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mare

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

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

world ocean review

Coasts – A Vital Habitat Under Pressure

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Living with the oceans. 2017

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mare

1 Coastal dynamics

> Coasts – the areas where land and sea meet and merge – have always been vital habitats for the human race. Their shape and appearance is in constant flux, changing quite naturally over periods of millions or even just hundreds of years. In some places coastal areas are lost, while in others new ones are formed. The categories applied to differentiate coasts depend on the perspective from which we regard them.

On the origin and demise of coasts

> Coasts are dynamic habitats. The shape of a coast is influenced by natural forces, and in many places it responds strongly to changing environmental conditions. Humans also intervene in coastal areas. They settle and farm coastal zones and extract resources. The interplay between such interventions and geological and biological processes can result in a wide array of variations. The developmental history of humankind is in fact linked closely to coastal dynamics.

Special allure

Coasts are a special habitat. They are the transition area between land and sea and are influenced by both realms. Rivers carry nutrients from the land to the coastal waters and thus represent the basis of the marine food chain. The seas transport sediments – washing them ashore, reworking them or carrying them away, all of which change the shape of the coast.

No other marine environment is more productive. Coasts provide nourishment in the form of fish and other seafood. But they are also important transportation routes for shipping and are intensively exploited for the production of natural gas and oil. At the same time, the coasts are highly desirable recreation areas for millions of vacationers. Numerous cities have been built on the coasts, and industries and power plants take advantage of their often well developed infrastructures.

1.1 > Many cities developed in coastal areas. The Beyoğlu district of Istanbul, for example, is thousands of years old. It lies on the Golden Horn, a fjord-like inlet that divides the European part of the city into southern and northern areas.

In general, the coastal zones of the Earth are extremely variable in shape and form. They are of great importance for humans, animals and plants, as well as for the atmosphere and climate because:

- they comprise around 20 per cent of the Earth's surface;
- they represent important transportation routes and sites for industry;
- they are attractive recreation and tourist areas;
- they are sources for mineral and fossil raw materials;
- they encompass key ecosystems with great species diversity;
- they act as important sediment traps that consolidate river sediments;
- in their role as a buffer between the land and sea, they affect many global parameters;
- 75 per cent of all megacities (populations greater than ten million) are located in coastal zones;
- 90 per cent of global fisheries operate in coastal waters.

The attraction of coasts for people is very strong today. Globally, coastal populations are growing at a rapid pace. According to estimates by the United Nations, around 2.8 billion people presently live within 100 kilometres of a coast. Of the 20 megacities in the world with populations of more than ten million, 13 are situated near a coast. These cities or areas of high population density include Mumbai (18.2 million), Dhaka (14.4 million), Istanbul (14.4 million), Calcutta (14.3 million) and Beijing (14.3 million). Many experts believe that the urbanization of coastal regions will continue to increase in the coming years.

The coast – where does it start, where does it end?

As a rule, maps depict coasts as lines that separate the mainland from the water. The coast, however, is not a sharp line, but a zone of variable width between land and water. It is difficult to distinctly define the boundaries of this transition zone. In the 1950s, scientists suggested using a definition of coast as the area that is influenced by the surf. Landward, this includes the extent to which the airborne saltwater spray can reach, thus encompassing some vegetation on the land. Seaward, this would extend to the area where the surf makes itself noticeable, for example, where it contributes to shaping the sea floor.

Although efforts are being made to establish a theoretical and universally accepted definition for the term "coast", in practice disparate conceptions come into play. Different aspects predominate in science, depending on the particular sub-discipline being applied. Biologists, for example, concentrate primarily on life in the sea or in wetland areas along the coasts or in estuaries. Coastal protection specialists, on the other hand, who make plans for dikes and other protective infrastructures, are also interested in the hinterland to the extent that it could be impacted by storm floods. Economists have an especially broad definition of the term "coast". As a rule they consider not only harbours and industrial areas near the coast, but also the flow of goods over the sea or to inland regions.

Over the past several decades, geologists and oceanographers have also attempted to systematically delineate and catalogue the world's coasts. Here there are also different approaches depending on the focus of the effort. Coastal types are differentiated based on whether they are characterized by "high-energy" formations such as rocky or sandy coasts that are directly bathed by the surf or, like the Wadden Sea, are characterized by relatively calm, "low-energy" areas that are protected by sand banks or offshore islands.

In spite of their differences, many coasts have one thing in common: their great importance for humans. Coasts have been the starting points for explorers and the targets for conquerors. Archaeologists and ethnologists believe that the coasts have played a great role in the settlement of new continents or islands for millennia. Before people penetrated deep into the inland areas they travelled along the coasts searching for suitable locations for settlements. The oldest known evidence of this kind of settlement history is found today in northern Australia, where the ancestors of the aborigines settled about 50,000 to 40,000 years ago, presumably arriving on boats from islands that today are part of Indonesia.

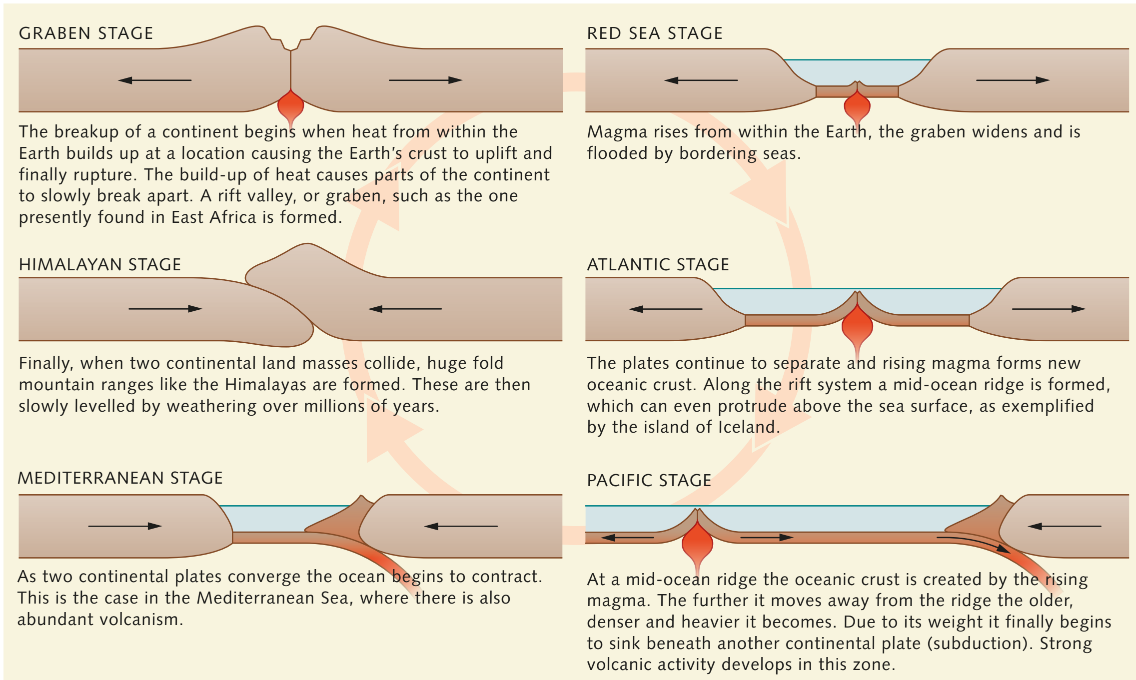
Dynamic habitat

Coastal contours are often viewed as fixed and immovable. People try to maintain a fixed line, not least of all to protect cities and systems that have developed and are concentrated at the coasts. But generally there is hardly any other area that is so dynamic and undergoes so much constant change as do the coasts. Experts call it a transient habitat.

Depending on the time span being considered, different kinds of change can be observed. The slowest, but at the same time most drastic changes that coastlines undergo are caused by the motions of the continents. Movement of the continents was first postulated by the German researcher Alfred Wegener, who published his theory of continental drift in 1912. In the subsequent decades this theory was constantly expanded and improved. Today it is

1.2 > Alfred Wegener (1880–1930) was a German meteorologist, polar researcher and geoscientist. He proposed the scientific principle of continental drift. His theory, however, was long considered a foolish idea. It was not generally accepted until the 1970s.

1.3 > Crustal material is created and destroyed at time scales of millions of years. In a continuous cycle, the individual continental plates collide, drift, and change their position relative to one another. It is possible to break the cycle down into individual stages, some of which are named after a present-day region that represents that stage. John Tuzo Wilson, a Canadian geoscientist, was the first to describe these cycles.



called plate tectonics. It states that the Earth is comprised of multiple layers, the uppermost of which, the lithosphere, is slowly moving. The lithosphere is made up of numerous large plates that lie side by side and move relative to each other by as much as 10 centimetres per year. The lithosphere includes the continents, but carry also the large ocean basins. It has an average thickness of around 100 kilometres and glides along atop a second Earth layer called the asthenosphere.

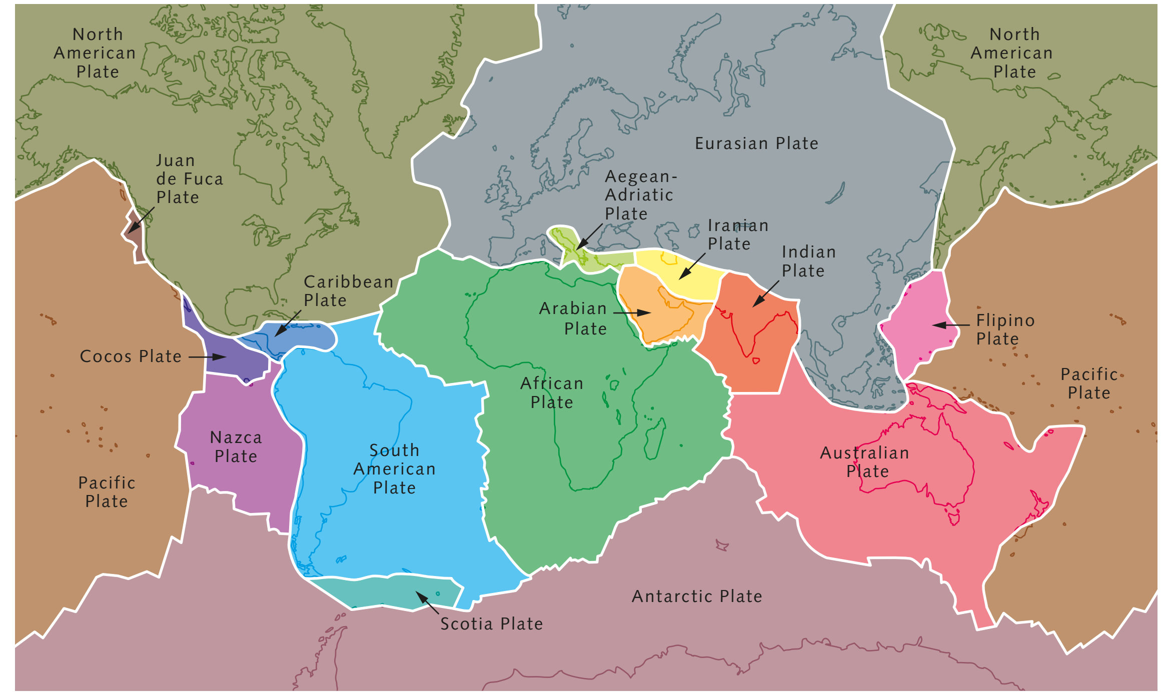
In some places one lithospheric plate is thrust over another, causing upward folding of the rocks over millions of years and forming high mountains like the Himalayas. In other regions the plates slide along beside each other or drift apart. Coastal regions and the shallow marine areas called shelves are especially affected by these movements because they are situated on the margins of the continental parts of the plates, and are thus strongly deformed by the drifting of the continents.

Today, the vestiges of coastal seas such as fossilized bivalves, snails and other organisms of the shallow coastal waters can be found in many mountain ranges worldwide, including the Alps.

Continental drift also changes the shape of coasts by another mechanism. When a mountain range is created on land by uplift and folding, that is, when part of a continental plate is thrust over another and rises out of the water, one result is a drop in sea level. However, sea level can also rise to the extent that magma gushes in at the mid-ocean ridges, displacing large volumes of water.

Breakup of the supercontinent

Throughout the **Earth's history** many alternating tectonic phases have occurred. There have been times when the continents were connected to form a single supercontinent or a few large continents. These were followed by phases when the giant and large continents drifted apart again. These repeating sequences are named the Wilson cycle, after the Canadian geologist John Tuzo Wilson who first described this principle in a journal article in the 1960s. The most recent cycle began about 300 million years ago when the continental plates collided to form the supercontinent Pangaea. Around 230 million years ago



1.4 > Continental plates carry both the land masses and the oceans. They move at speeds of up to several centimetres per year. At some places the continental plates move away from each other, for example, at mid-ocean ridges. At other places plates are thrust over or under one another. The Indian plate is being subducted below the Eurasian Plate, causing continued growth of the Himalayas.

1.5 > Millions of years ago the continental plates formed a largely contiguous land mass, the supercontinent Pangaea. At that time the Atlantic Ocean did not exist.

Pangaea began to break apart again, separating first into a northern (Laurasia) and a southern part (Gondwana). In the second phase, beginning about 140 million years ago, Gondwana split into the land masses that eventually developed into present-day Africa, South America, India and Australia. The breakup of Laurasia began around 65 million years ago with the separation of the North American and Eurasian land masses. This opened the North Atlantic, and India drifted more than 6000 kilometres to the northeast to collide with the Eurasian Plate about 40 million years ago. Over time the Himalayas were thrust and folded upward. India is still drifting northward today, causing the Himalayas to grow about one centimetre higher each year.

Evolutionary biologists believe that the early phase of the breakup of Pangaea, associated with the formation of new coasts, favoured the origin of new species.

Life goes ashore

As a result of the drifting of continents, coasts were not only created and destroyed, but also moved laterally. Entire coastal regions drifted into different climate zones, resulting in adaptation by existing organisms and the emergence of new life forms. An interesting aspect of these developments is assessing the role of coasts in the transition of life from the sea onto land. Today it is generally accepted that the first life forms developed in the sea and expansion to the land occurred at multiple locations at different times and at different rates. This took place within different groups of organisms completely indepen-

1.6 > Evidence for movement of the continental plates can be seen in Iceland. The island lies partly on the Eurasian and partly on the North American Plate. These two plates are drifting apart by a few centimetres every year. The fissure that cuts across the island is called the Silfra rift.

Evolution of the eel – a matter of continental drift

Many new animal species have originated when the population of an existing species was divided. Through the course of evolution these separated populations then developed along different paths, so that new species with different traits emerged. The major causes of separation included ice-age glaciers, which cut off entire regions from one another, and continental drift, which pulled land masses apart.

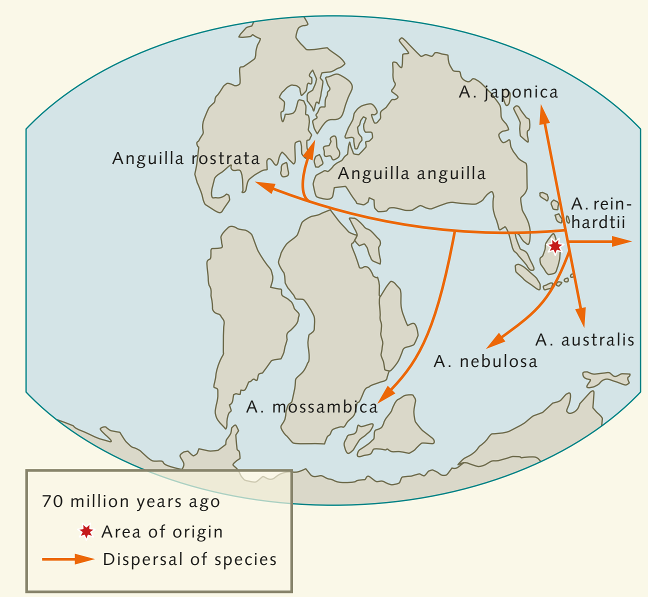
In many instances populations of marine organisms were also separated by continental drift. Such processes are exemplified by the eels. Today there are around 15 species of eels, including the American eel *(Anguilla rostrata)*, which lives on the east coast of the USA, the European eel *(Anguilla anguilla)* and the Japanese eel *(Anguilla japonica)*. It is assumed that all eel species in fact descend from a common ancestor. The home territory of that ancestor lay to the east of the supercontinent Pangaea, in the Tethys Ocean in the general vicinity of present-day Indonesia. The ancestral eel, like the modern eels, must also have made regular long migrations between its spawning region in the ocean and its nursery areas in the rivers.

As the northern part of Pangaea (Laurasia) separated from the southern part (Gondwana), an east-west waterway opened for the first time, connecting the Tethys Ocean in the east with the sea in the west. The ancestral eel was thus able to spread into the western sea. But continental drift continued. Around 140 million years ago Gondwana began to split into the land masses that became Africa, South America, India and Australia. Africa and the land mass of the Arabian Peninsula moved northward and eventually collided with the Eurasian Plate. This effectively closed the connection between the western and eastern oceans again. The two eel populations were isolated from one another and continued to evolve separately. This theory is known as the Tethys corridor hypothesis. Other hypotheses have been suggested for the genesis of eel species, but experts consider this to be the most probable.

The splitting of the Atlantic population into two distinct species, the European and the American eel, can likewise be attributed to continental drift. Although these animals are outwardly very similar, there are differences in detail that allow a distinction of the two species. Both the European eel and the American eel live in coastal waters and rivers until they reach sexual maturity. They both migrate from their regions in America and Europe into the Sargasso Sea in the Western Atlantic to spawn. Here they release sperm and egg cells into the water. Still in the Sargasso Sea, larvae hatch from the fertilized eggs and then embark upon the return trip toward Europe or America.

During the migration phase back to Europe of one to three years, larvae grow from an initial size of three millimetres to a length of up to 70 millimetres. A second larval stage follows this. While still in the sea, the larvae take on the shape of a willow leaf: at this stage they are also called willow-leaf larvae. These then develop into transparent juveniles called glass eels. They continue to migrate into coastal waters and rivers where they develop into mature animals. Because their respective spawning grounds only overlap slightly, the two species rarely crossbreed. Thus hybrids are only sporadically observed.

It is thought that the Atlantic eel split into two species over time because the Atlantic has continued to widen. Two populations were formed, one in the east and one in the west. Even today the Atlantic is widening by several centimetres each year. This is because two continental plates are slowly moving apart in the middle of the Atlantic. Today the European eel has to swim a distance of 5000 to 6000 kilometres to reach its spawning grounds in the Sargasso Sea.



1.7 > Before Europe and Africa were connected by a land bridge the eels could disperse from the east to the opening Atlantic Ocean region.

1.8 > Whales evolved from land mammals. Their terrestrial provenance can be recognized by the fact that they move their tail fins vertically, using the same up-and-down motion that large predatory cats employ. By contrast, fish move their tail fins horizontally back and forth.

dently of one another. It is thought that the arthropods, a group with jointed appendages that includes crustaceans, insects and spiders, settled on land independently of vertebrates. Genetic analyses have shown that the ancestors of present-day insects made the transition from an aquatic to terrestrial life habit around 480 million years ago.

It is assumed that the move to land for vertebrates began around 415 million years ago and lasted until about 360 million years ago. The first land vertebrates presumably evolved from the bony fishes. The first **amphibian** creatures may have been animals of the genus *Kenichthys*. Remains of this small animal, whose skull is only a few centimetres long, were found in China and have been age-dated at about 395 million years. It is possible that they preyed on insects at first. They might also have settled in near-coastal wetlands, river estuaries, wet river banks and brackish water areas where river water mixed with sea water. Among amphibians today there is still an animal group that lives both in the water and on land. Toads need water to reproduce. The development of their larvae takes place in water. For the adult animals, on the other hand, land is the predominant habitat, where they mate and hunt for prey.

Coasts as a bridge between sea and land

Fish of the sturgeon family also exhibit an amphibious adaptation. Sturgeons live primarily in the sea, but seek out freshwater areas to spawn. Interestingly, in addition to the gills typical for fish, sturgeons also have lung-like organs, small cavities in the skull. With a gulping action they fill these with air and can extract oxygen from it – presumably as an adaptation to possible arid conditions. Thanks to the ability to breathe air a sturgeon can survive these dry periods, for example, when a stream or lake shore dries up or carries less water for a short time.

But coasts have also played a role in the opposite direction by facilitating the return of life forms from land back into the sea. Today there are numerous animals whose ancestors lived on the land that have now readapted to the marine habitat. Whales, for example, derive from four-legged land animals, but their two rear appendages have regressed to rudimentary stumps of bone. Their mode of swimming, however, is similar to the motion of some four-legged animals on land whose lower body moves up and down at a fast run. The fluke, or tail fin, of the whale moves in a similar way because the spine and skeleton

are still much the same as those of the land mammals. By contrast, fish move their tail fins horizontally back and forth.

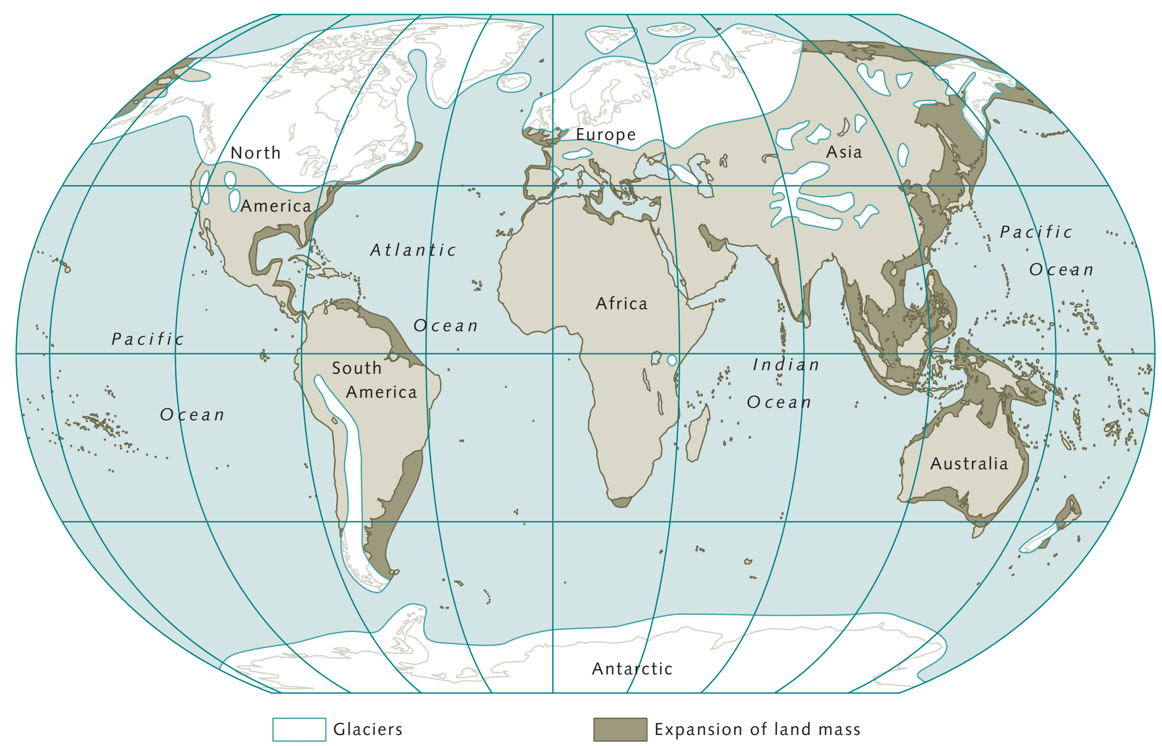
Some turtle species have also made the return from the coast back into the water, although they had originally evolved as four-legged land animals. Sea turtles have developed an amphibious habit, living between the land and sea. Many of these species search out a beach to lay their eggs at spring tide when the water reaches especially high levels. They can thus bury the eggs in the sand high up on the beach where they are protected from flooding. Later the hatchlings also break out during a spring tide, when the water is high again and the arduous and dangerous journey back across the beach into the sea is shortest.

Highs and lows through the millennia

Not only do coasts change their shape at a scale of millions of years, significant changes also occur over much shorter time periods. In cycles with magnitudes of several tens of thousands of years, alternating warm periods and ice ages, with the accompanying sea-level changes, play a significant role.

During the ice ages large areas of the land masses freeze. Precipitation in the form of snow forms glaciers thousands of metres thick. Because large volumes of water are bound up in ice on the land, and river flow into the sea is diminished, sea level falls gradually during an ice age. The most recent ice age ended around 12,000 years ago. The last period of heavy ice cover on the Earth was from 26,000 to 20,000 years ago. Sea level then was about 125 metres lower than today. Broad regions of the northern hemisphere were covered with glaciers, to as far as the Netherlands in central Europe. In warmer regions of the Earth the coastline looked completely different than today.

Around 15,000 years ago temperatures on the Earth began to rise rapidly again. This warm phase is still continuing today. The last warm phase before this one to see temperatures comparable with today's occurred between 130,000 and 118,000 years ago. Sea level at that time was about four to six metres higher than it is today.



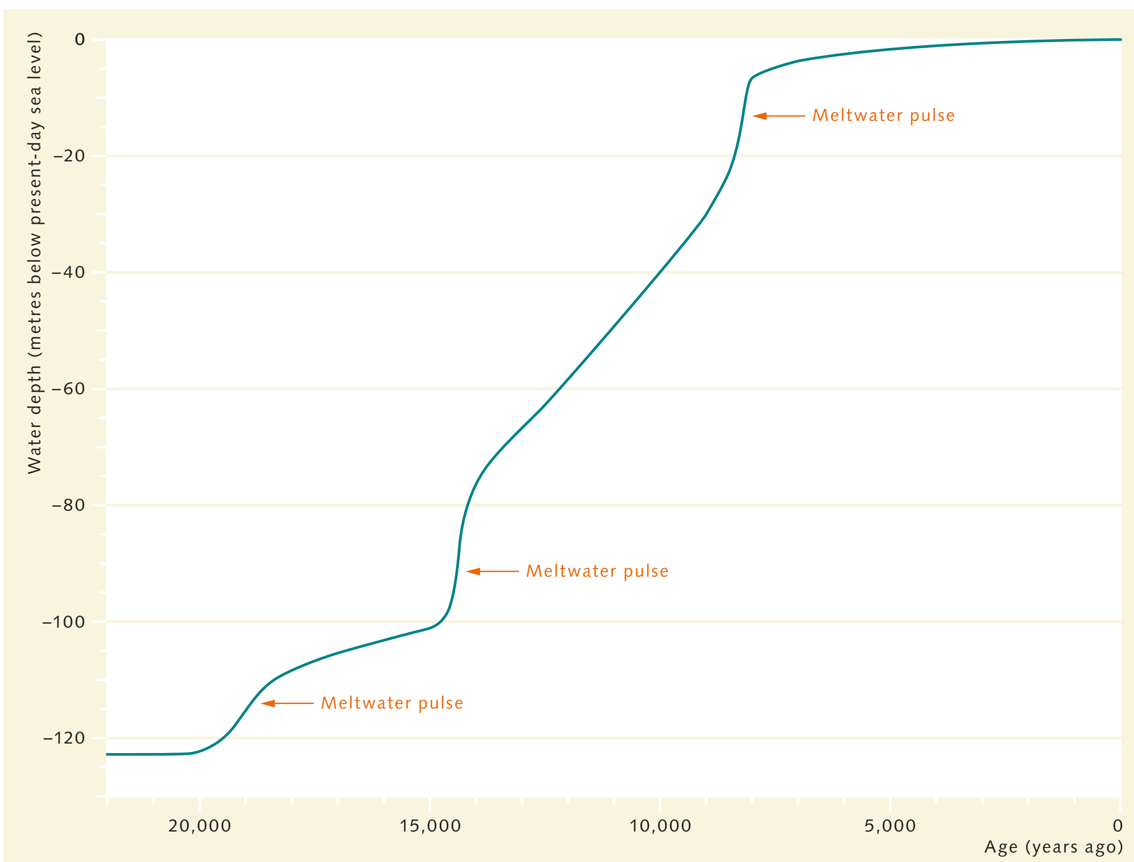
1.9 > At the peak of the last ice age sea level was around 125 metres lower than today. The total global land mass protruding out of the water was about 20 million square kilometres greater.

