This increases the electricity yield and balances out the high construction and start-up costs.

Such ocean facilities face much harsher stresses from currents and wave movements than wind turbines, for example, and for this reason extensive endurance testing is called for. Nonetheless, the SeaGen technology is closely based on the wind turbine model. The blade angle and rotational speed can be adjusted to suit the prevailing current. Other concepts focus on fixed, non-adjustable systems.

Energy derived from temperature differences

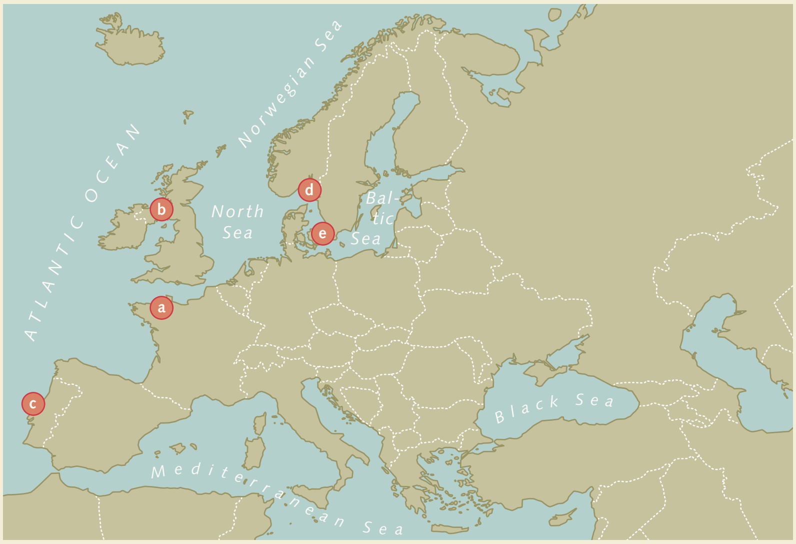
Ocean thermal energy conversion (OTEC) utilizes the temperature difference between warm surface water and cold deep water to generate power. In order to drive the steam cycle in an OTEC power station, the temperature difference must be at least 20 degrees Celsius. The technology is therefore more suited to warmer marine regions. The warm water is used to evaporate a liquid which boils at low temperatures, producing steam which drives a turbine. Cold seawater (4 to 6 degrees) is then pumped up from a depth of several 100 metres and used to cool and condense the steam back to liquid form.

Until now the cost of OTEC technology has been considered prohibitive, requiring pipelines of several 100 metres in length and powerful pumping systems. The US government supported OTEC development and initial testing in the mid 1970s, but withdrew its funding in the early 1980s. Interest in the technology has recently been rekindled, however. An American-Taiwanese consortium is now planning to construct a 10 MW facility in Hawaii. Furthermore, public institutions and businesses in France have launched the IPANEMA initiative, which aims to promote both ocean-based renewable energies and OTEC technology. It is estimated that OTEC has the potential to harness several 1000 TWh of electric power each year. Unlike wind and wave energy, this form of electricity production is not subject to fluctuating weather conditions.

Energy derived from the different salt content of freshwater and saltwater

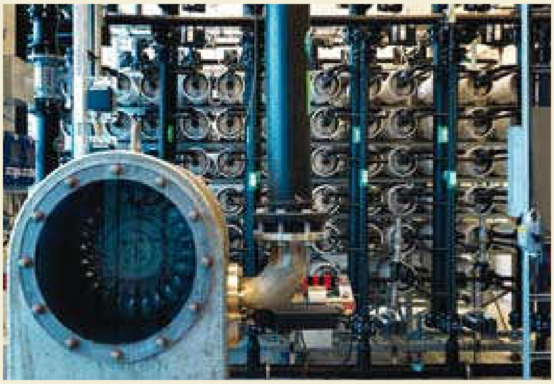
The osmotic power plant is an entirely new way of generating energy. It exploits the osmotic pressure which builds up between freshwater and saltwater when they are pumped into a double chamber and separated by a special semi-permeable membrane. The technology is

7.12 a > Power plants designed to harness ocean energy are already operating at several sites in Europe. The oldest is La Rance tidal power station near St. Malo in France, which was built in the 1960s. For many years it was the largest of its kind, with an output of 240 megawatts.



7.12 b > Tidal energy can be converted to electricity by underwater rotors, as at the SeaGen plant off the coast of Northern Ireland in Strangford Lough. One facility has already been constructed which feeds electricity into the grid onshore. Others will follow.

7.12 c > The Pelamis wave energy transformer floats on the ocean like a giant sea snake. It consists of several segments which move against each other and build up hydraulic pressure. This in turn drives a turbine. A new Pelamis generation is currently under construction.



7.12 d > The world's first osmotic power plant on the Oslo Fjord in Norway derives energy from the differences in salt concentration between saltwater and freshwater. A thin membrane separates the water masses, building up pressure which drives a turbine.

7.12 e > Offshore wind turbines produce electricity in many places around the world. One of the largest offshore wind farms, consisting of 48 turbines, is located in the Baltic Sea between Denmark and Sweden. A transformer station has been constructed here to feed power into the Swedish grid.

7.13 > Wind turbines are normally erected at a maximum water depth of 45 metres; otherwise, the cost of the towers is prohibitive. One alternative is to anchor floating turbines to the sea bed with holding cables. The first prototypes are currently being tested.

still in its infancy. In 2009, however, members of a Norwegian syndicate constructed the world's first osmotic power station on the Oslo Fjord. The plant is designed principally to develop this technology, at present generating only a few kilowatts of electricity. However, the sustainable global production capacity of osmotic power could in future amount to 2000 TWh annually.

Government support for the energy systems of the future

There is no doubt that major advances have been made in developing technologies to harness renewable energy from the oceans. Although many technologies show commercial promise, however, virtually all of them depend on subsidies because they are driven by small, young businesses. Apart from the technological and economic risk, one difficulty is to achieve project sizes which would make such investment viable. Subsidies for these technologies are therefore essential. Various nations offer such programmes. The US Department of Energy and the European Union are already investing several 100 million euros in their development. The complex approval procedures for plants and grid connections also need to be simplified. In Germany the approval of offshore wind plant is entirely in the hands of the Federal Maritime and Hydrographic Agency, but in the USA plant operators must battle their way through various agencies and approval processes. Relaxing the rules would be of great benefit.

Conclusion

Pressure on the ocean floor is growing

For centuries the oceans provided a single resource – food. Only during the past few decades have technologies been developed which can extract more from them – for instance drilling technology to extract oil and gas. Until now drilling has been in relatively shallow waters, but companies are now penetrating greater depths. It is a complex and expensive process, but is becoming more feasible as land-based reserves become scarce and prices rise. The same applies to the metal reserves which are embedded in manganese nodules, cobalt deposits, massive sulphides and ore slurry in the sea. As metal prices rise, mining from the depths will become more attractive – although this will only apply to valuable metals such as copper, nickel and gold. As yet, however, no mining technology is gentle on the environment.

With respect to methane hydrate, it is unclear to what extent it is possible to mine the ocean floor without harming people or the environment. Also, virtually no technology exists for the purpose. Many basic principles must first be clarified, such as whether laboratory results can be applied to mining practice. If it were possible to extract methane and at the same time safely store carbon dioxide from the burning of oil and gas, harnessing methane from the ocean bed might even prove to be a climate protection option.

The most sustainable system of marine energy production in terms of climate protection is probably from the ocean currents, waves and wind. In most cases there is considerable need for research into the impact of energy systems on the marine environment. Some technologies are ready for operation, while others are still in the pilot phase. Some nations have reduced the bureaucratic hurdles that planners and developers face. Before facilities can be utilized on a large scale, however, countries must decide whether and how they wish to promote ocean energy, because without initial governmental support none of the current technologies can be established in the medium term.

8 Maritime highways of global trade

> The volume of maritime traffic increased significantly over recent decades, but the global economic crisis brought the industry to its knees. Now there are promising signals for a recovery, however, nobody knows what the future holds for the process of globalization, the global imbalances still linger on and the world of finance continues to be in a fragile state. The growing threats of piracy and terrorism could also compromise shipping.

Global shipping – a dynamic market

> Tankers, bulk carriers and container ships are the most important means of transportation of our time. Each year they carry billions of tonnes of goods along a few principal trade routes. Containerization has revolutionized global cargo shipping, bringing vast improvements in efficiency. The maritime boom could continue, despite the economic crisis.

Growth through globalization

Throughout history the oceans have been important to people around the world as a means of transportation. Unlike a few decades ago, however, ships are now carrying goods rather than people. Since the rise of intercontinental air travel, sea travel has become limited to shorter trips (ferry services across the Baltic and North Seas, the Mediterranean, Japan and Southeast Asia) and recreational cruises. The latter have recently experienced a tremendous boom and represent an increasingly lucrative source of tourist income.

As markets became increasingly globalized, shipping volumes soared. From the 1950s to the latest global economic crisis, the growth rate of international trade was almost consistently twice that of economic activity as a whole. From 2000 to 2008 world trade increased by an average 5.4 per cent each year, while economic activity, as measured by the global Gross Domestic Product (GDP), increased by only 3 per cent per annum. Due to the spectacular rise of trade vis-à-vis economic growth, world trade since the 1950s has more than trebled to 45 per cent of the global GDP, while goods destined for the processing industry have in fact more than quadrupled.

With respect to the value of the goods, about 23 per cent of world trade is between countries with a common border. This percentage has remained fairly constant over recent decades. Between continents, however, it differs a great deal depending on their level of development. In Europe and North America the proportion is the highest at 25 to 35 per cent. This trade is predominantly transacted by road and rail. Cargo between countries without a common border is carried mainly by sea, although increasing quantities of manufactured goods are being forwarded by air. Growth rates for air freight are more than double those for shipping in recent years. Which mode of transport handles how much cargo depends on the (relative) transportation costs and the value-to-weight ratio of the goods – the higher the value per unit of weight, the less significant the cost of transportation. Punctuality and reliability are considered more important for valuable commodities.

According to research by economists, higher-income households purchase higher-quality products. The residents of wealthy countries therefore tend to buy more quality goods. Accordingly, rising incomes influence the demand for transport in three ways. First, quality goods are more expensive. Their value-to-weight ratio is therefore higher and the cost of transporting them is lower compared to their value. Second, as incomes rise, consumers are more likely to purchase certain expensive products and fancy goods. At the same time they expect to receive the articles within a very short time. Third, the delivery period itself is a key element of product quality, having an increasing influence on purchasing decisions; customers are no longer prepared to tolerate long delays. All of these factors have contributed to the even higher growth rates of air freight in comparison to shipping.

What fuels maritime traffic

As mentioned, the main reason behind the massive increase in shipping was the growth in world trade. But institutional and technological factors also had a role to play.

Key economic and business terms in brief

Gross domestic product (GDP):
Gross Domestic Product is a measure of a nation's economic output during a specific period of time. It is the market value of all goods and services produced within a country (value added), provided these are not used as intermediate input for the production of other goods and services.

General Agreement on Tariffs and Trade (GATT):
GATT came into force on 1 January 1948. This international agreement simplified world trade by systematically breaking down customs duties and other obstacles. GATT was replaced by the WTO.

Just-in-time production (JIT):
JIT focuses on producing and supplying a product at exactly the time it is needed. The individual production steps have to be coordinated. The supplier delivers goods and components directly to the production line as and when they are required. Only very small stocks need to be stored directly at the manufacturer's production line, dispensing with long storage periods and related costs.

North American Free Trade Agreement (NAFTA):
NAFTA is an agreement between Canada, the United States and Mexico that established a free trade zone in North America. NAFTA was founded in 1994 with the aim of eliminating or phasing out numerous tariffs.

Organisation for Economic Co-operation and Development (OECD):
The OECD is an international organization of European and non-European nations. It was founded in 1948 to create a joint concept for the reconstruction of Europe. Today it aims to support economic growth, to boost employment and raise living standards in the member states.

Offshoring:
Offshoring is a type of geographic relocation of business functions and processes to another country to take advantage of more favourable conditions, such as lower wages. When this happens the jobs in the home country are lost to locations in the low-wage countries.

Outsourcing:
Outsourcing is contracting with other companies or independent subsidiaries to provide tasks and services otherwise performed by in-house employees. This frequently means outsourcing jobs to cheaper subsidiaries that are not bound by labour agreements.

United Nations Conference on Trade and Development (UNCTAD):
The UNCTAD is a permanent organ of the United Nations General Assembly based in Geneva. Its goal is to promote trade between nations at different levels of development (mainly industrial and developing countries).

World Trade Organization (WTO):
The WTO is an international organization based in Geneva that regulates trade and economic relationships between nations. The World Trade Organization replaced the GATT in 1995 and currently has more than 150 members representing over 90 per cent of total world trade.

Economies of scale:
Economies of scale occur when the rate of production increases more strongly than the costs of production. In shipping, for instance, economies of scale result from the use of larger ships, which can carry greater amounts of freight, lowering the fixed costs per unit. Rationalizations, such as using standardized containers, can also increase economies of scale.

European Conference of Ministers of Transport (ECMT):
The ECMT was a forum of European Ministers of Transport which aimed to simplify transport, boost efficiency levels and break down barriers. Following a decision in 2006, ECMT was absorbed by an even larger international Conference, the International Transport Forum (ITF). To keep abreast of the increasing globalization of transport, ITF is now open to experts from outside Europe.

Globalization:
Globalization is a process which describes the increasing economic, social and cultural integration of nations, forging a greater interdependence between them. Globalization is responsible for a rise in demand for transportation and especially shipping.

In the past, the liberalization achievements of GATT and its successor the WTO provided a new momentum to world trade. China's economic opening to the outside world, which led to their admission to the WTO in 2001, was also very significant – its exports quadrupled within 5 years. Another example of integrated markets boosting international trade is a trebling of exports from Mexico to the USA within 6 years of NAFTA being established.

The appetites of the industrial nations and newly-industrializing emerging economies, particularly China and India, for energy and mineral resources led to increasing quantities of goods being transported from far-distant countries.

The information and communications technology revolution dramatically reduced the costs of mobility and accessibility. It allowed new network connections and production processes such as just-in-time production, outsourcing and offshoring, and provided a tremendous stimulus to logistics.

As a result of rising demand, transportation costs fell. Ships increased in size. Economies of scale were exploited. Furthermore, there were technological advances and organizational improvements in port management – of general cargo traffic, for instance. Of overriding importance was containerization, the greatest transportation revolution of the 20th century.

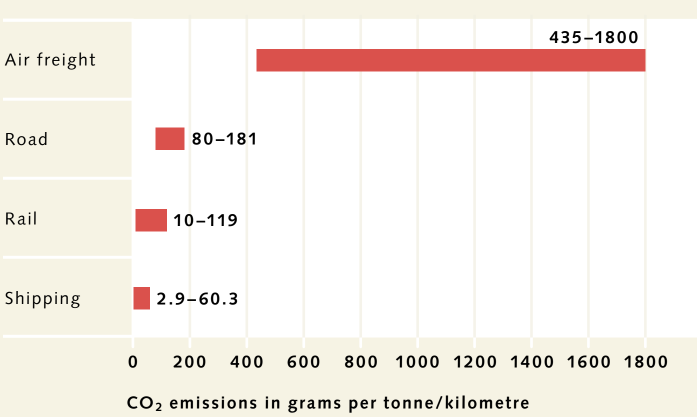
The increasing spread of open ship registries, most notably embraced initially by Panama and Liberia, allowed the shipping companies to combine the relatively low capital costs in the industrial countries with the low labour costs for seafarers from developing countries like the Philippines. It became possible to compensate for sharply rising labour costs, especially in the industrial nations. Furthermore, by changing to an open registry, ship-owners could avoid very costly regulations (such as national labour and employment laws). It is hardly surprising, therefore, that according to UNCTAD, the ten top open and international registries accounted for about 55 per cent of the global merchant fleet in 2008. In 1950 this figure was only 5 per cent. This development has helped shipping to become a genuine global economic sector. As far as ownership structure is concerned, however, it is far less global. A few countries own the bulk of the fleet. About 54 per cent of world tonnage (measured by carrying capacity or "deadweight tonnage", dwt) is controlled by owners (shipping companies) in Japan (16.0), Greece (15.3), Germany (9.5), China (8.4) and Norway (4.5).

In July 2009 the global merchant fleet consisted of a total of 53,005 vessels, made up of 31 per cent traditional general cargo ships, 27 per cent tankers, 15 per cent bulk carriers, 13 per cent passenger liners, 9 per cent container ships, and 5 per cent other vessels.

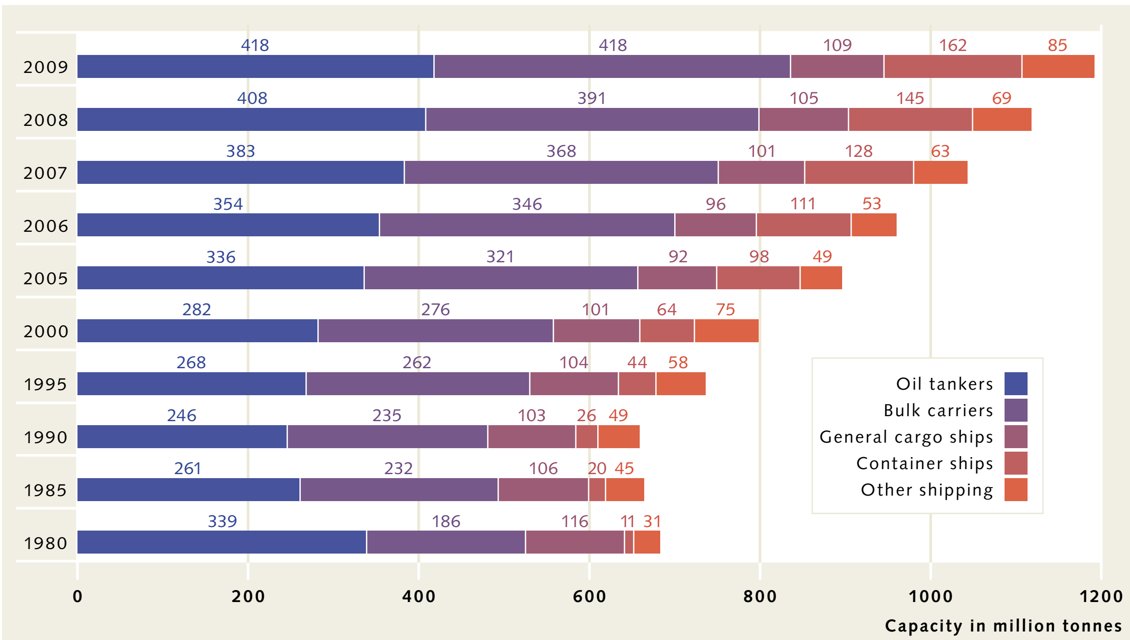
In terms of carrying capacity in dwt, however, the great variation in ship sizes gives quite a different picture. From this perspective tankers and bulk carriers each account for 35 per cent, container ships 14 per cent, general cargo ships 9 per cent and passenger liners less

Shipping and climate change

According to International Maritime Organization (IMO) estimates, world shipping is responsible for about 3 per cent of global CO_2 emissions. Of the total emissions from the transportation sector, shipping accounts for 10 per cent, road traffic 73 per cent and air traffic 12 per cent. Losses from pipelines contribute 3 per cent, and rail traffic 2 per cent. Experts predict that, unless further measures are taken to protect the climate, emissions from the transportation sector will double by 2050. From shipping they could approximately treble.



8.1 > Of all modes of transportation, ships are unbeatable in terms of efficiency.



8.2 > The growth of the global merchant fleet according to type of vessel (as at 1 January).

than 1 per cent. In all, the global merchant fleet has a capacity of just under 1192 million dwt.

Modern ships – large, fast and highly specialized

Marine innovations have helped to fuel the growth of maritime freight traffic. The following are significant:

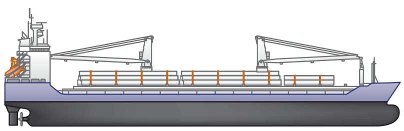
SIZE: The average size of ships has increased substantially. Larger vessels reduce the shipping costs per load unit for crew, fuel, demurrage, insurance, servicing and ship maintenance. Port authorities must respond to increasing vessel sizes by expanding port infrastructure (wharfage, transport connections inland) and improving port access (e.g. by deepening fairways). Therefore they too face increasing costs. This can bring the owners – usually the State or local authorities – into financial difficulty: the capital investment is usually funded from the public purse, but the full costs are not passed on to port users.

SPEED: The average speed of a merchant ship is about 15 knots (1 knot = 1 nautical mile per hour = 1853 metres per hour), or 28 kilometres per hour, the equivalent of about 670 kilometres a day. Newer ships are capable of 25 to 30 knots (45 to 55 kilometres per hour). Marine propulsion has improved considerably since the invention of the screw propeller, particularly the double propeller. This development reached its peak in the 1970s. Achieving even higher speeds is a challenge and is likely to prove extremely expensive. Experts are therefore predicting only limited increases to average commercial shipping speeds.

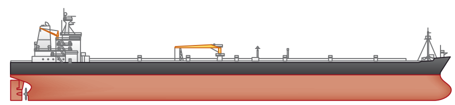
DESIGN: Ship design has changed radically – from timber to steel to vessels built mainly of aluminium and composite materials. Design innovations were aimed at dramatically reducing fuel consumption and construction costs while increasing safety at the same time.

SPECIALIZATION: Specialization in the shipbuilding industry has brought massive changes to ocean shipping. Special ships have increasingly been constructed for different types of freight:

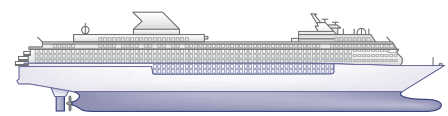
- Tankers for crude oil, petroleum products, chemicals, liquid gas and fruit juice concentrate;
- Bulk carriers for bulk goods such as ores, coal, grain;



General cargo ship



Oil tanker



Cruise liner

Key shipping terms in brief

Gross register tonnage (GRT):
Gross register tonnage or gross tonnage (GT) represents the total internal volume of cargo vessels. 1 GRT = 100 cubic feet ≈ 2.83 cubic metres. Although the term contains the word tonne, the gross register tonnage cannot be equated with measurements of weight such as carrying capacity – nor should it be confused with the standard displacement used to rate a warship, the long ton. Gross register tonnage (GRT) and net register tonnage (NRT) have been replaced by gross tonnage (GT) and net tonnage (NT) which express the size and volume of a ship as a simple dimensionless figure. Port fees and charges for canal passages, locks and pilots are calculated according to the GT or NT.

Deadweight tonnage (dwt):
Deadweight tonnage indicates the carrying capacity of a ship in tonnes.