The big melt

Sea level rose again with the melting of glaciers after the last ice age. This rise generally proceeded steadily but there were occasional periods of accelerated rise triggered by events called meltwater pulses. These involved large amounts of meltwater that were released within a relatively short time. One significant event was a meltwater pulse that began about 14,700 years ago and lasted 500 years. The cause of this, presumably, was calving of the large glacial masses in the Antarctic, or in the Arctic between Greenland and Canada. With the melting of glaciers, sea level rose globally during this time by around 20 metres. Other large events included the runoff of immense dammed lakes that had formed from the meltwaters of retreating inland glaciers. According to scientific estimates, Lake Agassiz in North America had a maximum area of around 440,000 square kilometres, making it even larger than today's Great Lakes.

It broke through the surrounding glaciers multiple times, pouring large amounts of fresh water into the ocean, with one especially significant episode around 8200 years ago. This one meltwater pulse alone is believed to have raised sea level by several metres within just a few months.

The magnitude of sea-level change since the last ice age can be reconstructed based on various lines of evidence, for example, by studies of coral reefs or sediments on the sea floor. Tropical coral banks on the slopes of South Pacific islands have been growing slowly upward along with sea-level rise over recent years and decades. They can only grow in shallow water that is flooded by sufficient light. When sea level rises, the zone in which corals can thrive also shifts slowly upward. By drilling deep into the coral banks, older dead corals are encountered whose age can be determined by special analytical methods. Sea-level elevation at different times can thus be estimated.



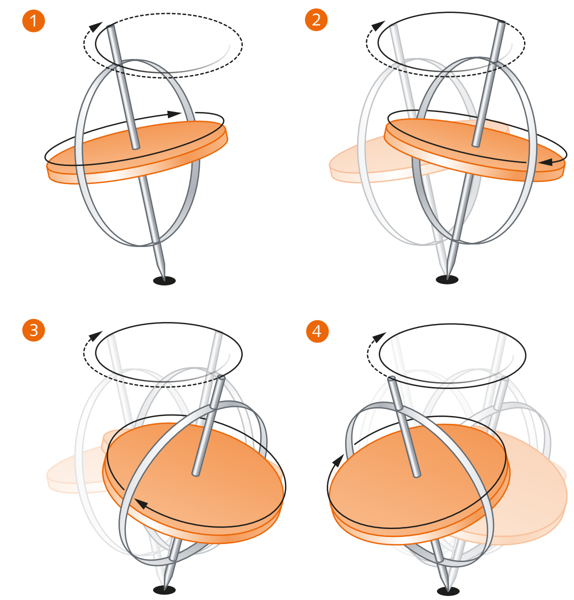
1.10 > Sea level has not risen at a constant rate over the years. It has been punctuated by surges resulting from events such as meltwater pulses.

The second method involves detailed study of sediments on the sea floor. By examining microfossils found in the sea-floor sediments, including the remains of single-celled organisms or fossilized fish bones and teeth, it is possible to determine when the bottom was part of the exposed land area, whether it was covered by fresh water from the melting glaciers, and when it was finally flooded by salt water from rising sea level. Depending on environmental conditions, different organisms are present and their organic remains are concentrated there. A sediment layer that derived from land plants can thus be clearly distinguished from one in which the remains of marine algae are found.

The sun – a climate engine

The cause for alternating warm and cold phases, with the associated rise and fall of sea level, is related to natural climate fluctuations at regular intervals. Milankovich Cycles, postulated by the mathematician Milutin Milanković in the 1930s, could have had an influence on the warm and cold periods. His theory maintains that the position of the Earth relative to the sun changes regularly, causing variations in the amount of incoming solar radiation received by the Earth. These variations particularly affect the northern hemisphere. According to Milanković there are three primary causes:

- Change in the precession of the Earth's axis, which varies on a cycle of around 23,000 years. Precession can be best explained by a spinning top that has been disturbed by a gentle push. The top continues to rotate, but the axis direction defines a larger circle. The cyclical change in direction of the axis is called precession.
- Change in the tilt angle (inclination) of the Earth's axis, with a cycle duration of around 40,000 years.
- Change in the eccentricity of the path of the Earth around the sun. The shape of the elliptical orbit of the Earth varies. The change occurs in cycles of around 100,000 years and 400,000 years.



1.11 > The Earth changes its precession, the rotation motion, over a period of about 23,000 years. This is comparable to a gyroscope that gradually begins to wobble. It continues to rotate but the axis makes increasingly large circles.

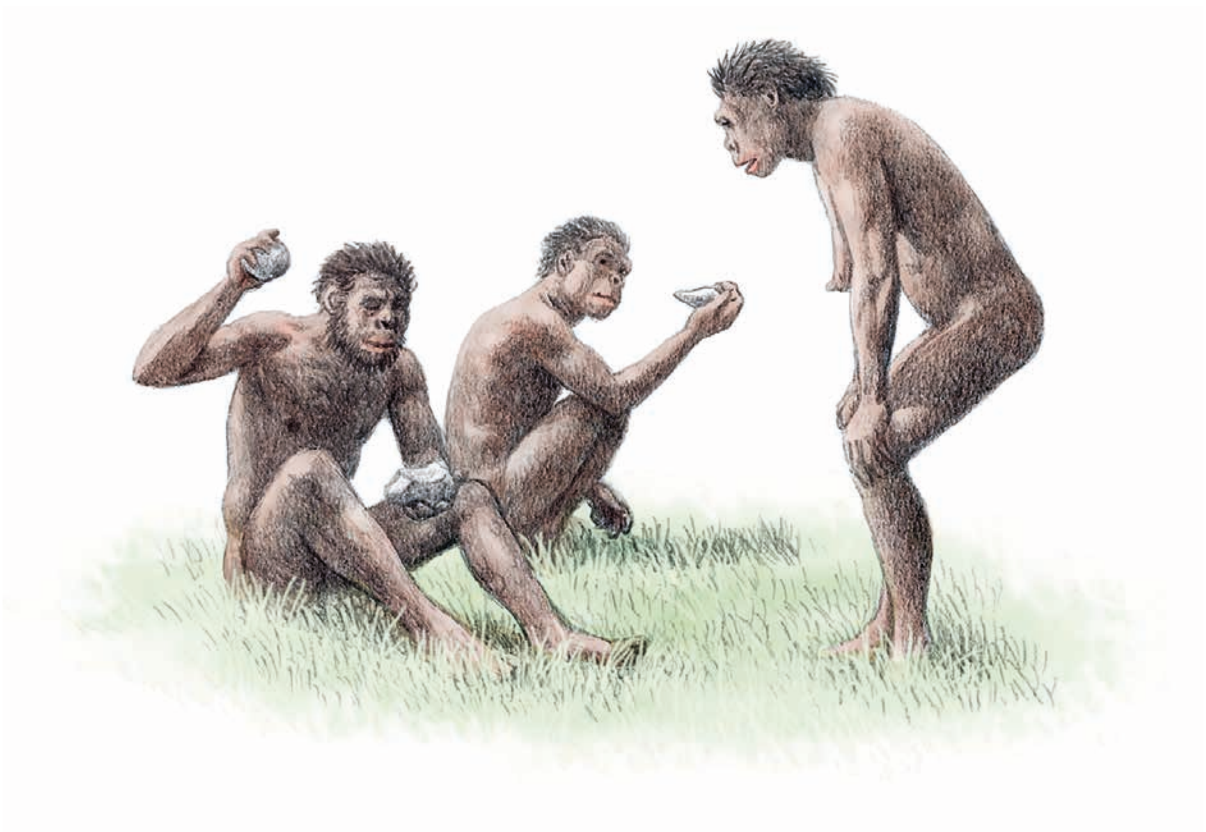
It is known today that the Milankovitch Cycles alone cannot explain the large temperature differences between warm phases and ice ages. But it is very probable that they contribute greatly to the change. There is also an amplifying effect that contributes to the origin of ice ages: the ice-albedo feedback. Ice and snow strongly reflect sunlight (the ratio of reflection is called albedo). The thermal radiation of the sun is thus also reflected, which results in further cooling. The growth of glaciers is thus enhanced.

Changing sea level – the pulse of human evolution

The rise and fall of sea level changed the available land area significantly with each cycle. Many areas that are flooded today were dry at the peak of the last ice age when sea level was about 125 metres lower. The land area in Europe was almost 40 per cent greater than it is today, and worldwide it was about 20 million square kilometres larger, which is approximately equal to the area of Russia. People thus had more extensive areas available that could be used for fishing, hunting and settlements. Experts believe that humans were already practising navigation then. At that time many land bridges between present-day islands and the mainland were still above sea level. Pathways that no longer exist today were available to people for exploiting new areas. These include the northern connection between America and Asia, which is cut off today by the Bering Strait. Another example is the 500-kilometre wide Arafura Sea, the marine region between Australia and the island of New Guinea to the north, which is an important fishing area today but was dry land at the peak of the last ice age.

Out of Africa

Today, it is widely accepted that humans originated in East Africa. The following important epochs of their dispersal are recognized. The first was around two million years ago. At this time the early man *Homo ergaster/Homo erectus* spread, presumably by land, to Europe, China and down to southern Africa. Whether *Homo ergaster* and *Homo erectus* are related, and to what extent, is an object of ongoing research. It is conclusive, however, that both became extinct and were not direct ancestors of modern humans, *Homo sapiens*. The second epoch involves *Homo sapiens*, who had a significantly wide range almost 200,000 years ago. Around 50,000 years ago they migrated to New Guinea from present-day Indonesia and finally to what would become the continent of Australia. New Guinea, which belongs half to Indonesia and half to Papua New Guinea, was separated from the rest of Indonesia by the sea, like today. But by that time, according to experts, the people already had simple boats and basic nautical skills. During this phase navigation on the water, from coast to coast over large distances, already played a role. America, however, was reached and colonized by crossing the land bridge in northern Asia about 15,000 years ago. Much of the evidence of these early human migrations is covered by water today, so there is often an absence of relics or prehistoric indicators of settlements. It is presumed, however, that people spread primarily along the coasts. Inland forests would have made migration difficult over the land, so the coastal pathways were simpler. In addition, fish and seafood were a reliable source of food. With the end of the last ice age, the conquest of new areas by *Homo sapiens* also received a boost. As the glaciers thawed they made room for modern humans, who were now able to spread northward as far as the arctic regions.



1.12 > The early man *Homo ergaster* had many of the skills of modern humans. He made tools. This could have helped in his migration two million years ago from Africa to the north and east.

Modern technology reveals old clues

To better reconstruct the spread of humans and to evaluate the importance of coasts, specialists from various disciplines have been collaborating intensively for several years. Teams comprising geologists, archaeologists and climatologists have joined forces to search for the traces of early settlements and, using modern submersible vehicles and high-resolution echo-sounder technology, to reveal structures in the sea floor in great detail. Underwater archaeology is important in this endeavour because areas on land have been continuously altered by people over thousands of years, while some evidence on the sea floor – including stone-age – has been covered and protected by sediment layers. Near the coasts, scientists now search systematically for underwater caves that were above sea level and dry during the ice age. These caves were used in the past as living areas and could hold interesting clues.

New knowledge is now being obtained from many areas of the world, for instance of the settlement pathways between Africa and Europe in the Mediterranean region. It was long believed that modern humans from Africa advanced to the north by land, along the eastern margin of the Mediterranean. But new finds indicate that migration over the sea from coast to coast must also be considered as a possibility. At present, there are ongoing intensive studies of the role that Malta, an island archipelago between Tunisia and the Italian island of Sicily, could have played. It may have been an important bridge between the two continents. At the peak of the last ice age Malta was significantly larger and was connected to present-day Sicily over a 90-kilometre long land bridge called the Malta-Ragusa Platform, so that the distance northward from Africa across the Mediterranean was much shorter than it is today.

The sea floor around Malta has been mapped in detail in recent years with the help of modern underwater technology. Bottom samples have also been taken. Ancient land structures on the sea floor that have hardly changed over thousands of years became visible: old river valleys, sand banks, stone-age shore lines and possibly even old lakes. In the past, the three present-day islands of the Malta archipelago were connected and there were evidently large fertile areas that would have been of great interest for settlers from Africa. According to the researchers, the trip would have been possible with simple boats. Efforts to find concrete evidence of early settlements are continuing.

Evidence of early settlements is also being sought on the sea floor 200 kilometres to the northwest. There lies the small island of Pantelleria, directly upon the shortest line between Tunisia and Sicily. It is known for its occurrences of obsidian, a black, glassy volcanic rock that was used by stone-age people. Scientists searched a small area for chipped obsidian and were successful. The flaked stones appear to be concentrated at an ancient shoreline that lies below 20 metres of water today. Closer investigation should be able to determine whether it is a stone age find. The scientists believe this is probable.

Sundaland – a melting pot for humanity

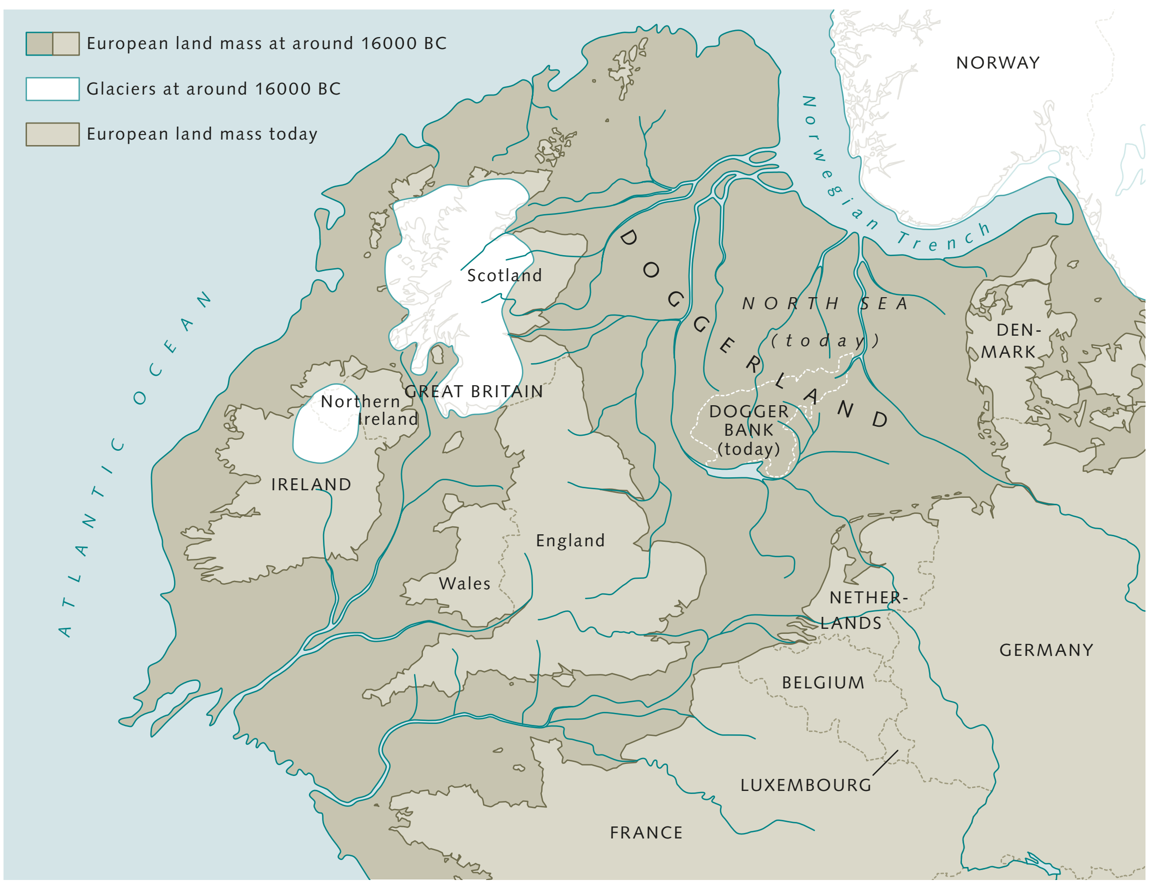
Efforts are also being made in Southeast Asia to locate flooded shorelines where evidence of prehistoric settlements may be found. The challenge here lies in the sheer immensity of the ocean region to be investigated. During the last ice age, the present-day marine area between the Asian mainland and the islands of Borneo, Java and Sumatra was a large contiguous land mass that is called Sundaland, and was at that time as large as Europe. Scientists believe that the climate and vegetation in parts of Sundaland changed repeatedly. During some periods there were dense rain forests and at others savannah landscapes predominated. These fluctuations led to periodic large-scale migrations. People migrated from the northern regions to Sundaland. At other times they moved in the opposite direction. Thus, according to genetic models and a few archaeological finds, different tribes intermingled repeatedly at certain times. The region was a genetic melting pot that probably played an important role in the development of modern humans. It is further assumed that during times when the savannahs were predominant, the people moved over particular corridors or plains, possibly also on elevated plains along the coasts.

Much is still unknown about the settlement history of this region. This is regrettable because the region represents an important stepping stone in the colonization of New Guinea and Australia, which were a contiguous land mass called Sahul during the last ice age. A land connection between Sundaland and Sahul, however, can confidently be ruled out because the marine area between them, the Banda Sea, was up to 5800 metres deep even at that time.

The Baltic Sea – a young coastal sea

Different factors played a role in the settling of the northern hemisphere as compared to the southern hemisphere. In addition to changes in sea level, the ice masses of glaciers also had an enormous influence on the natural environment and on the history of human settlement. The Baltic Sea is a good example of the extreme changes in landscape. Its history can be fairly accurately reconstructed based on numerous sedimentological studies. It began around 12,000 years ago when the glaciers of the last ice age had retreated back to as far as Scandinavia. At that time sea level stood about 80 metres below its present level. A meltwater lake formed near the centre of the present Baltic Sea, initially with no connection to the open sea because the present-day Kattegat Strait between Denmark and Sweden was still situated above sea level, and was thus dry land. It would have been possible to walk on dry land along the shore of this lake from the present site of Rügen Island to the area of the Danish island of Bornholm.

With rising sea level, as a result of meltwater pulses, this land connection was flooded some 10,000 years ago. However, the connection to the open sea was cut off again about 9300 years ago due to the gradual uplift of the Scandinavian land mass. During the ice age the weight of glaciers caused the land to subside, but this decreased



1.13 > Around 18,000 years ago the North Sea was largely dry land. The area between present-day Great Britain, Denmark, Germany and the Netherlands is called Doggerland, although the exact locations of land masses, glaciers and rivers are uncertain. Doggerland shrunk with the rising sea level until it completely disappeared about 7000 years ago.

steadily with the thaw. Incidentally, the rebound of Scandinavia is continuing today at a rate of approximately nine millimetres per year.

As a result of the meltwater pulses and accelerating sea-level rise, however, the Kattegat Strait was irrevocably flooded around 8000 years ago.

Disappearing land

At this time the North Sea was also formed. Until about 10,000 years ago the area between present-day Netherlands, Germany, Denmark and Great Britain was still a large contiguous land mass. It was crossed by large rivers that can be seen as precursors to the Rhine, Weser, Thames and Elbe Rivers. At that time they emptied into the sea several hundred kilometres further to the north than today. Archaeological evidence indicates that the landscape was characterized by moors and birch forests. This area is now called Doggerland, after the Dogger Bank, a shoal present in the North Sea today.

Discoveries of hunting weapons prove that people lived here during the Middle Stone Age or Mesolithic. Rising sea level also flooded Doggerland so that people living near the river mouths had to gradually retreat from the coasts. By around 7000 years ago it had probably completely disappeared. Sea level at that time was about 25 metres below the present level.

Today, the floors of the North Sea and the Wadden Sea on the Dutch, German and Danish North Sea coasts are largely covered with sand and soft sediments that the precursor rivers had carried far out into Doggerland. The cliffs of Heligoland probably projected as an imposing mesa above the vast plain. They are part of a red sandstone layer that actually lies 2000 metres underground but was pushed upward by an enormous salt dome that formed 100 million years ago and underlies the sandstone.

Meltwater disrupts the marine heat pump

With regard to life on the coasts, the most direct impact of the onset of warming 20,000 years ago was the rise in sea level and flooding of large regions. But the presence of Lake Agassiz in North America, which repeatedly released large meltwater pulses into the sea, again exemplifies the fact that these climate changes had other, much further-reaching consequences for people. At this time the northern hemisphere had already warmed significantly compared to conditions during the ice age. The massive release of fresh water interrupted this trend and led to renewed cooling of the northern hemisphere by up to 5 degrees Celsius. The reason is that the surge of fresh water into the Atlantic disrupted the oceanic heat pump, the global thermohaline circulation that moves water worldwide like a giant conveyor belt (*thermo* – driven by temperature differences; *haline* – driven by salinity differences). Through this phenomenon, which occurs in polar marine regions, cold, salty and comparatively heavy water sinks to great depths and flows toward the equator. As the surface water sinks, warm water flows in from the southern regions to replace it. The Gulf Stream, whose branches and extensions transport warm water from southern latitudes to the northeast, and which contributes to Western Europe's mild climate, also depends on this phenomenon.

Even at the time of Lake Agassiz this heat pump led to relatively warm climatic conditions in the northern hemisphere. Discussions continue among specialists regarding the extent to which the meltwater pulses reduced salinity, and whether the thermohaline circulation completely

1.14 > 12,000 years ago people used axes and daggers made of flint from Heligoland. At that time Heligoland, part of a colourful sandstone formation, protruded as a prominent mesa above Doggerland.

1.15 > The Sognefjord is one of the most popular travel destinations in Norway. It was formed during the ice ages by glaciers that slid into the sea here and gouged out the rock below. As the glaciers thawed and sea level rose, the glacial valley was slowly flooded.

stopped. It follows that a halt in the circulation would also interrupt the transport of warm water from southern ocean regions. The climate in Europe and the Near East became cooler and dryer. These changes could have had a decisive impact on **human history**, particularly on the Neolithic revolution, which began about 10,000 years ago. Many humans made a lifestyle transition from hunters and gatherers to sessile farmers and livestock breeders. There are various scientific theories for this transition. One explanation is the "oasis" hypothesis (also known as the "propinquity" or "desiccation" theory). This states that the hunters and gatherers could no longer find enough food, especially because certain prey animals became scarcer due to climate change, meltwater pulses and interruption of the thermohaline circulation. As a result people began to cultivate types of wild grain that grew well in the new prevailing climate.

With the thawing of glaciers the meltwater flow from Lake Agassiz gradually diminished, resulting in higher salinity in the Atlantic again. This gradually restarted the thermohaline circulation, causing temperatures in Europe and the Near East to rise again.

In summary, a comparatively strong rise in sea level began around 20,000 years ago and lasted until about 6000 years ago. Since then, sea level has only varied slightly, with fluctuations of a few centimetres per century. Now with the global warming caused by human activity, the rise has accelerated noticeably again in recent decades.

Glaciers shape coasts

Alternating warm periods and ice ages change coasts, but not only through the rising and falling of sea level caused by glacial melting and growth. They also influence the form of the coastal landscape. During the ice age, glacial ice packages several kilometres thick placed a heavy load on extensive areas of the northern hemisphere land masses. Glaciers typically move slowly across the underlying rocks. One way they move is by gliding on a film of meltwater that forms from ice at the base of the glacier under high pressure. They also move slowly as the ice

1.16 > The Stockholm coastal archipelago is composed of very hard granite and gneiss rocks that were abraded to gently rounded hills during the ice age.

undergoes internal plastic deformation under its own weight. The migrating glaciers act like giant planers that shape the coasts in different ways. The Stockholm coastal archipelago, for example, consists of 500-million-year old solid granite and gneiss that even a glacier could not strip away, but it abraded the rocks into smooth round hills. Geologists call this kind of region a glacial drumlin landscape. Rising sea level then transformed this region into an archipelago.

On the steep coast of Norway, by contrast, the round glacier tongues dug deep into the rock and created typical valleys that are sometimes very deep and have a u-shaped cross section. The Sognefjord, for example, presently has a depth of 1000 metres.

The physical character of the land in North Germany, on the other hand, is different. Here the bottoms are relatively soft and very wide glacier tongues formed that pressed the coastal lands downward and at the same time abraded them horizontally. Examples of this include the wide openings of the Kieler Förde and the Eckernförde Bay.

The myriad faces of the coasts

> Our coasts are multi-faceted in appearance. For the most part, their character is determined by the materials that they incorporate and by the physical forces shaping those materials. Attempts to categorize coasts are marked by the diversity of distinguishing features, resulting in the creation of a number of different types of classification schemes.

A million kilometres of coasts

The coasts of the world are highly diverse. The northern coast of Brittany in France is characterized by granite cliffs interspersed with numerous bays. In Namibia the high dunes of the Namib Desert extend to the Atlantic shore, where the coast runs nearly parallel to the dunes. In Siberia, by contrast, the flat coastal region is dominated by permafrost, a metres-thick layer of frozen soil whose surface thaws out for a few weeks each year during the short Arctic summer, when it is especially susceptible to wave action. During storm-flood events, several metres of the saturated banks can break off, creating a constantly changing shore face.

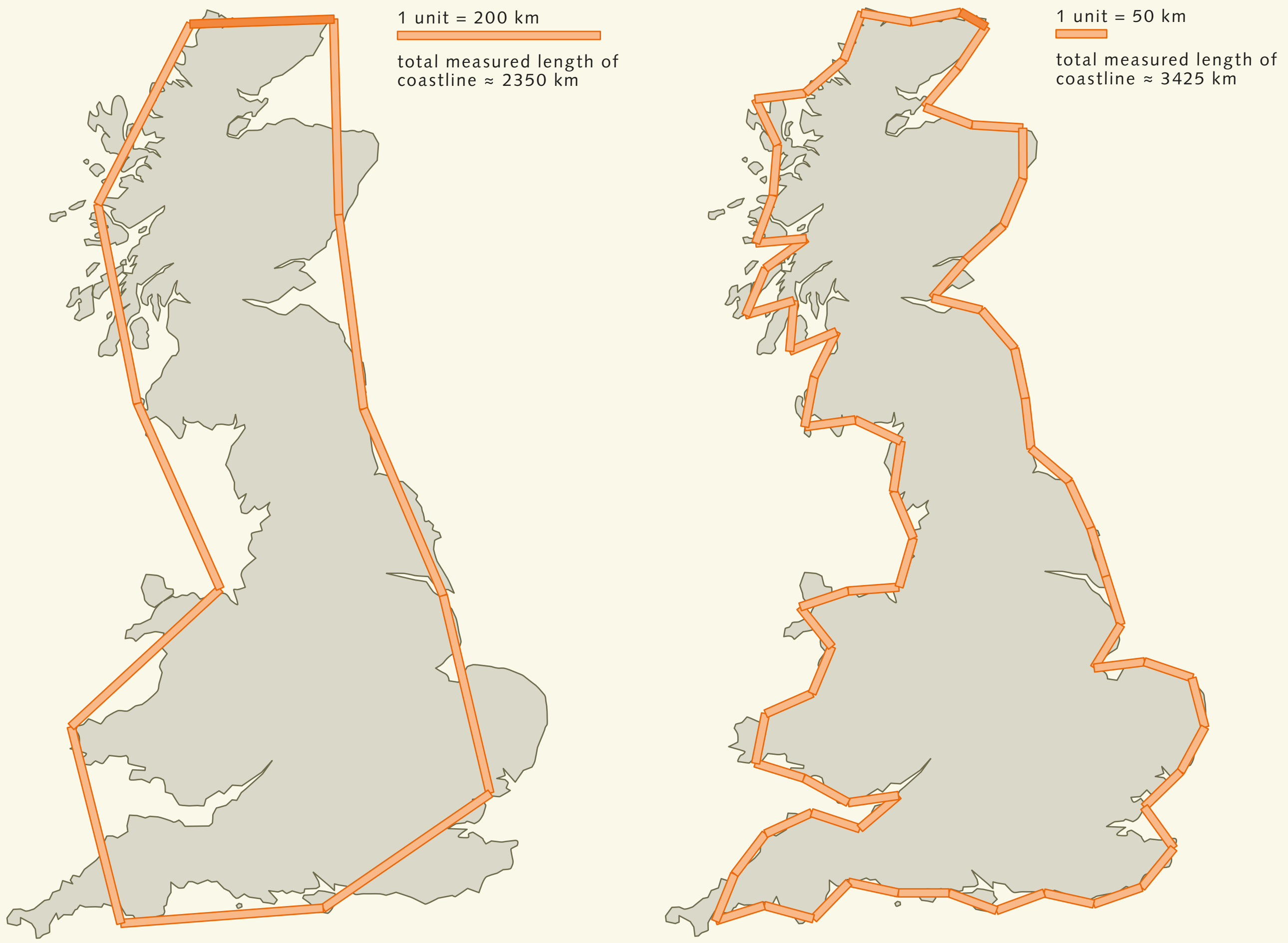
What all of these coasts have in common is that they are narrow strips of land exposed to the forces of the sea. Depending on the context they can be classified in different ways. Coasts can be distinguished based on whether they are strongly or weakly washed by the surf and currents. They can, alternatively, be classified according to the materials they comprise or by the rate that the material is eroded away by the sea. Coasts can furthermore be characterized by their ability to capture sediments that are delivered by rivers or currents. The ultimate form exhibited by a coast also depends significantly on the interplay between the materials that make up the substrate or that rivers transport to the coast, and the physical forces of wind and wave action that impact those materials.

1.17 > In Namibia the dunes of the Namib Desert run parallel to the Atlantic coast.

How long are the world's coasts?

The estimates for the global length of coastlines found in the literature vary widely. This is not surprising because the projected length of a coast depends upon the measurement scale applied. Reference to this fact was made in an article by the mathematician Benoît Mandelbrot published in 1967 in the journal *Science*. In his article, entitled "How long is the coast of Britain?", he also concluded that the answer to this question depended on the magnitude of the measurement scale selected. Using a coarser scale that does not take into account the length of shorelines in the bays, for example, results in a shorter total length. Applying a finer scale for measuring, taking into account smaller embayments, gives a longer coastline. Benoît Mandelbrot later linked his work to the mathematical concept of fractals, a term also coined by him.

A fractal is a mathematical object that is constructed from a repeating structural pattern down to the smallest dimension. In this sense, a coastline can also be resolved to an infinitely fine scale. It is thus theoretically possible when measuring a coastline to include the dimensions of every pebble or sand grain that makes up the coasts. There is a difference here with respect to mathematical fractals in that the structures do not repeat identically at all size scales.

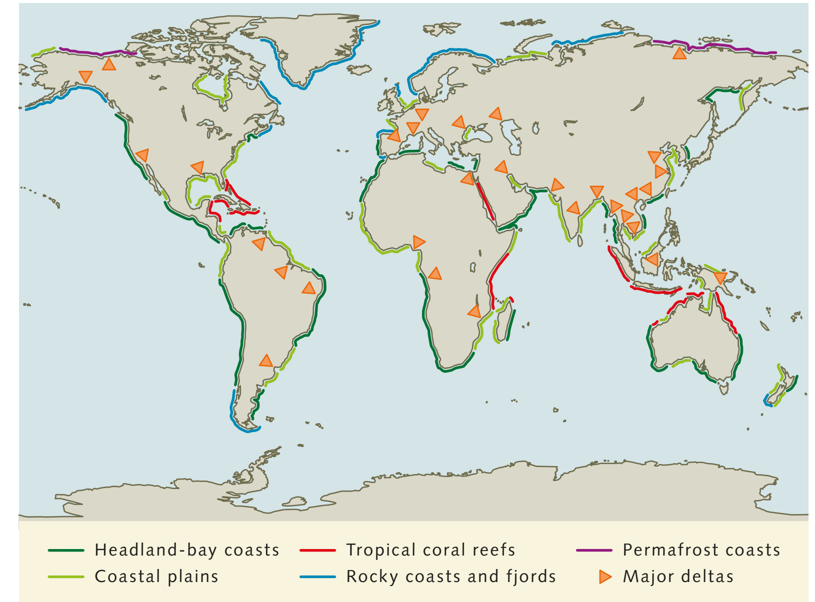


1.18 > The finer the scale used to measure a coastline, the greater the calculated length becomes.

1.19 > This satellite photo shows the Lena River delta in Siberia with all its fine structures, extending around 150 kilometres into the Laptev Sea. A large proportion of the sea ice that eventually drifts out into the Arctic Ocean originates in this marine region.

Geologists estimate the total global length of coastline to be around one million kilometres. This projection, of course, depends on how fine a scale is applied. When considering the entire globe, any differentiation of the coasts is only practical at a relatively coarse scale. For this categorization the continental margins can be traced in their present forms, which are in part a result of plate tectonics. Researchers created such a classification system in the 1970s, under which six different categories of coasts were distinguished.

- **Coastal plain:** an area where the land gently flattens toward the sea. An example is the coast of the West African country of Mauritania, where the land merges into the sea through a broad strip of coastal marshes and low dunes.
- **Major delta:** a large river mouth where sediments from the river are deposited because the ocean currents or tides are not strong enough to transport the material away. This is the case with the delta of the Lena River in Russia, which flows into the Laptev Sea in the Arctic Ocean.
- **Tropical coral reef:** a structure composed of carbonate produced by sessile corals (Cnidarians). It develops as a fringe along the coasts in near-surface waters penetrated by abundant light. Reef-building corals occur in tropical and subtropical waters at temperatures consistently greater than 20 degrees Celsius. A spectacular tropical coral reef is situated along the Central American Caribbean coast between Honduras and Belize. It is around 250 kilometres long and is among the most popular diving areas in the world.
- **Rocky coast and fjord:** a coast of solid rock. Fjords, like those found abundantly on the west coast of Norway, represent a special kind of rocky coast. They were formed during glacial periods, when the motion of the glaciers scoured deep valleys into the bedrock.
- **Permafrost coast:** a deeply frozen soil covering large areas of the Arctic land masses in the northern hemisphere since the last glacial period. Permafrost is found over many thousands of kilometres along the coasts of North America, Siberia and Scandinavia.



1.20 > The Earth's coasts can be roughly divided into six different categories.

- **Headland-bay coast:** a coast where rocky headlands extend into the sea. The headlands act as barriers to obstruct the surf and currents. Slow eddy currents form in the sheltered areas between headlands, gradually eroding the shore and forming bays. An example of this is Half Moon Bay on the Pacific Coast of the United States near San Francisco. There, over thousands of years, a half-moon shaped bay has formed behind a prominent headland.

Wind and waves shape the coasts

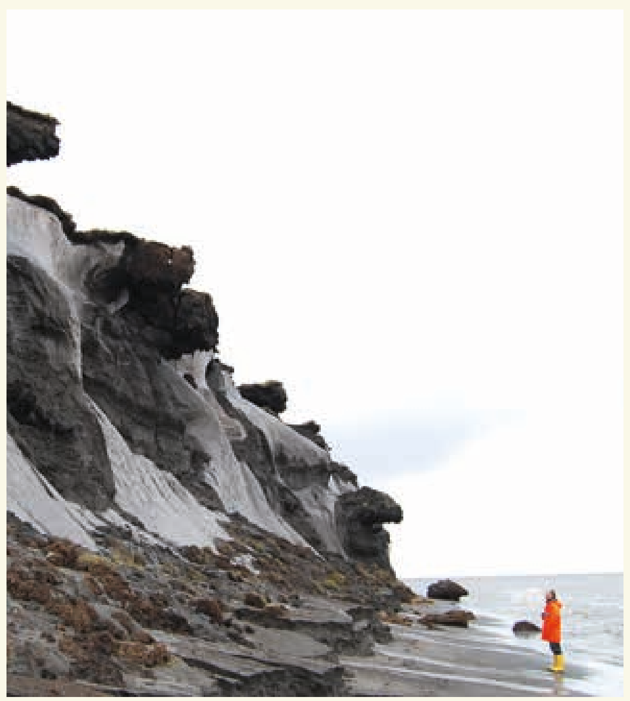
The physical forces of the sea – the waves, currents and winds – have a substantial effect on the shape of the coasts. The intensity of these forces is used to distinguish between low-energy and high-energy coasts.

The kind of material that makes up the substrate of a coastal area is also a key factor influencing the formation of the coasts. Tidal flats comprising relatively fine sediments can be reworked fairly quickly because these materials are easily transported by the currents. Fine sands can also be easily transported, as illustrated by the East Frisian Islands off the German North Sea coast. Because the prevailing winds there blow from

Deep-frozen coast – permafrost

Permafrost is the condition of a soil that has been permanently frozen to a depth of several metres since the last glacial period about 20,000 years ago. The largest permafrost regions are located in the Arctic areas of Alaska, Canada, Siberia and Scandinavia. In all, permafrost covers almost a quarter of the total land mass of the northern hemisphere. Although these areas are very remote and only sparsely settled, the permafrost is of global importance because, like a giant deep freeze, it conserves massive amounts of dead biomass, especially plant material.

A critical current problem is accelerated thawing of permafrost due to climate change. Previously conserved biomass is now being made available for degradation by microorganisms. The metabolism of the microorganisms, however, produces the greenhouse gases carbon dioxide and methane, whereby the amount produced depends upon various factors. One of these is the form in which the carbon is bound up within the biomass and another is the favourability of environmental conditions for the microorganisms.



1.21 > The Siberian island of Muostakh exhibits a permafrost coast that is increasingly susceptible to erosion due to global warming.

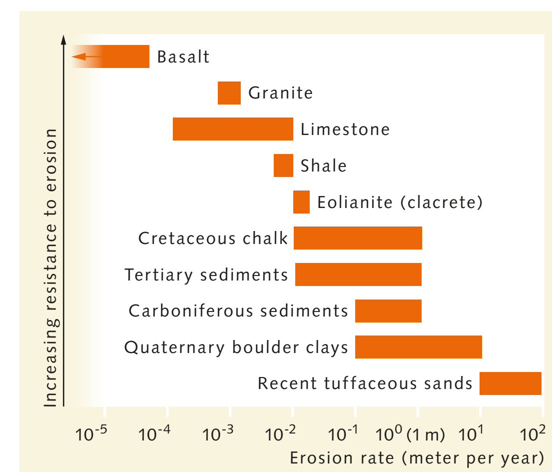
Carbon compounds bound up in the biomass are either stable or labile compounds. In wood pulp lignin, for example, the carbon bonds are very stable, so wood degrades very slowly microbiologically. This will remain the case in the future under cold Arctic conditions because at sub-freezing temperatures the microorganisms are very weakly or not at all active. Labile compounds like plant tissue that were frozen during the glacial period could virtually be degraded immediately. How rapidly biomass will be degraded in the coming years due to permafrost thawing has not yet been conclusively determined. The appearance of many thawed permafrost areas today is similar to moorlands, with standing water on the surface. Because of the low oxygen content of water in boggy soils, however, biomass is only weakly degraded. This is the reason that historical wooden objects or animal pelts remain well preserved in moors. Thus, the questions of whether and to what extent the thawing permafrost will release greenhouse gases are likewise still open. It is quite obvious today, however, that thawing is causing a reduction of permafrost on the coasts. This is releasing more biomass, which is becoming available to microorganisms. One factor is that summers in the Arctic are becoming longer as a result of global warming. The ground thaws earlier in the year and freezes later. The waves thus have a longer time window to erode the permafrost. Another factor is the shrinking ice cover in the Arctic Ocean, which promotes an increased intensity of the waves attacking the coasts. At some locations the permafrost grounds are breaking off at a rate of 20 metres per year.

Permafrost thawing is also a problem for local human populations. In Alaska many Inuit are losing their ancestral homes on the sea. According to reports by the U. S. Government Accountability Office (GAO) many villages are threatened by the accelerated melting of permafrost and loss of coastal land. Presumably, these villages will have to be abandoned in the future. At a meeting in August 2016, for instance, the community of Shishmaref decided to relocate to a safer site on the mainland that is yet to be determined. The village of 600 residents is located on an island in the Bering Strait off the coast of Alaska that has long been inhabited by the Inuit. Around 30 metres of shoreline have been lost over the past 20 years due to the thawing of permafrost. 13 houses have had to be dismantled and rebuilt. Although breakwaters were constructed to protect the island, they have not been able to stop the loss of land. Specialists estimate that relocation to the mainland will cost around 180 million US dollars. It has not yet been determined who will bear the cost.

1.22 > The village of Porthleven in the English county of Cornwall is located on an extremely high-energy rocky coast. Accordingly, the shoreline fortifications, including massive walls, are very substantial. Under conditions of very high seas, however, they are hardly noticeable.

the west, wave action carries sand away from the northwest side of the islands and redeposits it on the east side. In the past this has caused the islands to slowly migrate eastward. To impede this motion, rock jetties and breakwaters were built as early as the 19th century to fortify the islands. This greatly helped in preventing further migration.

While changes in the shape of sandy coasts are often visible with the naked eye, they can be more difficult to recognize when other material is involved. But even high-energy rocky coasts do change their appearance over time. The rate of change, however, depends largely on the properties of the rocks. Coasts composed of compacted but not yet lithified ash, generated over time by ash falls from volcanic eruptions, are especially easily eroded. Examples of this kind of coast are found in New Zealand. Up to ten metres of coast can be lost there within a single year at some locations. Chalk cliffs, like the White Cliffs of Dover in the extreme southeast of England are also relatively soft. When exposed to strong currents they can be eroded by several centimetres per year. By contrast, hard granitic rock is depleted at most by only a few millimetres in the same space of time. Harder still, black volcanic basalt is only destroyed by water each year by a maximum of a few hundred billionths of a metre.



1.23 > Depending on the material making up the coasts, they can be eroded slowly or more rapidly. Some can be depleted by several metres in a single year.

The intertidal zone
The intertidal zone is the area of the coast that is flooded and then exposed again by the rhythm of daily tidal cycles. The surface can be mudflats, sandy beaches or rocky cliffs. Rocky shores are exceptional because they occur on steep coastlines, while most other intertidal zones are found on flat coasts. Large-scale flat intertidal areas which include the salt marshes on the shore are called mudflats.

A question of particle size

Understanding the nature of the substrate in coastal areas is especially crucial for coastal protection, coastal management, and the planning of waterways and port installations. In particular, the size and density of the particles that make up the material play an important role. These can be factors, for example, in determining whether the shore of a populated island is in danger of erosion or whether shipping channels might shift their positions causing ships to run aground. With respect to the size of particles, the following coastal types are differentiated:

1.24 > The materials that make up the coasts are classified according to the size of the particles they are composed of. This scale extends from microscopically small clay particles to large boulders.

- muddy coasts,
- sandy coasts,
- pebble coasts,
- cobble coasts,
- rocky or boulder coasts.

The category that a coast belongs to is determined by the grain size of the particles present. Clay particles, transported from the mainland to the coastal waters by rivers, are the smallest. These are a maximum of 2 micrometres (1000 micrometres equal one millimetre) in size. The next size class incorporates silt particles with a maximum size of 62 micrometres. This is followed by the sand class, which is divided into additional subclasses. Fine sands, together with clay and silt particles, can form a mud substrate such as that found in the Wadden Sea. The subsequently larger size categories are pebbles, cobbles and boulders, which can likewise be divided into narrower subclasses.

The filtering function of the coasts

In many areas the character of the coasts is strongly shaped by rivers – through both their current strength and the material loads that they transport. They carry many minerals and nutrients that are incorporated to some extent into the sediments. Coasts that are rich in such sediments are also highly productive. A good example are the Sundarbans in Bangladesh and India, which, with a total area of around 10,000 square kilometres, comprise the largest block of mangrove forest in the world. The Sundarbans formed in the estuarine areas of the Ganges and Brahmaputra Rivers, which deliver immense amounts of material into the Gulf of Bengal. The Sundarbans are a vital unspoiled natural region. They are home to abundant birds, fish, crocodiles, pythons, deer and wild boar. Furthermore, rare animals such as the axis deer and Bengal tiger may also find refuge here.

Depending on the ability of a particular coast to filter and store the material transported by rivers, it can be designated as having an active or inactive filtering function.

A distinctive coastal form – tidal flats

On many low-energy coasts around the world tidal flats are formed when large amounts of clay, silt and fine sand particles are imported by rivers. These tidal flat areas, however, do not look the same everywhere. A distinction can be made between "closed" tidal flats, characterized by plant growth, and "open" tidal flat areas where the sediments are exposed. The largest tidal flat area in the world extends across broad stretches of the Dutch, German and Danish coasts of the North Sea and is an "open" tidal flat. It has been listed as a World Natural Heritage Site by UNESCO (United Nations Educational, Scientific and Cultural Organization) since 2009. The intertidal area here contains the typical mud consisting of 30 per cent clay, 30 per cent fine silt and more than 30 per cent sand as well as dead biomass. But technically this area cannot be referred to as a muddy coast because of the relatively high sand content in most areas. Thus, in the strict sense, this tidal flat is considered to be a sandy coast.

A true "open" muddy coast, on the other hand, is found in the South American country of Suriname, where the coastal Atlantic currents are very weak. Here, even the finest clay and silt particles can be deposited to form thick muddy sediment packages. The bulk of these are transported over a distance of around 600 kilometres from the mouth of the Orinoco in Venezuela, through the Atlantic and into the calm waters off Suriname.

On the east coast of the USA, however, the situation is quite different. Salt marshes have formed at many locations between Florida and the peninsula of Cape Cod in Massachusetts, which defines them as "closed" tidal flats. These form along low-energy segments of the coastline where rivers import large volumes of material that are primarily deposited in shallow areas near the shore. The tidal flats grow upward on the order of decimetres through time, and thus become less frequently inundated by water. Specialized salt-resistant plants can then colonize here. These salt marshes are important stopover and breeding sites for birds and thus represent a crucial habitat within the tidal flat environment.

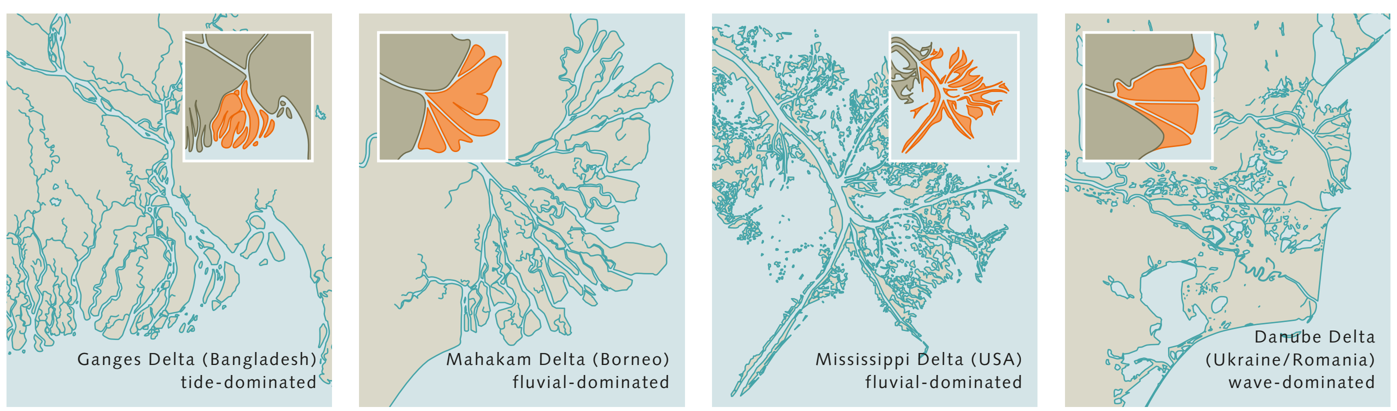
Tidal flats often form between the mainland and offshore islands. Because of the low-energy currents here, fine particles can be deposited on the sea floor. A prerequisite for the formation of these island or backshore tidal flats is a significantly large tidal range, the difference in the water level between low and high tide, so that the area is regularly flooded and exposed as in the western European Wadden Sea. As a rule, the tidal range here is between 3 and 3.5 metres. Island tidal flats are also found on the Pacific coast of Colombia, for example. These, however, are not "open" tidal flats, but covered by salt-resistant mangrove trees.

1.25 > The Wadden Sea on the margin of the North Sea is very popular with tourists. Many people are fascinated when they walk across the muddy sea floor at low tide for the first time.

Coasts with an active filtering function

- **Delta:** A river mouth that gradually grows outward into the sea due to the deposition of sediments is called a delta. The ocean currents or tides are not strong enough to carry the material away. Deltas can take on different forms. Ultimately they are shaped by the interacting forces of waves, river currents and tides. Depending on which of these forces is predominant, different types of deltas are created, which are then categorized as tide-dominated, fluvial-dominated and wave-dominated deltas.
  - Because of the constant cycle of advancing and receding tidal currents, sediments in a tide-dominated delta form long sand banks perpendicular to the coast. The surf here is comparatively weak. The combined mouth of the Ganges and Brahmaputra Rivers in India is an example of this kind of delta.
  - The influence of waves is also relatively minor in a fluvial-dominated delta. Furthermore, the tidal range, the vertical difference between low- and high-tide levels, is at most two metres, which produces a relatively weak tidal flow. A large amount of sediment can thus be deposited at the river mouth. Over time, this kind of river delta can become choked by sand. The river is then diverted to a new channel, creates new beds and bifurcates repeatedly to form a bird's foot delta.
  - Over time, in the wave-dominated form, the surf pushes the sediment into mouth bars, beaches and sand bodies orientated parallel to the shore. Neither the river nor the tides are strong enough to carry these mouth bars away. An example of this can be seen in the Danube Delta in the Black Sea.
- **Tide-dominated estuary:** In contrast to the delta, a tide-dominated estuary refers to a single large river estuary that is shaped by the tides. This usually has a funnel-shaped mouth that extends far inland, following old river valleys formed during the glacial period, as in northern Europe, for example. During high tide the river water is piled up into these funnels. At low tide the backed-up water then flows rapidly into the sea, washing a load of sediment out with it, so a delta cannot form within the estuary. Instead, large-scale tidal flats may be created on both sides of the funnel, such as those seen near the mouth of the Elbe River in Germany. The Elbe can thus be considered a typical tide-dominated estuary.
- **Lagoon:** Lagoons are characterized by relatively shallow coastal waters with a maximum depth of five metres. As a rule they are separated from the open ocean by barriers. These can be sandbanks, coral reefs, or offshore islands. Lagoons are usually elongate and orientated parallel to the coast. This is the case for those in the Baltic Sea, which are separated from the sea by elongated dunes, such as the Vistula Lagoon. In lagoons the interaction between the sediments and water is especially pronounced. Because wave and current action are virtually absent in lagoons, the water is relatively quiet. There is thus more time for suspended material to sink and be deposited. Lagoons often have narrow openings to the sea so that salt water and seawater mix to create brackish water. Chemical reactions can occur in this mixing area that result in a fine precipitation of flocculated material, which is then deposited in the sediment.
- **Fjord:** Generally, fjords are valleys that were formed by glaciers. These often very steep and deep valleys were flooded with the rise of sea level. Many fjords are closed off from the sea by coarse debris. This commonly consists of a deposit called moraine that was piled up by glaciers. The German term, "Förde", refers to a feature similar to a fjord that is also formed by glaciers, but is generally wider, shallower and more branching. Because no large rivers flow into the fjords as a rule, the currents are weak and material can also be deposited here.

1.26 > River deltas can be formed in different ways. Their shapes are ultimately determined by the interplay of the forces of tides, waves and river currents.

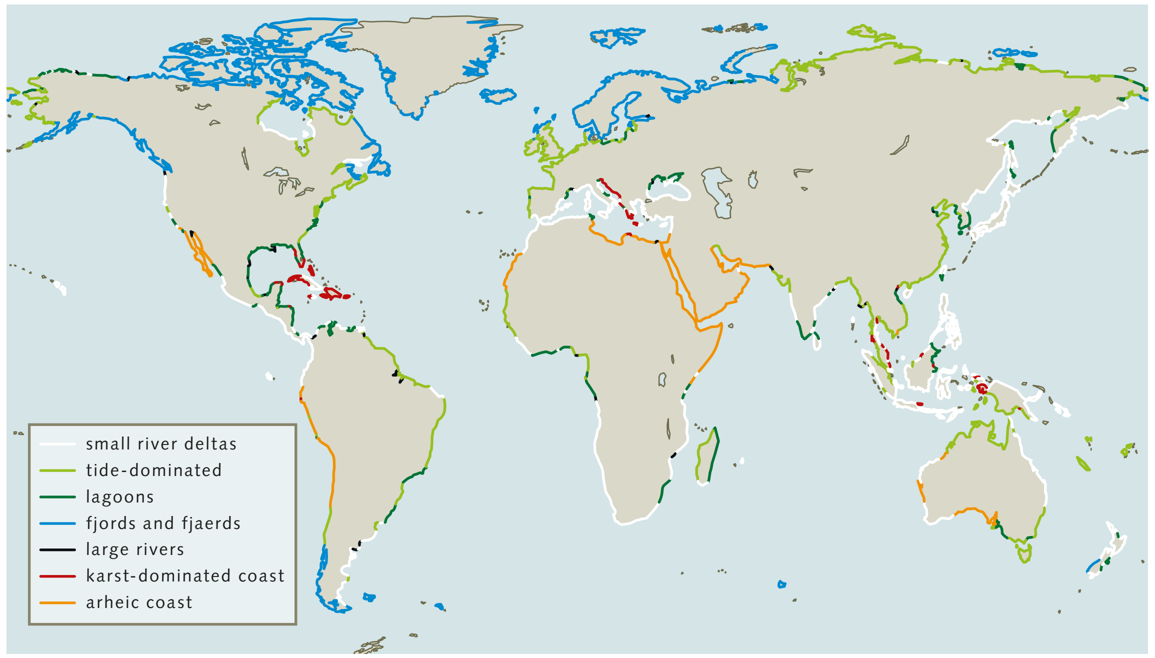


Coasts with an inactive filtering function

- **Coasts with rapidly flowing rivers:** In many cases large rivers flow with such a high velocity that, even though they carry a heavy load of sediment, the material is not deposited near the coast but carried out to sea in a kind of suspended cloud. To the extent that this occurs, the filtering effect of the river mouth is limited. An example of this is seen in the Columbia River in North America.
- **Karst-dominated coasts:** This kind of coast consists primarily of limestone. It was formed over millions of years from the carbonate shells and carapaces of marine organisms. Plate tectonic forces lifted these chalk masses up out of the sea, where they then consolidated and hardened over time to limestone. As a result of chemical weathering caves and passages are typically formed within the limestones, and rain and river waters flow underground through these into the sea. Karst landscapes form and rivers carve deeply into the rock. In some locations the karst landscapes have been flooded by rising sea level since the last glacial period. One example of this is the world famous Ha Long Bay in Vietnam, which was originally a river and karst landscape, but was later flooded by the rising sea level. Today, former cliffs on the river banks project out of the water as islands. Karst-dominated coasts are characterized by a paucity of sediment deposition due to their typical craggy structure and wave action.
- **Arheic coasts:** The coasts in very arid regions and deserts where precipitation is so low that no water at all flows into the ocean are called arheic coasts. The name derives from the geological term for rivers

1.27 > The karst cliffs in the Ha Long Bay in Vietnam are world famous. Tourists ride on boats through the archipelago.

1.28 > Coasts can also be differentiated based on how strongly they filter sediments that are delivered by rivers from the inland.