Freight rate:
In logistics, the term "freight rate" is used to indicate the price a carrier charges its customers for transporting goods from one place to another. There are so-called "all-in rates" which include all incidental costs, fees and documentation costs, while other rates cover the costs of transportation alone. Sea freight rates differ greatly across routes.

Tonnage measurements:
Tonnage measurements are used to indicate the technical data of a ship such as the total internal volume, displacement, carrying capacity, draught, length and speed. Ship sizes and performance vary according to function and national unit of measurement.

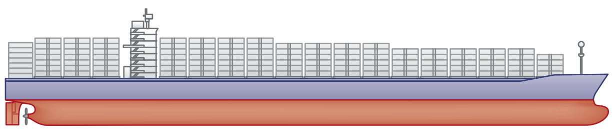
Register of shipping:
All ships must be registered in a country's shipping register. The ship is then considered part of the territory of the country under whose flag she sails. All the laws and regulations of this country (employment law, social security law etc.) apply on board the ship. Some nations (such as Panama, Liberia and the Bahamas), however, have so-called open shipping registries, where any ship-owner can register his ship. As the employment and social security laws of many countries do not protect workers as well as those in Europe, and safety practices are far less stringent, labour and thus transportation under these flags is much cheaper (flags of convenience).

TEU (twenty-foot equivalent unit, standard container):
A TEU is the standard container used today to transport goods worldwide. As the term suggests, a TEU is about 20 feet long. A foot is equal to 30.48 centimetres. A TEU measures about 8 feet in both width and height. Not only ships, but also railway wagons and articulated trucks are constructed according to this standard, meaning that containers can be transferred seamlessly between different modes of transport.

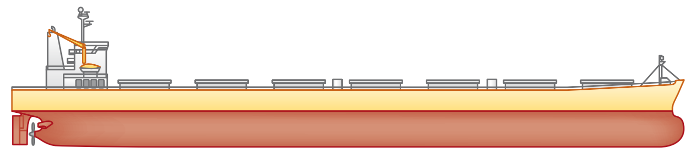
Tonne-miles:
A measure of freight transportation output. A transportation output of 1 tonne-mile is achieved when a tonne of cargo is moved 1 nautical mile (1.853 kilometre).

Dry cargo:
Dry cargo is a collective term for all non-liquid freight. Important types of dry cargo are iron ore, coal, grain, bauxite/aluminium oxide and phosphate.

GPS/AIS:
GPS is a global satellite-based navigation system that provides accurate location and time information. The Automatic Identification System (AIS) used by ships to communicate their positions and other data to each other has been employing GPS for some years now. AIS makes shipping safer and more efficient as it allows the maritime authorities to track and monitor vessel movements.



Container ship



Bulk carrier

- Bulk carriers for large-volume unit loads such as motor vehicles and iron;
- Refrigerated vessels (reefers) for fruit from the Southern Hemisphere;
- General cargo ships;
- Container ships, which are increasingly taking on the tasks of general cargo ships on long-haul routes;
- Ferries for shipping trucks as well as roll-on/roll-off (Ro-Ro) ships, which carry articulated lorries to drive the cargo onto the ship. These two are taking over the tasks of general cargo vessels on short-haul routes.

By speeding up cargo handling, specialization has been responsible for reducing the costs per transported unit. Where special ships can be utilized to capacity, therefore, economies of scale have been achieved.

AUTOMATION: Various automation technologies have been introduced to shipbuilding and ship operations, including self-loading/unloading systems, computerized navigation, and the global positioning system (GPS). Automation has markedly reduced the number of crew needed and at the same time substantially improved safety standards. According to data service provider "IHS Fairplay", total vessel losses (due to accidents or sinking) have declined from more than 200 a year in the mid-1990s to about 150 now – a remarkable improvement in safety when measured against the sharp rise in fleet numbers. Maritime freight traffic was booming for many years. The amount of cargo transported by sea exceeded the 8 billion tonne mark for the first time in 2007. Global shipping had therefore doubled since 1990 (an average annual increase of over 4 per cent). Transport capacity, too, virtually doubled in the same period to almost 33 trillion tonne-miles.

The global recession in 2008/2009 triggered a massive slump in world trade and, accordingly, shipping. Following a modest rise of nearly 3 per cent in 2008 – trade nosedived by about 14 per cent in 2009. Freight rates fell to historic lows on many sub-markets. As at the beginning of 2009 about 9 per cent of bulk carriers worldwide lay idle, unutilized, in ports, this capacity is coming back only slowly to the market in the 2010 recovery.

What ships carry – Oil, containers, and dry cargo

Ocean shipping can roughly be divided into two sub-markets – on the one hand liquid cargo such as oil and petroleum products, on the other dry cargo. Dry cargo is made up of bulk goods, the five most important being iron ore, coal, grain, phosphates and bauxite. Other dry cargo consists of bulk materials such as non-ferrous metal ores, feed and fertilizers, and particularly a variety of goods packaged in smaller transportation units. The latter are labelled as general cargo and shipped on liners, i.e. vessels with scheduled sailings, chiefly in containers. Liner shipping usually offers its services according to fixed conditions that are agreed on between competitors at so-called liner conferences.

The single most significant type of cargo worldwide is crude oil, which alone accounts for roughly a quarter of all goods transported by sea. The major importers are the European Union, the United States of America and Japan. All three are supplied by the Middle East, the most important oil-producing region. North America also obtains oil from West Africa and the Caribbean, while Europe imports from North and West Africa. The main shipping lanes therefore stretch westward from the Arabian Gulf around the Cape of Good Hope or through the Suez Canal, and from Africa northward and westward to Europe and North America. Others connect the Arabian Gulf to East Asia and the Caribbean to the Gulf Coast of the United States. Of course, crude oil is not the only commodity

8.3 > Most of the global merchant fleet consists of five types of ships: general cargo vessels such as heavy load carriers and multi-purpose vessels that transport machinery parts and even yachts; oil tankers; bulk carriers, which are loaded through hatchways; passenger liners, such as cruise ships; and container ships. All other types of vessels, such as vehicle transporters, together account for only about 5 per cent.

transported by sea. Smaller, specialized ships (product tankers) carry processed petroleum products from major peripheral refinery locations to the consumption areas of North America and Japan. This amounted to about 815 million tonnes worldwide in 2007.

In terms of quantity, iron ore and coal are significant dry-bulk goods. Iron ore is transported over long distances in very large ships, mainly from Brazil to Western Europe and Japan, and from Australia to Japan. The most important coal routes are from the major export countries of Australia and South Africa to Western Europe and Japan and also from Colombia and the East Coast of the United States to Western Europe, as well as from Indonesia and the West Coast of the United States to Japan.

Most of the coal transported is utilized as steam coal to generate electricity in power stations. A third is used as coking coal for smelting in the iron and steel industry.

The container revolution

Container shipping was first introduced in the USA during the 1960s, expanding to the shipping routes between the USA and Europe and Japan in the late 1960s and early 1970s. The developing countries followed from the late 1970s onwards, having originally baulked at the high initial fixed costs. To make full use of the advantages of container transportation requires properly equipped ships and port facilities with special cranes, storage space and railway systems. For this reason container traffic initially became established on the busiest shipping routes. There were ultimately two reasons that the developing countries were hesitant to embark on container transportation: price and the low volume of container traffic. In countries where there is little capital but plenty of labour, the capital cost of constructing a container port is relatively high. The labour costs it saves, however, are relatively low.

Regardless of this, many experts consider container shipping one of the key transport revolutions of the 20th century. The use of standardized containers saves tremendous costs, as the goods are packed only once and can be transported over long distances using various modes of transport – truck, rail, or ship. Time-consuming unpacking and repacking are no longer required, reducing both the direct costs of port charges for storage and stowage, and the considerable indirect costs of demurrage. It is estimated that traditional cargo ships, which need more time to unload their cargo, spend half to two thirds of their operating time in port. The containerization of shipping pays off especially at sea, as the large and fast container ships substantially reduce the cost per tonne-mile between ports.

Dry bulk goods also include grain and oil-bearing seeds (wheat, barley, rye, oats, sorghum and soya beans). Here however, the quantities and direction of transport routes fluctuate much more than other vital commodities depending on harvest seasons and yields. The USA, Canada, Argentina, Australia and France are the major grain exporters. Africa and East Asia are major importers due to frequent local shortages. Although the main grain producers (the United States, Russia, China and India) retain most or even all of their production in their own country, what remains for global trade is still enough to include grain among the bulk commodities.

Increased international division of labour, in motor vehicle production for instance, has led to general cargo such as cars and parts accumulating in such large quantities that entire shiploads can be forwarded on specialized ships outside the scheduled liner services. Large car carriers and special tankers for chemicals or fruit juice concentrate also belong to this special shipping sector, operating on contracted routes.

Today most other dry cargo is transported in container ships. These standardized containers have brought a flood of technical innovations (such as special cranes at transshipment points) and fundamental organizational innovations in their wake. Being standardized, they can be transported with any mode of transport and rapidly transferred to trucks or railway cars fitted with the appropriate equipment. From an economic point of view this has dramatically reduced transportation costs, mainly as a result of faster loading and unloading. Capital investment along the entire transport chain was necessary to ensure the containers were used efficiently, considerably increasing capital intensity. In contrast, labour intensity was sustainably reduced, as fewer dockworkers were needed for loading and unloading.

Since 1985 global container shipping has increased by about 10 per cent annually to 1.3 billion tonnes (2008). During the same period its share of the total dry cargo transportation rose from 7.4 per cent to a quarter. A total of 137 million containers, measured in TEU, were transported in 2008. This quantity, however, decreased again in 2009 by 10 per cent.

Typically the cost of transporting a TEU containing more than 20 tonnes of freight from Asia to Europe is roughly the same as a one-way Economy Class flight along the same route. This weight in everyday goods such as electrical appliances in most cases represents a transportation cost of less than 1 per cent of the selling price.

The key shipping routes

If all commercial goods are taken into account it becomes clear that there is a relatively small number of principal transport routes, and these pass through only a few areas of the oceans. The busiest are the approaches to the ports of Europe and East Asia, particularly Japan but also Shanghai, Singapore and Hong Kong, and the United States. The East Coast of the United States in particular is a major sender and receiver of cargo. Narrow straits further concentrate maritime traffic. Bottlenecks include the Straits of Dover, Gibraltar, Malacca, Lombok and Hormuz, and the Cape of Good Hope at the southern tip of Africa. Traffic builds up in these areas, making ships vulnerable to attack by pirates.

Cargo imbalances are a typical feature of the traffic with Asia – depending on the trade balance. Much more cargo is being shipped from Asia than in the opposite direction. This imbalance is particularly notable on the Pacific route, at almost 10 million TEU (2007). From Asia to Europe it is almost 8 million TEU. The North Atlantic traffic between the highly-developed economies of North America and Europe, however, are much better balanced, registering a difference of barely 2 million TEU. The reason for this situation is that since the mid-1980s so many manufacturing processes have been relocated from the traditional industrial countries to the developing nations and emerging economies, particularly China and the countries of South East Asia. With the prevailing exchange rates, China in particular has become the cheap "workshop of the world".

This process has been promoted by the introduction of the container and the corresponding increase in shipping productivity. The transportation costs between where goods are manufactured and where these goods are consumed have been reduced considerably. Dry cargo such as automobile and machinery parts – until now transported by conventional means – has been increasingly containerized, contributing to the growth in container traffic.

Until the global economic downturn the demand for new ships was great, but as the effects of the crisis were felt the tide turned and many companies cancelled their orders. All the same we can assume that even more marine transport capacity will become available in the near future as new ships are delivered, overtaking demand. Freight rates are therefore unlikely to recover from their current all-time lows any time soon.

The problem of empty runs – unbalanced cargo flows

Even more than container traffic, transport flows in the bulk sector are usually subject to directional imbalance. Mineral resources are often geographically distant from where they are processed. Large ore and coal freighters and crude oil tankers are therefore only transporting cargo in one direction, from the port of shipment to the port of discharge. They usually return empty. In many cases, therefore, the freight rate must cover the costs of returning the empty ship. This partially explains the great disparity of freight rates on individual routes depending on direction.

8.4 > The containerization of shipping has dramatically accelerated the unloading of cargo.

Obstacles to global shipping: Piracy and terrorism

> Pirate attacks have come to the fore in recent years. The growing threat could lead to higher costs such as increased insurance premiums. Ultimately, however, the risk of falling victim to pirates is relatively slim. Protecting against terrorist attacks, on the other hand, is proving to be an obstacle to international shipping because of the appreciable costs involved.

8.5 > Revered privateer: Sir Francis Drake (1540 to 1596) was considered a hero by the English, but a pirate by the Spanish for his raids on their trading ships. In 1581 he was knighted by the English crown.

The return of the buccaneer

As globalization progressed during the 1990s, pirate ships again appeared on the horizon, more than a century after their virtual disappearance. Piracy is an age-old maritime phenomenon, often sanctioned by the state, and in some cases it is even a highly respected profession. The English crown certainly welcomed the treasures explorer Sir Francis Drake (1540 to 1596) brought back from his raids on Spanish trading ships. Privateering was formally abolished by the Paris Declaration respecting Maritime Law issued on 16 April 1856.

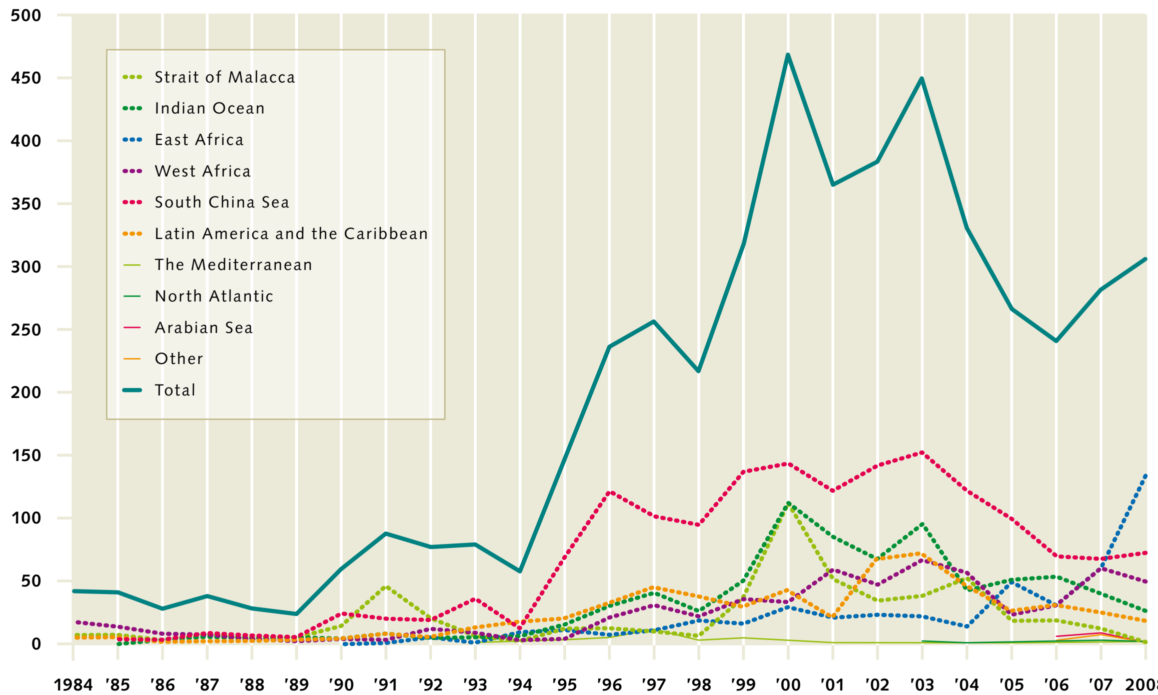
Now piracy is on the rise again, mainly off the coast of Somalia and the Gulf of Aden, i.e., along the major trade routes. Piracy frequently goes hand in hand with abject poverty, which drives people into this "line of business". It is often boosted by the complete collapse of government order in the nations concerned.

Piracy not only poses a threat to the crews of the ships and their cargo. It also makes maritime transportation more expensive. Shippers and ship-owners are feeling the costs of piracy quite substantially. The insurance premiums for a passage through the Gulf of Aden have increased more than tenfold, for example. The optional detour around the Cape of Good Hope takes weeks longer and uses much more fuel. Nevertheless, the risk of falling victim to a pirate attack is quite slim, even at piracy hotspots. Overall annual losses as a result of piracy in the straits are estimated to be 0.001 to 0.002 per cent of the total cargo value involved. According to experts, this amount is by no means alarming. The same applies to the current piracy hotspot, the Horn of Africa from the Somali coast to the Gulf of Aden, through which about 16,000 ships pass each year.

Terrorism – an incalculable risk

Since the terror attacks of 11 September 2001, the "worldwide threat to shipping" has become an increasingly significant topic. The International Maritime Organization (IMO) has adopted a number of binding security measures. The USA has taken the most drastic precautions, including the monitoring of containers during loading and along the entire transport chain. The United States' most important trading partners comply with these measures to prevent problems with container traffic. On the one hand they are designed to prevent terrorists at sea from acquiring supplies of weapons and materials, and on the other, to avoid ships being hijacked and used as weapons themselves – like the aircraft used in the 9/11 attacks.

Security is a huge challenge for container traffic. The maritime system of container transportation is complex, involving interactions between diverse stakeholders, industries, regulatory bodies, modes of transport, operations systems, legal frameworks and terms of liability. The European Conference of Ministers of Transportation (ECMT) maintains that all stakeholders are responsible for the safety of the container trade. One solitary breach of security can compromise the security of the entire logistics chain. In addition to seaport container terminals, other extremely vulnerable points are marshalling yards, street stops and parking areas. A number of studies have been carried out on the economic consequences of terro-



8.6 > Modern piracy: Following a steep increase in piracy at the start of this century, the number of attacks has now declined again worldwide. The exceptions are the waters off East Africa, and particularly Somalia.

rism on maritime traffic, most of which relate to US American ports. Their aim is to determine the total material losses in the event of a terrorist attack and subsequent port closures. Simulations, for instance, were used to calculate the economic damage of an attack on the port of Los Angeles with a radioactive "dirty bomb". As a result of the attack all US ports would be closed for a week; clearing the resultant container congestion would take 92 days. The overall damage is estimated to be USD 58 billion. This purely economic study did not take into account the number of people who could potentially be killed or the damage to buildings. The consequences would nonetheless be disastrous.

If it were to occur in one of the world's largest ports (to compare container turnover in 2007: Los Angeles handled 8.4 million TEUs, Hamburg 9.9 million TEUs and Singapore 27.9 million TEUs) the impact would be even more severe. However, as yet there are no reliable estimates of likely preventative costs or how these stack up against the potential damage of terrorist attacks. Preventative costs include the purchase of specific equipment to monitor cargo shipments (such as X-ray facilities) and the assignment of very highly qualified personnel. On the one hand private stakeholders such as the shipping companies themselves invest in such security measures. On the other, countries stipulate certain requirements. The OECD has estimated the initial cost to shipping companies for implementing the security measures at USD 1.3 billion, and subsequently USD 730 million a year. These increased costs are reflected in higher prices and/or lower profit margins, at least in the short term, and thus tend to decrease maritime traffic. Then again, the measures could in the long term help to reduce costs in various ways – by cutting delays and speeding up processing times, for instance. It is also conceivable that the improved monitoring in handling and loading equipment, the greater use of IT and resulting lower personnel costs, fewer thefts due to improved security, and the lower insurance premiums as a result of greater security could cut costs in the long run.

In spite of these potential reductions, experts believe that overall the higher security standards have driven up

8.7 > For fear of pirate raids, big guns are deployed in the Gulf of Aden. Japanese marines are among those hunting the freebooters. During a manoeuvre, the destroyer "Ikazuchi" goes alongside the supply vessel "Mashu".

transport costs substantially. The OECD estimates that the threat of terrorist attacks in the United States has cancelled out about half the productivity gains in logistics of the past 10 years. Fears have even been voiced that the permanent terrorist threat is compromising the entire globalization process of the past 3 decades. The consequences to the organization of production are not so easy to quantify at present. Will it be possible to maintain just-in-time production in the future? As an initial reaction to insecurity caused by the terrorism threat, some manufacturers no longer rely only on just-in-time consignments.

The price of fear

A comprehensive economic analysis of the overall costs and gains of the security measures has yet to be carried out. The question at what stage the cure becomes more costly than the disease cannot yet be answered. Nobody knows exactly when the costs of the extra safety will surpass the costs of potential damage and devastation caused by actual terror attacks. Nightmare scenarios of hijacked ships being blown up and triggering gigantic explosions in vital ports cannot be completely ruled out, but are considered by experts to be extremely unlikely.

Conclusion

A look at the future

The recent global economic crisis precipitated a sharp slump in world shipping. Yet the global economy rebounded in 2010. Global trade, in decline until the spring of 2009, has increased markedly since the summer of that year. On the other hand, the economic situation will continue to be depressed for some time yet. From a global perspective, Germany's major economic think tanks state in their autumn 2010 outlook that the 1 per cent decline in world production in 2009 is likely to be followed by an increase of 3.7 per cent in 2010 (2011: 2.8 per cent), driven mainly by rapid recovery in a number of newly industrializing economies and in China and several western European nations. World trade fell sharply by 11.3 per cent in 2009 but will grow about 12 per cent in 2010 (2011: 6.8 per cent). This has bolstered demand for transport somewhat. It remains to be seen whether market globalization will continue as before or will change tack. Fears that the financial crisis could compromise the international division of labour and thus world trade and shipping are not yet fully dispelled. The container success story came to an abrupt end in 2008 with the slump of the global economy. A.P. Moller-Mærsk A/S, owners of the largest container fleet in the world, estimate that container handling fell by 10 per cent in 2009 – the first decline since containers were introduced on global shipping routes in the 1970s! Following its many years of success, container shipping will also come under pressure from forthcoming fleet expansions. A great number of extremely large ships will be completed in the near future, which will have a negative impact on the recovery of freight rates.

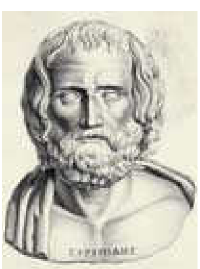
The extent to which climate change will affect shipping is difficult to foresee. Extreme weather conditions such as gales could impair transport and navigation conditions, increase the risk to ships and cargo and complicate loading and unloading operations. Sea freight transport, the world's most important medium of transportation, could become more expensive. On the other hand, if the Arctic polar ice cap melts new shipping routes could open up, providing considerable savings in time and energy. It is conceivable, for instance, that the Northwest Passage and the Northern Sea Route could be open to shipping for several weeks or even for months each year (Chapter 1).

9 Medical knowledge from the sea

> Marine organisms such as bacteria, corals and sea sponges contain thousands of interesting substances that could provide us with the medications of the future. Some of these agents have already been approved as drugs. Research on primordial organisms can reveal both how diseases occur and how they can be treated. Before the treasure trove beneath the sea can be claimed, however, some legal issues must be resolved.