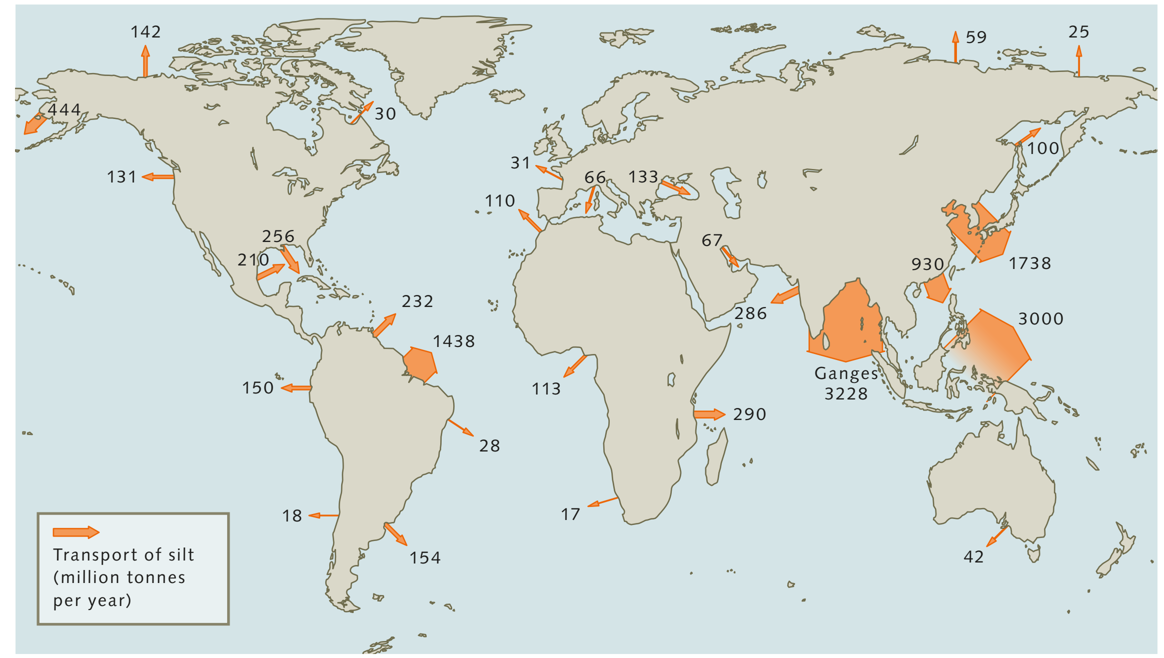
whose waters seep into the ground in a desert or salt flat before they can reach an ocean. These rivers are called arheic.

The amount of sediment transported into coastal waters annually is immense. The material basically originates as a weathering product of rocks on the land. It is eroded by rainwater either directly from mountainous regions or washed out of the soils in the flatlands. Over millennia the landscape is gradually flattened. The leading transporter of material is the Ganges River, which carries 3.2 billion tonnes annually into the ocean. It transports mostly silt particles from the central Asian highlands that are dislodged from the substrate by physical weathering. The same process occurs in the Yellow River in China, whose distinctive colour is derived from a particular type of silt particles.

Degradation and accretion

Depending on local conditions coasts can grow or shrink. While some coasts increase in volume with sediment deposition, others are eroded over time due to current or wave action, as evidenced on the Norfolk coast of England. The village of Happisburgh here, with a population of about 1400 living in 600 houses, has achieved a sad measure of fame as a result of its location. At the end of the 19th century Happisburgh was located several hundred metres from the coast. Because of perpetual erosion of the coast, the village now stands directly on the edge of a ten-metre high cliff at the coastal margin. It continues to break off due to its composition of a soft mix of clay, silt and sand. Large pieces break off when strong east winds pound heavy waves against the coast. A number of houses have already fallen into the sea. Within the next decade Happisburgh could lose its Norman church, its lighthouse and a 14th century manor house to the sea. Attempts were made to counteract the erosional forces by constructing breakwaters, but these have proved ineffective. It is thus only a matter of time before Happisburgh falls completely into the North Sea.

Accretion or degradation of a coast depends on various factors. A more detailed classification of constructive and destructive processes follows, whereby different time scales must be taken into account:



1.29 > The sediment loads that rivers carry to the sea can be enormous. The world record is held by the Ganges River in Asia with a load of 3.2 billion tonnes annually.

Destructive processes

- **Endogenous erosion:** destruction induced by the coasts themselves. This includes cliff slump and cracks (faults) resulting from earthquakes, or the collapse of volcanic islands, for example, when old craters cave in.
- **Mechanical erosion: abrasion** produced by wave action and drifting ice. This can generate many different coastal forms. Cliffs are one example, steep walls of rock that are by no means immutable, for even hard rocks are eroded over time. Cliffs begin to form when waves undercut the rocks at the base of a steep wall. The wall thus becomes unstable and breaks off, forming the typical high cliffs. Another coastal form caused by abrasion is the flat coast. This is characterized by a broad area in the littoral zone sloping gently seaward. Depending on the material, these can be categorized as sand, pebble, or rocky shores. On sandy beaches the shore is the gently sloping, wet part of the beach that is shaped by the forces of water. Seaward of rocky cliffs a flat wave-cut shore is found. These are recognizable by parallel deep ridges in the rock that are created when the bedrock is composed of different individual rock layers. Because the different materials are eroded at different rates by the energy of the surf, deeper and shallower areas result, creating a profile of ridges defined by the boundaries of the rock layers. Erosion can also wear away coasts in other ways. An example is the undercut cliff. These begin as notches in rocky coasts at the level of the water line caused by wave action.
- **Scouring of the coastline:** destruction that occurs on frozen coasts such as those with permafrost or glaciers. In the permafrost regions of the northern hemisphere summer thawing leads to softening of the soil that was frozen during the winter, making it more susceptible to erosion by the waves. This kind of destruction, called thermoabrasion, changes the coastline. In the Arctic and Antarctic, the coastline changes primarily due to the breaking off of large fragments of glaciers. Because of their massive weight, continental glaciers slide slowly from the land into the sea where they can sometimes project several kilometres out into the water as **shelf ice**. Because the ice is less dense than water, the glaciers float on the sea

1.30 > On the southern coast of Wales, near the city of Cardiff, abrasion has cut a flat shore into the limestone.

surface in spite of their great weight. Large chunks break off continually because the glacial mass is being pushed from the land out into the sea. This is called glacier calving.

- **Bioerosion:** destruction of hard substrates by microorganisms that slowly break down the rocks through their metabolism. This occurs, for example, in undercut cliffs.

Constructive processes

- **Endogenous build-up:** the formation of new coastal areas due to plate tectonic processes whereby land masses are uplifted. These include volcanic eruptions that through time release sufficient magma from the Earth's interior to create islands. In other cases new coastal segments are created when large amounts of lava from a volcanic eruption flow into the sea.
- **Potamogenic origin:** formation of deltas, tidal flats or wetlands by material imported by rivers.
- **Formation by ice:** accretion produced by coastal or pack ice shoving material together. The driving forces are provided by waves or tides pushing ice toward the coasts.
- **Formation by wind:** build-up of coastal dunes from loose sand that is piled up by wind.
- **Thalassogenic origin:** formation by materials that are deposited on a coast by waves, tidal currents or ocean currents.
- **Biogenic origin:** construction of coasts by living organisms. These include corals, which build solid and durable structures, or mangroves, which can abruptly curb the wave and current energy so that fine particles are deposited and tidal flats are formed. Not only do organisms contribute to the construction of coasts, however, but also to their protection. Corals and mangroves are natural breakwaters. Kelp forests can also absorb large amounts of wave energy. Furthermore, these plants also consolidate the sediments so that they cannot be washed away again by strong currents. Salt marshes also act as natural current barriers to protect the inland regions.

The extent to which these natural formation processes act is very well illustrated by the deltas of large rivers. Over time, the Mississippi River has transported so much material that the delta has grown to a width of around 200 kilometres. The weight of the sediments is so great that the delta is continuously subsiding. In addition, water is being squeezed out of the sediment, which represents a kind of compaction. In geological terms, compaction refers to the compression and decrease in volume of sediments, due in part to the pressure created by overlying sediment layers. The subsidence was formerly compensated by fresh material being constantly transported in. Human activity, however, has disturbed this compensatory process. Dams have been constructed along the river, trapping large volumes of material before they can reach the delta. Sediment replenishment at the coast has been thus cut off. But because the delta continues to subside under the weight of the old sediment packages, humankind is now exposed to the problem of a significant increase in the frequency of floods.

CONCLUSION

The shape of our coasts – a long and changing history

Coasts have a special significance for humankind. More than 90 per cent of global fishery is carried out in coastal waters. They are important transportation routes and significant sites for industrial and power plants. They are popular destinations for global tourism as well as a source of mineral and fossil resources. They are thus very attractive as working and living areas, which is evidenced by the fact that 75 per cent of all megacities with a population of more than 10 million are located in coastal areas.

Coasts are generally viewed as a thin line where the land and sea meet. They are transitional areas that are constantly subjected to change that can take place at very different rates: over millions of years through continental drift, in phases of tens of thousands of years through the alternation of interglacial and glacial periods, and over recent centuries through their settlement by humans.

Over relatively short periods of geological time, the fluctuations of sea level are primarily responsible for changes in the shape of the coasts. Because large amounts of water are sequestered in the form of ice and snow on the land during a glacial period, and the amount of water flowing from the land into the sea is diminished, sea level drops. Around 20,000 years ago, during the last glacial, sea level was about 120 metres lower than it is today. Many areas that are flooded today were dry at that time and the global area of land masses protruding from the water was about 20 million square kilometres greater than at present. Australia and the island of New Guinea were connected then by a land bridge and America was presumably being colonized by people from Asia over a land bridge across today's Bering Strait.

The formation of coasts in the northern hemisphere, however, was also strongly influenced by glacial ice. The Norwegian fjords, for example, originated when immense ice masses flowed from land into the sea and gouged out the bedrock. After the glaciers thawed and sea level rose, these grooves filled with water.

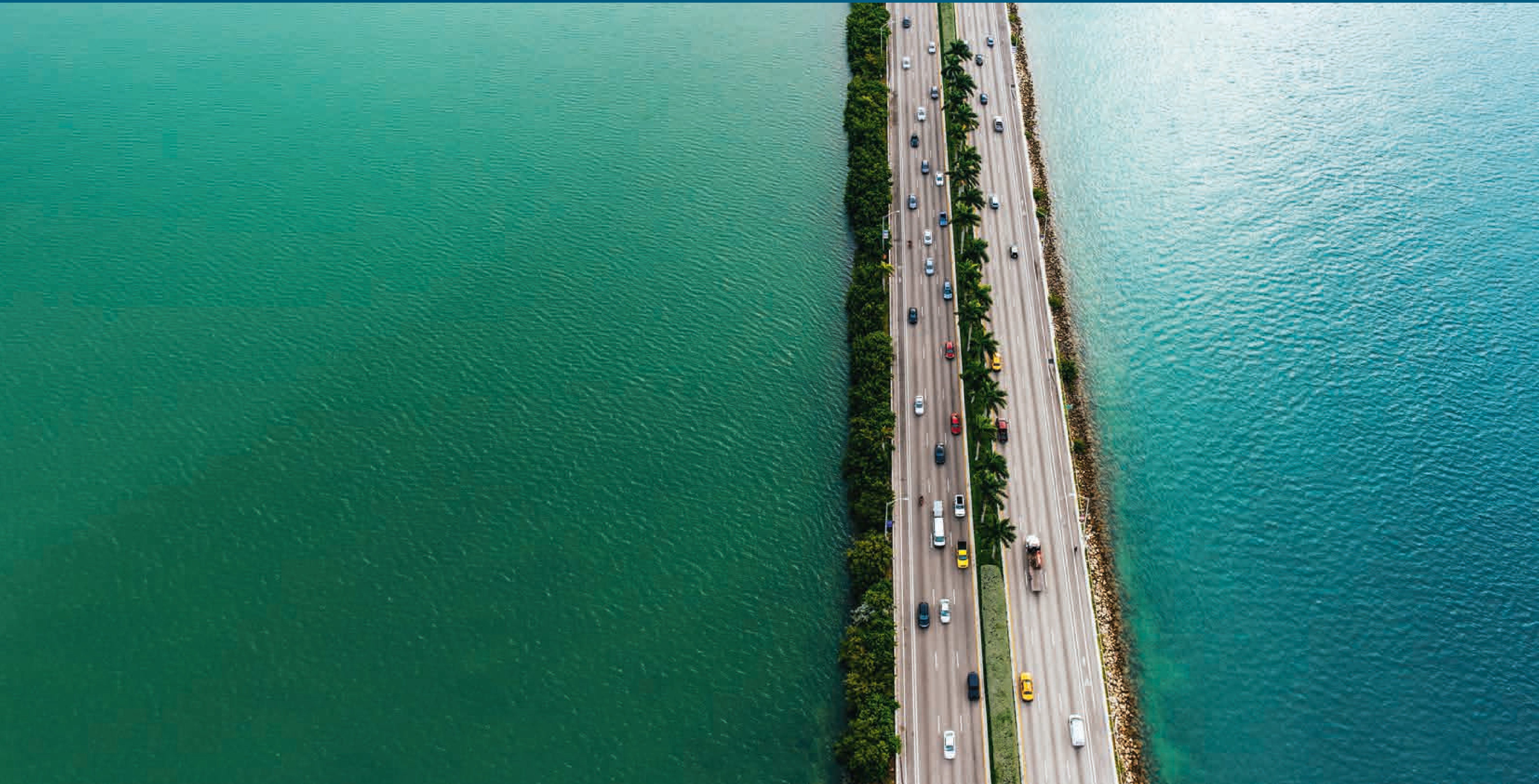
Over millennia, the movement of glaciers and numerous other processes have been instrumental in creating a large number of coastal types: bare granite coasts like those in Scandinavia, permafrost coasts frozen several metres deep in Arctic regions and dense mangrove forests in tropical areas. Scientists organize this diversity into a range of categories. For instance, coasts can be classified according to whether their form is heavily or weakly influenced by wave action and currents.

Coasts can also be categorized by the material that they are composed of, or by how strongly the material is eroded by the sea. They can be classified, furthermore, by how well they are able to trap sediments that are brought in by rivers or currents. This ability is referred to as the filtering function of the coasts. There are regions where large amounts of sediment are deposited on the coasts, such as the Mississippi Delta in the Gulf of Mexico. These coastal areas are often highly productive with abundant fish because the water receives a large volume of nutrients along with the sediments.

The amounts washed into the sea by individual rivers are sometimes gigantic. The Ganges River, for example, carries an extremely large load of material from the Himalayas to the Gulf of Bengal – around 3.2 billion tonnes annually. In many cases people have intervened in the natural sedimentation processes through various kinds of construction projects. The resulting changes have caused problems in many locations.

2 Living with the coasts

> For millennia, people have utilized the world's coastal areas. Coasts provide a space for trading, supply resources and underpin fisheries. It is no surprise that societies have always struggled to gain maritime supremacy. Now, however, humankind is exploiting coastal regions to such a degree that these areas are no longer able to render all of the ecosystem services that people value and need so much. Coastal areas are degraded particularly by construction and pollution.



Coastal functions

> Coastal habitats are highly diverse, as indeed are the functions they fulfil for humankind. Some of these functions, such as the production of fish, are available almost everywhere; others are highly localized – for instance, the provision of mineral resources like diamonds in the waters off Namibia. Moreover, people have been drawn to coastal locations as settlement sites and trading posts since time immemorial.

Close bonds between people and coasts

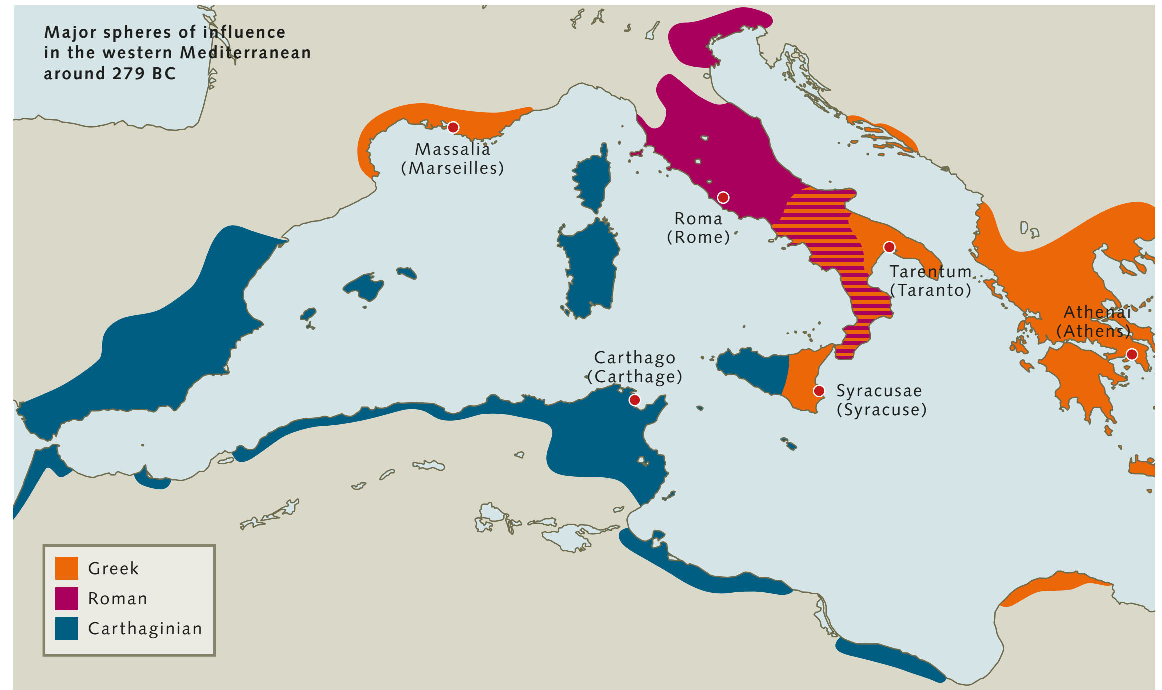
Coasts have been a significant human habitat for millennia. Initially the transition between land and sea functioned merely as a natural barrier. In time, though, people came to appreciate the advantages of the coastal region. From the earliest times, coastal waters supplied such resources as fish, algae or salt. As simple fishing boats were developed, coastal inhabitants became increasingly mobile. Fishers who were familiar with the ocean can largely be credited with venturing further out to sea and gradually discovering the islands along their native coastlines.

Early evidence of this exploration is found in China, for example. Archaeological finds in and around the southern Chinese city of Guangzhou indicate that by around 6500 BC, people in that area were using dugouts to navigate the expansive Pearl River Delta as well as open waters off the coast. From bases in the newly discovered territories, the more nautically experienced adventurers pushed ever further into previously unexplored sea regions. In time they discovered different cultures with different foods and tools at their disposal. Goods were exchanged between the different coastal peoples. This gave rise to the development of trading routes, which no longer just linked together coastal settlements but reached far inland via the traders involved.

2.1 > Excavations on the Isthmus of Corinth in the 1960s exposed a 2600-year-old portage cartway.

Trading focused mainly on goods and resources that were important for everyday life. In Cyprus, for example, remnants have been found of knives made from the glass-like volcanic rock obsidian and dating from the period around 6000 BC. Since this rock does not occur on Cyprus, it must have arrived there from overseas during that period. Archaeologists suspect that it came via a Neolithic settlement on the Anatolian plateau, which had several thousand inhabitants at the time and was 150 kilometres away from the Mediterranean. Today the excavation site, named Çatalhöyük, has been listed as a World Heritage Site by UNESCO (United Nations Educational, Scientific and Cultural Organization). The obsidian itself must have come from the Göllü Dağ volcano, located another 200 kilometres east of Çatalhöyük.

Other early evidence of maritime coast-to-coast trading routes is found in the Middle East. Inscriptions from Mesopotamia, a region extending over parts of modern day Iraq and Syria, indicate that as early as 2300 BC, Indian mariners were transporting copper, timber, ivory and pearls from the highly developed Indus valley into western Asia. On that evidence, a kind of long-distance trading across the sea developed in very early times.



2.2 > In the third century BC the most important powers in the western Mediterranean were Carthage, Rome and Greece. Rome especially expanded its sphere of influence in the following centuries.

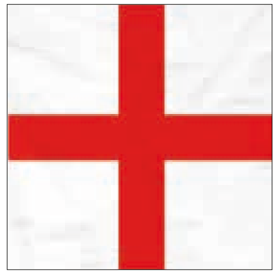
Coastal links

In the centuries that followed, maritime trade in Europe and Asia became increasingly important. Initially, strong regional trading zones emerged – for example, around the East China and South China Seas and around the Mediterranean. In the Eastern Mediterranean the traders along the most heavily frequented shipping routes sought ways of shortening the routes very early on. Around 600 BC a paved roadway known as the Diolkos was built across the Isthmus of Corinth so that ships could be portaged overland from the Gulf of Corinth to the Saronic Gulf. This shortcut at the narrowest part of the land bridge made it possible to avoid the 400-kilometre detour around the Peloponnese peninsula. The portage road remained in use in the first century AD until ships became large and fast enough to make it redundant.

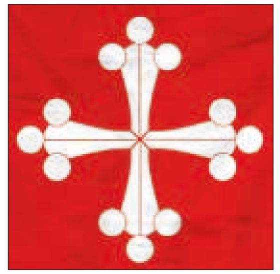
Supremacy in the Mediterranean

Coastwise trade was not solely about the pure exchange of goods, but also about gaining economic supremacy in a region. Time and time again, coastal dwellers fell into disputes over strategically important trading posts or mineral deposits, which not infrequently led to military conflicts. This is exemplified by the conflict lasting more than 300 years between the two main powers on the Mediterranean – the Romans and the Carthaginians. In the sixth century BC both powers were already vigorously engaged in commerce. Carthage dominated the area in the north of present-day Tunisia and traded predominantly in the western Mediterranean. At that time, Rome was beginning to expand its territorial dominion beyond the Apennine Peninsula. To avert competition, the two empires concluded several agreements over the course of time. The very first was negotiated around 500 BC and clearly defined each empire's sphere of influence. The Romans were not permitted to proceed westward along the North African coast beyond a certain point north of the city of Carthage. If Roman merchants wished to conduct business in the Carthaginian territories in North Africa and on Sardinia, they could only do so in the presence of a Carthaginian official. In the western part of Sicily ruled by Carthage, on the other hand, Roman merchants were given equal stand-

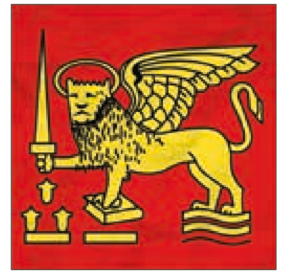
Amalfi



Genoa



Pisa



Venice

2.3 > To this day the emblems of Amalfi, Genoa, Pisa and Venice adorn the flag of the Italian Navy. The erstwhile city-states, whose growth owed much to a fortunate combination of ocean, city and hinterland, reached the heights of their prosperity in the Middle Ages.

ing with Carthaginians. For their part, the Carthaginians gave an undertaking not to attack Roman ruled cities in Latium, the region around the city of Rome.

Since both empires were still expanding, further treaties followed in 348 and 306 BC. These affirmed that both Rome and Carthage should respect each other's extended territories. Among other concessions, Carthage was granted sovereignty over Libya and Sardinia.

In the ensuing years Rome proceeded to expand, ultimately dominating the entire Apennine Peninsula. The old rivalry persisted, however. Finally it erupted into a series of conflicts known as the Punic Wars, from which the Roman Empire emerged victorious in 146 BC. The city of Carthage was completely destroyed. From that time onward, Rome enjoyed a long period as the dominant power in the Mediterranean.

From the fifth century AD, the Roman Empire fell into decline. In the aftermath, various Islamic peoples rose to prominence around the Mediterranean and in the Middle East. Cities that became important trading posts at that time were the Syrian city of Damascus, the city of Cairo's precursor settlements, Isfahan in present-day Iran, and Baghdad, later the capital of Iraq – inland cities which were nevertheless centres for the bulk of the trade between the coasts of the Mediterranean and China and India. For several centuries, Muslims controlled the trading routes along the North African coast, the Mediterranean, and the Red Sea which gave access to the Indian Ocean. In the view of historians, their great accomplishment is to have linked the trading routes of central and western Asia and the Mediterranean region into one large system.

In the early ninth century, the western Mediterranean was dominated largely by Muslim pirates who plundered the coasts and took control of Sardinia and Sicily. Christians referred to them indiscriminately as Saracens although they belonged to various Islamic peoples. The city of Amalfi on the present-day Italian Riviera was safe from the attacks due to its particular location. Situated on a steep coast on the Sorrentine Peninsula on the Gulf of Salerno, it was well protected. Its merchants succeeded in striking up business ties with the Saracens – and thus in gaining access to the important Islamic markets in North Africa. At that time the Saracens had key trading contacts with North Africa. This enabled Amalfi to grow into a major trading centre and build up a larger fleet. The city became so powerful that it eventually defeated the Saracens in the port of Ostia near Rome and significantly weakened their influence on trade in this region. Amalfi, along with Genoa, Pisa and Venice, ranks as one of the Italian maritime republics – city-states which rose to become major economic powers through astute trading and tactics, and whose trading ties reached as far as Byzantium, the empire in the eastern Mediterranean whose capital city was Constantinople, modern-day Istanbul.

Also impressive is the history of the Maritime Republic of Venice, which developed into an important economic metropolis from around the seventh century. The city had major advantages with regard to the exchange of goods. It possessed a well-established textile industry and a river port with water of considerable depth, and controlled the hinterland by means of a functioning network of rivers. Part of the reason for Venice's dynamic development was the city's aggressive actions towards its neighbours. Venice subjugated neighbouring competitors and controlled Dalmatia, the region that is now part of Croatia and Montenegro. Diplomatic skill, military brutality and trade boycotts targeting competitors: this was the mix with which Venice ultimately extended its sphere of influence to Crimea and Cyprus. Only in the course of the eighteenth century did the Maritime Republic decline in significance because trade in the Mediterranean no longer played such a major role. Thereafter, intercontinental trade to America and Asia took on more economic significance and was dominated by other powers such as England and the Netherlands.

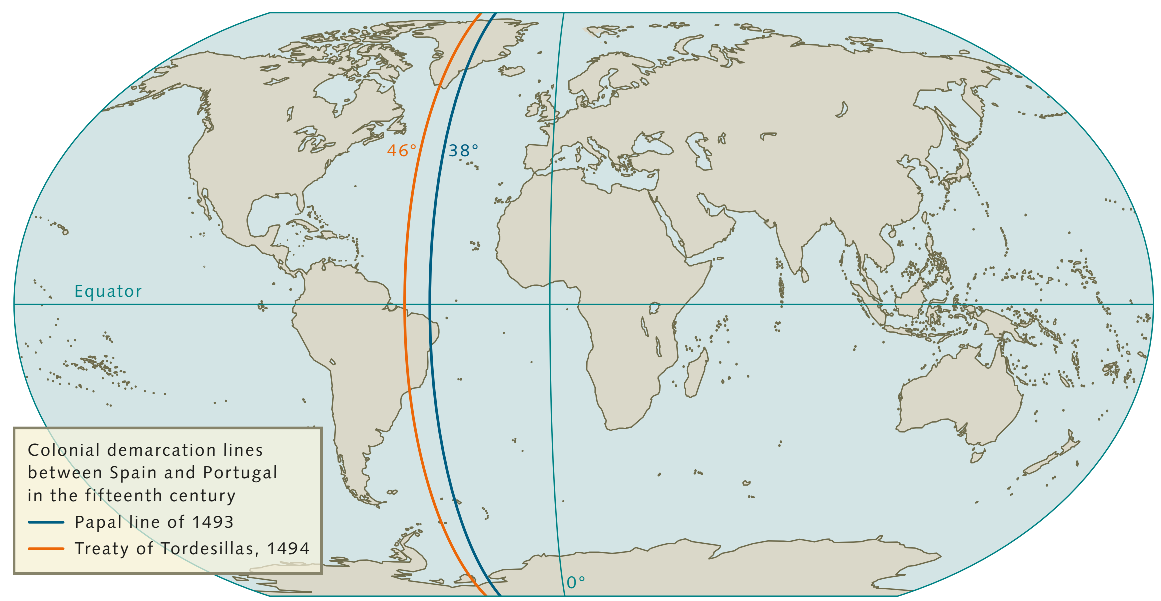
The Hanseatic League – a strong alliance for 500 years

From the middle of the twelfth century, the Hanseatic League was a large trading alliance that formed in the Baltic and North Sea region, ranging from Bruges in present-day Belgium to Reval (now Tallinn) in Estonia. Originally it consisted of an alliance of merchants whose most important aim was safe passage through the coastal waters of the North Sea and the Baltic, and who joined forces for protection against pirates. Ultimately almost 300 cities in northern Europe became members.

Not all of these were on the coast; some – like Cologne, for example – were a long way inland. The success of the Hanseatic League rests particularly on the fact that it shipped goods which were only produced in certain regions to others where they were in heavy demand. Cloths, furs, wax, salt, dried or salted fish, cereals, timber and beer accounted for the bulk of the volume of goods. For some long time, textiles were the most significant commodity. The Hanseatic League was not dissolved until the mid-seventeenth century.

Coastal prosperity and animosity

The extent to which power interests dominated merchant shipping after Christopher Columbus discovered the New World in 1492 is underlined by the way in which intercontinental trade unfolded between Europe and the ports of the newly discovered continent. The most powerful maritime nations at that time were Portugal and Spain. Spain had taken possession of the New World, while Portugal was keen to secure the newly opened trade routes to India along the African coast. Furthermore, the Portuguese had already seized Madeira and the Azores at the beginning of the fifteenth century. In 1493 Pope Alexander VI therefore issued a decree that the world beyond Europe should be



2.4 > At the end of the fifteenth century two maritime powers, Portugal and Spain, wielded such huge influence that Pope Alexander VI shared out the world between them. Territories to the west of the blue line in the Atlantic were awarded to Spain, and those to the east, to Portugal. The demarcation line was adjusted in the Treaty of Tordesillas.

Small-scale raiding tactics – privateering

Conflicts over supremacy at sea were not always fought out in open battles. In the dispute between the English and Spanish Crowns in the mid-sixteenth century, for example, Queen Elizabeth I decided to adopt special tactics. She hoped to use small-scale raiding to cause economic damage to the Spaniards. Instead of sending a fleet of warships, the battle against Spain was privatized. With royal permission, experienced sea captains were hired as privateers to prey upon the trading ships of the Spanish Crown. For this purpose the English Crown issued them with letters of marque – official licences for international piracy. Moreover, contracts regulated what share of the spoils the captains were allowed to keep or had to surrender to the royal court.

One of the most famous privateers of his time was Francis Drake, who embarked on his circumnavigation of the globe in 1577. Drake's role was not merely to plunder merchant ships. He was additionally given the risky mission of sailing round the southern tip of America via Tierra del Fuego and attacking the Spanish colonies on the Pacific side by the back door, as it were. He accomplished his mission. He sailed north up the Pacific coast of South America and ambushed the Spanish colonial rulers of the Pacific towns. He even raided Lima, the port of the Spanish Viceroy. Drake plundered gold, silver, precious stones and costly spices. The value of the booty at the time was legendary – an estimated 500,000 pounds, the equivalent of around 100 million euros in today's money. Drake was knighted for his exploits, which amounted to an insult to the Spanish Crown.

For several centuries more, privateering was commonplace on the world's oceans – particularly on the routes from Europe to Asia in the Indian Ocean and in the Pacific. Finally, in the Paris Declaration Respecting Maritime Law of 1856, the issuing of letters of marque was internationally outlawed.

2.5 > A hero in England, a villain in Spain: the privateer Sir Francis Drake (1540–1596).

divided up between Spain and Portugal. Spain received possession of the hitherto known western world and all western territories that were yet to be discovered. Portugal was allotted the eastern world. The proposed boundary between west and east was a longitudinal line in the middle of the Atlantic Ocean at the level of the 38th meridian. However, the Portuguese protested and demanded that the boundary be shifted about another 1000 kilometres to the west, i.e. approximately to the longitude of 46 degrees west. Their protest was ultimately successful; in 1494 the demarcation line was defined accordingly in the Treaty of Tordesillas. Today it is suspected that the Portuguese already knew the course of the South American coastline, because thanks to the westward displacement of the line, a large part of present-day Brazil was apportioned to Portugal. Just a few years after the Treaty, the exploitation of South America commenced. The conquered territories were turned into colonies. Large quantities of gold and silver were shipped from the New World to Europe. Important seaports for this early intercontinental cargo traffic between Europe and America were Seville and Lisbon. The Spanish fleet was the largest and most powerful of its time.

But in the following decades, another maritime power began to stake its claim: England. The early decades of the sixteenth century saw the rising influence of an English bourgeoisie which venerated its own king, rather than the Pope, as the head of its church. Conflicts between Spain and this upstart newcomer were frequent, and in time they began to escalate. In the mid-sixteenth century, the English discovered the waters off Newfoundland to be rich fishing grounds because of the large stocks of cod to be found there. The Spaniards considered this fishing to be poaching in the waters of the western hemisphere granted to them by the Pope. Tensions rose when the Spaniards attacked English ships which were docked in the Gulf of Mexico awaiting shipyard work. Although no overt military conflicts broke out at that stage, Queen Elizabeth I sent English captains on sea raids. For a long time the conflict therefore remained more of a trade war.

Not until 1588 did a major naval battle break out between the powers. The Spanish King Philip II sent the large Spanish fleet, the Armada, to attack England and overthrow

2.6 > In 1607 Spain fought the Netherlands off the coast of Gibraltar. The Spaniards lost a substantial part of their fleet and consequently their maritime supremacy.

Elizabeth I. The invasion of England failed, however. The English were able to repel the Armada in the English Channel. But contrary to many accounts, the Spanish fleet was not destroyed completely. Spain remained a strong maritime power. Only a surprise attack by the Netherlands in the Bay of Gibraltar in 1607 was so resounding that Spain lost a substantial part of its fleet and its role as the strongest maritime power.

Historical shipping hubs

To trade between coasts separated by vast distances, it was necessary to establish ports on certain routes where crews could replenish their food and fresh water. Many of these ports developed into shipping hubs. One example is Mauritius. The island had been recorded on the maps of Arabian mariners since the tenth century. Portuguese sailors discovered it at the start of the sixteenth century as a stopover for their ships on their way to Asia and back to Portugal. The Portuguese only used Mauritius as a staging post, however, and did not turn the island into a colony. In the mid-seventeenth century the Dutch eventually settled on the island as colonial rulers, introducing sugarcane and commencing rum production. Then, in 1715, the island was occupied by the French. They not only sold food, water and, most importantly, sugar and rum to the merchant ships that headed for Mauritius during their long voyages, but also used the prime strategic location to attack English ships in transit between Europe and Asia as they traversed the waters around Mauritius. The British put a stop to this piracy in 1810 by themselves mounting an attack on the French and taking control of the island. Thereafter Mauritius was used mainly by European merchants engaged in very active maritime trading between Europe, South America, India and South East Asia. Goods transshipped on Mauritius included textiles and spices from India, porcelain from China and ivory from Africa. Only the advent of modern motorized ships that could cover long distances non-stop, and finally the construction of the Suez Canal, caused the island's significance to decline. In contrast, other ports managed to maintain their status as important shipping hubs for centuries. For instance, from as early as the beginning of the seventeenth century, the Dutch port of Rotterdam was an important base for the Dutch East India Company, which was active in the spice trade. From that time to this, goods from all over the world have been shipped to Rotterdam and then transported onward into mainland Europe – by ship down the Rhine, in the past, but today also by freight trains and heavy goods vehicles. Measured in terms of the volume of goods transshipped, Rotterdam ranks as the world's sixth largest port today. Containers, natural gas and petroleum are mainly unloaded here.

Coasts develop as holiday destinations

The world's coasts are more than just trading zones, military border zones or sources of food supply. Very early in human history, people also discovered the significance of coasts as a place of recreation, health and a wellspring of strength for the soul. In 414 BC the Greek philosopher Euripides wrote: "The sea washes away and cleanses every human stain." He was referring particularly to the coastal zone where the elements of earth, water and wind meet. The Romans embraced the idea of the ocean's healing power. Strolls and banquets on the beach were integral to the cultivated leisure of the aristocracy. For this sweet idleness, the Romans used the word "otium". They did not bathe in the sea, however. Instead they established numerous thermal baths at warm volcanic springs, like those on the Italian island of Ischia which are still in use today.

In the Middle Ages, humans became more estranged from the ocean again. Despite the spread of trade between coasts, some of which were very long distances apart, the oceans were generally considered to be menacing and inhabited by monsters. The beaches of the Mediterranean were thought of as forbidding, pirate-infested territory.

2.7 > Back in 1907 the promenade at Brighton was already popular with visitors, and the appeal of the English coastal resort for tourists remains undiminished to this day.

It was not until the seventeenth century that the ocean reverted to being a yearned-after location. One influence in this direction was the English scholar Robert Burton, whose book *The Anatomy of Melancholy* published in 1621 was a collection of historical and philosophical reflections from the previous 2000 years on the theme of melancholy. In this treatise he praised summer retreats beside the sea and advised those suffering from melancholy to observe the restless ocean.

The English gentry, or country nobility, also began to appreciate the importance of physical exercise in the fresh air. In the town of Scarborough on the east coast of England, acidic mineral springs were discovered in 1626. The population credited the water with healing effects, and the fame of the springs quickly spread throughout the country. By the beginning of the eighteenth century the town was developing into an established spa resort, although at first it was normally only members of the gentry who could afford to stay there.

The English doctor Richard Russell prompted a surge in popularity with his studies on the healing effect of sea water. In 1747 he settled in the seaside resort of Brighton on the south coast of England. He wrote that people with glandular illnesses would recover more quickly thanks to healing baths in the cool water, and that women suffering from physical weakness also recovered quickly. Countless people now began to travel, particularly from London, to convalesce in Brighton and it developed into one of the most popular coastal resorts in the country – no longer just for the nobility but also for members of the well-off middle classes.

Germany's first seaside resort, Heiligendamm on the German Baltic coast, was founded in 1793. In the decades that followed, many other coastal locations in Europe turned into seaside resorts.

An entirely different kind of coastal tourism was launched by the Hamburg shipowner Albert Ballin in the 1890s: the passenger cruise, visiting a series of ports of call along the coasts. Ballin had been operating passenger ships on the route between North America and Europe for some long time. Many of those who set off in Ballin's ships were emigrating. Since the ships were not sufficiently used in the winter period, Ballin came up with the idea of filling the ships' capacity by offering pleasure trips to warmer regions. On 22 January 1891 the passenger ship *Augusta Victoria* put out to sea from Cuxhaven on the world's first pleasure cruise. It was at sea for 57 days, 22 hours and 3 minutes, and headed for regions which sounded very exotic to most northern Europeans in those days: Egypt, the island of Malta or the port of Lisbon.

2.8 > The Hamburg shipowner Albert Ballin is acknowledged as the inventor of the cruise. In order to make better use of his passenger ships' capacity in winter, from 1891 he began to offer cruise trips to cities all around the Mediterranean.

What coastlines can do

From a human perspective, coastal habitats perform a range of other functions, the "ecosystem services", which can be categorized as follows:

- Supporting ecosystem services, which are necessary for the provision of all other ecosystem services and include, for example, primary production and nutrient cycles;

- Regulating ecosystem services, which provide benefits and utility from the regulating effects of coastal waters and their ecosystems;
- Provisioning ecosystem services, which encompass products and goods for human use on the one hand and spaces provided by the sea on the other;
- Cultural ecosystem services, which include a range of functions and utility serving the nonmaterial well-being of humans.

The concept of ecosystem services is well-suited to a systematic categorization and analysis of the multitude of services provided by coastal regions that are of material or nonmaterial benefit to humankind. However, such analyses often do not address societal issues such as, for example, the question of equitable distribution or of which societal groups benefit from services. In this respect a critical view must be taken of one-sided, purely economic assessments of ecosystem services that do not embrace sociocultural or ethical considerations.

Where habitats are considered solely with respect to the services they provide to humankind, all too often no consideration is given to the fact that every habitat can be of value whether it is utilized by people or not. Environmental ethicists speak of "non-utility value". This includes the existence value ascribed by humans to beings such as corals or habitats such as mangrove forests regardless of whether they will ever be able to utilize or experience these organisms or habitats. The existence value is based purely on a sense of joy as to the fact that these species or habitats exist at all.

The non-utility value also includes the bequest value which is based on the human desire to pass on natural assets to future generations in as intact a condition as possible. Non-utility values, which are categorized as cultural ecosystem services, are not easily measured. Assessments of non-utility values must also obtain, for example, knowledge held by local communities and other stakeholders – such as knowledge of special religious or spiritual significance of a habitat for the population. Only if such knowledge is taken into account can the value of a habitat be measured.

SUPPORTING ECOSYSTEM SERVICES – THE BASIS OF FOOD WEBS

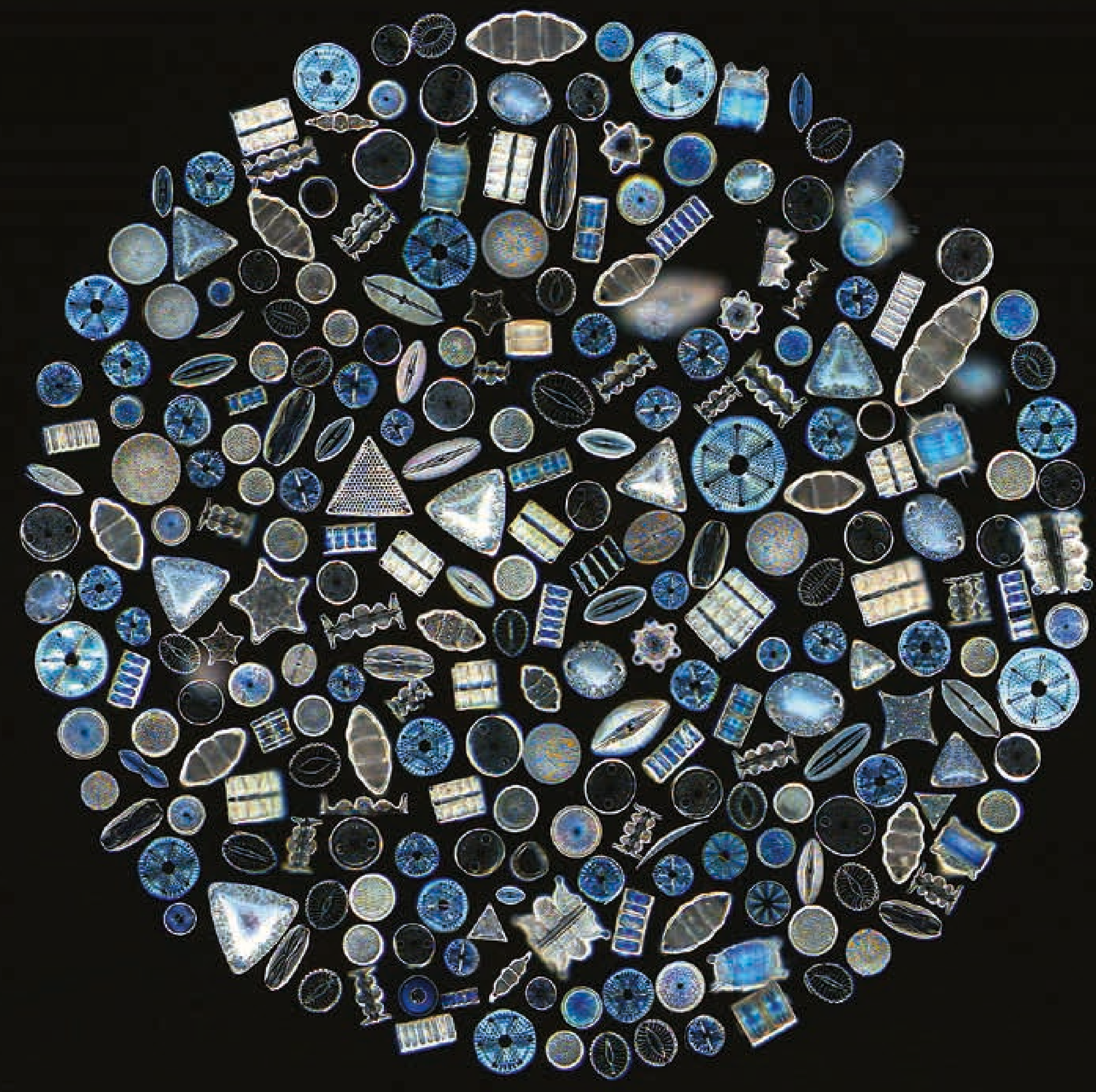
Small but productive

Primary production, the production of biomass by plants and microorganisms, is the basis of all marine life as well as the most important ecosystem service. Plants and microorganisms mostly obtain their energy from **photosynthesis** or from certain chemical compounds; they produce high-energy substances such as glucose (sugar). The most important primary producers in the oceans include microscopically small components of marine phytoplankton such as diatoms, coccolithophorid algae and cyanobacteria (formerly called blue algae). Since phytoplankton is dependent on sunlight, it lives exclusively in surface ocean waters. Similar to terrestrial plants, in addition to sunlight the phytoplankton needs nutrients such as phosphorus and nitrogen compounds. These are primarily transported by rivers into the sea. As coastal waters offer both sufficient sunlight and nutrients, they are among the particularly productive oceanic regions. This productivity also gives rise to particularly abundant fish stocks since tiny crustaceans as well as larvae of fish and bivalves feed on phytoplankton, and they in turn are a food source for fish.

However, not all the nutrients are derived from rivers. In the upwelling systems, for example, nutrient-rich cold water rises from the depths of the oceans. Such systems can be found along the coasts of Chile, California, Mauritania and Namibia. Their primary production is correspondingly high. Similar to the productive coastal waters, these upwelling systems give rise to particularly abundant fish stocks.

But the level of primary production in coastal waters is not only dependent on the nutrient quantities transported by currents and rivers but also on the intensity of water mixing. This mixing of water masses results in major variations in nutrient concentrations between different coastal segments and water depths. In the Bay of Bengal, where the Ganges and Brahmaputra form a large delta and transport a great amount of nutrients from the

2.9 > Productive preciousness: Diatoms are among the most important primary producers. The beauty of their cell walls only becomes evident under high magnification. Microscopic samples such as these were popular souvenirs a century ago, especially among diplomats.



Himalaya Highlands into the ocean, the level of primary production changes with the monsoon. In the summer, when the moist monsoon winds blow, there is a lot of precipitation which strongly dilutes the coastal waters, thus reducing their nutrient concentration.

Another one of the world's particularly productive coastal regions is the South China Sea. This is because the Pearl River reaches the sea west of Hong Kong. It has several tributaries and forms South China's largest river system. Its watershed basin measures approximately 452,000 square kilometres, which is roughly equivalent to the land area of Sweden. Corresponding to the size of the river system, it transports enormous quantities of nutrients into the South China Sea.

Seagrass meadows
Seagrass meadows are special habitats found on sandy soils in shallow waters and mudflats. While seaweeds use holdfasts to attach to rocks, seagrass sets roots with which it stabilizes sandy marine sediments. Numerous organisms, such as smaller seaweeds or molluscs, can gain hold among the plants, often making seagrass meadows particularly biodiverse habitats. Moreover, seagrass is an important food source for many species of marine fauna and waterfowl.

REGULATING ECOSYSTEM SERVICES – PROTECTION FROM POLLUTION AND STORMS

The coast – a wastewater treatment plant

Coastal waters play an important role in purifying effluent and removing pollutants conveyed by rivers and sewers and deposited from the atmosphere. They thus have a regulating function and are vital for nutrient decomposition, especially for the breakdown of nitrogen compounds. Plants need nutrients, notably nitrogen and phosphorus, in order to grow. To increase the productivity of arable land and achieve higher yields, these nutrients are applied to agricultural land in the form of slurry, sewage sludge or artificial fertiliser.

In intensive agriculture regions high levels of nutrients enter the soil as the crop plants grown tend to not fully take up the fertilizers applied. Rainwater washes these surplus nutrients into the groundwater, streams and rivers, and ultimately into the sea. The phosphorus and nitrogen compounds also increase algal growth. Where there is an oversupply of nutrients, algal growth can be so rapid that it results in pronounced algal blooms. The more abundant the algae, the more intensive is their decomposition by oxygen-consuming microorganisms in deeper water layers. This phenomenon is called eutrophication. In extreme cases it results in zones devoid of oxygen in which fish, crustaceans and molluscs can no longer survive.

With the intensification of farming, the number of oxygen-deficient or oxygen-depleted zones in coastal waters has sharply increased since the 1960s, especially in the northern hemisphere. Worldwide some 400 coastal areas are regularly affected by oxygen-deficiency; these areas cover a total of 245,000 square kilometres, which is roughly equivalent to the size of Romania. Oxygen-deficiency primarily affects coastal waters in Europe, along the eastern US seaboard, the Gulf of Mexico and increasingly also in China. The decomposition of nitrogen compounds is of particular significance in this context as these enter the seas in large quantities. Fertilizers, slurry and excrements mostly contain nitrogen in the form of ammonium ions (NH_4^+). In the presence of oxygen, ammonium oxidizes to nitrate. In environmental waters, microorganisms (denitrifying bacteria) convert the nitrate to gaseous nitrogen (N_2) in a process called denitrification. Algae cannot use gaseous nitrogen as a plant nutrient. Thanks to denitrification, coastal waters to a certain degree function as the ocean's wastewater treatment plants.

However, if the quantities of nutrients entering the ocean are too large, these can no longer be fully decomposed, thus leading to eutrophication.

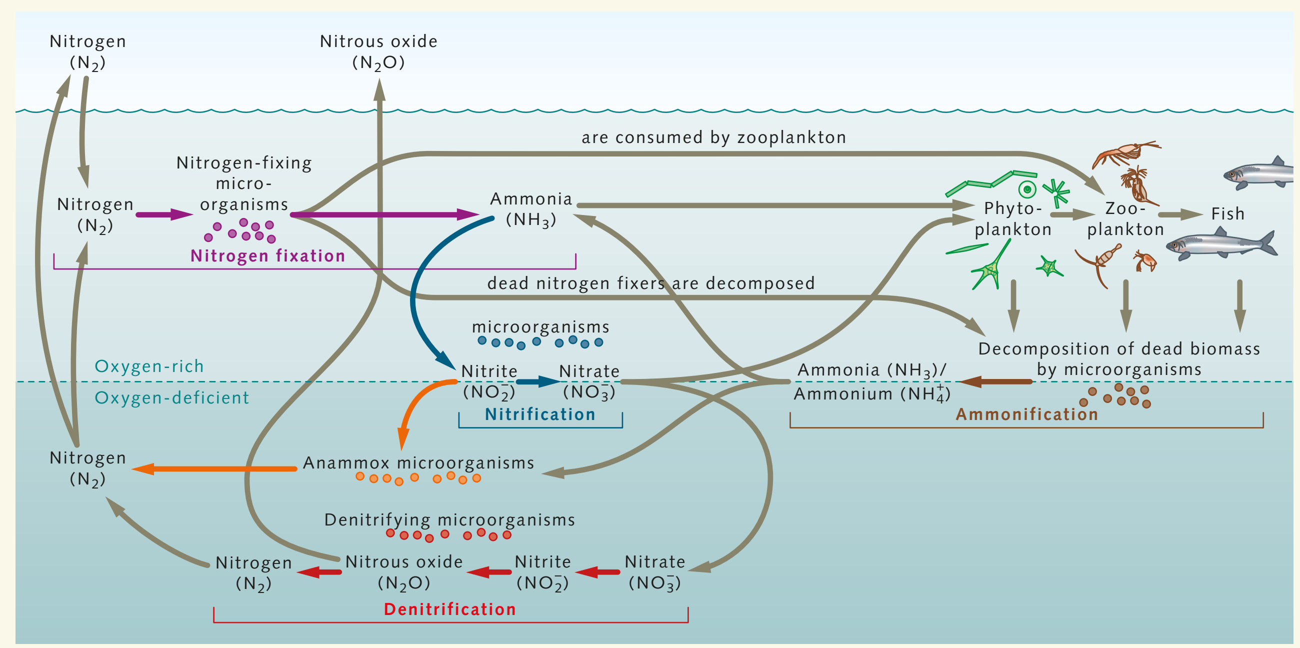
The various plant communities occurring in coastal waters contribute significantly to the elimination of nutrients. These communities include, in particular, mangroves and seagrass meadows, the roots of which take up large quantities of nutrients in the same manner as terrestrial plants. Nutrient decomposition is further enhanced by the numerous organisms living in the seabed, such as molluscs or worms. Millions upon millions of these organisms live buried in the seabed. Their several centimetres long burrows give many sediments the appearance of sponges. Compared to the normally solid and dense sediment which water can only enter through the spaces between the sediment grains, the numerous burrows enlarge the surface area on which microorganisms can engage in denitrification. This significantly enhances the effluent purification function of coastal waters.

Transformations of a key nutrient – the nitrogen cycle

Nitrogen is a nutrient vital to plant growth. In the environment, nitrogen undergoes several conversions in a natural cycle through biological processes along various pathways. Gaseous atmospheric nitrogen is largely converted into nitrogen compounds by microorganisms; this makes these compounds available to macro-algae, phytoplankton and terrestrial plants. When the biogenic nitrogen compounds are converted back into gaseous nitrogen the cycle is completed.

Elementary (pure) nitrogen (N_2) constitutes 78 per cent of the Earth's atmosphere, but this element cannot be used by plants directly. However, a number of microorganisms are capable of using gaseous nitrogen. These organisms include the marine cyanobacteria (formerly termed blue algae) as part of the phytoplankton, and the terrestrial rhizobia associated with legumes such as beans. They can take up pure nitrogen and convert it into ammonia (NH_3) or ammonium ions (NH_4^+). This process is called nitrogen fixation. In the further course of the cycle, the ammonia or ammonium is taken up by other groups of microorganisms, and especially by *Nitrosomonas* bacteria, which convert it into nitrite ions (NO_2^-) and ultimately into nitrate ions (NO_3^-). This conversion process is called nitrification. These ions can be taken up directly by macro-algae, phytoplankton and terrestrial plants which use it to assemble amino acids among other organic compounds. When they die, their dead biomass is decomposed by a multitude of other microorganisms.

Along with the rest of the biomass, the nitrogen compounds contained in the macro-algae, phytoplankton and terrestrial plants are also decomposed, primarily through a process called ammonification. As part of this process, the nitrogen compounds contained in dead biomass, such as the amino acids, are converted back into ammonia and ammonium. The ammonia and ammonium are then once again available for nitrification by microorganisms, and by *Nitrosomonas* in particular. The nitrogen cycle is completed by a process of decomposition called denitrification, which ultimately is also of particular importance to keeping waters clean. Nitrate ions (NO_3^-) contained in water are converted directly into elementary nitrogen (N_2) as well as nitrous oxides (NO and N_2O) by microorganisms (denitrifying bacteria). As a result, terrestrial plants and the majority of phytoplankton can no longer use these substances as nutrients.



2.10 > Nitrogen is the most plentiful element in the Earth's atmosphere as well as an important plant nutrient. In nature, nitrogen circulates and is continuously converted chemically from one form into another by bacteria and plants.

2.11 > The estuary of the Salak River on the island of Borneo is dominated by mangrove forests. They protect the coastline from hurricanes and storm surges.