Active substances from marine creatures

> Substances from the sea are already used as cancer drugs and painkillers, while other preparations are undergoing trials. But searching for new substances is a time-consuming business. Genetic analysis could speed up the process.



9.1 > Works by the ancient Greek dramatist Euripides (ca. 480 to 406 B.C.) are still being staged today. The sea is a fateful element of his tragedies, acting as both a threat and a source of life.

Source of healing since ancient times

For thousands of years people have believed in the healing power of the sea. As the Greek dramatist Euripides says in one of his plays about Iphigenia, "The sea washes away the stains and wounds of the world". The ancient Egyptians and Greeks examined the effects of seawater on human health. They credited the sea and the substances it contained with healing properties. Marine products have for centuries been an integral part of folk medicine all around the world. For example, sea salt has traditionally been used to treat skin diseases, and algae to treat parasitic worms.

In 1867 the French doctor La Bonnardière introduced the classical thalassotherapy (seawater therapy) and climatotherapy to Europe, reinforcing people's belief in the therapeutic properties of the sea. However, mythologizing these powers has also brought forth irrational fruit – the notion that eating turtle eggs or shark fins increases virility, for instance. Unscrupulous businesses have exploited this superstition and are contributing to the decimation of numerous animal species.

High-tech equipment seeks out promising molecules

Modern biomolecular and genetic techniques now make it possible to identify promising marine substances very rapidly. We have long known that the oceans are awash with unfamiliar bioactive substances that have healing or other beneficial properties. In many cases researchers have been able to ascertain the roles played by certain substances within the living organisms – the immune system for instance – and to explain the biochemical processes that occur. They believe that many new agents will be found in the sea and in marine organisms in future, since the oceans are home to millions of plants, animals and bacterial strains. Today there are approximately 10,000 known natural substances, most of which were isolated from marine organisms over the past 20 years. New technology such as nuclear magnetic resonance, which can be used to identify and analyse unknown molecules, even if the organism contains only a trace of them, has made the search much easier. More research is now being conducted on the ocean floor than ever before. Unmanned submersible robots are capable of diving to depths of several 1000 metres to take samples.

In spite of these advances and the enormous biodiversity in the oceans (Chapter 5), few marine substances have so far been officially approved for clinical use. A new substance must not only attack the molecules that are key to the disease process, but it must also not interact negatively with food or other medication taken at the same time. It must also be capable of manufacture on a large scale.

Active agents from the sea – perfect for people

The appeal of most of the marine substances already approved lies in their potency. They are valued because they are produced from different source materials and compounds than their land-dwelling counterparts. The special structure of the molecules and components such

9.2 > Europe did not rediscover the benefits of the sea until the late 19th century. People living inland began to travel to the coast for rest and recuperation – as here on the East Frisian island of Norderney, off the North Sea coast of Germany.

as bromine and chlorine apparently help to make them so effective. The substances are not normally used in their pure form. First the molecules must be chemically modified and tailored to the human metabolism. The following marine substances are either already in clinical use or show promise for the future:

Nucleosides

Some of the best-known natural marine products are the unusual nucleosides spongouridine and spongothymidine derived from the Caribbean sponge *Cryptothetya crypta.* These have been in clinical use for more than 50 years. Nucleosides are components of DNA. For a cell to divide it must first replicate the DNA in its genetic material, incorporating the nucleosides precisely into the new DNA. Nucleosides contain a sugar component, usually ribose. Spongouridine and spongothymidine, however, are arabinose-containing nucleosides. When these exogenous nucleosides are incorporated in the DNA, they inhibit the replication of genetic material, which is known as nucleic acid synthesis.

It was not long before this principle was being used to treat cancer and viruses because tumour cells divide extremely quickly, and even viruses need an active DNA synthesis in the cell to proliferate. Administering substances that interrupt the nucleic acid synthesis can greatly inhibit tumour growth. Thus the sponge nucleosides were developed into a substance for this particular purpose, a cytostatic drug. They were the basis for the synthesis of Ara-C (Cytarabine®), the first marine-derived drug approved by the U.S. Food and Drug Administration (FDA), in 1969. The virostatic agent Ara-A (Vidarabin®), which inhibits the proliferation of viruses, was approved in 1976, and is still used today to treat serious herpes simplex infections.

9.3 > **Many effective agents are derived from marine sponges. Substances from the Elephant Ear Sponge *Lanthella basta* inhibit tumour growth. This sponge is abundant in the waters off the coast of Australia or Indonesia.**

9.4 > **Scientists first isolated prostaglandins from the coral *Plexaura homomalla* in the 1960s. This coral is found in the Caribbean and the western Atlantic Ocean at depths of up to 60 metres.**

Prostaglandins

In 1969 it was established that *Plexaura homomalla,* a common coral found in the Caribbean and the western Atlantic, is a rich natural source of prostaglandins. Prostaglandins are important hormones produced from tissues that control essential body functions such as blood clotting and extremely complex inflammatory responses. The coral prostaglandins from *Plexaura homomalla* and other species have been researched exhaustively and have provided vital knowledge on the prostaglandin metabolism of humans. No drugs have yet resulted from this research.

Peptides

It took nearly 30 years after the development of Ara-C for the next marine-derived substance to be approved for the treatment of human medical conditions. This was the peptide Ziconotide (Prialt®), which is derived from the venom of various species of marine cone snail. Peptides are large protein components. Accordingly, the cone snail toxin consists of a highly complex mix of different protein components called conotoxins. These conotoxins attack the metabolism of animals and humans at different points. In their natural environment the toxins paralyse their prey by blocking ion channels in the cell membrane – small apertures that are important to the transmission of nerve impulses. Instead of the pure snail venom, a modified version of the venom cocktail is used to treat severe chronic pain. The drug Ziconotide prevents ions from entering pain-sensing nerve cells. By doing so it blocks the nerves in the spinal cord that send pain signals to the brain. This drug is used for patients whose pain is so severe that it cannot be controlled by morphine medication. It is also used in cases of morphine-intolerance.

Alkaloids

Ecteinascidin 743 (also known as trabectidin) is an alkaloid, or nitrogen-containing organic compound marketed under the brand name of Yondelis®. It is the latest marine-derived compound and was originally extracted from the tunicate *Ecteinascidia turbinata,* a simple filter

9.5 > Cone snails such as *Conus textile* mainly inhabit tropical marine areas. They inject venom into their prey with a harpoon-like tooth. Scientists have succeeded in deriving a very effective painkiller from this venom.

9.6 > Moss animals are tiny animals that live in branch and leaf-like colonies. Bryostatin – an inhibitor of tumour cell growth – is extracted from the bryozoan *Bugula neritina*. It is probably produced by bacteria on the surface of the colony.

feeder living on the sea floor. The substance was only approved as a drug in 2008. Ecteinascidin 743 interferes with a complex metabolic mechanism that confers drug resistance on cancer cells. It binds in the minor groove of DNA, slightly distorting the shape of the DNA, which obstructs the metabolism of the cancer cell. In greater detail, ecteinascidin 743 unites with the DNA repair protein TC-ER, then links with the DNA, thus preventing the MDR1 gene (MDR = multi drug resistance) – vital to the cancer cell – from being selected. This gene contains the blueprint for the MDR1 protein, the function of which is to discharge toxins and exogenous substances from cells. In cancer therapy, therefore, its effect is counterproductive because it also discharges medication from the tumour cells. This can ultimately lead to resistance and failure of the therapy. Ecteinascidin 743 blocks the production of MDR1 and thus prevents it from discharging the drug. Scientists hope that ecteinascidin 743 will reinforce the potency of other chemotherapy drugs by preventing resistance. Yondelis® has so far been approved for the treatment of soft tissue sarcomas – rare, malignant connective-tissue tumours.

Other cancer drugs from the deep

A number of other marine anti-tumour agents are currently under study in clinical trials. They include bryostatin extracted from the bryozoan *Bugula neritina,* squalamine lactate from the spiny dogfish *Squalus acanthias* and sorbicillactone which comes from bacteria present in sponges.

Substances such as dolastatin 10 and dolastatin 15 isolated from the *Dolabella auricularia* snail and their progeny appear less promising. Clinical studies show that these anti-cancer agents alone are not capable of healing breast cancer or pancreatic cancer. They could conceivably be effective, however, when combined with other preparations.

What is the true potential of marine substances?

Many substances derived from the sea are already in commercial use as pharmaceutical drugs. Others have future potential. The following are some interesting

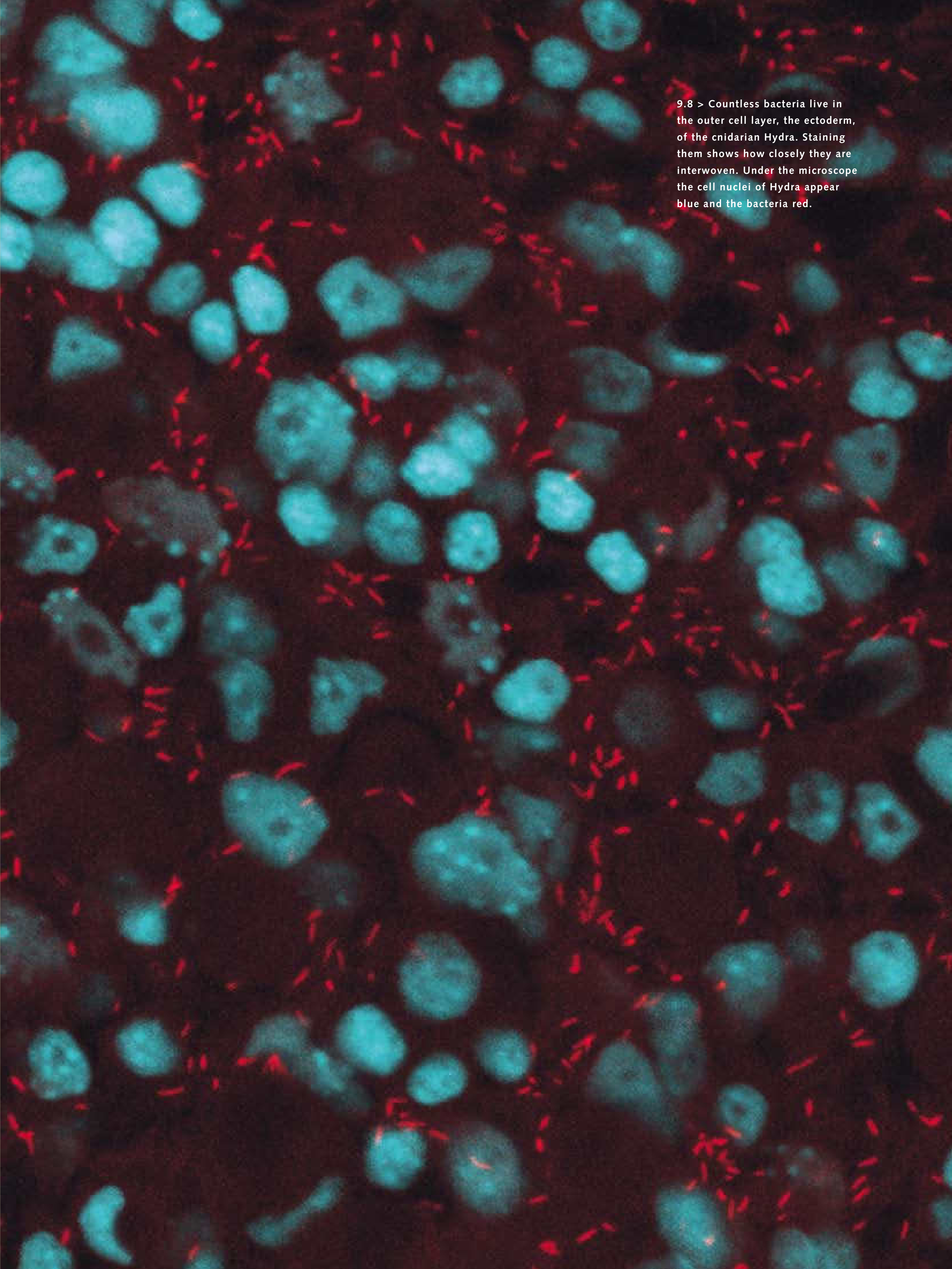
9.7 > Scientists have successfully extracted many active agents from organisms that live in the sea or fresh water. Some substances have already been developed into drugs.

Isolated substance	Class	Primary effect	Application	Source of organism
Ara-A	Nucleoside	Inhibits viral replication (Virostatic agent)	Herpes simplex virus infections	Sponge
Ara-C	Nucleoside	Inhibits tumour growth (Cytostatic agent)	Leukaemia	Sponge
Ecteinascidin 743	Alkaloid	Obstructs tumour drug resistance	Soft tissue sarcomas (malignant connective tissue tumours	Tunicate
Hydramacin (not yet approved)	Peptide	Antimicrobial effect	To fight penicillin resistant bacteria	Fresh water polyp
Ziconotide	Peptide	Obstructs ion channels	Painkiller	Sea snail

theories and questions on the future of research into marine substances:

1. The sea provides prime candidates for new medications. But locating them and then producing them on a large scale is not easy. This, on the one hand, is because the living organisms are difficult to find in the endless expanses of the ocean, and they often occur in very limited quantities. On the other, it is impossible to keep many of these organisms under laboratory conditions for long periods, or to cultivate them. For many years the pharmaceutical industry has had automated procedures in place for analysing variations of known substances and testing their suitability as drugs. This high-output screening allows researchers to test entire catalogues of related substances very rapidly. However, the molecular structure of marine substances is often so complicated that, even after being proved effective, they cannot easily be replicated or modified. This is what makes them so difficult to locate and develop.

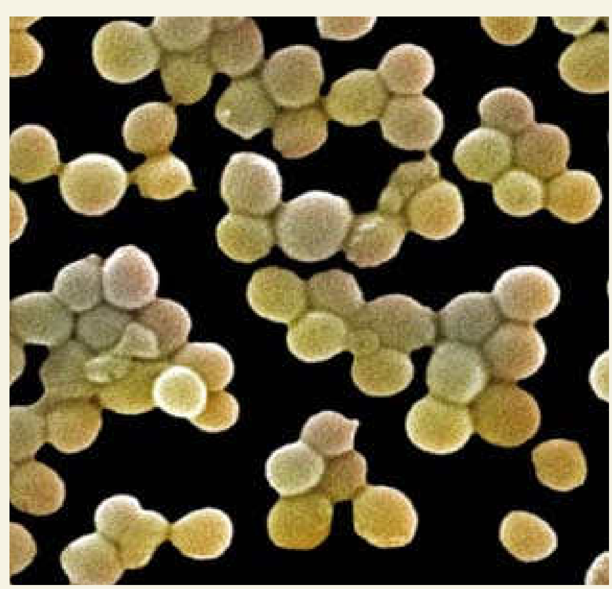
Finding them is also an extremely time-consuming process that requires expensive equipment. The time and effort involved are usually considered too great by the industrial sector. For this reason, most marine substances have thus far been discovered, isolated and analysed by researchers at scientific institutes. Moving the substance from the laboratory to the marketplace can also prove difficult – partly because patent law can create a barrier between universities and industry. The researcher would like to publish his findings. But the industrial sector wants to keep the agent and the drug formula secret, for fear of competition. Professional articles published too soon can also obstruct patent approval. This is why the pharmaceutical industry has long overlooked the ocean as a major and important source of new drugs. But industry and academia are now collaborating in promising new ways, such as the creation of start-up ventures. During the past few years these kinds of young businesses have sparked important new initiatives in this field. A vital question will be how to fund these risky schemes, and how appealing such individual paths out of academic research are likely to be considering the overall economic situation.



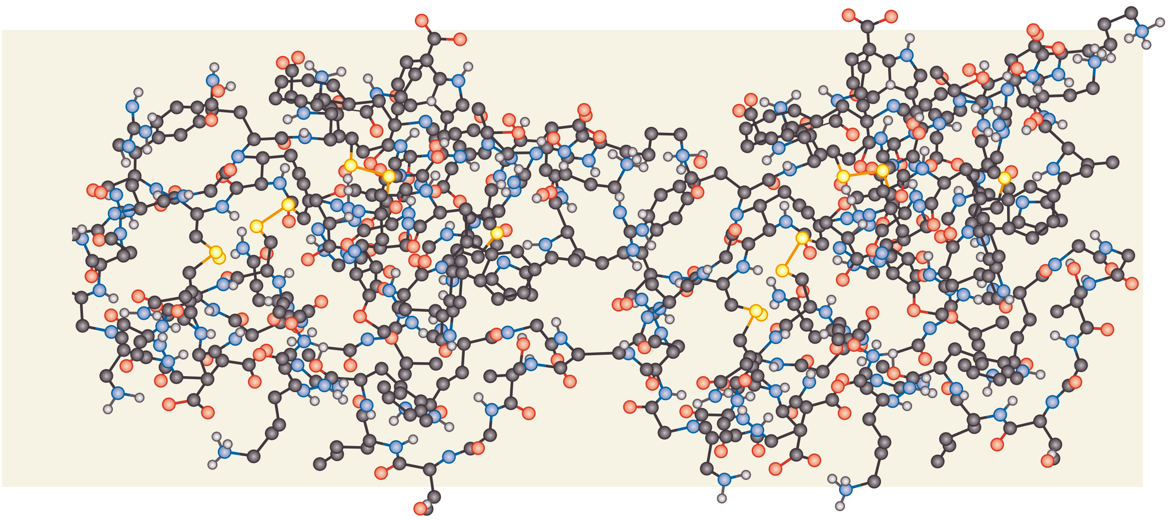
9.8 > Countless bacteria live in the outer cell layer, the ectoderm, of the cnidarian Hydra. Staining them shows how closely they are interwoven. Under the microscope the cell nuclei of Hydra appear blue and the bacteria red.

The fight against antibiotic resistance

The number of antibiotic-resistant bacteria has increased dramatically over the past 10 years. People who become infected with such bacteria can be extremely difficult to treat as scarcely any medication will help. Highly virulent is the methicillin-resistant *Staphylococcus aureus* (MRSA), a widespread bacterial strain resistant to the classic antibiotic methicillin, which has been prescribed for 50 years. The strains known as *Enterococcus faecium* and *Enterococcus faecalis*, resistant to the established substance vancomycin, are also problematic. Both types of bacteria are found in the healthy intestinal flora of humans, but pathogenic (disease-causing) varieties also exist. Virtually no antibiotic is effective against these bacteria. It is quite conceivable that the answer to this problem may be found in marine substances. For instance, cnidarians – a phylum of organisms that include jellyfish and are found both in seawater and freshwater – appear to be a very rich source of antimicrobial substances that specifically target certain bacteria. One of these substances is hydramacin, a peptide derived from the polyp Hydra, a tiny cnidarian armed with tentacles. Hydramacin kills off a range of germs that are resistant to penicillin – including certain strains of *Escherichia coli*, intestinal bacteria, as well as *Klebsiella oxytoca* and *Klebsiella pneumonia*, bacteria that inhabit the gastro-intestinal tract and can trigger diseases such as pneumonia and septicaemia (blood poisoning). As bacteria can scarcely develop a resistance to hydramacin as they can to conventional antibiotics, it is currently seen as a promising model organism for a new generation of antibiotics. Cnidarians are so interesting that their tissue has now been systematically tested for novel antibiotics that can kill multi-resistant bacteria. This process has yielded another antimicrobial peptide, arminin, which has been used to produce a synthetic molecule. The resultant molecule is potent against many of the pathogens mentioned here. But that's not all Hydra can do: Hydra's immune system also contains a serine protease inhibitor, which has proved highly effective against *Staphylococcus aureus*. This substance inhibits serine proteases, proteins that control essential metabolic processes such as blood clotting. The discovery of this antimicrobial serine protease inhibitor in the Hydra polyp shows that evolution has developed different ways for organisms to defend themselves against bacteria. It also gives credibility to the assumption that substances extracted from marine animals can be turned into new classes of highly-efficient anti-staphylococcus antibiotics.



9.9 > Over time the iridescent gold-coloured *Staphylococcus aureus* bacteria have developed a resistance to the classic antibiotic methicillin. Infections with these bacteria are extremely difficult to treat.



9.10 > Biomolecules of water organisms such as hydramacin isolated from the Hydra polyp are often complex. This makes them difficult to reproduce in the laboratory.

2. Which organism is the actual source of the marine substance is not always clear-cut. Many substances have been isolated from invertebrates in the past. In many cases, however, these did not originate from the animal itself but from the bacteria or fungi living in or on it. Microorganisms can make up as much as 40 per cent of the biomass of sponges, many of which are also colonized by microalgae. It is crucial to know when microorganisms are the actual producers of the agent, because it is hoped that they are more easily cultivated under laboratory conditions than the sea-dwellers upon which they colonize. It was initially believed that harvesting sponges and other animals on a grand scale was possible, but it soon became clear that the species could easily be completely wiped out. The focus then shifted to breeding bacteria in the laboratory, a process which is seldom successful. In some cases researchers have achieved results, however. For instance, large quantities of sorbicillactone, a substance mentioned above, were extracted within a short time from fungal cultures derived from sponges. Nevertheless, the difficulty remains that cultivating unknown bacteria can be a time-consuming process.

3. Today the search for new substances is facilitated by culture-independent methods of genetic analysis. This does away with the painstaking and complicated laboratory culture of bacteria and other organisms. For many decades expensive chemical and biochemical analyses alone were used to verify the presence of effective substances. Today, thanks to modern genetic analysis, this can be done much more quickly and easily. The latest procedures search the genetic material of marine organisms for conspicuous gene segments that contain the blueprint for promising enzymes. Such enzymes are the tradesmen of the metabolism, building different substances. The development of such DNA-sequencing techniques is definitely the greatest advance in substance research of recent years. Large-scale sequencing projects can now trawl through the genetic material of thousands of marine organisms within a short time, searching for promising gene segments. One example is the Global Ocean Sampling expedition by the J. Craig Venter Institute in the USA, which played a significant part in decoding the human genome a few years ago. The focus of this institute is now turning increasingly to the sea. Its objective is to search the genetic material of marine organisms for economically significant metabolic pathways. Entire habitats can be subjected to sequence analysis. Such major projects process both the organisms and the microbes growing on them at the same time. Therefore the findings can no longer be attributed to individual species, but the researchers anyway are mainly preoccupied with learning about the genetic make-up of an entire habitat within a short time, and finding out whether that location harbours any interesting substances at all.

Searching for the causes of disease

> The immune systems of humans and animals are remarkably similar, so much so that comparing them has become a prime subject of scientific study. Researchers hope that examining simple marine organisms will lead to a better understanding of immunity disorders of the bowel, skin and lungs. It is safe to say that bacteria play a major role here – not only as pathogenic agents, but especially as an element of the body's defence system.

How does an organism protect itself from pathogens?