Coastal waters also have a regulating function when it comes to the decomposition or neutralization of pollutants such as persistent chemical compounds or heavy metals transported into the coastal seas by rivers or the atmosphere. The dilution of pollutants is one of the processes, while they are also sequestered into the sediment through the activities of sediment-dwelling organisms which, for example, filter pollutants from the water with their feed and subsequently deposit them in the sediment with their faeces. While the pollutants are not removed from the environment in this manner, their sequestration into the sediment prevents other marine organisms from ingesting them. Ultimately these processes also prevent pollutants from being ingested by humans through the food chain.

Taming the ocean's force

Coastal habitats such as dunes, coral reefs and mangroves perform a key protective function for humans as they are able to break winds and swells, thus regulating the oceans' physical forces. For example, Abidjan, the Ivory Coast town, is protected by seaward dunes, as are the Dutch city of Amsterdam, the Nigerian city of Lagos or Durban in South Africa.

The importance of mangrove forests for coastal protection has become particularly evident in recent years. Tropical storms can produce tidal waves of up to 7 metres in height. As a study conducted by British researchers has shown, mangroves provide outstanding protection against such storm surges and hurricanes. Using mathematical modelling the scientists were able to demonstrate that a one kilometre wide mangrove forest can be expected to reduce surface wind energy by 75 per cent and wave height by up to half a metre. Considering that natural mangrove forests can be many square kilometres in size, they offer significant protection, for example along the southern coastline of Florida where they cover an area of roughly 2000 square kilometres. However, mangrove forests along many tropical coasts have suffered large-scale destruction over many years. In Indonesia, for

instance, they were removed to make space for aquaculture. Colombia has lost almost 20 per cent of its mangrove forests – here they fell victim to timber extraction. Studies have shown that the damage caused by the 2004 tsunami in the Indian Ocean, and especially the damage caused along the Indonesian coast, would not have been anywhere near as severe if the mangrove forests had not been cut down over many years.

PROVISIONING ECOSYSTEM SERVICES – FISH, DIAMONDS, AND A WHOLE LOT MORE

Protein for a growing world population

Since time immemorial humans have eaten fish and seafood from the oceans. For thousands of years marine fish were only consumed near the coasts as it was not possible to transport fish inland over long distances. Over time, however, processes were developed that made it possible to preserve fish. At first, fish was preserved in salt. Later it was canned, which made it possible to transport it over great distances. Only when freezing technology was invented and allowed for the almost indefinite preservation of food did fish become a staple food even far away from coastal regions. Today fish is consumed in significant quantities worldwide and plays a major role in human protein supply. This is particularly true for West African countries such as Senegal or the small island states in the South Pacific where fish is one of the most important staple foods.

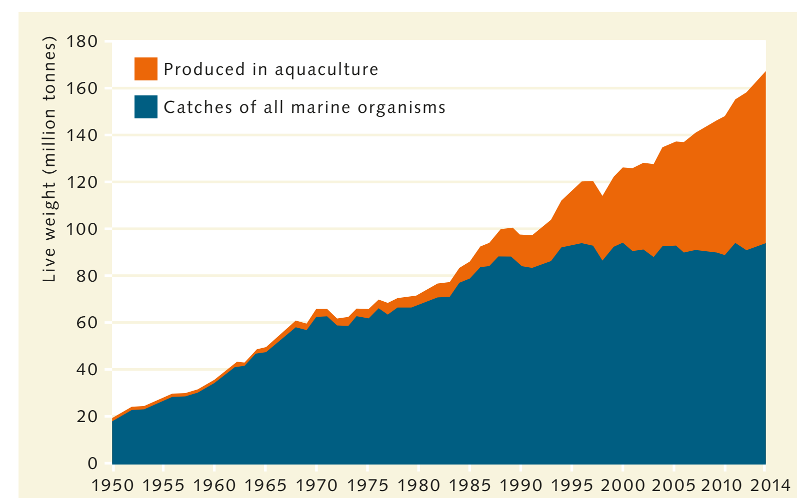
With the growth of the world population, the consumption of fish and seafood has increased vastly since the middle of the previous century. While in the 1960s the per capita consumption level stood at 9.9 kilograms, it passed the 20 kilograms mark for the first time in 2014, as the Food and Agriculture Organization of the United Nations (FAO) reports. This means that the consumption of fish and seafood doubled in just half a century. According to the United Nations, the world population will grow from 7 billion to approximately 9.5 billion people by 2050. More than an additional 2 billion people will need to be supplied with food and with protein in particular. Fish will contribute a significant proportion of this protein but it is obvious that wild caught fish cannot supply these additional quantities of protein if fish stocks are no longer to be subjected to overexploitation.

The degree to which coastal waters contribute to the supply of wild caught fish and seafood is difficult to quantify. Since the FAO's global statistics do not differentiate between coastal waters and other waters, there are only rough estimates in the region of 90 per cent. In Europe, fisheries experts distinguish between coastal fishing, middle water fishing and distant water fishing, differentiating by size and levels of motorization of fishing vessels. Coastal fishing is dominated by smaller trawlers that are mostly 18 to 24 metres in length and have engine sizes of up to 300 HP. It overlaps with middle water fishing with trawlers that are mostly 18 to 32 metres long and have engine sizes of no more than 600 HP. Distant water fishing is carried out by even larger vessels up to and including factory ships with on-board facilities for processing and freezing caught fish.

Another definition of coastal fishing is that it is limited to the shelves – a term that describes the areas of relatively shallow water near the coastlines. The shelves slope gently to an average depth of 130 metres, ending at the break to the continental slope, which falls more steeply to greater depths. According to this definition, the fisheries in many of the shallow marginal seas, such as the East

Aquaculture
The term "aquaculture" covers several different forms of production. Traditionally the term was used for freshwater fish production such as carp farming. However, aquaculture also includes mariculture, i.e. the cultivation of marine organisms at sea. There are now also hybrid forms in which marine animals are bred on land in special salt water tanks.

2.12 > The quantities of fish and seafood produced today are many times greater than they were in 1950. While aquaculture was insignificant at first, it now provides almost half of the global production.



China Sea or the North Sea, would be considered coastal fisheries in their entirety, despite the fact that in purely legal terms a country's coastal sea is limited to the 12 nautical mile zone.

Fish to feed the world

Aquaculture – the production of fish and other organisms in specialized installations – can play an important role in securing fish supplies in the future. This form of production has grown significantly in recent years while the quantities of fish and seafood caught in the wild have hardly changed. In 2014 a total of 167.2 million tonnes of fish and seafood were consumed worldwide. Of these, 93.4 million tonnes were caught in the wild, 73.8 million tonnes originated from aquaculture production, and 26.7 million tonnes of the latter were produced at sea, exclusively in coastal waters. However, a much larger quantity, i.e. 47.1 million tonnes, now comes from land-based aquaculture installations. China accounted for the largest share of global aquaculture production at 60 per cent.

Aquaculture must be carried out in a sustainable way if it is to offer hope for the future, as major mistakes have been made in recent decades. For example, in the 1990s hundreds of kilometres of mangrove forests along the coast of Indonesia were cut down in order to establish shrimp farms in the form of aquaculture monocultures. In many places, shrimp as well as fish continue to be produced intensively and with a view to maximum yields. As a result they are more susceptible to diseases than their wild relatives and are preventively given antibiotics and other medication – with unforeseeable repercussions for the marine environment as well as for the end consumers. Another problem is the fact that the animals' faeces lead to regional marine eutrophication, which considerably impairs water quality.

Meanwhile there has been something of a shift in thinking towards environmentally sound aquaculture. Mixed aquaculture systems in which several organisms are kept together and in which the faeces of one species serve as a food supply for other organisms are regarded as a promising alternative. Such systems are termed Integrated Multi-Trophic Aquaculture (IMTA). They allow for the combined production of, for example, fish, algae, molluscs and sea cucumbers. The fish are fed, while the sea cucumbers feed on excess fish feed and fish faeces. The algae, for their part, take up inorganic substances exuded by the fish. The molluscs, finally, filter particles from the water and keep the installation clean. The feed is thus put to optimum use while several different products can be harvested from a single installation.

2.13 > China contributes 60 per cent of the global aquaculture production. Aquaculture installations such as the one shown here in Tolo Harbour near Hong Kong can be found in many of China's coastal regions.

Natural gas and oil extraction

Subsea deposits of natural gas and oil are a significant provisioning service from an economic perspective. Although the bulk of both resources are extracted onshore, the proportion coming from the ocean (offshore gas and oil) is now substantial. Currently, offshore oil accounts for about 40 per cent and offshore gas for about 30 per cent of global extraction. It is not always possible to draw a hard and fast line between coastal and offshore drilling rigs, but one certainty is that offshore extraction began directly on the coast and then shifted ever further out to sea. One reason for this is the increasing exploitation of coastal deposits, but another factor is the technical progress that has made it possible to extract gas and oil from ever greater depths.

Offshore oil extraction began surprisingly early on. The first oil rigs in the sea were built back in 1896 in the Summerland field off the coast of Santa Barbara in California. In 1937 for the first time, oil was drilled from a platform two kilometres off the Gulf Coast of the United States. In the 1970s the relatively shallow North Sea with an average water depth of 90 metres was exploited as a natural gas and oil field. The first drilling platform was erected in 1971 in the Ekofisk oilfield on the Norwegian continental shelf. The Ekofisk field is 270 kilometres away from the Norwegian coast – in the middle of the North Sea, and thus a very long distance from the coast. Exactly as for fisheries, it is unclear how much of this sea area can reasonably be classified as coastal.

For example, in Ghana where the shelf is relatively slender and only extends 60 kilometres before dropping steeply into the deep sea, the large Jubilee oilfield is markedly closer to the coast. It is located on the steep slope at the edge of the continental shelf where the water depth is already around 1100 metres. The Iara oilfield off the Brazilian coast, only discovered in the year 2008, is in a similar situation. It is located around 230 kilometres off Rio de Janeiro at the foot of the continental slope at around 2200 metres depth.

It is now rare for oil drilling to take place directly on the coast within sight of land. With a few exceptions, most natural gas and oil fields today are found at water depths of several hundred metres. Among the exceptions are smaller and older natural gas or oil drilling rigs on the Dutch and German North Sea coast, which are just a few kilometres offshore.

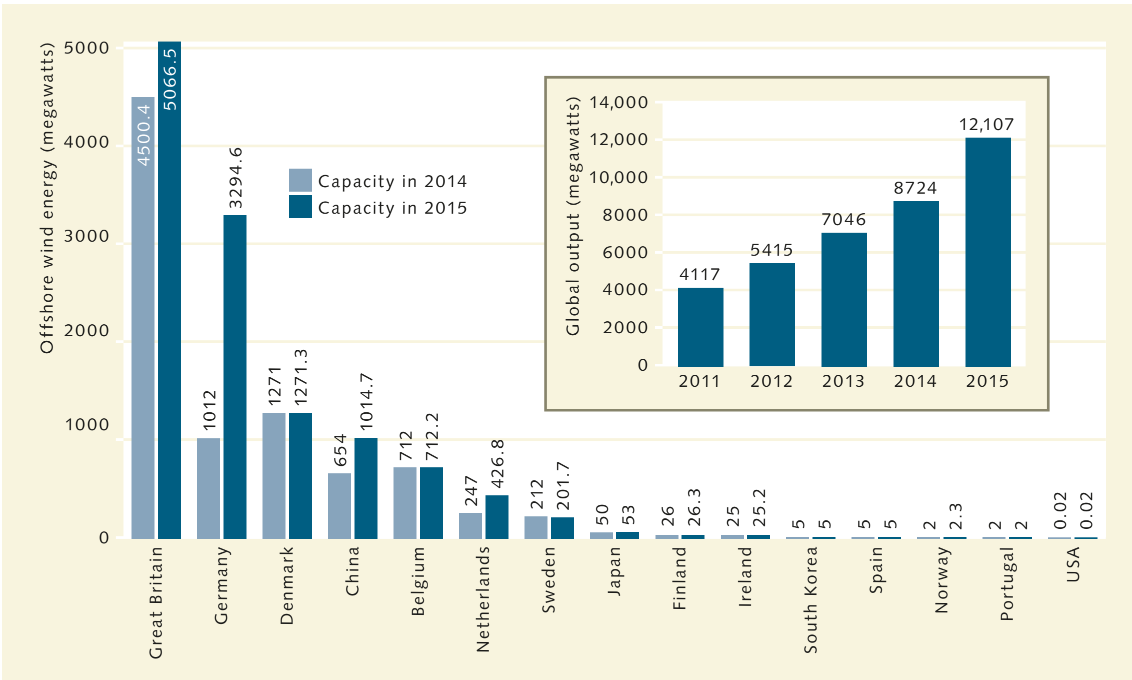
Harvesting energy at sea

Coastal waters have also recently begun to attract more interest for the generation of electricity from wind power. The number of offshore wind turbines has risen rapidly over the past few years. Global installed capacity trebled between 2011 and 2015 alone. The wind is stronger and more constant over the ocean than inland, and the electricity output from the open sea is distinctly higher than on the mainland. On land, markedly less land area is available in any case because minimum distances from buildings or conservation areas must be respected. By making use of special ships and new technologies, it has now become possible to install wind turbines at sea far more cheaply, quickly and in larger numbers than a few years ago.

Manufacturers of wind power plants have now even begun to manufacture rotor blades directly on the coast, in the vicinity of large offshore wind farms, so as to avoid the need for costly and cumbersome transportation on special trucks. This has given rise to new jobs in structurally weak coastal areas, especially in Great Britain. Nevertheless, because of the higher cost of constructing foundations for offshore turbines and the expense of deploying special ships, it is still more expensive to construct wind farms offshore than onshore at present. The costs of one kilowatt-hour of offshore electricity, known as the levelized costs of electricity generation, currently range from 12.8 to 14.2 euro cents depending on the site. In contrast, the onshore levelized electricity generation costs are between 5.3 and 9.6 euro cents.

The wind turbines in operation worldwide at the end of 2015 had a **rated capacity** of well over 12,000 mega-

Levelized electricity generation costs
To determine how much it costs to generate electricity using a particular technology, generally the levelized cost of electricity generation is calculated. The levelized generation costs take account of all investment and operating costs and the costs of financing the technical plant. These are divided by the electricity output achieved over the plant's lifetime, meaning that levelized electricity generation costs are usually stated in euros per megawatt-hour or euro cents per kilowatt-hour.



2.14 > Great Britain leads the expansion of offshore wind power. Germany connected several large wind farms to the power grid in 2015, taking second place in the worldwide rankings ahead of Denmark.

watts, which is roughly equivalent to the capacity of 24 nuclear reactors. A good 5000 megawatts of this was attributable to the coastal regions of Great Britain alone. The next-highest ranking countries in terms of installed wind farm capacity are Germany, Denmark and China.

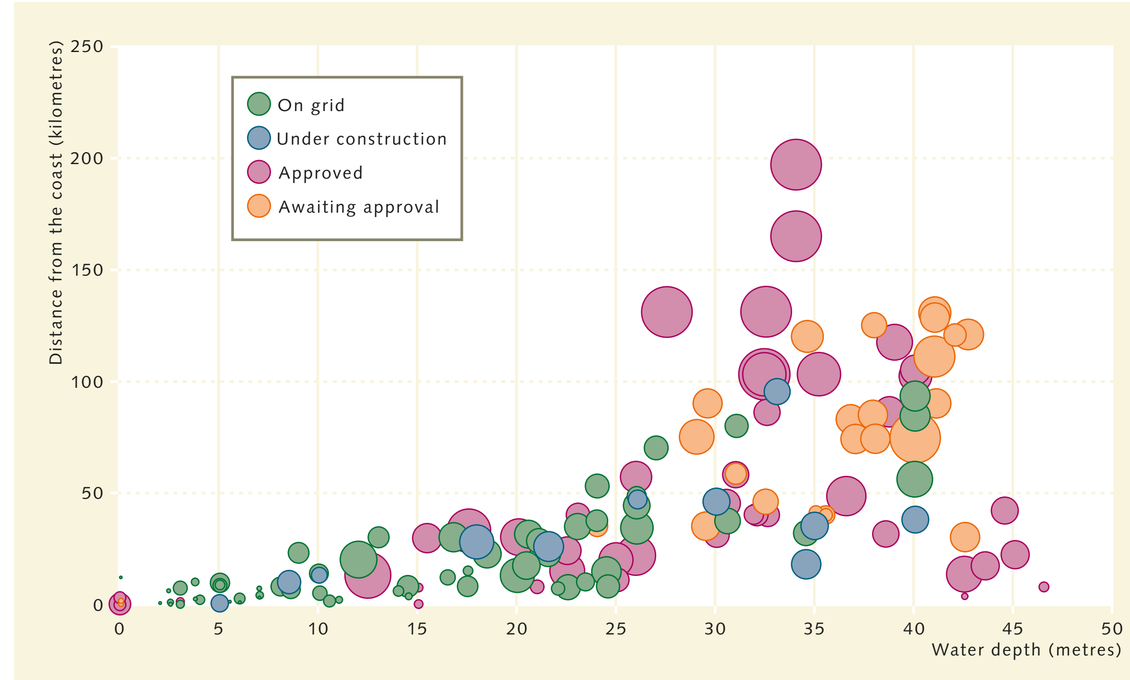
Paralleling the trend in natural gas and oil extraction, offshore wind turbines are no longer being installed directly adjacent to the coast but further out at sea. The world's first offshore wind farm was commissioned in 1991 and consisted of eleven wind turbines just two kilometres off the Danish island of Lolland at a water depth of two to four metres. Today, offshore wind farms are constructed at average water depths of 27.1 metres and an average distance of 43.3 kilometres from the coast. A substantial distance is observed particularly in Germany and the Netherlands because the Wadden Sea along their coasts is an important resting site for migrating birds. Furthermore, wind speeds are higher at greater distances from land. German wind farms are an average of 52.6 kilometres from the mainland, as opposed to an average of 9.4 kilometres from the coast for those around Great Britain. The world's largest wind farm, with 175 wind turbines over an area of 100 square kilometres, is the London Array wind farm in the outer Thames estuary on the east coast of England.

Wind power is not the only renewable form of energy that can be utilized in coastal waters. Additional forms are:

- wave power,
- tidal power,
- marine current power,
- salinity gradient power (osmotic power),
- ocean thermal energy conversion (power generated from temperature differentials at different ocean depths).

The role of these forms of energy is still relatively minor in comparison to wind power. In recent years facilities harvesting wave power have been taken into commission, but have not yet proven economically viable to operate. Generally they consist of research and development projects.

Also still in its infancy is the technology for generating power from differentials in salinity. Commissioned in 2009, a small power plant in Norway was the first of its kind in the world to feed electricity into the public grid. In terms of its developmental status, however, it is considered a prototype. The technology for ocean thermal energy conversion is likewise at prototype status. In 2015 a pilot plant was commissioned off the coast of Hawaii with a capacity of 105 kilowatts. It now supplies 120 households with electricity.



2.15 > So far the majority of the world's wind farms have been constructed at distances of up to 40 kilometres from the coast and water depths up to 20 metres. In the meantime, offshore technology is so fully developed that installations can now be planned and built at far greater distances offshore. Proposed sites are located 120 kilometres offshore in extreme cases.

In comparison, the use of tidal and marine current power plants to harvest energy is a fully developed technology. An example is the La Rance tidal power plant near the French city of Saint-Malo, which has been in operation since 1966. All told, only a few larger plants exist worldwide because they are extremely elaborate to construct, since dams and barrages with large turbines have to be installed in order to harness energy from tides and currents.

Valuable minerals

Another resource supplied by coasts are mineral raw materials, particularly sand and gravel which are used in concrete production, as filling sand on building sites, or for hydraulic filling to create new port or industrial sites on the coast. Well-known examples are the hydraulic fills that created land for the expansion of Hong Kong airport, the artificial Palm Islands off Dubai, or the new container terminal in Rotterdam, Europe's largest port. Sand and gravel are either dredged from the sea floor using suction dredgers or extracted onshore – especially by demolishing dunes. Exact quantities are very difficult to estimate because data are not recorded centrally. Nonetheless, sand and gravel extraction and the export of both resources are considered to be a lucrative business.

For example, the island city-state of Singapore constantly consumes large quantities of sand in order to expand the city's area by means of hydraulic filling. As a result of these activities, the area of the former British colony has expanded by a good 20 per cent since the 1950s. Singapore has much of the sand shipped in from very long distances. Many other countries also import sand. Sand from Australia is in particular demand because of its extremely hard, resilient and angular grains. On the one hand, this sand is good for concrete production because the grains adhere well to one another as the cement sets. On the other hand, the sand is used

2.16 > Particularly on the west coast of Africa, as here in the Western Sahara but also in Morocco, sand is extracted on a large scale close to the coast. This is exported worldwide for use as building sand and for other purposes.

in industry as a blasting abrasive for sanding or smoothing other materials. According to data from the Australian Bureau of Statistics (ABS), Australia exports sand, gravel and stones valued at 5.5 to 8.5 million euros per month. It is extracted both from the coast and from inland sites.

Natural gold-panning effect

A more uncommon type of mineral resource are mineral placers: shallow deposits of metal or phosphorus compounds which form along coasts near to river estuaries. They come about through a kind of natural gold-panning effect: particles ranging from light to heavy are transported from the hinterland by flowing river water. In and around the estuary these are deposited in the shallow water off the coast. If the ocean swell is strong enough, the lighter particles are washed away while the heavier ones are buried more deeply in the sea floor. Over the course of millennia this process results in the formation of deposits several metres thick, which can be recovered by mining. Mineral placers can contain metals like iron, gold, platinum, tin or **rare earth metals**. At present, extraction is confined to especially valuable mineral placers only, such as those containing gold, platinum or diamonds. The latter are found along the coast of Namibia, where there is a strip just a few kilometres wide with a relatively shallow ocean depth of up to 150 metres. Ever since it was discovered in the late 1950s that large quantities of diamonds occurred in this part of the ocean, it has been the site of intensive offshore mining. Initially the sediments were only harvested by divers with large suction tubes. Currently extraction is taking place at depths of 90 down to 150 metres on an industrial scale using special ships. The area was divided up into several concessions in which different consortiums of firms operate. Today some two-thirds of all Namibian diamonds are obtained from the sea.

The fact that the sea floor off Namibia happens to be so rich in diamonds is thanks to the Orange River. The frontier river between Namibia and South Africa washed the gemstones from their region of origin, South Africa's volcanic areas, into the sea. Over time, sea currents transported the sediment containing the diamonds northwards from the Namibian coast, where they concentrated in the sea floor as a result of the gold-panning effect.

Currently it is under discussion whether the mineral placers here containing phosphate compounds should also be extracted in future. These would be sold as fertilizers. Because the sea level has risen by around 130 metres since the last Ice Age, today these phosphate deposits lie deep below the waterline.

Resources from hydrothermal vents

Another type of valuable minerals that are likely to be recovered from the sea in future are the massive sulphides. These are found around hydrothermal vents on the sea floor, either at active undersea volcanoes or at plate boundaries where two continental plates are diverging.

Massive sulphides originate when cold seawater penetrates through fissures several kilometres deep in the sea floor. Around magma chambers at this depth, the water heats to temperatures of more than 400 degrees Celsius and dissolves sulphides, i.e. sulphur compounds, as well as minerals containing metals from the surrounding rock. Because it has been heated the mineralized water rises very quickly and shoots back into the sea. As soon as it mixes with the cold seawater, the minerals form a precipitate that settles around the plume in the form of massive ore deposits.

Normally the active volcanic sites are in the middle of the oceans and far from land. One exception is the Bismarck Sea off New Guinea, where a plate boundary is found just 30 kilometres from the coast. Known as the Solwara-1 field, its deposits are easily accessible by ship and contain copper, zinc, lead, gold and silver as well as numerous important trace metals like indium, germanium, tellurium and selenium. But despite the proximity to the coast, the water depth is around 1600 metres because the sea floor drops away steeply at this point. The Canadian mining company Nautilus Minerals has long been planning the extraction of the valuable ore deposits and has already had heavy underwater mining machinery built. In addition, a production ship is currently under construc-

The Palm – artificial islands alter a whole coast

A unique example of the exploitation of new land along coasts is the Palm Islands construction project on the coast of Dubai in the United Arab Emirates. It uses hydraulic filling to create archipelagos of artificial islands, each of which, when viewed from the air, is shaped like a palm tree with a trunk and palm leaves. The purpose of land reclamation on coasts is normally to enlarge existing ports or to create industrial facilities or new residential property close to the water. Dubai is going considerably beyond the scale of normal enlargement, however. The construction of the Palm Islands will create entirely new island worlds for an especially well-heeled clientele.

One archipelago, The Palm Jumeirah, has already been completed with hotels and villas. The total area of the islands is 560 hectares, the equivalent of around 780 football pitches. Building work on the next archipelago, The Palm Jebel Ali, has not been realized as yet because the construction company got into financial difficulties during the 2009 economic crisis. When building will actually be completed is uncertain. Since 2001 the sand required for The Palm Jumeirah and The Palm Jebel Ali has been obtained from the Persian Gulf using hopper suction dredgers; these are special ships that suck sand from the floor of a water body and store it in large holds known as hopper tanks. The sand can then be pumped off the ship again through pipes. This is the technique used to build up the islands artificially by means of hydraulic filling.

2.17 > Luxury built on sand: The Palm Jumeirah off Dubai.

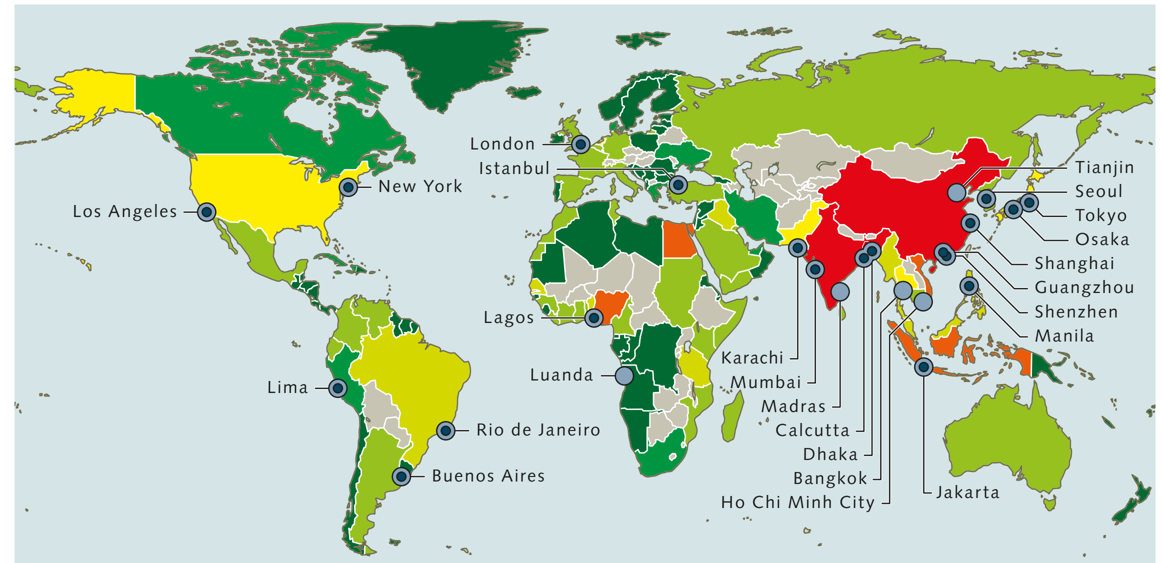
tion. So far the commencement of mining activities has been repeatedly postponed because the financing of the project was not adequately secured or no agreement could be reached between Nautilus Minerals and the Papua New Guinea authorities. When the mining of massive sulphides might begin therefore remains to be seen.

Areas for growing coastal cities

The availability of areas for particular uses can also be understood in a broader sense as an ecosystem service provided by coastal waters. This includes areas used for military training and for pipelines, residential complexes, port and industrial facilities, hotels and wind farms. Due to the growing population in coastal regions, land use along the coasts will increase, as new projections by a German-English team of researchers show. On the basis of various global population growth scenarios the scientists estimated how large the coastal population will be in the years 2030 and 2060. The study applied to the coastal strip located a maximum of 10 metres above sea level, which is known as the Low Elevation Coastal Zone (LECZ). This is especially under threat from sea-level rise, and is therefore of great interest. In the most extreme scenario assumed by the researchers, the global population will have grown to 11.3 billion people by the year 2060. In that scenario, up to 12 per cent of the global population will be living in the LECZ: around 1.4 billion people. For comparison: in the year 2000 it was inhabited by some 625 million people. The study predicts that megacities close to the coasts will grow proportionately.

According to this study, the most drastic population increases will occur along the coasts of Bangladesh, China, India, Indonesia and Nigeria. It is also expected that cities such as the Angolan capital, Luanda, Madras in India and the Chinese city of Tianjin will turn into megacities of far in excess of 8 million inhabitants.

Future population growth will not be the only reason for greater land consumption along the coasts. There is demand for new land even today for growing international trade – particularly for the enlargement of container ports such as Rotterdam. A start was made in 2008 with



Estimated population in the LECZ (low elevation coastal zone) in the year 2060 in millions (extreme scenario)
- below 1
- 1 to below 2
- 2 to below 10
- 10 to below 25
- 25 to below 50
- 50 to below 100
- 100 to below 200
- 200 to below 250
- Landlocked (no data)

Megacities over 8 million in the LECZ
- 2010
- 2025

2.18 > Global population growth means that low-lying coastal areas, especially in Africa and Asia, will be increasingly densely settled in future.

reclaiming an area of around 2000 hectares to form a site for what is now the Maasvlakte 2 container terminal. Surrounded by a foredike 12 kilometres long, it protrudes like a nose into the North Sea, i.e. into deep water. In contrast to many shallower parts of the port, even the largest container ships in current use with a capacity of 19,000 containers and a loaded draft of up to 20 metres can dock here.

The drastic expansion of offshore wind power in Great Britain and Germany is another factor that is changing the character of original marine landscapes. At these construction sites the sea floor of the North Sea normally consists of sandy sediments, and solid structures like rocks are seldom found. Now, to accommodate the hundreds of wind turbines, increasing numbers of solid structures – also referred to as hard substrates – are being created. These can increasingly be colonized by species that require a hard substrate – for example, sea anemones, various snail species and calcareous tubeworms. How this will change the species composition in the North Sea is a current subject of research.

Since shipping and the operation of fishery vehicles are prohibited in the vicinity of windfarms for safety reasons, it is possible that these areas might also contribute to the recovery of sea-floor biotic communities that have been adversely affected by years of fishery.

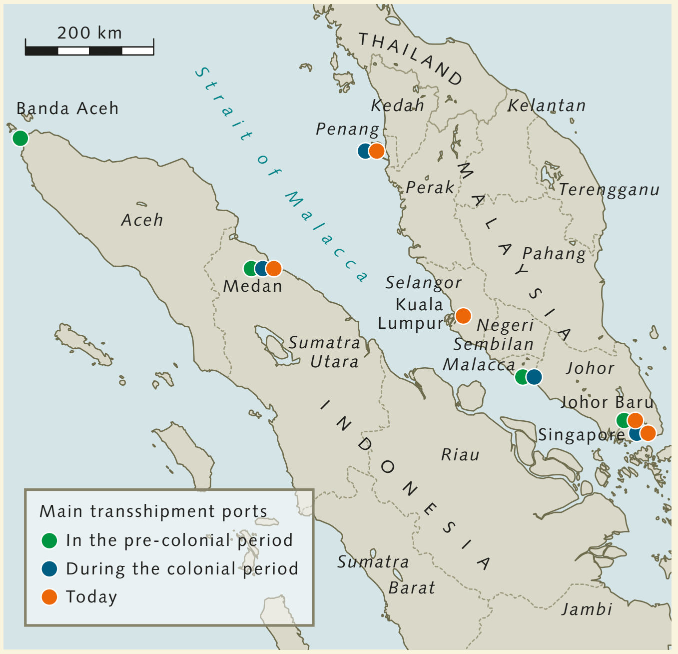
The highways of global trade

The transportation routes afforded by coastal waters are one of the provisioning ecosystem services that are taken for granted. Land-based transportation entails the great expense of constructing infrastructure in the form of canals, rails or roads. By contrast, coastal waters essentially provide waterways that are almost entirely cost-free. Today around 90 per cent of all goods worldwide are transported by ship – a total of almost 10 billion tonnes of goods per year according to the latest data from the United Nations Conference on Trade and Development (UNCTAD). The lion's share is made up of crude oil, containerized goods, and what are known as "minor bulk" cargoes such as steel, cement or sugar.

The Strait of Malacca – a historical shipping metropolis

For centuries, ports along the coasts have been more than transshipment sites for goods; they are also places of interaction between people from foreign cultures. The chequered history of the Strait of Malacca and the city-state of Singapore illustrate how maritime transportation has influenced the development of a coastal region in the course of history. The Strait of Malacca is the shortest shipping route between the Far East and the Indian Ocean. Ships have passed through it for centuries, and trading posts grew up from an early stage, which simultaneously became centres of education, science and art. People with different religious backgrounds – Hindu monks, Christian priests, Muslim scholars – from many regions of the world met here. There was lively exchange about navigation techniques and the art of shipbuilding.

An important trading and knowledge centre from the seventh into the thirteenth century was the Buddhist maritime and trading empire Srivijaya, which encompassed parts of the island of Sumatra and the Malayan peninsula as well as the western part of the island of Java. At that time Srivijaya controlled commercial shipping through the Strait of Malacca. The state disintegrated in wars from the end of the thirteenth century, and two important power centres emerged: first Malacca in the fifteenth century, and later Aceh (in northern Sumatra) and Johor (in present-day Malaysia) at the beginning of the sixteenth century. Whereas Aceh was primarily an important Muslim centre of commerce, Johor grew in importance because of the tin mines located in its hinterland and the valuable pepper that was cultivated. The seaport town of Malacca was used mainly by Muslim merchants as a major transshipment port on the route between India and China. In 1511 it was conquered by the Portuguese, not least to weaken the Muslim dominance of shipping in the region. But despite the conquest, the Muslim merchants remained influential in the region, for ultimately they brought fresh impetus to Aceh which remained Muslim-dominated. The seaport of Malacca then developed into an important centre for European mariners. Various European nations attempted to bring Malacca under their own control by means of blockades and attacks. For instance, the Dutch initially blockaded the seaport of Malacca in 1640 with the aim of cutting off the town's cargo flows and weakening the influence of the Portuguese. In 1641 they finally captured the town and expanded their territorial power from there. In the following years they took over other seaports in the region, including Aceh, and sporadically diminished the influence of Muslim merchants.



2.19 > Over the centuries there have been several different major transshipment ports along the Strait of Malacca. Although the city that gave the Strait its name has little influence nowadays, before and during the colonial period it was a significant power base.

2.20 > Today goods from Southeast Asia and China are delivered to Europe via the Suez Canal. As the ice masses in the Arctic increasingly melt, during the summer months the shorter route via the Northeast Passage could become more attractive in future.

The new major rivals were now British merchants. In 1786 they established the port of George Town in Penang on the northwest coast of the Malaysian peninsula. It was later expanded to become a main transshipment port for the British East India Company. To avert conflicts, in 1824 the two powers agreed to divide up the South East Asian region between them. The Netherlands ceded to Great Britain all property rights northward along the Strait of Malacca, and in return received the areas south of the Strait, including some British territory.

Great Britain developed into the dominant power on the Strait of Malacca, with Malacca, Penang (George Town) and Singapore as its most important trading posts. Unlike Malacca, Singapore – an island at the southern tip of the Strait of Malacca – was still rather insignificant in economic terms at the beginning of the nineteenth century. It was predominantly inhabited by Malayan fishing families. In 1819, just a few years before the Anglo-Dutch Treaty of 1824, the British East India Company had founded its first trading outpost there. Its massive expansion into a major trading port finally began in 1867, when Singapore was declared a British Crown colony.

Today Singapore is the most important location on the Strait of Malacca. Measured in terms of container transshipments, Singapore is the second-largest port in the world. In addition, Singapore has invested heavily in research since the 1980s to establish itself as a modern centre of excellence for high-tech and science. Back in 1987 it had just one research institute; today it boasts more than twenty. And under its Biopolis programme, the city-state even established an entire campus for biotechnology research between 2003 and 2006.

Other important locations along the Strait of Malacca today are the Medan agglomeration on Sumatra and the Special Economic Zone in the Malaysian state of Penang at the Strait's northern extremity. Today Malacca itself is a relatively insignificant port, not least because the coastal waters are too shallow for modern ocean-going vessels.

Recently, however, there have been signs that the maritime trading situation in the region might be subject to renewed changes in future. Climate change and the large-scale melting of sea ice in the Arctic may mean that in the next few decades, the sea route north of Siberia – the Northeast Passage – will become navigable during the summer months. This would be a shorter and quicker route for cargo transport between Europe and East Asia than the route via the Suez Canal and the Strait of Malacca.

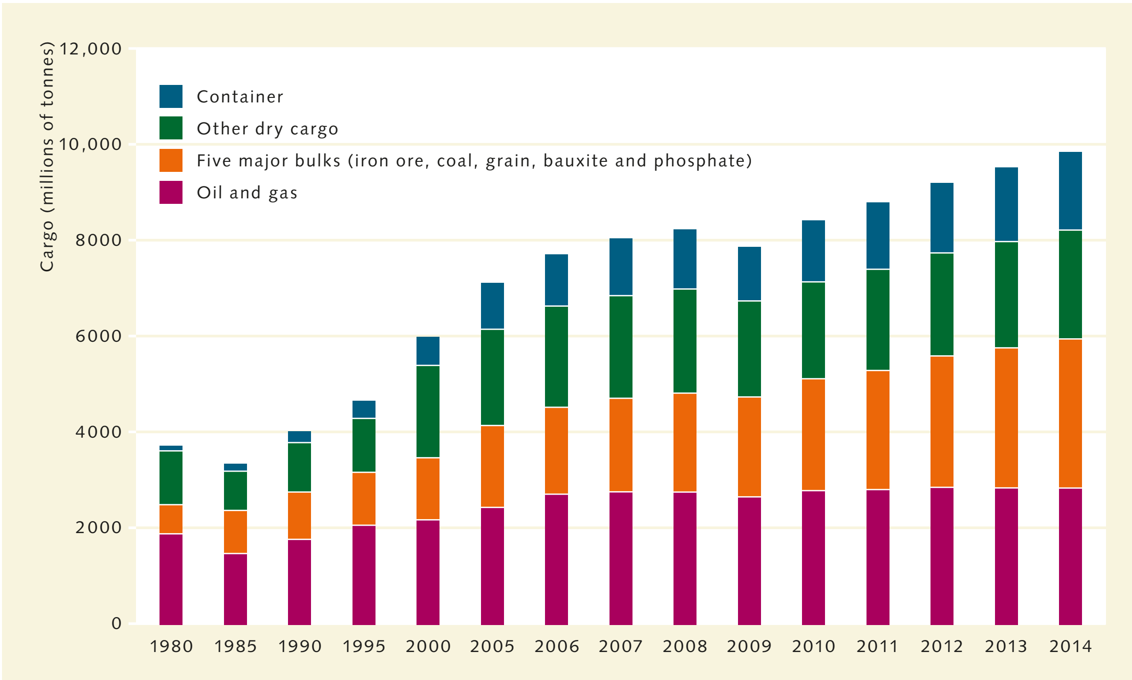
Plans for a future northern route are now taking shape in China, where the 250,000-strong city of Hunchun in the northeast, on the border with Russia and North Korea, is already being promoted as a future hub. According to Chinese thinking, this city on the Tumen River could become as significant as Singapore and supply China with goods via the northeastern route. In July 2016 the large Chinese shipping company Cosco sent five merchant ships from the eastern Chinese port of Tianjin via the northern route, carrying components for wind energy plants to Europe. In August and early September 2016 the ships reached their destination ports in Belgium, Germany and England. For now the point of these voyages is to continue testing the feasibility of a regular shipping link. Nevertheless, Cosco is already planning to send far more ships via the north in future.

Another sign that the Northeast Passage could become established as a sea route in the near future came in September 2016, when a major Chinese mineral corporation acquired a 12.5 per cent shareholding in the mining corporation Greenland Minerals and Energy, which extracts such resources as rare-earth metals, uranium and zinc in Greenland. Experts believe that far more of these resources will be transported to China in future via the Northeast Passage.

Currently it is still impossible to foresee what impact the development of this northern sea route will have on trade in Singapore in the next few decades. Whatever the case, Singapore is endeavouring to diversify by introducing measures such as research promotion to avoid being too heavily dependent upon trade in future.

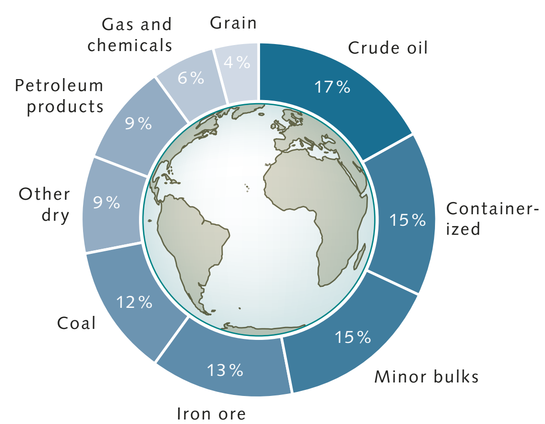
2.21 > Heavy traffic in the Strait of Malacca, the main artery of global intercontinental shipping. Almost a quarter of international maritime trade flows are moved through this seaway, which is around 800 kilometres in length and 50 kilometres in breadth at the narrowest point.

2.22 > Ships are the most important means of cargo transportation. Every year they move almost 10 billion tonnes of goods around the world.



The most significant shipping routes today are those between South East Asia and Europe and between South East Asia and America. Particularly container freighters operate a regular schedule of crossings between the continents nowadays. Freighters often cover extremely long routes non-stop and in most cases offload their cargoes at large central ports which act as hubs for onward distribution. A share of the containers are transferred to the mainland transport networks and transported by truck or rail into the country's interior. Another share of the containers are taken to smaller ports by smaller ships known as feeder ships.

From the container terminal in the port of Hamburg, some 40 per cent of containers are transported onward by heavy goods vehicle. 30 per cent are transshipped onto feeder ships and 30 per cent are transported inland on rail freight wagons. A noteworthy aspect is that in many cases, transportation inland remains in the hands of the terminal operators on the coast, meaning that the influence of the coastal hubs reaches far into the hinterland. From the seaport of Hamburg, for example, onward connections extend as far as Eastern and South Eastern Europe. One large terminal operator in Hamburg even maintains its own railway company which transports containers to its own terminals elsewhere, in Slovakia for example, in order to supply goods to the markets there and in neighbouring countries.



2.23 > The most important goods transported by ship are crude oil, containerized goods and minor bulk goods like steel, cement or sugar.

CULTURAL ECOSYSTEM SERVICES –
COASTS OFFER RECREATION AND FORGE IDENTITY

The value of coastal aesthetics

In aesthetic and cutural terms, too, the world's coasts play a special role. Moreover, they have religious and spiritual value for many people.

By way of an example, the significance of this ecosystem service is reflected in the traditions of the islanders of the Torres Strait, the relatively shallow seaway some 185 kilometres wide between Australia and the island of New Guinea. Within the strait are around 270 islands surrounded by extensive coral reefs, parts of which fall dry during the tidal cycle. Hence the transition from land to open sea is not abrupt but relatively gentle, over an area of many square kilometres. Therefore the language of the indigenous inhabitants does not have distinct concepts for "land" and "sea"; they refer to their environment as "sea country" or "saltwater country". Traditionally they conceive of the islands, coral reefs and open sea as a kind of continuum without strict boundaries. Their sense of identity is bound up with the coastal habitat in its totality.

In past centuries the ocean has increasingly become a landscape that people yearn for and a destination for coastal tourists. Tour operators entice customers with images of palm beaches and blue water. Although comprehensive global data on coastal tourism does not exist, its huge economic importance is undeniable in the view of the United Nations Environment Programme (UNEP). It sees coastal tourism as based on a unique combination of factors resulting from the conjunction of land and sea. Among these are the intense sunlight that frequently prevails, the recreational value of the water and its numerous opportunities for sporting activities, panoramic views and a vast biological diversity of birds, fish and coral species.

According to data from the World Tourism Organization (UNWTO), the global added value of tourism is immense, accounting for a 7-per-cent share of all worldwide exports of goods and services. In 2015 alone, it gene-

2.24 > Wyer Island which is fringed with a coral reef is situated in the seaway between Australia and the island of New Guinea, the Torres Strait. The indigenous inhabitants refer to this marine landscape as "saltwater country", a concept encompassing both the dry land of the islands and the ocean with its coral reefs.

2.25 > The town of Positano on Italy's Amalfi Coast illustrates the attraction that the coasts exert on people. They are aesthetic areas which offer cultural and spiritual enrichment and recreation.

International tourist arrivals					
Rank		2014 (millions)	2015 (millions)	Change '14/'13 (per cent)	Change '15/'14 (per cent)
1	France	83.7	84.5	0.1	0.9
2	United States of America	75.0	77.5	7.2	3.3
3	Spain	64.9	68.2	7.0	5.0
4	China	55.6	56.9	–0.1	2.3
5	Italy	48.6	50.7	1.8	4.4
6	Turkey	39.8	39.5	5.3	–0.8
7	Germany	33.0	35.0	4.6	6.0
8	United Kingdom	32.6	34.4	5.0	5.6
9	Mexico	29.3	32.1	21.5	9.4
10	Russia	29.8	31.3	5.3	5.0

2.26 > The importance of coastal regions for tourism can be seen from the list of the ten most popular travel destinations. Four of these countries with well-developed tourism sectors are on the Mediterranean alone.

rated income amounting to 1.26 trillion US dollars. Whereas the number of tourists travelling internationally was put at just 25 million in 1950, by 2015 the figure had reached almost 1.2 billion worldwide.

Measured in terms of numbers of tourists entering the country, the global rankings of the most popular countries for holidays are headed by nations with highly developed coastal tourism. Four of the top ten travel destinations are countries bordering the Mediterranean, led by France with 84.5 million foreign visitors, although it should be borne in mind that the French holiday destinations also include inland locations like Paris or the châteaux of the Loire Valley. In second place is the USA with 77.5 million visitors. Spain is placed third with 68.2 million and China fourth with 56.9 million holidaymakers from abroad. Narrowing the perspective solely to international travel within Europe, Spain actually achieves first place, being the destination for a good 20 per cent of all foreign travel by Europeans within Europe.

Highly developed coastal tourism also has its downsides, however. In many locations, the construction of hotel complexes has resulted in the loss of natural areas. Moreover, the wastewater and waste from tourism centres have polluted coastal waters, while coral reefs have been severely degraded by heavy use for tourism. Original, unspoiled coastal landscapes are ever more seldom found; a state of affairs that is criticized by many. Ultimately it can be said that the uniqueness, beauty and special aesthetic quality of the coasts is an ecosystem service in its own right.

Even more of a good thing

Coastal areas in their entirety provide numerous other ecosystem services, although it is not always possible to differentiate strictly between coastal waters and the open sea. The ocean absorbs large quantities of carbon dioxide, thus regulating the climate and having a very significant effect on the global climate system. What share of this is attributable to coastal waters alone is impossible to quantify with certainty. Nevertheless, it is evident that they are under particular threat since they are far more severely exposed than more remote ocean regions to human-induced negative impacts.

Coastal pressures

> Human overexploitation constitutes the greatest threat to the coasts today. Coastal sites attract increasingly high-density building development. Coastal waters are being contaminated by pollutants or excessive nutrient run-off. And because population growth and migration continue unabated, pressure on the coasts is unlikely to diminish in future.

Overuse harms habitats

The appeal of the coasts is explained to a great extent by the large number of ecosystem services that they provide. In past decades the power of this attraction led to many coastal regions becoming increasingly heavily populated and pressured beyond their carrying capacity – be it through excessive fishery or the challenges of wastewater treatment. By using the coasts unsustainably, people harm themselves in the end because there will come a time when certain ecosystem services can no longer be provided.

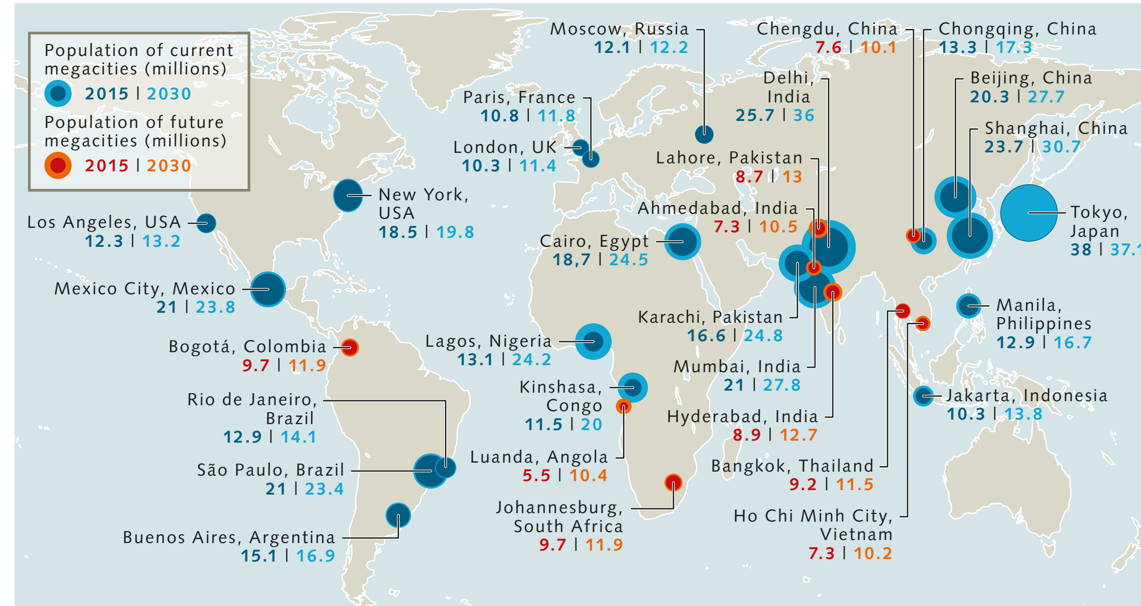
One example is the development of mass tourism in many locations. Coastal regions want to attract holidaymakers to their beaches with attractive landscapes and clean water, yet obtrusive hotel-building destroys the pristine appearance of the landscape, while immense quantities of wastewater from the hotel complexes cause water pollution. This is how overuse blights the recreational value of a landscape, undermining its provision of cultural ecosystem services.

2.27 > As seen in this view of Cancún, Mexico, the effects of mass tourism have obliterated the pristine appearance of many coastal regions. This kind of overuse can blight the recreational value of these areas.

Hard-to-pinpoint threats

Some forms of overuse are not always easy to identify and measure. Humans and the environment are closely interwoven in socio-ecological systems. Coastal regions extend over vast areas between land and sea and are very difficult to define in precise spatial terms. There can also be a lengthy time lag between cause and effect.

One example is the industrial use of polychlorinated biphenyls (PCBs): chlorine compounds that were used until the end of the last century in transformers, in hydraulic fluids and as softeners in sealants and plastics. Because they were applied in such diverse uses, significant quantities found their way into the environment. Only in the early 1970s was it recognized that the substances are toxic and have carcinogenic effects. Moreover, it was observed that in sea mammals such as seals they cause pathological changes to the uterus. This has resulted in a drastic decline in the number of successful seal births in the North Sea and the Baltic, particularly since the 1970s. Finally, in 2001 the use of PCBs was prohibited by the Stockholm Convention, an international treaty to protect the environment from particularly dangerous chemicals. Thus, several decades elapsed between the actual cause, the emergence of the environmental problem, the identification of the substances and the systematic ban on their use.



2.28 > Many of the megacities of the future, cities of over 10 million inhabitants, are in Asia and Africa.

Ever expanding megacities

Within socio-ecological systems where people live in large numbers or sources of pressure are multifarious, the interactions can be especially complex and in many cases difficult to discern. Today this applies particularly to coastal megacities of over 10 million inhabitants. Such regions are characterized by high population density and high-density building development. Many people need to be supplied with fresh water, food and electricity, which imposes high demands upon infrastructure, logistics and waste disposal. Because people from poorer rural regions inland are constantly moving to the coastal megacities in search of work or training, these metropolitan centres will continue to grow in future – above all in Africa, South America and South East Asia.

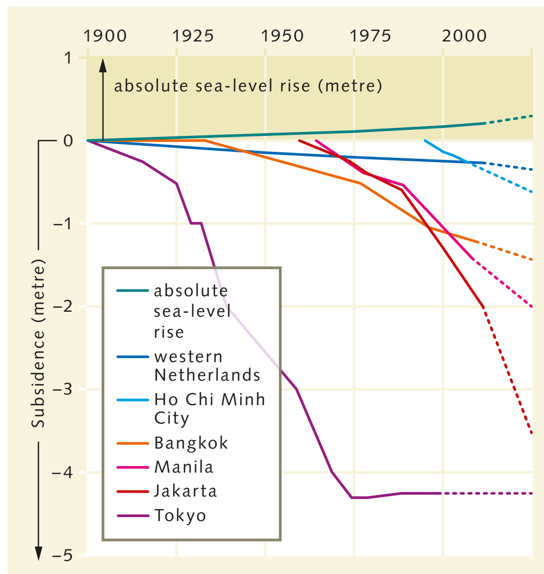
One of the biggest problems in the wake of this continuous urbanization has been the increasing frequency of floods affecting entire urban districts. Flooding can be caused both by heavy rainfall events and by storm surges in the sea level. Apart from the immense economic damage caused by floods, they pose a very real risk to life and limb. Interestingly, so far these have been attributable not so much to global climate change and sea-level rise than to bad urban planning. The following causes have been identified:

- Subsidence due to building density: the construction of high-rise buildings and other large structures has significantly increased the load on the ground. Under the heavy weight, the densely built-up sites slowly subside.
- Subsidence due to groundwater abstraction: because ponds, lakes and rivers at ground level in many coastal cities are heavily polluted by untreated wastewater and detritus, they cannot be used as sources of drinking water. Drinking water for many millions of inhabitants therefore has to be abstracted from the groundwater in the deeper geological rock layer, the aquifer. Since groundwater normally acts as a natural abutment against the downward force of buildings, pumping it away in large quantities exacerbates the subsidence of densely built-up areas. Construction measures themselves also lead to a fall in the groundwater level. Deep excavations are made for large buildings and any water that penetrates is pumped out, with the result that the ground in the excavations settles and the pore volume that was previously filled by the groundwater shrinks. The land surface then sinks.

Aquifer
The term "aquifer" denotes a subsurface body of rock containing pore spaces through which groundwater flows.

- Construction on low-lying river catchments and marshlands: many of the migrants to cities from poorer rural regions settle at the growing periphery of the cities in what are known as informal settlements. These are often located in low-lying areas that are unsuitable for building development, which are frequently along the banks of rivers or on marshes and meadows at especially high risk of flooding.
- Poor sewer construction: in many cities, developments have been built across natural watercourses or flood-prone areas such as alluvial plains. As a result, natural rainwater drainage areas have disappeared in many places. Added to that, surfaces have been sealed by the construction development so that rainwater no longer has much seepage area, but drains away torrentially instead.
- Natural subsidence: in some coastal regions the land is slowly sinking naturally. There can be a number of causes for this. For example, in some areas the land mass may slowly subside due to the movement of a continental plate. In other coastal areas, particularly in river deltas, the ground sinks because sediment layers become more densely packed over time and sag under their own weight.

Apart from increasing the general risk of flooding, subsidence also gives rise to very obvious urban planning problems and structural damage, including cracks in roads and buildings, broken gas and water pipes, and leakages in the sewage system.