The first line of defence against potential pathogens in humans, other vertebrates, and invertebrates such as sponges, is natural immunity. Even infants have an innate immune system, although they have hardly been exposed to any pathogens. This ancient phylogenetic defence mechanism consists of scavenger cells that destroy germs (phagocytosis), metabolic processes that attack and dissolve foreign proteins, and the production of antimicrobial peptides. These peptides are found in animals, plants and microorganisms. They are produced by certain body tissues such as the intestine, skin and lungs, and provide protection against infection. The human immune defence system – or at least part of it – is very old and is related to the lower-order organisms. These organisms include sponges and cnidarians (corals, jellyfish, sea anemones and freshwater polyps), which have lived in the sea for hundreds of millions of years in constant contact with bacteria and viruses. For this reason it is quite possible that they can teach scientists how an efficient defence system develops and how it can be mended in the event of disease.

Model marine organisms
Cnidarians and sponges are among the oldest life forms on Earth. They have been living in the oceans for hundreds of millions of years. In spite of their simple body structure they possess an amazing number of genes. These control metabolic processes that have been lost to some extent by higher organisms during the course of evolution. For this reason cnidarians and sponges can be viewed as a kind of prototype for all animals, and represent ideal models to study the basic principles of life.

Cnidarians, among the most primordial of sea-dwellers, seem ideally suited to the study of how an organism keeps bacteria and other pathogens at bay. They are relatively simple organisms, but nonetheless numerous complex metabolic processes take place within and between their body cells. At first glance cnidarians appear to be vulnerable and defenceless against pathogens because they have neither immune cells to destroy pathogenic intruders nor a lymphatic system to circulate defence cells through the body. They also lack a solid protective covering, having only an outer layer of cells, the epithelium. They have nonetheless managed to survive for millions of years. This makes them extremely interesting subjects of study.

Researchers are trying to find out how their tissue interacts with microbes, and how the metabolic processes in their outer skin fend off enemies. They have successfully bred genetically-modified cnidarians in which the antibacterial defence molecules are visible. This enables them to examine the living creature to see both where the antibodies are released and where they are deployed. It seems amazing that such weak and insignificant little creatures can survive in an environment that is literally teeming with potential pathogens, despite their lack of an immune system and patrolling immune cells. As we know, the exterior surface of many marine creatures, such as sponges, is permanently colonized by bacteria. And furthermore, a litre of seawater can contain up to 2 trillion bacteria and an even greater number of viruses. These microorganisms include many potential pathogens. Despite all this the creatures survive. If we wish to gain greater insight into how the body interacts with its environment, and to explore the principles of evolution, ancient marine organisms seem to be the ideal models.

Thanks to new analytical capabilities, cnidarians play an interesting role in trying to understand the evolution of immune reactions, identifying the genes involved and explaining the universal mechanisms of animal-microorganism interaction.

The body and its bacteria – a finely-tuned instrument

Higher life forms and bacteria are in constant contact with each other. Bacteria act either as disease-causing pathogens or as symbionts that take over some vital functions. For example, the intestine is colonized by a complex and dynamic community of microorganisms that support a range of metabolic functions. The intestine is gradually colonized by bacteria from birth onwards, continuing through the early stages of life until each individual ultimately develops his or her own specific intestinal flora.

Questions that largely remain unexplained include how the intestinal epithelium (the outer cell layer) interacts with the microorganisms, how the body differentiates between useful bacteria and potential pathogens, and how the bacteria influence the metabolic processes and efficiency of the human intestinal epithelium. It is possible that studies of Cnidaria could help here. Their epithelium, or outer body surface, is also colonized by a complex and dynamic community of microorganisms. Tests on the freshwater polyp Hydra have shown that individuals from different Hydra species differ greatly in the composition of their microfauna.

Having said that, however, when the bacterial composition of individuals kept under controlled laboratory conditions for many years, are compared to individuals of the same species taken directly from their natural habitat, the results are strikingly similar. This means that the colonizing bacteria remain faithful to the Hydra individuals for long periods. They are constant inhabitants of the epithelium.

These findings suggest that a rigorous selection process is at work on the epithelium. It appears that under specific conditions, certain bacterial communities that are ideally suited to the habitat become established on the epithelial tissue, remaining constant for a long time. These observations as well suggest that the epithelium actively shapes the composition of the microbial community. In case the bacterial growth on mammals or invertebrates is removed, the animals usually fall ill. The metabolic system is disrupted and the immune system weakened. Disorders of the alimentary canal are extremely severe. The animals can no longer defend themselves against infections caused by pathogenic bacteria and viruses.

9.11 > Sea anemones belong to the species-rich phylum Cnidaria. They are related to corals and jellyfish.

We are also aware that certain genetic defects in the human immune system can disrupt the collaboration between the epithelium and its colonizing microbes. People affected are usually prone to inflammatory diseases of the barrier organs – the parts of the body that are open to the outside world, such as the skin and lungs. Although we have no definite immunobiological explanation for the effect of the microbes, it is clear that symbiotic bacteria actively contribute to the critical balance between health and disease.

Bacteria are therefore essential to a large number of organisms. For instance, during its juvenile stage the bioluminescent squid *Euprymna scolopes* develops light organs on the surface of its skin. Like a firefly, the squid is therefore capable of generating light pulses by means of a biochemical reaction. However, the light organs cannot grow without a certain component being contributed by *Vibrio fischeri,* a symbiotic bacterium present in the epithelium of the squid. It is therefore clear that both the physical development and the immune system of verte-

More than the sum of its parts – the holobiont

The healthy microbial fauna of human beings and animals is highly diverse. The genetic information contained in all these microorganisms is much greater than that in humans alone. For this reason we can regard the human body, together with all the species inhabiting it, as a rich ecosystem of microbes, single-celled organisms, and other organisms – as a super-organism, a holobiont. Some scientists argue that the microbiota is essential, not only to the immediate life of the host, but also to the host's evolution. This hypothesis implies that the holobiont, including all the microbes – not the human being or animal alone – should be regarded as a unit of evolution. We still have no idea of how the parts of this super-organism interact with each other, or how they influence health. We need to learn how the organisms cohabiting in the super-organism interact at a molecular level. How have the crucial genes of the many different species of the holobiont collectively evolved? How do the microorganisms ultimately influence the biology of their hosts, and how do the hosts influence the colonizing microbes?

How does the holobiont function? This is one of the most difficult questions to answer. Cnidarians and their efficient epithelial defence systems appear to be valuable objects of study in the effort to tackle this question. The reason is that these simple organisms contain many old genes that no longer exist in higher animals such as the fruit fly *Drosophila melanogaster* or the roundworm *Caenorhabditis elegans*, which have already been studied extensively by geneticists. If we wish to understand primary metabolic processes and the principles of immune response, cnidarians would therefore be the creatures of choice. It is also interesting to note that the microbial community colonizing the freshwater polyp Hydra are extremely complex and yet exactly tailored to Hydra. They clearly differ from the microbes living in the surrounding waters. Each species of Hydra has its own microbial menu, which is very stable and scarcely changes. The microbial fauna very likely takes over a range of metabolic functions for the host. Disturbing the balance between Hydra and its colonizing microbes appears to pave the way for disease. Studying host-microbe interactions in Hydra is of fundamental interest to researchers because it helps them understand the molecular language between host and microbes in the collective ancestor of all mammals, and thus to unravel the causes of human disease.

9.12 > Single-celled algae live in a symbiotic relationship with corals, feeding them with the byproducts of their photosynthesis. When these algae die off, the corals turn white, a process called coral bleaching. One cause may be an abnormal change in bacterial growth.

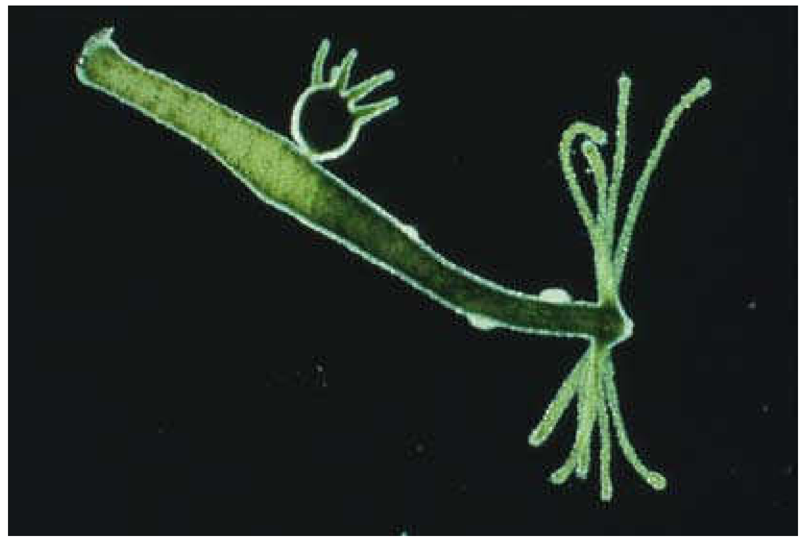
brates and invertebrates are significantly affected by their colonizing microorganisms. However, little is understood about how bacteria influence the immune functions and the mechanisms that control the complex interactions between the microbial communities and the animals.

Neither do we know how the metabolism of the epithelium impacts the composition of the symbiotic bacterial community. Initial experiments on the polyp Hydra showed that changes to the cells do in fact alter the bacterial flora. When a certain type of cell was removed from the tissue, the bacterial composition on Hydra's body surface changed conspicuously. The marked decrease of normally predominant proteobacteria was accompanied by a similar increase in the formerly rare bacteria of the bacteriodetes group. There certainly appears to be a direct interaction between the host epithelium and the microbes.

A new understanding of human disease

A large number of modern human diseases stem from dysfunctions of the boundary between the body and the outside world. These include chronic inflammatory diseases of the barrier organs, those organs that are in contact with the external environment – the skin, the lungs and the intestine, which is fed from outside sources. Examples are bronchial asthma (lungs), psoriasis and neurodermatitis (skin) as well as Crohn's disease and ulcerative colitis, chronic inflammatory bowel diseases (intestine).

Interestingly, these conditions are entirely unknown in animals. Systematic genetic tests have shown that many of them are triggered by so-called risk genes, which are ancient in an evolutionary sense. It is ironic that such complaints have proliferated in recent years, especially in the industrial nations. All diseases have one thing in common, that the human immune system breaks down at the barriers to the environment, and attacks its own body structures. New technologies have enabled us to trace individual abnormal elements on the molecular roadmap for disease. These individual components should now be combined to create an overall model for understanding the mechanisms underlying malfunctions of the immune system.



9.13 > The polyp Hydra, a cnidarian, is an ideal model organism. It is resilient and regenerates rapidly. Its reproduction process is also uncomplicated, with one method being to simply form a round polyp bud on the side of its body.

Current research indicates that immune system malfunction involves a large number of genes that control the evolutionarily old forms of immunological engagement with the environment, such as the surrounding microbiota.

One question is how, during the course of evolution, genetic variability could occur in those genes that determine the characteristics of the barriers. How do erratic food conditions or different microbiota in the water change the genetic variability of the barriers? How do such changes influence the evolutionary fitness of organisms or, in other words, the likelihood of genes surviving and reproducing? Understanding the processes on the surface of marine animals may help us to comprehend how diseases of the barrier organs occur in humans. Once we have unravelled the evolution and function of the barrier organs, we may find new strategies to treat or even prevent these diseases. Over past decades selected model organisms such as the mouse and the fruit fly *Drosophila melanogaster* have taught us a lot about recognizing and fighting the triggers of disease. But even today the question of why the outer skin of all organisms is colonized by microbes and how these microbes interact with the host remains a mystery.

Legal issues in marine medical research

> In response to the growing interest in marine substances, legal scholars are trying to clarify which state has the right to exploit these resources. The main issues concern where the organisms are found, and the extent to which a natural substance or gene sequence can be patented. The fact that different patenting rules apply in different parts of the world further complicates matters.

What makes the substances so interesting

Interest in the genetic resources found on the deep seabed has increased dramatically in recent years. They include microorganisms which occur in enormous quantities around hydrothermal vent sites, known as black smokers (Chapter 7) on the ocean floor. In complete darkness the microorganisms produce biomass from carbon dioxide and water. The energy they need for the conversion of carbon dioxide is extracted/obtained from the oxidation of hydrogen sulphide that discharges from the sea floor via the black smokers. Experts call this type of biomass production "chemosynthesis". In contrast, plants produce biomass by photosynthesis, which is driven by energy-rich sunlight.

Chemosynthetic bacteria are of great interest, as they possess unique genetic structures and special biochemical agents which could play a key role in developing effective vaccines and antibiotics, or in cancer research.

It would also appear desirable from the industrial sectors point of view to exploit these organisms. After all, the bacteria which are active at the black smokers can tolerate high water pressures and extreme temperatures. Heat-stable enzymes have now been isolated from these resilient extremophilic bacteria and could potentially be used by industry. For instance, many manufacturing processes in the food and cosmetic industries operate at high temperatures, and heat-resistant enzymes would greatly simplify these. The ability to convert and thus detoxify deadly poisonous hydrogen sulphide into more benign sulphur compounds makes the chemosynthetic bacteria even more attractive.

Who "owns" the marine substances?

Against this background, one key question arises: who has the right to utilize and research the genetic resources of the deep seabed? International law initially differentiates only according to country of origin. If a scientific research institute applies to collect samples of deep sea organisms during an expedition, its activities are attributed to the flag state of the research vessel. Alternatively, the country of origin of the syndicate or biotechnology enterprise involved is the determining factor.

Where the sample microbes are to be taken from is also relevant. According to the United Nations Convention on the Law of the Sea (UNCLOS) (Chapter 10), marine scientific research in the exclusive economic zone generally requires the consent of the coastal state. Provided these are required purely for research purposes, the coastal state should allow third countries to take samples from the waters over which it exercises jurisdiction. In the event that the research findings could ultimately have commercial potential (bio-prospecting), the coastal state may exercise its own discretion. In case of doubt it may withhold its consent to the conduct of the activities in its waters. This applies particularly to measures which are of direct economic significance, such as the exploration of natural resources: in other words, exploring the seabed with the intention of exploiting its resources.

In the case of maritime regions beyond the limits of national jurisdiction, the legal situation is less clear-cut. Who has the right to exploit the biological resources of the high seas, and the legal provisions that should govern such activity, have long been matters of dispute within

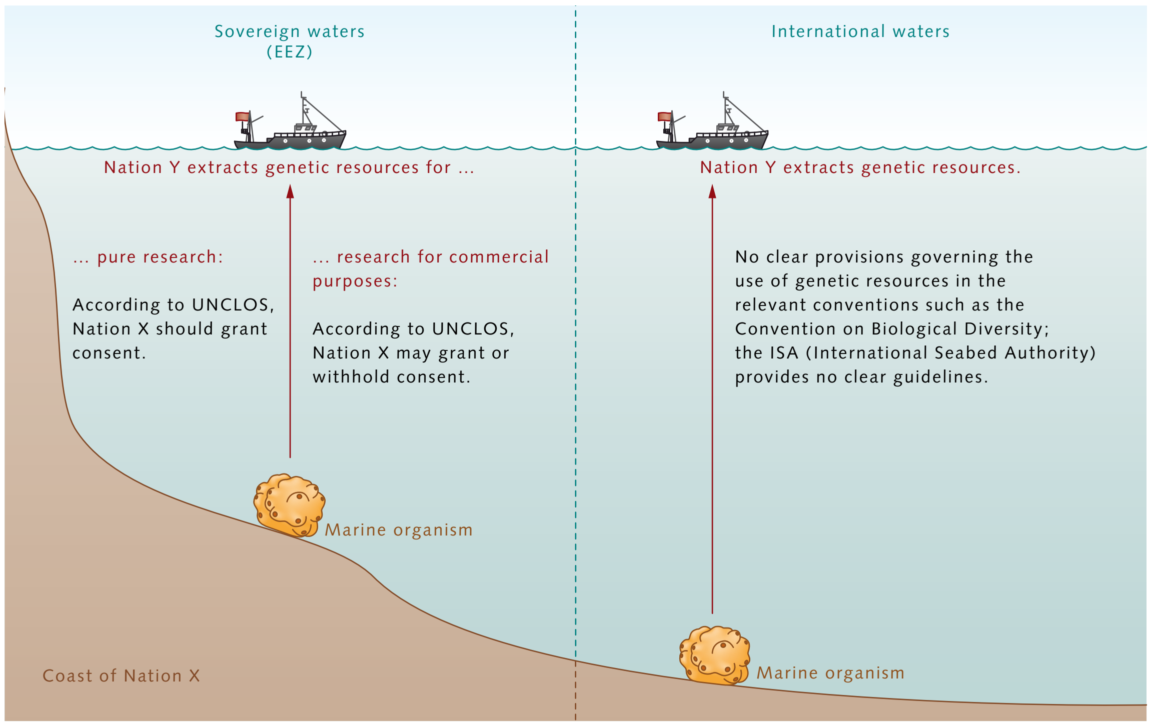
9.14 > Some microbes, e.g. the single-celled archaea, live in the vicinity of hot springs. Some contain substances which lend themselves to industrial production. Certain marine bacteria can be used to manufacture polymers, special synthetics which could even be utilized for future cancer therapy.

the international community. This includes those areas far from the coast where the black smokers are to be found, such as the mid-ocean ridges. The problem is that none of the international conventions and agreements contains clear provisions on the exploitation of genetic resources on the ocean floor. For this reason one section of the international community considers that they should be fairly shared between nations. The other, however, believes that any nation should have free access to these resources. Clearly, these views are diametrically opposed.

With regard to the deep seabed, the United Nations Convention on the Law of the Sea (UNCLOS) stipulates that "the area of the seabed ... beyond the limits of national jurisdiction, as well as its resources, are the common heritage of mankind". But this provision applies only to mineral resources such as ores and manganese nodules. If a state wishes to exploit manganese nodules on the deep seabed (Chapter 10), it must obtain a licence from the International Seabed Authority (ISA) and share the benefits with the developing countries. This explicit provision does not apply to genetic resources on the deep sea floor, however.

On the other hand, the Convention on Biological Diversity (CBD) adopted in Rio de Janeiro in 1992 calls for "the fair and equitable sharing of the benefits arising out of the utilization of genetic resources"; in other words, nature's biological bounty should be shared fairly between the industrialized nations and the developing countries. However, this objective refers only to the area within the limits of national jurisdiction and not to maritime regions far from land.

So the situation remains unresolved, with each side interpreting the content of UNCLOS and the Convention on Biological Diversity according to its own best interests. The situation is further complicated by UNCLOS allowing yet another interpretation. It establishes the "freedom of the high seas", under which all nations are free to utilize resources and carry out research at will. This includes the right to engage in fishing in international

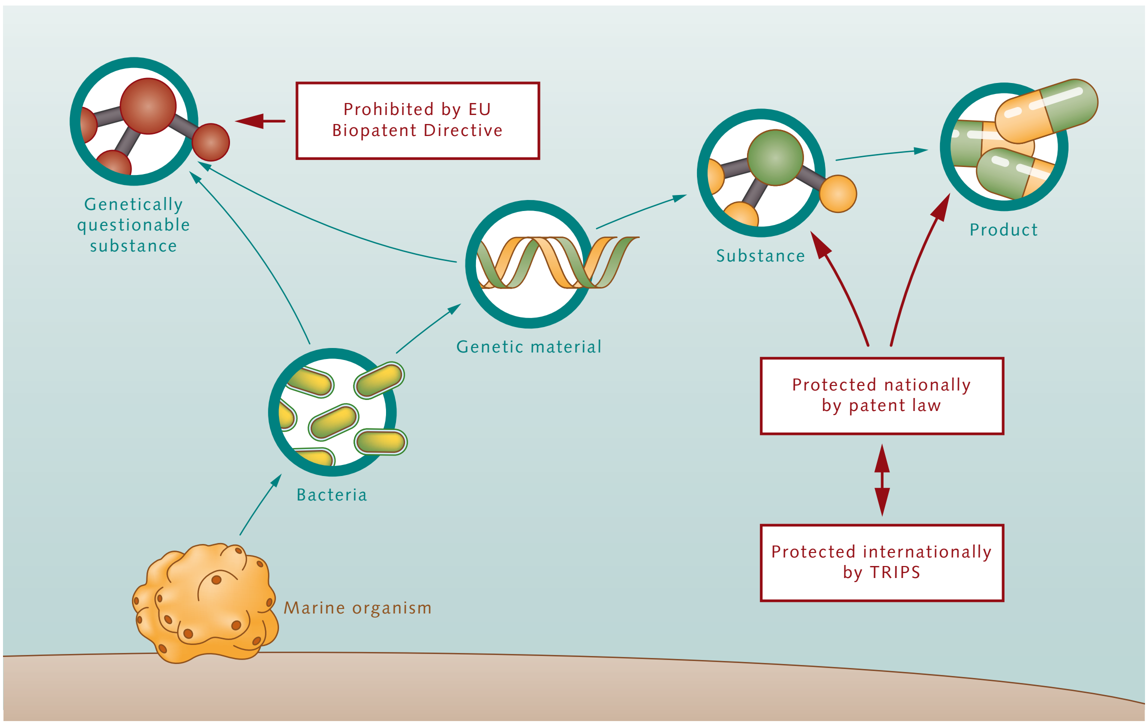


9.15 > Regulation of the exploitation of genetic resources on the seabed bed has so far proved inadequate. A state may withhold consent within its EEZ. There are no clear guidelines governing international waters, which can lead to conflict between states.

waters. All states are entitled to take measures for "the conservation and management of the living resources of the high seas". As the regime of the high seas under UNCLOS also covers the deep seabed and to the extent to which the convention does not contain any special rule to the contrary, this implies that the biological and genetic resources there are no less freely available than the fish. As a result all nations should be at liberty to research and utilize the genetic resources found on the deep seabed. This opinion is shared by most members of a special United Nations working group set up by the United Nations General Assembly in 2005 to address the protection and sustainable use of marine biodiversity beyond national jurisdiction.

Other members of the UN working group are opposed to this interpretation. As mentioned above, they want the biological resources – similar to minerals – to be shared equally between the individual states. The impasse has triggered heated debate at international meetings of the UN working group, and agreement is not expected any time soon. It is likely that at least one of the two conventions would need to be amended, and there is little chance of this happening at present.

There could be another solution, however. Some experts argue that neither UNCLOS nor the Convention on Biodiversity should primarily apply to genetic resources. Ultimately this is not about harvesting resources such as fish, minerals or ores from the seabed. It is about searching for substances in a few organisms, using these substances to develop new drugs and, later, manufacturing the drugs in industrial facilities. Strictly speaking, therefore, it is the information itself contained in the ocean organisms which is of interest, not the organisms themselves. Arguably this is more an issue of intellectual property than the traditional exploitation of natural resources – indicating that patent law would most closely fit. There is a lot to be said, therefore, for leaving international marine and environmental law as it stands, and liberalizing the provisions of international patent protection.

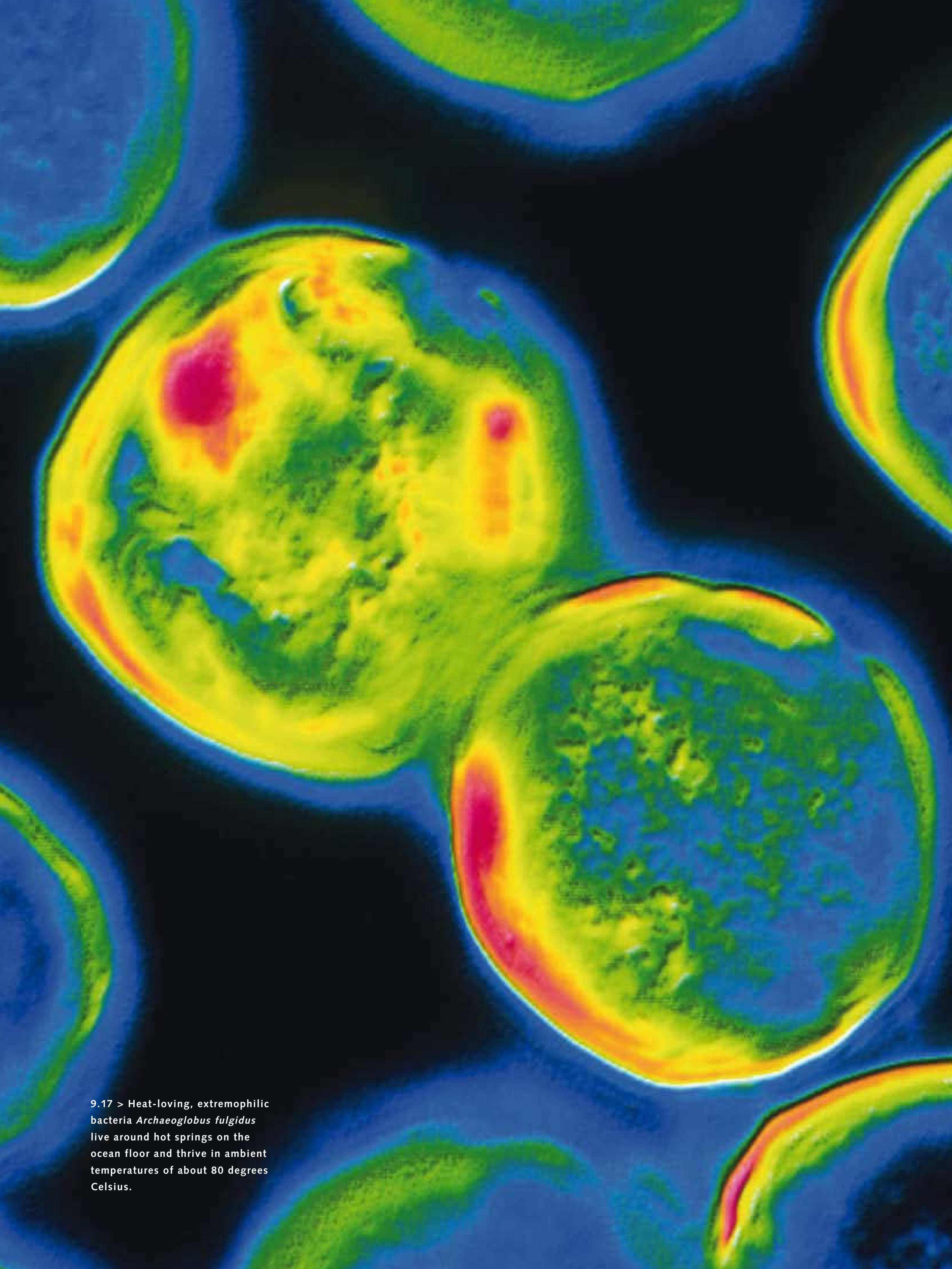


9.16 > National and international patent law governs the exploitation of natural resources and genetic information from living organisms. Substances extracted from organisms are patentable. The same applies to individual isolated gene sequences and genetically modified organisms. Newly-discovered species of animal and all their genetic material, however, cannot be patented.

The limits to patent law

If the search for marine substances touches on legal issues, then it is important to settle the question of how the research findings may be commercially utilized and exploited. In principle, patent protection of utilization and exploitation rights is governed by the provisions of domestic law. In Germany these are anchored in the Patent Act (PatG). In general this Act protects inventions, including findings from genetic research. The protection afforded by this Act ends at Germany's national borders. International protection of intellectual property is provided by the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), which applies within the sphere of influence of the World Trade Organization (WTO). The TRIPS agreement provides for mutual recognition of intellectual property rights by the signatories provided that these rights are protected by national patents. The intellectual property of all TRIPS signatories is thus protected.

Patentable objects basically include any microorganisms, animals or plants modified in the laboratory, such as genetically-modified varieties of maize. They may also be elements isolated from the human body or otherwise produced by means of a technical process, especially living cells, including the sequence or partial sequence of a gene. The discovery of a new species, however, is not patentable as a species cannot be patented as a matter of principle. On the other hand, biological material found in nature or the genetic code can be considered new in terms of patentability if it is isolated by a technical process and, by written description, is made available for the first time. Every state has the right to exclude from patentability animals, plants and the biological processes used to breed them – such as new breeds of animals, as has occurred in Germany with the Patent Act and in the EU with the Biopatent Directive. The same applies to other inventions and individual DNA sequences where economic exploitation is to be prevented for reasons of ethics and security, such as the cloning of human embryos.



9.17 > Heat-loving, extremophilic bacteria *Archaeoglobus fulgidus* live around hot springs on the ocean floor and thrive in ambient temperatures of about 80 degrees Celsius.

According to the TRIPS Agreement, commercial exploitation may be prevented when, in the opinion of the state concerned, this is necessary for the protection of "ordre public or morality; this explicitly includes inventions dangerous to human, animal or plant life or health or seriously prejudicial to the environment". According to the Biopatent Directive adopted by the EU in 1998, inventions are not patentable if their commercial exploitation may offend against ordre public or morality. This includes processes for cloning human beings and uses of human embryos for industrial or commercial purposes.

The different institutions are divided on the question of how far patent protection of DNA sequences should go. In the EU, protection is limited to the functions of the sequence or partial sequence of any gene described in the patent application. In contrast, in the USA the principle of absolute protection applies, without limitation to the functions described by the inventor. This means that in the USA not only the invention explicitly described in the application is protected by patent law, but also any developments and products which may follow in future. US patent law is therefore much more comprehensive than its European counterpart, but both approaches are compatible with international provisions. The different concepts constantly lead to controversy. The level of protection afforded by patent law to marine-derived drugs, too, will vary from region to region. This situation is unlikely to change in the near future. Behind this argument lie historic and cultural differences in concepts of individual freedom and a government's duty to protect.

Conclusion

The dawn of a new era?

The extraction of marine substances for medical or industrial use is attracting greater interest from both scientists and the business sector. In recent years a range of substances has been derived from marine organisms which are now used in cancer therapy and the treatment of viral infections. Modern methods of genetic analysis greatly simplify the search for substances – because they by-pass the need for laborious cultivation in laboratories. Businesses long hesitated to become involved in the expensive search for marine substances, and this remained the province of academic institutions. But as young start-up businesses become established, the commercialization of marine-derived drugs is gaining momentum. However, the lack of venture capital providers often leaves a substantial innovation gap between pure research and the pre-commercial development of a substance. Government funding could be crucial in helping to bridge the gap, especially during the long phase of clinical testing. But it is not only the prospect of new substances which is making the exploration of marine organisms so interesting. It seems that the metabolic pathways of primitive marine organisms and humans are in many ways remarkably similar. Simple life forms such as sponges and cnidarians provide ideal models for understanding human biochemical processes and diseases. Research is focusing on disorders of the human barrier organs – the skin, lungs and the intestine. Experts believe that these are triggered when the human immune system and the symbiotic bacteria colonizing the bodys surface are not interacting as they should. Here too cnidarians, as relatively simple host-bacteria systems, can provide new insights. We are certain that bacteria in the barrier organs play a major role in the critical balance between health and disease. But what exactly happens between humans and microbes is still virtually unknown territory, requiring years of research. Given the new interest in the topic, clarification is also needed on how the biological resources of the oceans should be shared between nations.

10 The law of the sea: A powerful instrument

> Today, a raft of international treaties determines which state has jurisdiction over coastal waters and the seabed and where a country's fishing fleet may legally operate. However, the extraction of mineral resources from the ocean floor and climate change are confronting the international law of the sea with new challenges. Balancing the protection of the marine environment with intensive use of the oceans is also a difficult task.

A constitution for the seas

> Humankind has exploited the sea for centuries, and this has frequently led to conflict. With the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982, the international community created a comprehensive framework for legal governance of the seas which, over time, has evolved into a powerful body of law. However, it cannot provide an answer to every problem that arises.

One set of rules for all states

The international law of the sea comprises all the legal norms pertaining to the sea and applicable to relations between states. It contains rules on the delimitation and exploitation of maritime areas as well as provisions on the protection and exploration of the oceans. However, some fields fall outside its scope; these include matters covered by national legislation, such as regulations on port and harbour operations, and maritime law, which in Germany is mainly enshrined in the Commercial Code and regulates activities such as the transportation of goods.

The end of legal freedom

For thousands of years, the sea was simply a source of food and was only of interest to people to that extent. With the rise of the great seafaring nations such as the Netherlands, Portugal and Spain from the 15th century onwards, however, these kingdoms increasingly sought to expand their spheres of influence. Access to mineral resources and other new commodities aroused ambitions and triggered a race to conquer the oceans, faraway islands and coastlines and thus achieve dominance in the world. This led to numerous wars and sea battles.

Early on, scholars sought answers to one important question: who does the sea actually belong to? It is a question which the international law of the sea has been unable to resolve satisfactorily to this day. From the outset, the quest for an answer was dominated by the tension between the concept of the freedom of the seas, or *mare liberum (the free sea)*, formulated by the Dutch philosopher and jurist Hugo Grotius (1583 to 1645), and the concept of *mare clausum (closed sea)* developed by the English scholar and polymath John Selden (1584 to 1654). The pivotal issue was – and is – whether the sea is international territory and all nations are free to use it, or whether it can be claimed by individual states. Neither of these two positions has ultimately prevailed, and the conflict between the positions is still apparent in the present structure of the international law of the sea.

Currently, the primary instrument of governance for the seas is the United Nations Convention on the Law of the Sea (UNCLOS), which was adopted in 1982 as the outcome of the Third United Nations Conference on the Law of the Sea (UNCLOS III). Various norms of customary international law supplement UNCLOS. The Convention is the most comprehensive international treaty ever concluded. It is based on the four Geneva Conventions on the Law of the Sea adopted in 1958: these are the Convention on the Territorial Sea and the Contiguous Zone; the Convention on the High Seas; the Convention on Fishing and Conservation of the Living Resources of the High Seas; and the Convention on the Continental Shelf. These treaties codified the – unwritten – customary law which had previously applied. For example, since the mid-17th century, countries had generally accepted that national rights applied to a specified belt of water, known as the territorial sea, extending from a nation's coastlines, usually for three nautical miles – roughly equivalent to the distance travelled by a cannon shot.

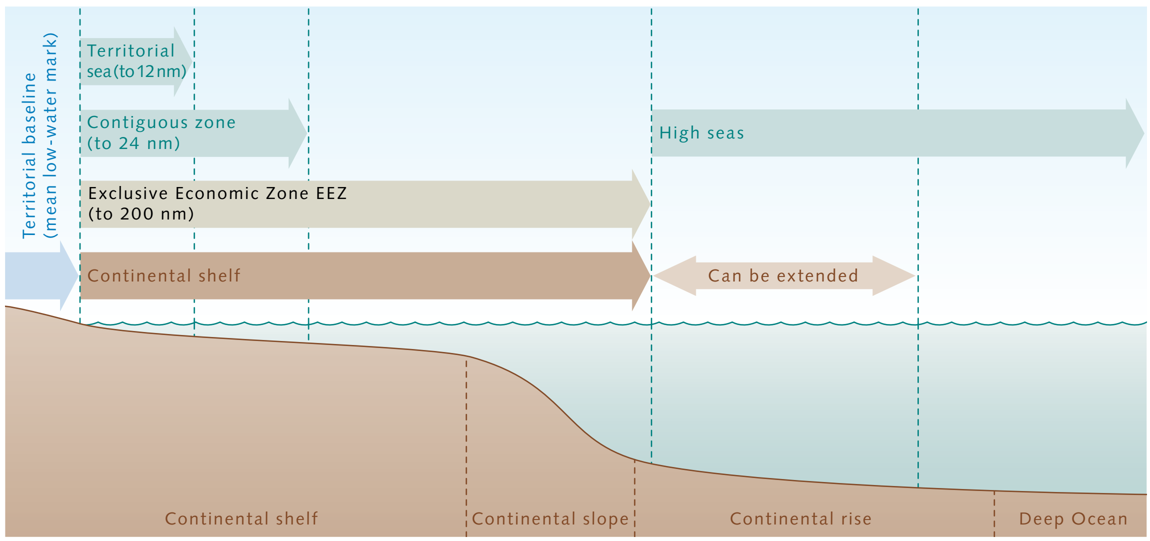
From the mid-20th century, the seas became an increasing focus of interest as a source of natural resources such

10.1 > The Dutch jurist Hugo Grotius (1583 to 1645) formulated the principle of "freedom of the seas", arguing that the sea was international territory and all nations were free to use it. He immortalized his idea in his book *Mare Liberum* (also known as *De mare libero*) in 1609.

as oil and gas. Many coastal states therefore attempted to extend their national jurisdiction over ever-larger areas of the sea and the seabed. Some laid claim to a 200 nautical mile zone. The concept of *"mare liberum"* appeared to have been consigned to history. After an initial attempt to regulate the maximum permissible extent of the territorial sea in an international treaty failed in 1930, the four Geneva Conventions were finally adopted under United Nations auspices in 1958. The aim of these international agreements was to prevent the sea from being divided up, once and for all, between various countries. However, this aim was not achieved in full. For example, the discovery of major deep seabed deposits of manganese nodules in the eastern and central Pacific Ocean, at considerable distance from the coast, in the 1960s sparked new ambitions among the industrial countries (Chapter 7). At present, the key question being discussed is which nations can lay claim to the wealth of mineral resources located in the Arctic, which in future will become easier to access as the sea ice retreats.

More scope for coastal states

Today, UNCLOS draws together the four Geneva Conventions – the "old" law of the sea – in a single unified treaty. In substantive terms, however, it actually goes further than the four. For example, under the "new" law of the sea, the rights of the coastal states are expanded, in some cases substantially, in both qualitative and quantitative terms. For example, each coastal state has exclusive rights to exploit the fish stocks in the Exclusive Economic Zone (EEZ) which extends to a distance of 200 nautical miles out from the coastal baseline. Under the Geneva Conventions, the EEZ did not exist. UNCLOS also provides the legal basis for the International Tribunal for the Law of the Sea (ITLOS), which commenced its work in Hamburg in 1996. However, the Tribunal is not the only judicial institution responsible for safeguarding compliance with UNCLOS. The states parties to UNCLOS are free to choose whether they wish to submit disputes concerning the interpretation and application of



10.2 > UNCLOS divides the sea into various legal zones, with the state's sovereignty decreasing with increasing distance from the coast. Every state has the right to territorial sea, not exceeding 12 nautical miles, in addition to its internal waters. In the territorial sea, the sovereignty of the coastal state is already restricted under international law, as ships of all states enjoy the right of innocent passage through it. In the contiguous zone, which may not extend beyond 24 nautical miles from the relevant baselines, the coastal state may merely exercise rights of control, for example to prevent infringement of its customs regulations. In the Exclusive Economic Zone (EEZ), which extends for up to 200 nautical miles, the coastal state has sovereign rights for the purpose of exploring and exploiting the natural resources, whether living or non-living, of the waters. On the continental shelf, which may extend beyond the EEZ, the coastal state has sovereign rights for the purpose of exploring and exploiting the natural resources, whether living or non-living, on or under the seabed.

Jurisdiction
"Limited jurisdiction" means that a state enjoys exclusive rights to make certain types of use of the resources of the EEZ and the continental shelf, such as the right to fish in these areas.

UNCLOS to ITLOS, or whether they prefer to apply to the International Court of Justice (ICJ) in The Hague or another international arbitral tribunal.

It took some years for UNCLOS to be accepted: most industrialized countries rejected it at first due to a number of highly contentious provisions on deep sea mining. For example, UNCLOS initially required these nations to share their deep sea mining know-how with the developing countries. Once the provisions had been watered down, reinforcing the position of the industrial nations, UNCLOS entered into force in 1994, 12 months after Guyana became the 60th country to sign the Convention and 12 years after its adoption. As of July 2009, 157 states had acceded to the Convention. Countries which have not acceded to UNCLOS are still bound by the provisions of the 1958 Geneva Conventions and the norms of customary international law.

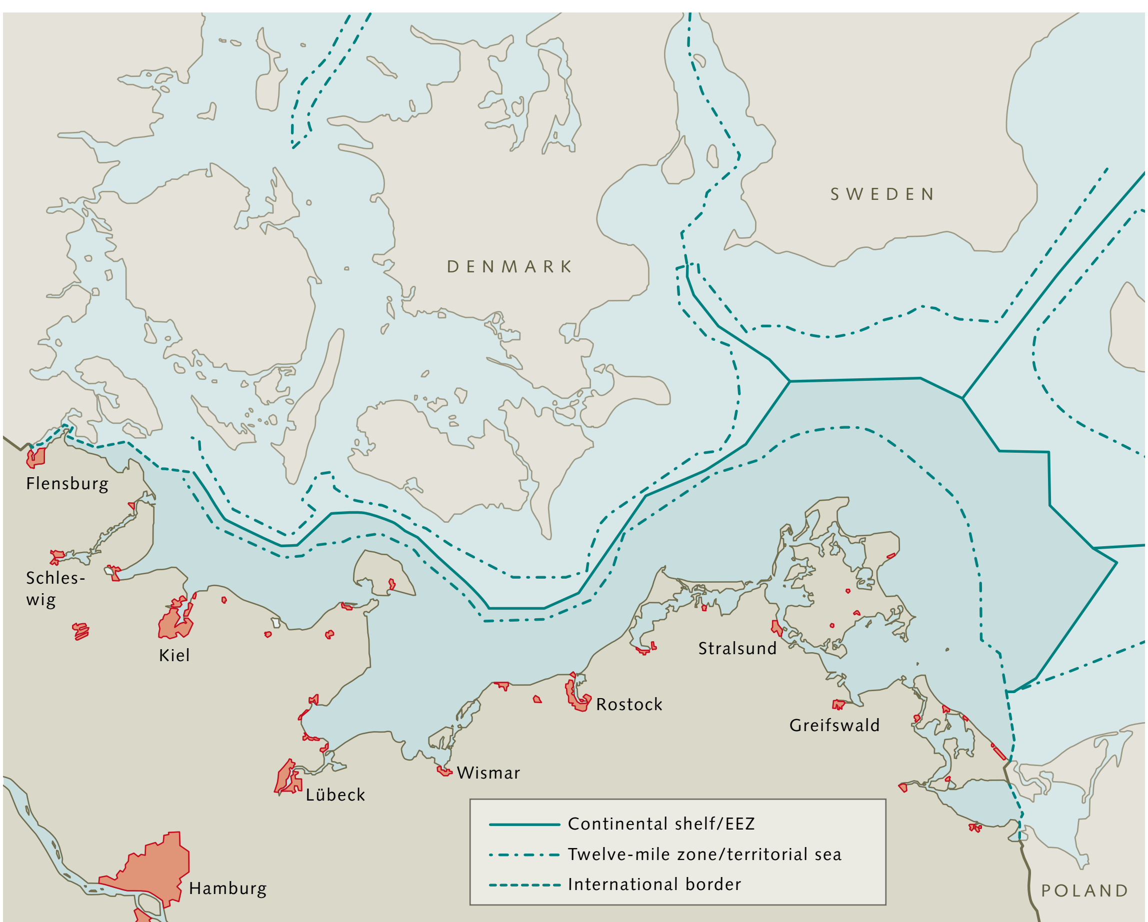
Clear rules, clear limits

The international law of the sea establishes a framework for conduct, especially in relation to economic interests, with which compliance is mandatory. It regulates fishing and navigation and the extraction of oil and gas at sea. Also the exploitation of other resources of the deep seabed and the protection of the marine environment are regulated.

The law divides the seas into various legal zones. It defines the legal status and extent of these zones and establishes norms governing the rights and jurisdictions of the coastal and flag states in respect of these zones. A state's jurisdiction decreases as the distance from the coast increases. Jurisdiction ranges from full territorial sovereignty (in internal waters) to limited "aquitorial" sovereignty (in the territorial sea) and limited jurisdiction (in the EEZ and continental shelf). The reference for the calculation of the various maritime zones is known as the baseline. The normal baseline is the mean low-water line along the coast as marked on charts officially recognized by the coastal state.

Waters on the landward side of the baseline belong to the state's internal waters. They form part of the national territory of the coastal state, which has complete jurisdiction over them. In some cases, however, it is not the low-water line which delimits the internal waters; this applies in cases where straight baselines or closing lines across a bay are drawn. The law of the sea permits this approach if the coast is characterized by deep indentations and inlets (as in Norway), if a chain of islands stretches along and immediately adjacent to the coast (as with the North Frisian Islands) or if the coast has a bay. For example, the Wadden Sea, to the extent that it lies landwards of the outermost points of the North Frisian Islands, is just as much part of Germany's internal waters as the ports of Kiel, Hamburg and Bremen.

The territorial sea extends seawards of the baseline to a limit not exceeding 12 nautical miles. It is here that international law begins to restrict the sovereignty of the coastal state: ships of all states enjoy the right of innocent passage through the territorial sea. The coastal state may not make passage through the territorial sea subject to permission or similar restrictions. Under certain circumstances, however, it may take steps to channel ships in transit, e.g. by creating shipping lanes, in order to ensure the safety of navigation.



10.3 > Neighbours Denmark, Germany, Poland and Sweden lie so close together that their Exclusive Economic Zones are limited to a narrow belt of water. In some areas, e.g. east of Flensburg, the limits actually lie within the twelve-mile zone.

A complex legal issue – protecting marine mammals

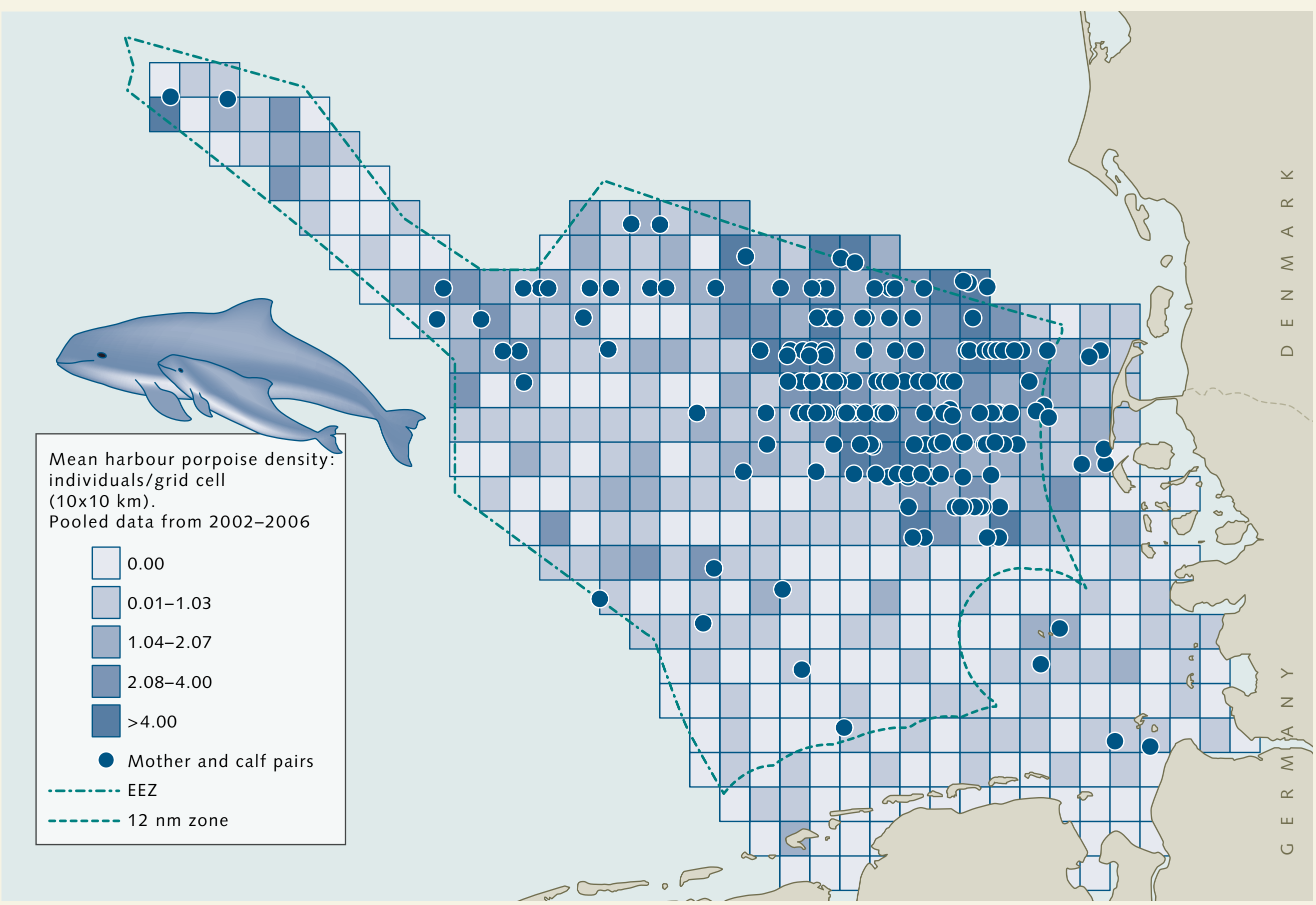
The protection of marine organisms is regulated not only by UNCLOS, but also by international environmental law and legislation adopted at national and European level. In its articles on the Exclusive Economic Zone (EEZ), UNCLOS contains numerous provisions on the management of fish stocks, and these provisions have been further elaborated in a number of more recent international agreements (Chapter 6). The same applies to the protection of marine mammals, a topic addressed as early as 1946 by the International Convention for the Regulation of Whaling, which is still in force today. Originally, the management of stocks of large whales was the key focus of attention, but following the almost complete collapse of commercially significant whale populations in the 1970s and 1980s, the states parties shifted the focus of the Convention towards species conservation by imposing a comprehensive moratorium on commercial whaling. The **International Whaling Commission** was established at the same time. For some years now, its annual meetings have been dominated by heated arguments between those countries which are in favour of a resumption of commercial whaling (mainly Japan) and the majority of other countries which are strictly opposed to whaling. At present, Japan circumvents the moratorium by invoking a clause in the Convention which authorizes the killing of whales for purposes of scientific research. However, as the whales killed are in fact utilized for commercial purposes, most experts in international law take the view that Japan's conduct is an abuse of the law. It is still unclear how the stalemate at international level between those in favour of whaling and those opposed to it can be resolved. From an economic perspective, whaling is a loss-making business, even in Japan. There is no doubt, however, that supporters of whaling are extremely dissatisfied with the work of the Commission, so they may continue to ignore the moratorium in future. A possible way out of the crisis would be a cautious easing of the moratorium. One option could be to agree a small catch quota for minke whales, which – in view of the positive development of stocks of this species – could be justified on ecological grounds. The prerequisite, however, would be stringent controls of whaling, including the presence of foreign inspectors on board the whaling vessels. A very limited resumption of commercial whaling could offer Japan a way out of illegality. But is this ethical? World opinion remains divided.

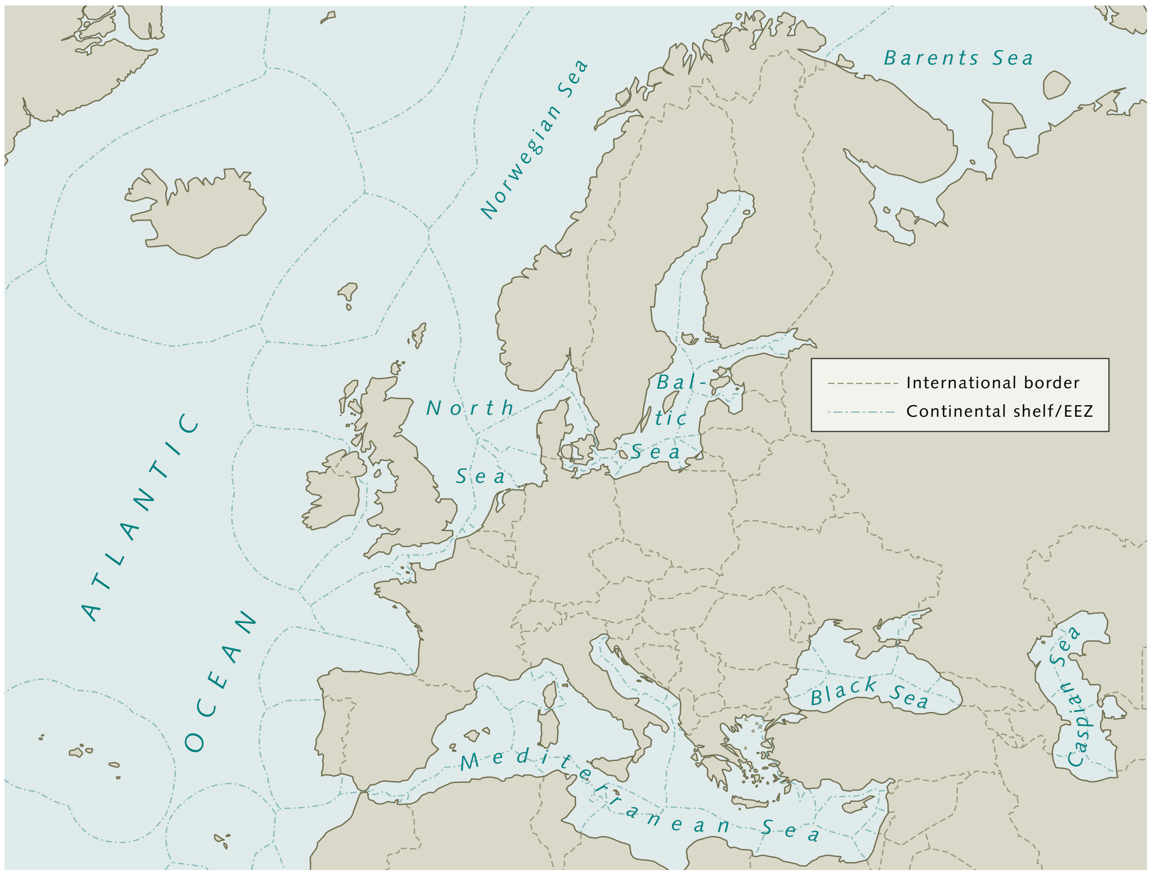
The harbour porpoise *(Phocoena phocoena)* is the only native species of cetacean inhabiting the North and Baltic Seas. In the German EEZ, harbour porpoises are found mainly at the Sylt Outer Reef, where the number of mother and calf pairs is particularly high, indicating that this area is important for the species' reproduction. The intensive use of the German EEZ is having a major impact on harbour porpoise stocks. Fishing is a particularly relevant factor here as it reduces the porpoises' food sources. In other cases, harbour porpoises die as bycatch in fishing nets. Underwater noise pollution, caused for example by offshore structures such as wind turbines, can drive harbour porpoises off their ranges and can also cause direct damage to the animals' health. Pollution, too, can affect the health status of porpoise in various ways. Current legislation therefore aims primarily to make economically significant human activity in and on the seas more ecologically sustainable, with a view to protecting and preserving the harbour porpoise.

10.4 > Whereas most countries have agreed to protect whales, Japan is continuing to hunt them, as seen here in the South Pacific. The Japanese invoke a clause in the whaling moratorium which allows the killing of whales for scientific research purposes. Ultimately, however, their underlying interests are commercial.

10.5 > Off the German coast, harbour porpoises are mainly found at the northern periphery of the EEZ on the border with Denmark. As this example shows, transboundary species conservation schemes such as the EU's Natura 2000 system are essential to preserve marine mammals.

The Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS), for example, is significant here. However, in internal waters, the territorial sea and the EEZ, it is the nature conservation legislation adopted at the national level which is primarily relevant. Furthermore, in European waters, the legislation on species and habitat conservation introduced by the institutions of the European Union (EU) plays a key role. The EU's Habitats Directive, for example, covers the EU member states' internal waters and territorial sea, the EEZ and the continental shelf. This Directive aims to create a coherent European network of protected areas, known as "Natura 2000", as a key instrument to preserve European species diversity. The Directive requires protected sites to include habitats of specific species, one of which is the harbour porpoise. Within the designated protected areas, any plan or project which is likely to have a significant effect on the environment, such as the construction of offshore wind farms, must undergo a stringent environmental impact assessment before it can be carried out. In some cases, however, a plan or project must nevertheless be carried out for imperative reasons, such as overriding public interest, in spite of a negative assessment of the project's implications for the environment. In such cases, the member state is required to adopt compensatory measures.





10.6 > In densely populated Europe with its many borders, the Exclusive Economic Zone (EEZ) often extends for less than 200 nautical miles. This applies to the Adriatic, the North Sea and the Mediterranean. Nonetheless, worldwide, around 90 per cent of all commercially relevant fish species are caught in the relatively narrow belt of water which forms the EEZs.

Adjacent to the territorial sea is the contiguous zone, which extends up to 24 nautical miles seawards from the baseline. In this area, which partly overlaps with the territorial sea, the coastal state may merely exercise rights of control. For example, it may verify compliance with or infringement of its national laws and regulations, including customs, fiscal, immigration or sanitary laws and regulations, within its territorial sea. Further out to sea, there is the Exclusive Economic Zone (EEZ), which stretches to 200 nautical miles seawards of the baseline.

Unlike the internal waters and the territorial sea, the EEZ does not form part of the national territory. Here, the coastal state merely has specific limited rights which apply not to the maritime area itself but only to the resources existing within it. As the term "Exclusive Economic Zone" implies, only the coastal state may erect and utilize structures such as oil platforms and wind turbines here, or engage in fishing: third countries are excluded from such activities. This is highly significant from an economic perspective: for example, around 90 per cent of all commercially relevant fish species occur in the coastal states' EEZs. This figure is even more striking given that these economic zones make up just 35 per cent of the seas' total area.

The coastal state also has jurisdiction over marine scientific research. The conduct of marine research activities by third countries in the Exclusive Economic Zone therefore generally requires the authorization of the coastal state. In matters pertaining to the protection and preservation of the marine environment, too, the coastal state enjoys specific rights in the Exclusive Economic Zone. It alone may propose the designation of a marine protected area within its EEZ to the International Maritime Organization (IMO) in order to protect the area concerned against pollution from ships. However, a coastal state may not assert territorial claims to any part of the Exclusive Economic Zone. All states enjoy freedom of navigation in the EEZ and have the right to lay subma-rine cables and pipelines there.

UNCLOS also contains specific provisions relating to the continental shelf, of which parts may lie well beneath the EEZ. Like the EEZ, this is an area of jurisdiction where only the coastal state has the right to explore and exploit natural resources. Nature and law dictate that every coastal state in the world has a continental shelf, but the width of that shelf varies considerably, according to geological conditions. As the law stands, however, each coastal state may claim a continental shelf of up to 200 nautical miles. If the natural continental shelf extends beyond 200 nautical miles, an even larger area can be designated as the continental shelf. In that case, under international law, the maximum outer limit may not exceed 350 nautical miles from the baseline or, alternatively, 100 nautical miles seawards from the 2500 metre isobath.

In cases where a coastal state intends to establish the outer limits of its continental shelf beyond 200 nautical miles, it is required to provide evidence to the UN Commission on the Limits of the Continental Shelf (CLCS) that the submarine area concerned is genuinely a natural prolongation of its territory. The Commission scrutinizes the geological and hydrographic data submitted and finally makes a recommendation. The outer limits of the shelf established by a coastal state on the basis of these recommendations are final and binding.

However, there is still disagreement within the international community concerning the legal implications of a Commission recommendation. The Commission has no powers of judicial control: scrutiny by the CLCS is merely intended to ensure that the limits of the continental shelf are established in compliance with scientific standards. The CLCS is not a paper tiger, however: a recommendation by the Commission, once published, puts a coastal state under considerable political pressure. Any deviation must be justified, and not once has a recommendation by the CLCS been disregarded.

The outer limits of the Exclusive Economic Zone mark the start of international waters (the high seas). This term applies to the water column beyond the EEZ rather than to the seabed. The high seas are open to all states. No state may subject any part of the high seas to its sovereignty. The "freedom of the high seas" – just as Hugo Grotius envisaged – comprises, in particular, freedom of navigation, freedom of fishing, and freedom of marine scientific research.

The non-living resources of the seabed beyond the continental shelf on the seaward side have been declared part of the common heritage of mankind. Extraction of the manganese nodule deposits located in this area (Chapter 7) will henceforth be subject to rules that are geared towards the benefit of mankind as a whole and take into particular consideration the interests and needs of the developing countries. Mining operations will be organized and monitored by the International Seabed Authority (ISA) based in Kingston, Jamaica, which was established specifically for this purpose by the states parties to UNCLOS. The ISA is responsible, in particular, for ensuring the equitable sharing of the benefits arising from deep seabed mining activities. Notably, half the seabed areas for which industrialized nations in future acquire exploration and mining licences are reserved for the developing countries. At present, however, extraction is still unprofitable and the requisite technology is lacking. Only time will tell how well the rules operate in practice.

As a "constitution for the seas", UNCLOS merely provides the normative framework for international legal governance of the oceans and leaves a number of questions unanswered. This applies especially to aspects which have only been recognized as significant, based on new scientific findings, since UNCLOS was adopted in 1982. There have been new discoveries of ore deposits in the seabed, for example. Global warming is also causing changes. UNCLOS may therefore need to be supplemented by additional treaties in response to these new challenges.

Continental shelf
There is a legal and a geological definition of the term "continental shelf". Legally speaking, the term denotes the zone which extends out to a maximum limit of 200 nautical miles seawards from the baseline. Geologically, the term is applied to the broad, relatively shallow submarine platform adjacent to the coast, which slopes gradually to an average depth of 130 metres. The steep continental slope with a gradient of up to 90 degrees adjoins it on the seaward side.

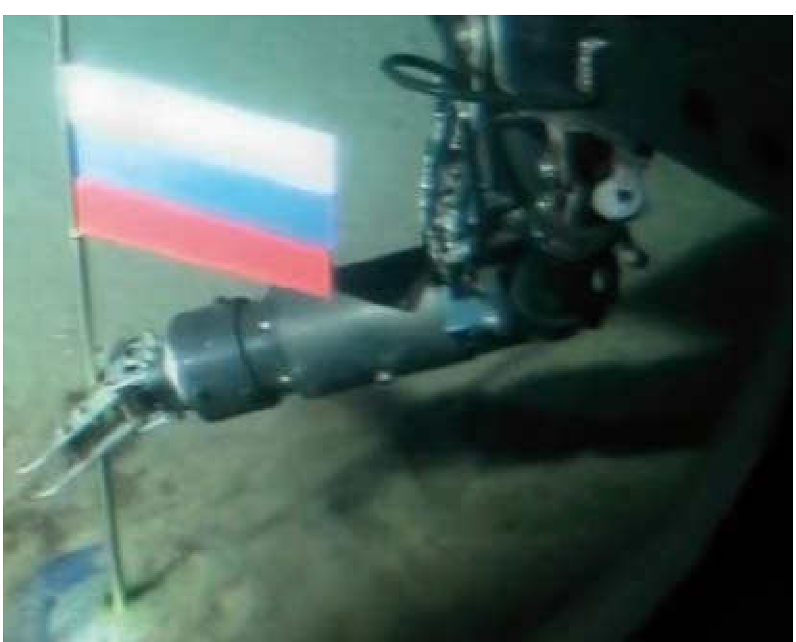
The limits to the law of the sea

> The changes in the marine environment resulting from global warming are clearly revealing the limits to the law of the sea in its present form. The Arctic ice sheets are shrinking, opening the way to the long-hidden mineral deposits in the seabed and sparking a new rush for resources. Another hot topic at present is to what extent humankind is permitted, as the law stands, to interfere with the marine ecosystem in order to cushion the impacts of climate change.

Underwater land grab

Most experts agree that climate change is causing the Arctic ice cap to melt faster. From an economic perspective, this is a very interesting development: firstly, because it could open up alternative and much shorter shipping routes during the summer months, such as the Northwest Passage and the Northern Sea Route, thus benefiting international trade, and secondly, because it will make the oil and gas deposits thought to lie under the Arctic seabed much easier to access. With the Arctic littoral states now vying for control over these natural resources, the public was given an initial taste of things to come on 1 August 2007, when Russia – using manned mini-submarines – planted a Russian flag on the seafloor at the North Pole and symbolically proclaimed the area concerned to be Russian territory.

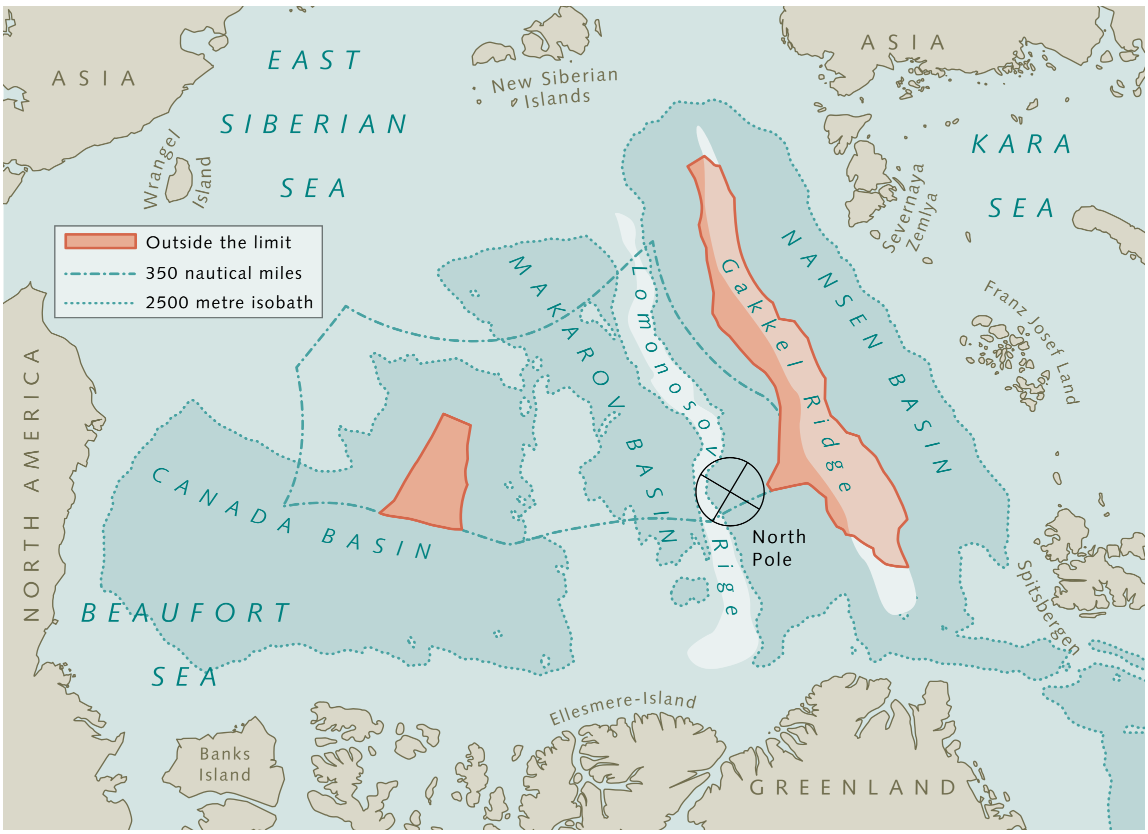
Besides Russia, the other Arctic littoral states – Denmark (Greenland), Canada, Norway and the United States – have also launched expeditions to prove that areas of the ocean floor are submerged prolongations of their territories, prompting media speculation about the possible outbreak of an "ice-cold war" in the polar north.



10.7 > On 1 August 2007, Russian explorers captured the attention of the world's media when they planted their national flag on the seafloor in the Arctic Ocean.

Bickering over borders

But to what extent do the Arctic territories form part of the coastal states' continental shelf? This is still an unresolved question. If the answer is affirmative, the United Nations Convention on the Law of the Sea (UNCLOS) grants the Arctic state on whose continental shelf they are located the exclusive rights to exploit any resources potentially existing there. These resources would, in consequence, not be subject to the rules applicable to the common heritage of mankind, which are administered by the International Seabed Authority. The Arctic states are currently attempting to prove that geologically, their continental shelf extends for more than 200 nautical miles out into the Arctic Ocean. As explained above, in this case too, the maximum outer limit may not exceed 350 nautical miles from the baseline or, alternatively, 100 nautical miles seawards from the 2500 metre isobath. In the Arctic, the – permissible – combination of these two methods would offer Russia, in particular, the prospect of extending its continental shelf to the maxi-



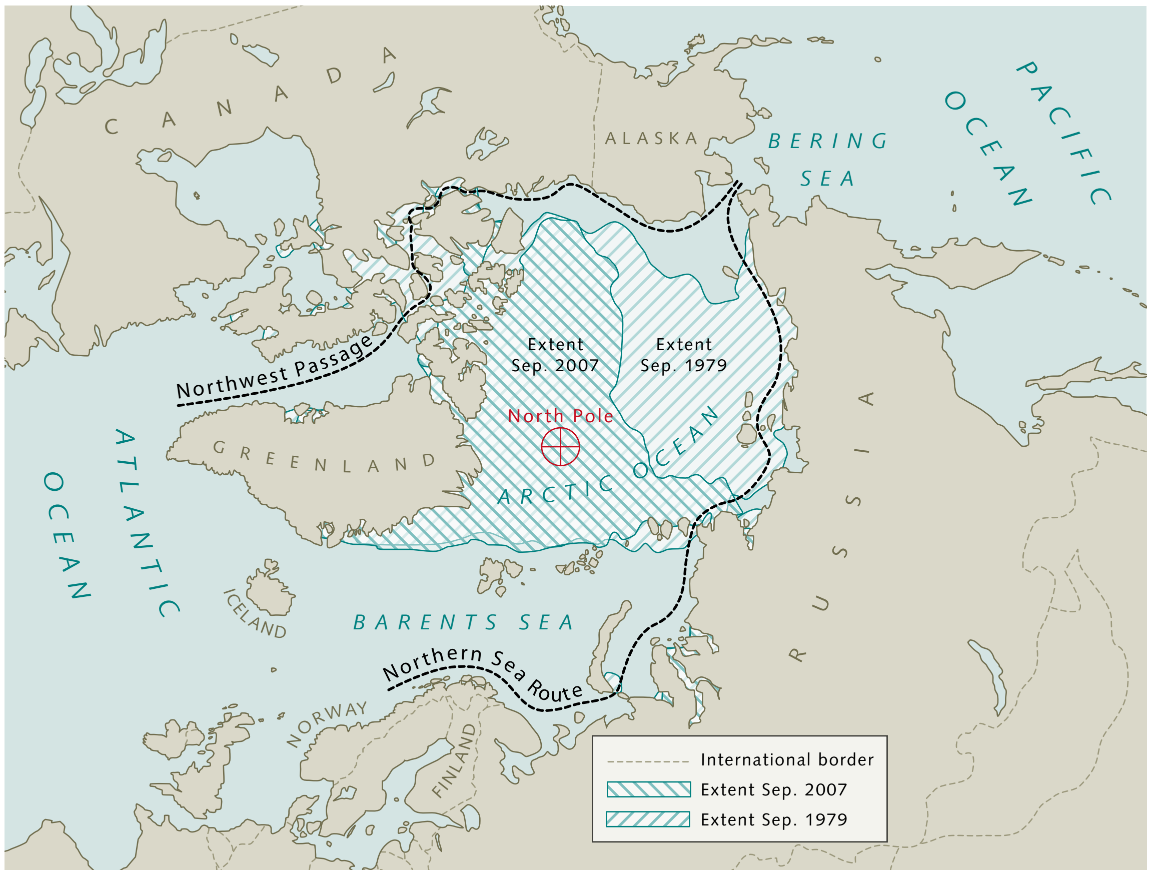
10.8 > Prolongation of the continental shelf in the Arctic. The Gakkel Ridge is shown in red on the right. The area marked in red on the left cannot be claimed by any littoral state as it is circumscribed by the 2500 metre isobath. The Lomonosov Ridge lies to the left of the Gakkel Ridge between two 2500 metre isobaths.

mum possible extent. There are just two relatively small areas ("donut holes") in the Arctic which could not be claimed by any littoral state: the first is the Gakkel Ridge, an oceanic ridge which lacks a "natural" connection with the continental margins, while the second area is circumscribed by segments of the 2500 metre isobaths.

The situation in the Arctic is further complicated by the fact that an exception to the rule on measuring the outer limit of the continental shelf applies here. UNCLOS makes a distinction between "oceanic ridges", which are not directly connected to the continental margins, "submarine ridges", and "submarine elevations". On submarine ridges, UNCLOS states that the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured. In other words, only the 350 nautical mile cut-off line applies to submarine ridges: the outer limit of the continental shelf cannot be measured according to the 2500 metre isobath, which in the case of submarine ridges is, by its very nature, a more advantageous method of calculation. If the feature concerned is merely a submarine elevation, however, this restriction to the 350 nautical mile method does not apply. This is because unlike submarine elevations, submarine ridges generally consist of volcanic rock and are hence formed from a different material than the continental shelf. Although connected, they therefore differ in origin. Submarine elevations, by contrast, are similar in composition to the continental margin. In other words, the elevation and the continental shelf are geologically identical.

So to determine whether the structural features of the Arctic seabed are submarine ridges or elevations, a geological analysis of the rock must first be carried out. And this is exactly where the problem lies in the Arctic: it has

Oceanic ridges
Oceanic ridges are formed when underwater tectonic plates drift apart and magma rises from the Earth's interior at this fracture point. Over time, this creates a ridge which may reach a height of several thousand metres. Oceanic ridges are generally located mid-ocean, some distance away from the continental shelf areas and continental slopes.



10.9 > The area covered by Arctic sea ice has been shrinking for many years, offering access to untapped oil and gas deposits during the summer months in future. It could also open up new shipping routes, such as the Northwest Passage and Northern Sea Route, which are much shorter than the Panama and Suez Canal routes.

numerous submarine mountain ranges. According to prevailing opinion, all of them – with the exception of the Gakkel Ridge – are connected in some way with the continental margins and could thus be regarded as integral parts of the continental shelf of one or more littoral states. Their geological composition will therefore be the crucial factor in determining which of UNCLOS's provisions ultimately applies. Russia, for example, takes the view that the Lomonosov Ridge is a submarine elevation within the meaning of the Convention, such that the 2500 metre isobath rule would apply. However, explorations carried out to date indicate that geologically, the Lomonosov Ridge is not a natural component of Russia's continental margin.

So which country will ultimately be able to lay claim to the Arctic seabed? That will depend on how the Commission on the Limits of the Continental Shelf (CLCS) evaluates the data submitted by the coastal states. And time is pressing: for countries such as Russia, which acceded to UNCLOS before 13 May 1999, the deadline for submission to CLCS of data relating to the prolongation of its continental shelf beyond 200 nautical miles expired on 13 May 2009. It is likely to be many years before all CLCS's recommendations are available. Countries which acceded to UNCLOS after 1999 or whose accession is planned must submit their documents within 10 years of accession. For Canada, the deadline expires in 2013, while Denmark's deadline is 2014. Given that new oil and gas deposits were discovered in the Arctic seabed in 2004, it remains to be seen whether the states parties to UNCLOS will opt to extend the deadline envisaged in the Convention. However, the Commission is not responsible for the delimitation of the continental shelf between states with opposite or adjacent coasts. In such cases, UNCLOS merely obliges the states concerned to effect agreements in order to achieve an equitable solution. Moving in that direction, in the Ilulissat Declaration of 28 May 2008, the five Arctic states reaffirmed their commitment to the international law of the sea and the orderly settlement of any possible overlapping claims.

The law of the sea and climate change mitigation

One of the most pressing issues on the climate policy agenda is reducing emissions of CO_2, a climate gas. This issue has implications for the law of the sea as well. At present, great hopes rest on the storage of atmospheric CO_2 in the oceans and seabed. From a law-of-the-sea perspective, however, this is a complex issue, as is apparent from a topical example, namely the fertilization of the oceans with iron providing plant nutrients. The idea is to stimulate primary production of phytoplankton, which, gradually sinking to the sea floor, would remove CO_2 from the atmosphere over the longer term. The concept was trialled in the Indo-German "Lohafex" marine research project in 2009. The question which arises, however – not only in relation to Lohafex – is whether this type of **geo-engineering** activity is compatible with the law of the sea as it stands. Although UNCLOS contains detailed provisions on the protection of the marine environment, it makes no reference to the permissibility of geo-engineering measures in general or iron fertilization in particular. The dumping of waste and other matter at sea is generally prohibited, however, and this prohibition is fleshed out in two other international treaties: the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, adopted in 1972 (London Convention – LC), and the 1996 London Protocol (LP) which tightened and specified the provisions of the London Convention. Accordingly, in October 2008, the states parties agreed that legitimate scientific research should not conflict with the objectives of the London treaties, which means that iron fertilization of the oceans on a commercial basis continues to be prohibited. There was some discussion as to whether industrial enterprises should be able to fertilize the oceans to stimulate algal growth and thus qualify for carbon credits, but it is now accepted that iron ferti-lization on a commercial basis is prohibited.

Carbon Credits
The term "carbon credits" means the same as "emissions allowances". These allow industrial enterprises, such as power plants or cement works, to emit a specific amount of carbon dioxide (CO_2). If a company installs technical systems to reduce its CO_2 emissions, it uses up fewer of its emissions allowances. This means that it can sell the surplus to other companies which are still producing high levels of emissions and therefore need more allowances. CO_2 reduction measures, which often generate additional costs, thus become economically viable.

Conclusion

The future of the law of the sea

Under pressure from climate change, species extinction, overfishing and maritime navigation, the law of the sea – the constitution for the seas – faces numerous challenges. There is ongoing tension between the freedom of the seas and their territorialization as epitomized by the concept of "mare clausum". While occasional amendment of established provisions may be required in response to new knowledge and developments, this invariably harbours the risk of expanding national jurisdiction over the sea. The United Nations Convention on the Law of the Sea (UNCLOS) must always be the starting point for any legal analysis. With this Convention, the international community's desires and aspirations have been incorporated into a framework which enjoys almost universal acceptance and which has so far proved to be more flexible and open than often assumed. UNCLOS will therefore continue to develop its normative effect in the international law of the 21st century. The prerequisite, however, is states' willingness to cooperate and seek peaceful solutions to any disputes that may arise – especially in view of, and in response to, the new challenges arising on and beneath the seas.

world ocean review
Living with the oceans.

Overall conclusion

In this first "World Ocean Review", we present a report on the state of the oceans which will be followed by periodic updates in the future. Our aim is to reveal the consequences of intense human intervention for the ocean realm, including the impacts of climate change. We already understand some of the effects, but many unanswered questions remain. What is certain, however, is that human society must change its behaviour with the goal of achieving sustainable interaction with the environment and the oceans in particular. Worldwide, the winter of 2010 was the warmest in the past 131 years. Global climate change has caused a gradual rise in the Earth's average temperatures. In the coming years the rate of glacial melting will probably accelerate. Sea-level rise will become more rapid. Present calculations indicate that there will probably be a rise of at least 80 centimetres within this century, with as much as 180 centimetres being predicted for the worst-case scenario.

The immense water masses of the ocean act as a buffer, storing considerable amounts of carbon dioxide and heat from the atmosphere. Climatic changes therefore only gradually become noticeable. Scientists anticipate that if greenhouse gas emissions continue unchecked, the sea level could rise by as much as 5 metres by the year 2300. Most of the "mega-cities", with populations greater than 10 million, are located on or near the coasts. It would require enormous sums of money to protect them, and presumably many of them will have to be abandoned. The ocean may be buffering the most severe consequences of climate change for now. But in the long run we can only hope to avoid these if we strictly curb greenhouse gas emissions today. Experts are concerned that hundreds of thousands of tonnes of methane hydrate could break down due to the warming of seawater – gas masses that are lying inertly in solid, frozen form in the sea floor sediments today. A portion of the methane, which is a powerful greenhouse gas, could then rise into the atmosphere and further accelerate the process of climate change – a vicious circle.

The oceans absorb many millions of tonnes of carbon dioxide annually. They are the largest "sink" for anthropogenic CO_2 emissions. The excess carbon dioxide, however, upsets the chemical equilibrium of the ocean. It leads to acidification of the oceans, the consequences of which are unpredictable. Acidic water disrupts the sense of smell in fish larvae, carbonate formation by snails, and the growth rates of starfish. The phytoplankton, tiny algae in the ocean and vital nutrient basis for higher organisms, are also affected by acidification.

The coastal environment is still being damaged by effluent and toxic discharges, and especially by nutrients conveyed to the ocean by rivers. Thousands of tonnes of nitrogen and phosphorus compounds flow into the ocean around the world, causing an explosion in algal reproduction. In many coastal regions the catastrophe begins with the death of the algae. Bacteria feed on the algal remains and consume oxygen in the water. In these oxygen-depleted zones all higher life forms die off. Efforts to reduce nutrient levels have been successful in Western Europe. Worldwide, however, the input of nutrients is becoming increasingly problematical. People are, without a doubt, abusing the oceans in many respects, and this is increasing the stress on marine organisms. Through over-fertilization and acidification of the water, rapid changes in water temperature or salinity, biological diversity in the ocean could drop worldwide at increasing rates. With the combination of all these factors, the disruption of habitats is so severe that species will continue to disappear.

It is still uncertain what consequences will ensue from the gradual poisoning of the marine environment with pollutants such as polyfluorinated compounds, which have been used for years as components in non-stick surfaces for pans and in outdoor jackets. These substances become concentrated in the nutrient chain and have recently been detected in the tissue of polar bears. Clearly the oceans continue to be the "last stop" for the dregs of our civilization, not only for the persistent chemicals, but also our everyday garbage. Six million tonnes of rubbish end up in the ocean worldwide every year. The trash is a fatal trap for dolphins, turtles and birds. Plastic is especially long-lived and, driven by ocean currents, it collects in the central oceans in gyres of garbage covering hundreds of square kilometres. A new problem has been identified in the microscopically small breakdown products of plastics, which are concentrated in the bodies of marine organisms.

In the medium term, however, there is a positive trend with regard to ocean pollution. The number of oil spills has decreased. Spectacular tanker accidents now only contribute around 10 per cent of the oil contamination in the oceans. Less conspicuous oil pollution, on the other hand, continues to be a problem. Around 35 per cent of the worldwide oil pollution originates from everyday shipping operations. This source is much more difficult to deal with. As was demonstrated by the explosion of the "Deepwater Horizon" drilling rig, new problems may arise with the trend towards producing oil and gas from wells from greater water depths.

Humans are destroying the marine environment not only through pollution, but also through greed. 80 million tonnes of fish with a market value of around 90 billion US dollars are caught every year. As a result, the fish stocks are now severely overfished or are completely depleted. This situation has been caused by a flawed fisheries policy that strongly subsidizes fishing. Protection of jobs has always been more important than the protection of living resources. This is an extremely short-sighted view. The Common Fisheries Policy (CFP) adopted by the European Union is a notorious example. The European Union's Council of Ministers has regularly set the catch quotas too high, overriding the recommendations of fishery biologists who have long been warning of overexploitation and depletion of stocks.

Fish are not the only living resource that humans harvest from the ocean. The recovery of medically and industrially useful materials from the sea is becoming more interesting for scientists and commercial enterprises. In recent years substances extracted from marine organisms have been used in cancer therapy and to fight viruses. Businesses have long resisted joining in the expensive search for active agents in the oceans. But with the establishment of new start-up companies, the commercialization of marine medicine has accelerated. The young businesses, however, rely heavily on government subsidies initially.

The large oil and mining companies are looking for very different kinds of marine resources. Drilling for oil in the oceans has been going on around the world for decades. The proportion of gas and oil extracted from the ocean has been growing steadily, and today it represents around one-third of worldwide production. Moreover, in the coming years the mining of ores and manganese nodules will likely begin on a large scale. Methane hydrates are also becoming increasingly interesting. If the industrial production of methane becomes viable, we will have tapped a gigantic energy reservoir. In theory, the hydrates would be dissolved at the sea floor under controlled conditions and the methane extracted. However, it is not sure that this will work. Critics are concerned that large quantities of methane could escape uncontrolled from the sediments.

Humankind is forging into the deeps as never before. Because of the scale at which resources on land are being depleted, mining in the ocean depths is becoming more attractive and potentially lucrative. In 2007 and 2008, before the economic crisis, mineral resources had reached exorbitant prices. The mining of the ocean, which experienced a period of high interest in the 1970s before becoming inactive for a time, thus became attractive again in spite of the subsequent crisis. Presently, the precious-metal rich ores near once-hot submarine springs and manganese nodules in the central Pacific appear to be especially promising. Mining of the ore deposits could begin in the near future. Environmentalists, however, fear that this could cause the destruction of deep-sea habitats. The large-scale harvesting of manganese nodules is also viewed critically by some. The first claims in the Pacific have already been awarded to various countries, including Germany.

The development of renewable energy in the oceans as an alternative resource, on the other hand, harbours much less risk. Present approaches include systems for wind and wave energy, tidal and ocean-current power plants, and even plants that use salinity and temperature differences to produce electricity. All of these technologies combined could satisfy a considerable proportion of the world's energy needs. As a general principle, however, before environmentally friendly techniques of energy production can be established, their potential impacts on the marine environment need to be investigated. Some marine regions will undoubtedly be excluded from development for ecological reasons. Scientists recommend that regions be identified where different technologies can be combined, such as wind turbines and ocean-current systems.

Just a few decades ago, no one took it for granted that ocean regions could be surveyed and exploited. There was frequent controversy over the ocean regions. The international community was not able to find any common ground until the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982. This convention is the most comprehensive agreement in international law that has ever been achieved in the history of humankind. It regulates the areas of interest for coastal nations as well as exploitation of the high seas. A UN agency, in turn, oversees the extraction of resources from the sea floor and equitably allocates claims for the mining of manganese nodules, for instance. In spite of these regulations, there has long been a smouldering controversy among the Arctic countries over who can exploit the resources of the floor of the Arctic Ocean if the sea ice continues to melt.

On the other hand, shipping traffic, which has undergone huge changes in recent decades, is efficiently regulated today. One important milestone was the introduction of the standard shipping container, which has so expedited the loading and unloading of ships that the shipping companies can run their freighters under tight schedules not unlike those of a city bus line. There are now over 53,000 cargo ships, tankers, bulk freighters and container ships carrying goods around the world. The total carrying capacity of the commercial fleet amounts to over 1000 million tonnes.

It is both fascinating and unsettling to think that climate change could open up the legendary Northern Sea Route through the Arctic. Because the Arctic sea ice now thaws extensively in the summer, the sea route from Europe to the Pacific Ocean along the Siberian coast will be open in the future for several weeks a year. This route is much shorter than travelling through the Suez Canal or around the Cape of Good Hope, but its cost-effectiveness, considering stray sea ice and possible passage fees, is not yet clear. Nonetheless, it would allow traffic to avoid the dangerous route through the Gulf of Aden and past the Somali coast, at least in the summer. The number of pirate attacks there has greatly increased recently. The situation in the waters east of Africa, however, should not detract from the fact that piracy has been declining worldwide in recent years.

During the more than two years of work on this report, we have often asked ourselves whether it is possible to portray the ocean in all of its facets. The only honest answer to this question is "no". The oceans are too large and the subject matter too complex to even begin to claim complete coverage of the topic. Moreover, many scientific questions are still unresolved. We have nonetheless tried to draw as comprehensive a picture of the state of the oceans as possible. We hope that this report will make at least a small contribution towards steering a sustainable course.

Nikolaus Gelpke and Martin Visbeck

Glossary

> 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 and are easy to identify.

Anthropogenic: Changes in nature caused by humans, such as the increase of CO_2 concentrations in the atmosphere, are referred to as anthropogenic.

Atmosphere: the gaseous shell that surrounds the Earth. Its major components are nitrogen and oxygen. The carbon dioxide content is only around 0.038 per cent. This gas, however, apart from water vapour, is the most important cause of the →greenhouse effect.

Azores High: an atmospheric high-pressure area that regularly forms in the central North Atlantic near the latitude of the Azores. Cold air sinks here, is warmed by the →Gulf Stream, and is transported eastward toward Europe.

Biodiversity: the biological variety of the Earth. This includes not only the species as such, but also the genetic variability present within the individuals of a species, or the variability of habitats in a region.

Biogenic: substances produced by living organisms such as plants, animals, fungi or bacteria are referred to as biogenic.

Biogeochemical: Biogeochemistry is an interdisciplinary scientific field that encompasses chemical, biological and physical processes and their interactions. Many processes in nature can only be understood when all three of these aspects are taken into account. One accordingly refers to biogeochemical phenomena or processes.

Biosphere: the part of the Earth's crust inhabited by living organisms. The biosphere also includes the ocean.

Carbon cycle: the cycle of the chemical element carbon. It includes the transformation of carbon chemical compounds within the global lithosphere, hydrosphere, atmosphere, and biosphere systems, as well as the exchange of carbon compounds between these systems. The carbon compounds can be in the form of gas (in the atmosphere), or bound up in solid material, for example, in water-soluble carbonate or in the solid biomass of plants in the form of carbohydrates.

CO_2 Carbon Credits: CO_2 Carbon Credits allow industrial enterprises worldwide to emit a certain amount of CO_2. If a company reduces its CO_2 emissions through technical measures, it uses fewer of its Carbon Credits, and can sell them to other companies. Measures designed to reduce CO_2 output thus become more attractive economically despite the initial additional cost they entail.

Convection: In the context of the ocean or atmosphere, convection refers to vertical turbulent motion of the water or air, usually caused by density changes (for example, due to cooling or warming). Convection in the ocean plays a primary role in driving the →thermohaline circulation.

Convention on Biological Diversity (CBD): The Convention on Biological Diversity (CBD) was negotiated in 1992 in Rio de Janeiro, during the United Nations Conference on Environment and Development (UNCED). It pursued three primary goals: 1. conservation of biological diversity, 2. sustainable use of natural resources, and 3. assurance that the utilization of genetic resources and information (for example, for medically useful substances) is equally beneficial for all countries.

Coriolis force: The Coriolis force or Coriolis acceleration, caused by the Earth's rotation, causes freely moving masses such as air and water currents to be diverted from straight linear motion. In the northern hemisphere, the Coriolis force deflects linear flow to the right, in the southern hemisphere to the left, and at the equator there is no effect.

Cryosphere: the portion of the Earth covered by ice. The cryosphere includes antarctic glaciers, mountain glaciers, sea ice and shelf ice.

Diatoms: single-celled, hard-shelled algae with a carapace of silica. Most diatoms in the ocean are a component of the →plankton, and they are among the most important producers of oxygen in the ocean. They are also an important nutrient base for higher organisms. Diatoms also occur in freshwater and on the sea floor.

East Pacific Rise: a →mid-ocean ridge located in the southeast Pacific.

Flagellates: single-celled organisms that move through the water using a whip-like appendage called the flagellum. They are found in both freshwater and saltwater.

Geoengineering: technical measures that could influence the natural cycles on a grand scale, applied to counteract the impacts of climate change. These measures are broadly divided into two groups: Solar Radiation Management (SRM), and Carbon Dioxide Removal (CDR). SRM deals with the release of certain substances into the atmosphere to influence incoming solar radiation, while CDR generally refers to the large-scale breakdown or storage of CO_2. The techniques are controversial because they severely intervene with natural processes, and because their direct consequences and side effects, as well as possible reciprocal impacts, are difficult to predict.

Greenhouse effect: Water vapour, carbon dioxide (CO_2) and other climate-relevant trace gases in the atmosphere, including methane (CH_4), initially allow short-wave radiation from the sun to pass through to the Earth. At the Earth's surface these are transformed, and reflected back for the most part as long-wave radiation. Like the glass panes in a greenhouse, however, the gases then prevent the long-wave heat rays from escaping into space. The Earth warms up. The greenhouse effect is a natural phenomenon that protects the Earth from overcooling. With increasing concentrations of CO_2 and other trace gases, however, the greenhouse effect is intensifying.

Greenland Sea: The Greenland Sea extends from Greenland to Iceland and Spitsbergen, thus forming the boundary between the North Atlantic and Arctic Oceans. Large water masses sink to greater depths in the Greenland sea due to →convection.

Gulf Stream: a relatively fast, warm ocean current in the Atlantic. The Gulf Stream flows out from the Gulf of Mexico, around the Florida peninsula toward the northeast, and into the North Atlantic Current. It contributes significantly to the relatively mild climate in western Europe because it transports large amounts of heat.

Habitat: a characteristic natural environment inhabited by a particular species.

Icelandic Low: a semi-permanent, low-pressure area over the North Atlantic. A large proportion of the precipitation in western Europe is transported in by this low. Interplay between the Icelandic Low and the →Azores High is a significant factor in determining the weather in western Europe.

Interhemispheric dipole: a regular fluctuation of water temperatures in the Atlantic, occurring about every ten years. Scientists refer to this as a temperature anomaly.

International Whaling Commission (IWC): The International Whaling Commission (IWC) provides information annually on the status quo of the worldwide whale stocks, the establishment of protection areas, and on extensions of the whaling moratorium. It was established by the International Convention for the Regulation of Whaling (ICRW). This convention is an agreement created under international law whose aim is the preservation and management of whale stocks. The IWC comprises representatives from around 80 signatory nations.

Labrador Sea: the area of the North Atlantic between Greenland and Canada. As in the →Greenland Sea, large water masses sink to greater depths here due to →convection.

Lithosphere: the solid rock shell of the Earth.

Mean sea level (NN): mean sea level (German – Normalnull, NN) is a reference point for standardizing measures of elevation in Germany, Switzerland and Austria. It is equal to the average elevation of sea level. This point is also used as the reference when specifying the elevation of buildings or mountains. It was originally derived from the Dutch usage of the Normal Amsterdam Level (NAP – Normaal Amsterdams Peil) standard since the 19th century, which referred to the average water level in the Zuidersee, known today as the IJsselmeer.

Mid-ocean ridge: ridges or mountain ranges on the sea floor similar to the seams of a baseball, extending around the entire globe. They originate in areas where continental plates drift apart beneath the ocean. Hot magma rises at these fracture zones in the central ocean regions, is cooled in the water, and piles up through time to form enormous mountains.

Monsoon (region): a large-scale, strong and constant air current in the tropics and subtropics. The monsoon changes direction twice a year. This is caused by annual changes in the altitude of the sun. When the sun is high, the amounts of heat assimilated by the land and water masses are very different, which leads to distinct air-pressure differences and strong winds. When the monsoon blows from the sea it brings humid air masses and causes strong monsoon rains. This sometimes results in large floods.

North Atlantic oscillation (NAO): North Atlantic oscillation (NAO) refers to the fluctuation of the pressure relationship between the →Azores High and the →Icelandic Low. The NAO is especially important in driving the winter climate in Europe, but also in North Africa, Greenland and the eastern USA. Researchers believe that the NAO determines 30 per cent of the European winter weather. The NAO also exists during the summer, but during this time it seems to be less critical for climate. A systematic change in this air-pressure system has been observed in recent years compared to earlier measurements. One result has been an increase in warm winters in Europe with less snowfall.

Pedosphere: The pedosphere is the part of the continental land masses that is referred to as soil. It is the interface between the →atmosphere and the →lithosphere. The pedosphere is a layer of loose, small grained rock material that is enriched in organic substance and usually contains some amounts of water and air.

Pelagic system (pelagial): The term pelagic system is used to indicate the main body of the open water (pelagial) including all of its inhabitants. Pelagic organisms comprise the →plankton and the nekton. The nekton includes organisms such as fishes and whales, which, in contrast to the plankton, are able to actively swim against the currents.

Permafrost ground: ground that is permanently frozen, year-round, below a particular depth. Among other areas, permafrost grounds are found in the arctic tundra, in northern evergreen forests, and in the high mountains. In these regions the sun's energy is not sufficient, even in summer, to warm the ground to depth. Only the upper layers thaw out for a few weeks.

Plankton: all free-floating organisms in the open water. Most planktonic organisms are microscopic in size. They include protozoans, microalgae, krill, and the larvae of fish and mussels. A distinction is made between plant plankton (phytoplankton) and animal plankton (zooplankton). Planktonic organisms are able to propel themselves, but only very weakly, so they are forced to drift with the water currents. In contrast to the plankton, the nekton includes all marine animals that can actively swim independently of the currents.

Population: a group of individuals of one species that inhabit the same area at the same time. A population forms a reproductive community. One species can develop multiple populations at different locations.

Primary production, primary producers: the production of biomass by plants or bacteria. The primary producers obtain their energy from sunlight or from certain chemical compounds, and through their metabolism synthesize energy-rich substances such as carbohydrates. These substances, in turn, represent a subsistence basis for animals and humans.

Shelf area: the near-coastal, shallow part of the sea floor. The shelf falls gradually to an average depth of 130 metres. The shelf ends at the continental slope.

Sink: a natural reservoir that can hold large amounts of a given substance, such as carbon dioxide. For example, carbon sinks include forests, the deep ocean, and even corals, because of the carbon dioxide bound up in the carbonate.

Stratospheric, stratosphere: The stratosphere is that area of the atmosphere that lies at an altitude between around 15 and 50 kilometres. Within the stratosphere at around 20 to 40 kilometres there is a band with higher ozone concentrations. This "ozone layer" blocks a large portion of the ultraviolet solar radiation that can be harmful for living organisms.

Substrate: the material that an organism lives upon, for example, stones to which barnacles are attached.

Thermodynamics: a subdiscipline of physics that deals with the relationships between heat and other forms of energy, as well as their possible transformations. Important parameters include pressure, temperature and mechanical work, as well as changes in volume, density and physical state, which also play a role in the origins of currents in the ocean and atmosphere.

Thermohaline circulation: a global system of near-surface and deeper ocean currents that is driven by density differences between water masses with different salinities and temperatures. →Convection is an important motor for thermohaline circulation.

Tidal zone: the area of the coasts defined by the limits of high and low tide. The water level falls and rises here in phase with the tides. This creates some areas that are periodically not covered by water. Characteristic biotic communities often colonize these areas.

Trade winds: winds that constantly blow in the tropics and are thus a driving force for the ocean currents. The trade winds occur up to around 23 degrees latitude north and south of the equator. In the northern hemisphere they are called the northeast trades, and in the southern hemisphere the southeast trades. The direction of the trade winds is primarily determined by the diverting effect of the →Coriolis force.

United Nations Conference on the Law of the Sea (UNCLOS): Between 1973 and 1982, three United Nations Conferences on the Law of the Sea (UNCLOS) were held with the aim of establishing internationally enforceable maritime law. This was accomplished with the third Convention (UNCLOS III) in 1982. The result was the adoption of the UN Convention on the Law of the Sea. So far the Convention has been ratified by 157 nations.

Upwelling region: usually near-coastal marine regions where cold, nutrient-rich deep waters rise to the ocean surface. The motion is commonly driven by →trade winds blowing parallel to the shoreline. The winds force the surface water away from the coasts and deeper water rises to replace it. Biologically, upwelling regions are highly productive, and are thus very important for fisheries, which are often concentrated at the western margins of continents, particularly off the coasts of Chile, California and Namibia.

Abbreviations

AABW Antarctic Bottom Water

ARGO International Deep-Sea Drifter Programme

ASCOBANS Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas

AUV Autonomous Underwater Vehicle

BB Bornholm Basin

CBD Convention on Biological Diversity

CCS Carbon Capture and Storage

CFCA Community Fisheries Control Agency

CFP Common Fisheries Policy

CIS Commonwealth of Independent States

CLCS Commission on the Limits of the Continental Shelf

DIC Dissolved inorganic carbon

dwt Deadweight Tonnage

ECJ European Court of Justice

ECMT European Conference of Ministers of Transportation

EEZ Exclusive Economic Zone

EU European Union

FAO Food and Agriculture Organization of the United Nations

FDA Food and Drug Administration

FMPs US Groundfish Fishery Management Plans

GATT General Agreement on Tariffs and Trade

GB Gotland Basin

GD Gdansk Basin

GDP Gross Domestic Product

GLODAP Global Ocean Data Analysis Project

GPS Global Positioning System

GRT Gross Register Tonnage

HABs Harmful Algal Blooms

HNLC High nutrient, low chlorophyll

ICC International Coastal Cleanup

ICES International Council for the Exploration of the Sea

ICJ International Court of Justice

IEA International Energy Agency

IMO International Maritime Organisation

IPANEMA Initiative Partenariale Nationale pour l'émergence des Energies Marines; National Initiative for the Promotion of Marine Energy

IPCC Intergovernmental Panel on Climate Change

ISA International Seabed Authority

ISM Code International Management Code for the Safe Operation of Ships and for Pollution Prevention

ITLOS International Tribunal for the Law of the Seas

ITQs Individual transferable quotas

IUU-fishing Illegal, unreported and unregulated fishing

IWC International Whaling Commission →Glossary

JIT Just-in-time production

LC London Convention – Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

LGM Last Glacial Maximum

LNG Liquefied Natural Gas

LOHAFEX Experiment of fertilizing the ocean with iron

LP London Protocol; updating →LC

MARPOL International Convention for the Prevention of Pollution from Ships

MEY Maximum economic yield

MRSA Methicillin-resistant Staphylococcus aureus

MSC Marine Stewardship Council

MSFD Marine Strategy Framework Directive

MSY Maximum sustainable yield

NADW North Atlantic Deep Water

NAFTA North American Free Trade Agreement

NAO North Atlantic oscillation →Glossary

NEAFC North East Altlantic Fisheries Commission

OECD Organisation for Economic Co-operation and Development

OPA Oil Pollution Act

OSPAR Oslo-Paris-Convention; Convention for the Protection oft the Marine Environment of the North-East Atlantic

OTEC Ocean Thermal Energy Conversion

PatG Patentgesetz; Patent Act

PCBs Polychlorinated Biphenyls

PDV Phocine Distemper Virus

PFCs Polyfluorinated compounds

PFOS Perfluorooctanesulfonic acid

POPs Persistent organic pollutants

ppm Parts per million

ppt Parts per thousand

ROV Remotely Operated Vehicle

STECF Scientific, Technical and Economic Committee for Fisheries

TAC Total allowable catch

TEU Twenty-foot Equivalent Unit

TRIPS Agreement on Trade-Related Aspects of Intellectual Property Rights

TURF Territorial use rights in fisheries

UNCED United Nations Conference on Environment and Development

UNCLOS United Nations Convention on the Law of the Seas →Glossary

UNCLOS III Third United Nations Conference on the Law of the Sea

UNCTAD United Nations Conference on Trade and Development

UNEP United Nations Environment Programme

VDS Vessel Detection System

VMS Vessel Monitoring System

VOS Voluntary Observing Ships Programme

WEP Wind Energy Plant

WSSD World Summit on Sustainable Development

WTO World Trade Organization

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"**The Future Ocean**"**:** The Kiel-based Cluster of Excellence brings together marine scientists, earth scientists, economists, medical scientists, mathematicians, lawyers and social scientists to share their knowledge and engage in joint interdisciplinary research on climate and ocean change. The research group comprises more than 250 scientists from six faculties of the Christian-Albrechts-University of Kiel (CAU), the Leibniz Institute of Marine Sciences (IFM-GEOMAR), the Institute for World Economy (IfW) and the Muthesius Academy of Fine Arts and Design.

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.

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.

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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.

Table of figures

Cover: mauritius images/Bluegreen Pictures, p. 2: plainpicture/Daniela Podeus, p. 6 from top: Nick Cobbing, Steve Gschmeissner/Science Photo Library/Agentur Focus, Seth Resnick/Getty Images, U.S. Coast Guard/digital version by Science Faction/Getty Images, Phillip Colla/SeaPics.com, p. 7 from top: Arctic-Images/Corbis, Steve Bloom/Getty Images, Justin Guariglia/Corbis, 2009, George Steinmetz/Agentur Focus, US Navy/action press, pp. 8–9: Nick Cobbing, Fig. 1.1: after Meincke and Latif (1995), Fig. 1.2: maribus, Fig. 1.3: NASA Goddard Institute For Space Studies, Fig. 1.4: after IPCC (2001), Fig. 1.5: action press/Ferrari Press Agency, Fig. 1.6: maribus, Fig. 1.7: maribus, Fig. 1.8: after Meincke et al. (2003), Fig. 1.9: NASA, Fig. 1.10: maribus, Fig. 1.11: after Barnier et al. (1994), Fig. 1.12: after Trenberth and Solomon (1994), Fig. 1.13: [M], Bryan & Cherry Alexander/Arcticphoto/laif, pp. 26–27: Steve Gschmeissner/Science Photo Library/Agentur Focus, Fig. 2.1: after IPCC (2007), Fig. 2.2: dpa Picture-Alliance/DB Philipp Assmy/Awi, Fig. 2.3: Stephan Köhler/Zoonar, Fig. 2.4: after Sabine et al. (2004), Fig. 2.5: Nicolai, IFM-GEOMAR, Fig. 2.6: top: Martin Hartley/eyevine/interTOPICS; left: mauritius images; mid: Carmen Jaspersen/Picture-Alliance/dpa; right: Cliff Leight/Aurora Photos, Fig. 2.7: Fine and Tchernov (2007); Foto: Avinoam Briestien, Fig. 2.8: after Gutowska et al. (2008), Fig. 2.9: Steve Gschmeissner/Science Photo Library/Agentur Focus, Fig. 2.10: Reprinted by permission from Macmillan Publishers Ltd.: Nature Publishing Group, U. Riebesell et al., Nature 407, 2000, Fig. 2.11: Mike Watson Images Limited/Getty Images, Fig. 2.12: Hall-Spencer et al. (2008), Fig. 2.13: after Vaquer-Sunyer and Duarte (2008), Fig. 2.14: maribus, Fig. 2.15: after Keeling et al. (2010), Fig. 2.16: dpa Picture-Alliance/MARUM, Fig. 2.17: after Kvenvolden and Lorenson (1993), Fig. 2.18: maribus, Fig. 2.19: after IFM-GEOMAR, Fig. p. 51: after Treude, IFM-GEOMAR, Fig. 2.20: imago/ITAR-TASS, pp. 54–55: Seth Resnick/Getty Images, Fig. 3.1: maribus, Fig. 3.2: Brian Harris/eyevine, Fig. 3.3: imago/Photoshot/Evolve, Fig. 3.4: after Vermeer and Rahmstorf (2009), IPCC 2007, Church et al. (2008), Fig. 3.5: after Cohen and Small (1998), Fig. 3.6: Patricia Kreyer/PictureNature/Photoshot, Fig. 3.7: Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (NLWKN), Fig. 3.8: Keystone France/laif, Fig. 3.9: www.bildagentur-online.com, Fig. 3.10: after Brooks et al. (2006), Fig. 3.11: Werner Baum/dpa Picture-Alliance, Fig. 3.12: Andrew Biraj, Fig. 3.13: [M], Beate Zoellner/Bildmaschine.de, Fig. 3.14: Swart/Hollandse Hoogte/laif, Fig. 3.15: Schrottke, Stattegger and Vafeidis, Universität Kiel, Fig. 3.16: after Sterr, pp. 74–75: U. S. Coast Guard/digital version by Science Faction/Getty Images, Fig. 4.1: Jochen Tack, Fig. 4.2: AP Photo/Eye Press, Fig. 4.3: Andre Maslennikov/Still Pictures, Fig. 4.4: after van Bennekom and Wetsteijn (1990), www.waterbase.nl, Fig. 4.5: with courtesy of Nancy Rabalais, Louisiana Universities Marine Consortium, with MODIS true color image from the Earth Scan Lab, Louisiana State University, Fig. 4.6: www.deff.de, Fig. 4.7: after Böhlmann (1991), Fig. 4.8: after Dietz et al. (2008), Fig. 4.9: maribus, Fig. 4.10: after South Carolina Sea Grant Consortium, South Carolina Department of Health & Environmental Control; Ocean and Coastal Resource Management, Centers for Ocean Sciences Education Excellence Southeast; NOAA 2008, Fig. 4.11: maribus, Fig. 4.12: Frans Lanting/Agentur Focus, Fig. 4.13: maribus, Fig. 4.14: after GKSS, van Bernem, Fig. 4.15: David Woodfall/Getty Images, Fig. 4.16: Frederic Larson/San Francisco Chronicle/Corbis, Fig. 4.17: ITOPF, Fernresearch, Fig. 4.18: Xinhua/Landov/interTOPICS, pp. 100–101: Phillip Colla/SeaPics.com, Fig. 5.1: after Wahl, Fig. 5.2: Laurie Campbell/NHPA/Photoshot/dpa Picture-Alliance, Fig. 5.3: maribus, Fig. 5.4: after Wahl, Fig. 5.5: after Sommer, Lengfellner et al. (in prep.), Fig. 5.6: David B. Fleetham/SeaPics.com, Fig. 5.7: www.learner.org/jnorth/tm/manatee/RedTide.html, Fig. 5.8: Arco/NPL Kim Taylor, Fig. 5.9: after Molnar et al. (2008), Fig. 5.10: after Molnar et al. (2008), Fig. 5.11: David Wrobel/SeaPics.com, pp. 118–119: Arctic-Images/Corbis, Fig. 6.1: after Quaas, FAO Fishstat, Fig. 6.2: imago/Xinhua, Fig. 6.3: after FAO Fishstat, Fig. 6.4: after FAO, Fig. 6.5: after FAO Fishstat, Fig. 6.6: after FAO Fishstat, Fig. 6.7: left: dpa Picture-Alliance/PA, right: dpa Picture-Alliance/UPI, Fig. 6.8: after Quaas, FAO Fishstat, Fig. 6.9: after FAO Fishstat, Fig. 6.10: after Quaas, Fig. 6.11: Jean Gaumy/Magnum Photos/Agentur Focus, Fig. p. 129: after Quaas, Fig. 6.12: Pierre Tremblay/Masterfile, Fig. 6.13: after Quaas, Fig. p. 133: after Quaas, Fig. 6.14: maribus, Fig. 6.15: M. Tristao/UNEP/Still Pictures/OKAPIA, Fig. 6.16: after Rudi Voss/Bastian Huwer, DTU-Aqua, Fig. 6.17: Peter Verhoog/Foto Natura/MINDEN PICTURES/Getty Images, Fig. 6.18: www.msc.org, pp. 140–141: Steve Bloom/Getty Images, Fig. 7.1: after the German Federal Institute for Geosciences and Natural Resources (BGR), Fig. 7.2: after the German Federal Institute for Geosciences and Natural Resources (BGR), Fig. 7.3: after the German Federal Institute for Geosciences and Natural Resources (BGR), Fig. 7.4: after Petersen, Fig. p. 147: Manganese nodule: Charles D. Winters/NatureSource/Agentur Focus, Fig. 7.5: MARUM, Universität Bremen/MARUM, University of Bremen, Fig. 7.6: maribus, Fig. 7.7: after Klauda & Sandler (2005), Fig. 7.8: http://de.wikipedia.org/wiki/Datei:Gashydrat_mit_Struktur.jpg [Date: 05.10.2010], Fig. 7.9: after IFM-GEOMAR, Fig. 7.10: after Energy Outlook 2007, Buffett & Archer (2004), Fig. 7.11: Marc Steinmetz/Visum, Fig. 7.12: map: maribus, a: EDF/Tierry Dichtenmuller; b: Marine Current Turbines Limited; c: Pelamis Wave Power; d: Statkraft; e: Siemens-press picture, Fig. 7.13: Solberg Production/Statoil, pp. 162–163: Justin Guariglia/Corbis, Fig. 8.1: after IMO 2009, Fig. 8.2: after UNCTAD, Lloyd's Register – Fairplay, Fig. 8.3: from left: after Beluga Shipping GmbH; Schulte Group/www.eiga.de; TUI Cruises GmbH; Rickmers Holding GmbH & Cie. KG; Rickmers Holding GmbH & Cie. KG, Fig. 8.4: Cultura/plainpicture, Fig. 8.5: Sammlung Rauch/INTERFOTO, Fig. 8.6: after IMO 2010, Fig. 8.7: action press/KYODO NEWS, pp. 176–177: 2009 George Steinmetz/Agentur Focus, Fig. 9.1: Bettmann/Corbis, Fig. 9.2: Haeckel/Ullstein Bild, Fig. 9.3: J. W. Alker/TopicMedia, Fig. 9.4: Humberg/imago, Fig. 9.5: Steve Parish/Steve Parish Publishing/Corbis, Fig. 9.6: Dean Janiak, Fig. 9.7: maribus, Fig. 9.8: Bosch, picture: Sebastian Fraune, Fig. 9.9: YourPhotoToday/Phanie, Fig. 9.10: after Bosch, Fig. 9.11: R. Dirscherl/Juniors Bildarchiv, Fig. 9.12: R. Dirscherl/blickwinkel, Fig. 9.13: NAS/M. I. Walker/OKAPIA, Fig. 9.14: Thierry Berrod, Mona Lisa Production/Science Photo Library/Agentur Focus, Fig. 9.15: maribus, Fig. 9.16: maribus, Fig. 9.17: Pasieka/Science Photo Library/Agentur Focus, pp. 196–197: US Navy/action press, Fig. 10.1: left: Private Collection/Ken Welsh/The Bridgeman Art Library; right: Peace Palace Library, Fig. 10.2: after Proelß, Fig. 10.3: after he German Federal Maritime and Hydrographic Agency (BSH), Fig. 10.4: Rex Features LTD/action press, Fig. 10.5: after Gilles et al. (2009), Fig. 10.6: maribus, Fig. 10.7: ddp images/AP Photo/RTR Russian Channel, Fig. 10.8: after Macnab et al. (2001), Fig. 10.9: after Kaleschke, Klimacampus University of Hamburg, p. 210: Hans Strand

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