2.30 > Tokyo managed to halt its land subsidence from the mid-1970s, unlike most other cities.

2.29 > Many of the world's largest cities are sinking today, primarily due to groundwater abstraction and massive building development. In many cities this subsidence will continue into the future.

Subsidence in sinking cities				
	Mean cumulative subsidence from 1900 to 2013 (millimetres)	Mean annual subsidence (millimetres)	Maximum annual subsidence (millimetres)	Estimated additional subsidence by 2025 (millimetres)
Bangkok	1250	20–30	120	190
Ho Chi Minh City	300	up to 80	80	200
Jakarta	2000	75–100	179	1800
Manila	1500	up to 45	45	400
New Orleans	1130	6	26	> 200
Tokyo	4250	around zero	239	0
Western Netherlands	275	2–10	> 17	70

2.31 > Inundation of an entire industrial zone in the province of Ayutthaya, north of the Thai capital of Bangkok, in November 2011. Among those affected by the disaster is a Japanese car manufacturer based there.

2.32 > Jakarta is currently the world's fastest sinking metropolis. Because the city pumps groundwater on a large scale for its drinking water supply, the modern city centre is subsiding dramatically.

A sinking metropolis

An extreme example of a sinking city is Jakarta, the capital of Indonesia, which is currently the fastest sinking metropolis in the world. Particularly since the 1980s the city has grown drastically in terms of both population and road and building construction – especially high-rise buildings. In 2015 Jakarta already had at least 10 million inhabitants, and its population is forecast to reach 13.8 million by the year 2030.

Jakarta is in a very low-lying region, partly on peaty soils. The densely developed northern area, with its many high-rise buildings, and the commercial centre in particular are sinking in the soft subsurface – currently by up to 10 centimetres a year. The abstraction of groundwater for drinking water supply is also contributing to this effect, and it is feared that the sinking will accelerate. Without countermeasures and a reduction of groundwater abstraction, by the year 2025 parts of Jakarta are likely to have sunk by a further 180 centimetres.

Floods occur with growing frequency, leaving the city's highways and commercial centre half a metre under water, both after heavy rainfall events and higher than usual sea water levels. Natural watershed and floodplain areas have been built upon repeatedly over time so that rainwater has almost nowhere to seep away. The alarming fact today is that more and more people are affected by the floods. New arrivals in the city predominantly settle close to the economically attractive north of the city. This increases their prospects of finding work or reduces the length of the commute to their workplaces.

Flooding also has grave financial consequences, as seen for example in the year 2007, when a good one-third of Jakarta's area was inundated after severe rainfalls. Around 300,000 people lost their homes. The damage to infrastructure and buildings amounted to the equivalent of some 860 million US dollars.

Floods affect not just the city itself but also, indirectly, its surroundings – the city of Jakarta is part of an urban conurbation, also comprising the adjacent cities of Bogor, Depok, Tangerang and Bekasi. This is one of the largest agglomerations in the world, reflected in the name it is commonly known by today: the acronym "Jabodetabek". Every year around 250,000 people move into this agglomeration, which means that about 35 million people will be living there in the year 2020.

Every time that Jakarta is flooded, it causes transport chaos in the neighbouring areas. And another issue affects the region as a whole: if diseases or epidemics break out in the flooded areas because of the standing dirty water, these can rapidly spread throughout the whole of Jabodetabek.

A giant bird to defend Jakarta

In order to defend the city of Jakarta from greater floods in future, the Indonesian authorities are currently planning to create hydraulically filled islands that will shut off the approximately 35-kilometre wide Bay of Jakarta and be developed with residential, office and hotel complexes.

2.33 > As a defence against flooding, there are plans to create artificial islands off the coast of Jakarta by hydraulic filling. The largest island will be 10 kilometres long and shaped like Indonesia's emblematic bird. But the project is controversial. It is feared that wastewater could accumulate in the artificial lagoon, ruining the livelihoods of fishers.

The largest island alone is 10 kilometres long and will be given the form of a garuda bird with wings spread wide, the emblem of Indonesia. But resistance is stirring within the population. Wastewater could collect in the artificial lagoon landscape because there will barely be anywhere for it to flow into the open sea. Diseases could spread. The small-scale fishers fear losing their livelihoods because in future they will have to travel many kilometres further offshore in order to reach fishing grounds. But that is not possible, argue the fishers, since they only possess simple boats which are often in poor condition and not suitable for longer trips out to sea.

Construction projects on land which are planned in the course of the hydraulic filling are another major source of potential conflict. The intention is to construct new office, business and residential quarters along the shoreline. In the interim, residents who previously lived in simple shacks and houses in this area are being resettled. Although they are obtaining cheap living space in high-rise buildings in other districts of Jakarta, how can they possibly be compensated for the impending loss of their culture and identity? If the fishers are resettled inland, closer to industrial plants and factories, they can hardly continue in their traditional occupation: fishers will turn into factory workers.

Doubly threatened – by rains and storm surges

Another example of a sinking coastal metropolis that is also plagued by flooding is Manila, the capital of the Philippines. It is likewise threatened by heavy rainfall events and storm-induced high seawater levels. Between 1900 and 2013, parts of Manila sank by 1.5 metres, and further subsidence of around 40 centimetres is expected by the year 2025. This is worrying because Manila is in a region that is often affected by typhoons, huge cyclonic storms. They bring large quantities of rain and churn up the sea so violently that huge breaking waves arise. Typhoon Ketsana in 2009 was a cyclone of catastrophic proportions. The rain and the storm surge inundated some districts of Manila with 2 metres of floodwater.

The fact that flooding is increasingly affecting coastal cities that are not notably subsiding is demonstrated by the example of Mumbai. A large-scale flood hit the Indian megacity on 26 July 2005, when almost 950 millimetres of rain fell within a 24-hour period. That is roughly equivalent to the total volume that normally falls in Mumbai during the entire month of July. In the hour from 15.30 to 16.30 alone, there was 190 millimetres of rain. Since this coincided with a relatively high sea tide, the rainwater could barely seep away and instead backed up in the drains and particularly in the River Mithi which flows through the middle of the city.

Whereas most previous flooding had only affected the unauthorized (informal) settlements on the city periphery, this time the city centre was also hit, and the water rose by more than 1 metre in next to no time. Streets, shops and office buildings were inundated and traffic came to a complete standstill for many hours. In the end 22 per cent of Mumbai's area was flooded. The flood that day took a tragic toll: over 400 dead and around 100,000 badly damaged homes and businesses. 30,000 vehicles were reduced to scrap metal.

The analysis of the events made it clear that such large-scale flooding in Mumbai could only have happened because major swathes of the natural inundation areas along the rivers had gradually been sealed over, partly by the construction of informal settlements and partly in the course of official projects like the extension of the airport. Moreover, many watercourses were blocked with waste and building debris, impeding the rainwater's run-off. Elsewhere, rainwater sewers were poorly maintained, river banks had slipped and concrete walls collapsed.

USA also has self-inflicted problems

From a worldwide comparison of coastal metropolises, it is clear that the cities worst affected by flooding are mainly megacities in emerging economies. Experts attribute this to the fact that the required standards are not always adhered to in the planning of structures – particularly with regard to forward-looking land-use planning, disaster preparedness, and functional infrastructure, which includes such features as flood channels, a functioning sewerage system, flood banks and flood control barriers. On the other hand, cities in industrialized countries certainly also have to contend with subsidence. That is evident from the New Orleans conurbation, for example, in which around 1 million people live. New Orleans is in the US state of Louisiana, directly in the Mississippi Delta. Between 1900 and 2013 the city sank by a full 1 metre and is subsiding every year by a further 6 to 26 millimetres.

This is happening for several reasons. As in other affected coastal cities, the abstraction of groundwater plays a part in the subsidence – but how much of a part is very difficult to assess, because the particular characteristics of the soil in New Orleans give rise to another phenomenon: if the groundwater table falls, oxygen from the air penetrates deeper ground layers and activates the soil bacteria that live there. These decompose soil organic matter. Since the soil contains large quantities of organic material that has been carried into the delta by the Mississippi over centuries, the bacteria find large amounts to decompose. This loss of organic substance contributes substantially to the subsidence.

Additionally, in the region around New Orleans, the drilling of petroleum and natural gas and the emptying of those deposits are also causing the ground to sink. The loss of sediment that used to be transported into the delta by the Mississippi should not be underestimated, either. Today, because it is slowed down by numerous weirs, the Mississippi carries distinctly less sediment into the sea. The old sediment packages deposited in the delta are so heavy that the delta is slowly subsiding naturally. Whereas this subsidence used to be evened out by fresh sediment from the Mississippi, today the markedly reduced sediment load is far from sufficient to compensate.

These problems had been known about for decades, just like the fact that New Orleans was vulnerable to flooding in the event of even moderately severe storms. Experts had last published a warning in a scientific journal in 2003 about the consequences of severe hurricanes, which often threaten the coast on the Gulf of Mexico in the summer months. The existing flood control works were too low, and others were badly designed, maintained or constructed, their report read. The authorities had in fact planned a hurricane protection system, but due to a shortage of funding it was not built. In the view of experts, even this protection system would have failed because it would have been constructed according to outdated and unduly low design criteria.

Thus, New Orleans was relatively poorly protected when the extremely forceful Hurricane Katrina hit the city at the end of August 2005. It caused a 7-metre rise in the coastal water level. Consequently the flood banks (levees) were breached in around 50 places and the city, which lies in a hollow, filled up with water. Only after that did the authorities react and decide to construct a modern and effective flood protection system, the Hurricane and Storm Damage Risk Reduction System (HSDRRS). This was completed in 2011. It includes higher and more resilient levees and flood control barriers as well as floodgates and emergency pumps at the outlets of the pipes that drain runoff from New Orleans. These measures have considerably reduced the risk of major flooding.

Furthermore in 2012 the US authorities passed a new master plan for the protection of the delta, which will help to protect not only the city of New Orleans but the entire delta region from hurricanes and especially floods in future. A complete package of measures, including dredging works or the pumping of sediment, will allow the delta to grow again over the next 50 years. A good 700 square kilometres of new delta will be created in this way. Added to that will be 500 square kilometres of salt marshes to temper the force of the waves in the event of storms and hurricanes.

Halting the subsidence

The examples of Tokyo and Shanghai demonstrate that the subsidence of a city can be stopped if appropriate action is taken. After parts of the Japanese capital had subsided by around 4 metres since 1900, the decision was taken in the late 1960s to drastically restrict groundwater abstraction. Thereupon the soil strata carrying the groundwater slowly filled up again, so that towards the mid-1970s the subsidence had already been halted.

The Chinese metropolis of Shanghai was faced with similar problems. Its response was not only to heavily regulate groundwater abstraction but also to deploy pumping technology, which permitted more rapid replenishment of the groundwater reservoirs with water.

2.34 > Hurricane Katrina struck the southeast of the USA in late August 2005. Months later, traces of the destruction were still plain to see.

2.35 > In the past 40 years the Pearl River Delta in China has developed from an agricultural to a highly industrialized and heavily populated region. The left side of the photomontage is a satellite image from the year 1979, and the right side of the image dates from 2003. Vegetation is shown in red and built-up areas in grey. Watercourses can be seen in blue.

The largest agglomeration on Earth

The development and settlement of coastal areas is probably the most conspicuous change to these habitats. In many cases species-rich wetland biotopes like mudflats and salt meadows, marshes and peatlands have been dried out and irreparably destroyed by construction measures. An extreme example of this urbanization in coastal wetlands is the Pearl River Delta in the middle of the coastal province of Guangdong in the south of China. This is the location of a huge agglomeration consisting of eleven cities, including Hong Kong and Macao. The entire region, covering an area of almost 40,000 square kilometres, is almost the size of the Netherlands.

The region comprises several Special Economic Zones and has undergone a rapid economic upturn since the 1970s. Back then the delta was still characterized by small villages and expansive wetlands, but by the year 2000 the increasingly urban area that formed within it through the merging of the cities took up 3500 square kilometres, which is roughly four times the area of Berlin. Today the drained area covers as much as 4500 square kilometres and the population density is immense. Currently around 60 million people live in the Pearl River Delta – around 3.5 times more than in the Netherlands, which is a densely settled country by European standards. Thus, within a few decades it has developed into the most highly populated agglomeration on Earth. Experts expect growth in this region to persist until the Pearl River Delta is home to around 100 million people by 2030.

With the drainage and redevelopment of the wetland areas, the habitats of many amphibians and birds have disappeared. Furthermore, as a consequence of water pollution, today around 90 fish species in this area are threatened. Aside from that, many river branches in the region carry less water, particularly during the dry months, since numerous dams and power plants were built for drinking water abstraction and electricity generation. Overall this means that considerably less freshwater flows into the delta, and at times when sea levels are high, such as spring tides or storm surges, seawater can penetrate deeper into the delta. Plants and animals that are not adapted to brackish water or higher salt content retreat from the affected zones. The habitat is changing enormously.

2.36 > The Chinese sturgeon *Acipenser sinensis* is considered to be at acute risk of extinction.

Another consequence of dam construction is to interrupt the upstream migration routes of some fish species between the sea and their spawning grounds. In the opinion of experts, this substantially contributed to the collapse of stocks of the threatened Chinese sturgeon *Acipenser sinensis*, for example.

The removal of sand and stones for building projects represents another extreme case of interference with nature. The building material is taken from the river beds with dredgers and special ships. This alters the rivers' flow regimes, which in turn leads to changes in the composition of species assemblages. Many water organisms lose their breeding and spawning sites as a result of dredging works.

Big business built on sand

It is not just in China that sand and minerals are extracted but in many of the world's regions. According to estimates by the United Nations Environment Programme (UNEP), every year between 47 and 59 billion tonnes of minerals are mined worldwide, of which sand, gravel and crushed rock make up between 68 and 85 per cent. Since there is no standardized recording of the statistics, the quantities can only be estimated approximately. Between 25 and 30 billion tonnes of sand are needed for the cement industry alone. But in numerous places this colossal demand entails major encroachments on the landscape. Such resource extraction is therefore viewed very critically in many regions. In South Africa, for instance, dune sand is extracted for the construction industry. Critics fear that the coasts will be less well protected as a result because dunes are a natural bulwark against the breaking waves. In India fishers are protesting against sand extraction from

Blockage of a lifeline

It is not just in the Pearl River Delta that construction measures are causing broad-scale destruction of rivers and wetlands. Also under threat is the Mekong in South East Asia, a significant river system and a lifeline for millions of people. At 4350 kilometres in length, the Mekong is one of the world's longest rivers. It flows through China, Myanmar, Laos, Thailand, Cambodia and Vietnam, and splits into a large delta before discharging into the South China Sea. The Mekong is extremely rich in biodiversity; it is home to around 1500 different species. What a high number this is can be seen from a comparison with the Mississippi, where only 250 species occur. Around 120 species in the Mekong are fished. Since the river carries large quantities of minerals and nutrients as it flows down from the Tibetan highlands, it is very productive and supplies large quantities of fish. Particularly in the lower-lying Mekong Basin in Laos, Thailand and Cambodia and in the Mekong Delta in Vietnam, there is a well-developed fishery supplying around 2.6 million tonnes of fish per year. Its market value is estimated at 2 to 3 billion US dollars.

Fish is not just a trading product, however, but first and foremost an important source of protein for the approximately 60 million people living in the Mekong Basin and Delta. Depending on the region, fish contributes between 49 and 82 per cent of the population's intake of animal protein. But several dam projects are about to place the Mekong's abundant fish stocks under threat. Laos, Thailand, Cambodia and Vietnam are all planning new dams for hydroelectric power generation. Laos has set itself particularly ambitious goals and intends to commission several dams in the next few years and establish itself as the "battery of South East Asia" – a major electricity exporter. Dam construction will disrupt many fish species' migration routes between the sea and their spawning grounds up river. Some commercially important species will be affected. Thus, decisions made far inland have consequences that extend to the coastal areas.

The dam projects are colossal. The first to be commissioned, in Laos in 2019, will be the Xayaburi Dam: a structure 50 metres in height and 800 metres wide, it will impound the river into a lake of around 50 square kilometres – roughly the area of the Italian island of Ischia. Although there are plans to build fish ladders into the dam to facilitate fish migration, environmentalists warn that very few fish species can make use of these artificial passages upstream. Overall it is feared that the abundance of fish in the Mekong could decline substantially. If that happens, many people stand to lose a vitally important source of income or protein.

2.37 > Protest outside the administrative court in Bangkok against the construction of the Xayaburi Dam in Laos.

beaches. They are critical that the dredging up of suspended sediments is driving fish away. For the local small fishers, this means the loss of their livelihood.

Similarly in Indonesia and Cambodia, the removal of large quantities of sand – mainly for export to Singapore – has led to major destruction of the coasts, which prompted the government of Indonesia to prohibit the export of sand completely in 2008 while the government of Cambodia markedly restricted official exports in 2009. Nevertheless, sand extraction in Cambodia is continuing on a grand scale. Cambodian nature conservation organizations draw attention to the fact that sand is being traded in some cases by Mafioso groups. They complain that Cambodian authorities are not carrying out any controls. To what extent the government has secretly awarded permits for this extraction, or how far the corruption of officials is involved, remain unanswered questions. Sand is being extracted using suction dredgers in a coastal protection area in the Koh Kong region west of the capital Phnom Penh, among other sites. This is destroying mangroves and seagrass meadows – important habitats for the dugong, a species of sea cow.

Turning now to Singapore, the South East Asian city-state is an extreme example of sand imports. Being an island, Singapore constantly requires sand for the enlargement of its urban area. Between 1995 and 2014, around 500 million tonnes of sand were imported – for the most part from Indonesia and Cambodia. Since those countries adopted their export restrictions, sand has been imported to Singapore illegally, say the Cambodian nature conservation organizations.

Overexploited fishing grounds

The overexploitation of coastal areas is particularly evident when it comes to fishing. Not only is too much fish taken from the oceans, but fishing can also destroy marine habitats such as coral reefs. Humans take more fish out of the sea than the sea can continue to produce. As a result, **fish stocks** decline over time. It is not possible to state exactly the degree to which coastal regions are overfished, since the Food and Agriculture Organization of the United Nations (FAO) does not differentiate in detail between coastal fisheries and deep sea fishing. However, given that coastal waters worldwide constitute the most productive marine regions they no doubt provide the bulk of fish, and fisheries experts believe that they are the most intensively fished waters. According to current FAO data roughly 30 per cent of all commercially fished stocks worldwide are overfished. Given that there are more than 38 million fishers in the world who could lose their livelihoods or their food source, this situation is alarming. At particular risk are the small-scale fisheries on which approximately 20 million fishers depend in the developing countries alone, where fishing makes a significant contribution to the food supply and livelihoods of coastal people. In the tropics, small-scale fishing is primarily carried out on coral reefs. The number of coral reef fishers is estimated to be in the order of 6 million, 1.7 million of whom live in Indonesia, roughly 950,000 in India and 910,000 in the Philippines. Roughly half of the 6 million reef fishers primarily dive for sea cucumbers. These sausage-shaped echinoderms are related to starfish and are exported to Hong Kong in particular where the dried animals are valued and traded as medicine.

In many areas, coral reef fisheries are not currently managed in a sustainable manner. Not only are their stocks being overfished but the reefs are also damaged in a variety of ways. This is tragic as in the long-term people are destroying their own livelihoods.

Estimated number of reef fishers in coral reef regions worldwide

Region	Number of reef fishers (millions)	Reef fishers as per cent of rural coastal population
South East Asia	3.35	5
Indian Ocean	1.50	13
Eastern Pacific/Atlantic	0.50	18
Western Pacific	0.45	68
Middle East	0.34	24
Total	6.14	

2.38 > South East Asia, and especially Indonesia, has particularly high numbers of reef fishers. However, as a ratio of reef fishers to rural coastal population, Western Pacific island nations have the highest percentage, as these islands offer scarcely any other livelihood options.

Seagrass meadows
Characteristic plant communities which typically grow in sandy sediment in coastal waters and on tidal flats. They have long, herb-like fronds and thus resemble – but are unrelated to – the grasses that grow onshore. They are important habitats, providing young fish with food and protection from predators. Various species of fish lay their eggs directly on seagrass, so these meadows are often key nurseries for fish. They are also a vital foraging ground for birds, such as Brent geese during their autumn migration across Western Europe's Wadden Sea.

Reef fishing at the limit – Spermonde Archipelago

The Spermonde Archipelago is an example of the contribution made by fishing to the gradual destruction of coastal ecosystems. The Archipelago is located just off the large Indonesian island of Sulawesi. It consists of approximately 70 coral islands and was known even to European seafarers in colonial times as a particularly species-rich and productive marine area. It is home to crustaceans, large groupers, numerous smaller species of reef fish, squid and many species of corals. Chinese traders purchased sea cucumbers in this region as early as the seventeenth century. These sausage-shaped animals are related to starfish. In China and Hong Kong they are still in demand to this day for medicinal preparations.

For a long time the Archipelago's coral reefs appeared to be inexhaustible. The local population saw the abundance of fish as a God-given gift and a never-ending supply. However, some of the fish stocks in the area have been considered to be overfished since the 1960s. Several scientific studies have been conducted in the area in order to understand the underlying causes. The studies also included interviews with the islands' inhabitants. As the islands largely lack fertile soil and thus do not lend themselves to farming activities at any major scale, it was found that 80 per cent of households directly or indirectly depend on fish and other marine life for their livelihood. Depending on demand, available gear and the productivity of stocks in question, different marine organisms have been under particular pressure at different times. If it became uneconomic to catch a particular species because there was no demand or the local stocks had declined, the fishers simply switched to another species.

In the past, the fishers mostly used traditional gear such as longlines and fish traps. In the 1980s however fishers added specialized equipment to their arsenal, such as diving gear that allows them to hunt for sea cucumbers for which there is such a strong demand in China. The divers use rubber tubes to take air that is pumped down to them by on-board compressor pumps. This allows them to stay under water for longer and collect a much greater number than before. This has resulted in sea cucumbers of the species *Holothuria nobilis,* among others, to disappear completely from many of the Archipelago's reefs.

Some of the fishing methods used today are not only unsustainable but illegal. Dynamite fishing has been practised in the Spermonde Archipelago since World War II in order to catch culinary fish for local consumption. The explosions also kill numerous other animals that are not consumed. It has been estimated that between 10 and 40 per cent of the locally consumed fish comes from dynamite fishing, that proportion varying between islands. Moreover, cyanide fishing has been practised since the 1960s. This method involves the addition of poisonous sodium cyanide to the water in order to stun fish. They can then simply be gathered up and exported as live fish with smaller fish mostly used in aquariums and larger ones in restaurants. Fishers receive much higher prices for live fish than for culinary fish sold in local markets.

Groupers are among the species caught with cyanide. After being caught, the fish are kept in basins for several days in order for them to excrete the poison prior to being sold. But many of them perish before reaching the recipient countries, partly due to conditions during transport and partly because of after-effects of the poison.

One of the major problems with cyanide fishing is that the cyanide drifting in the water also kills many other organisms. It kills minute algae living in symbiosis with the corals as well as juvenile fish growing up in the reefs. It is questionable whether a reef can recover from cyanide poisoning or how long this might take.

A better understanding of the unsustainable fishery practices can only be gained by an examination of the underlying social context. From a sociological perspective, there is a system of patron-client relationships in the Spermonde Archipelago (with fishers being the clients) – a kind of two-class society. The patrons are the link between local clients and external traders and buyers. They know which products are currently in demand in the marketplace. In addition, the patrons provide gear for the different fisheries and extend credit to fishers and their families. They are well connected in civilian and military circles that are supposed to protect the coral reefs and pay significant amounts of bribes to inspectors in order to avoid sanctions for illegal or prohibited catches.

In most cases, the fishers sell their catches directly to the patrons in order to pay back the loans they have taken out. While the price they are paid is well below the patrons' sales price, it provides them with a relatively safe income and a relatively stable social safety net for their families in economically difficult times.

As advantageous as the patron-client system might appear to those involved, it brings with it long-term risks to the coral reef ecosystem and thus to the only source of income for the growing population. As the markets sell fisheries products from all the fishers participating in this system, there is always enough fish to meet the demand. If yields decline in one fisher's fishing area, this loss is hardly felt in the marketplace. If some reef areas are overfished, catches in other areas make up the shortfall. Information on overfishing in a particular area therefore rarely reaches the patrons, which means that ecological warning signals are easily overlooked and it is impossible for an awareness of the necessity of sustainable fisheries to develop. The reefs will have even less time to recover from local overexploitation if the impacts of climate warming are brought into the mix.

2.39 > The Spermonde Archipelago is centrally located in the island state of Indonesia, just off the south-western tip of Sulawesi. Some 70 coral islands make up this archipelago.

2.40 > Stocks of the sea cucumber species *Holothuria scabra* are particularly heavily exploited in the Spermonde Archipelago as they are considered a delicacy in many parts of Asia and command high prices.

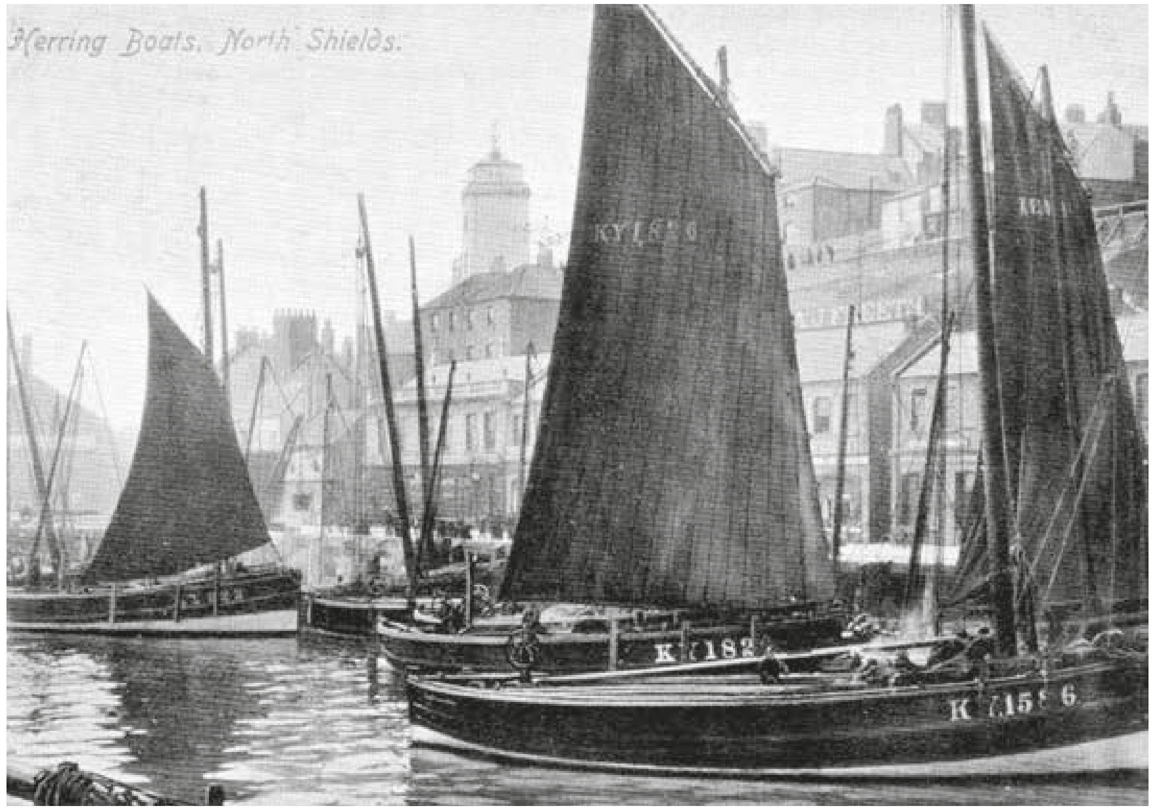
2.41 > Cyanide fishing involves the addition of poison into the water in order to stun the fish. Once they have been collected, they can later be sold as live fish.

Stronger engines, greater destruction

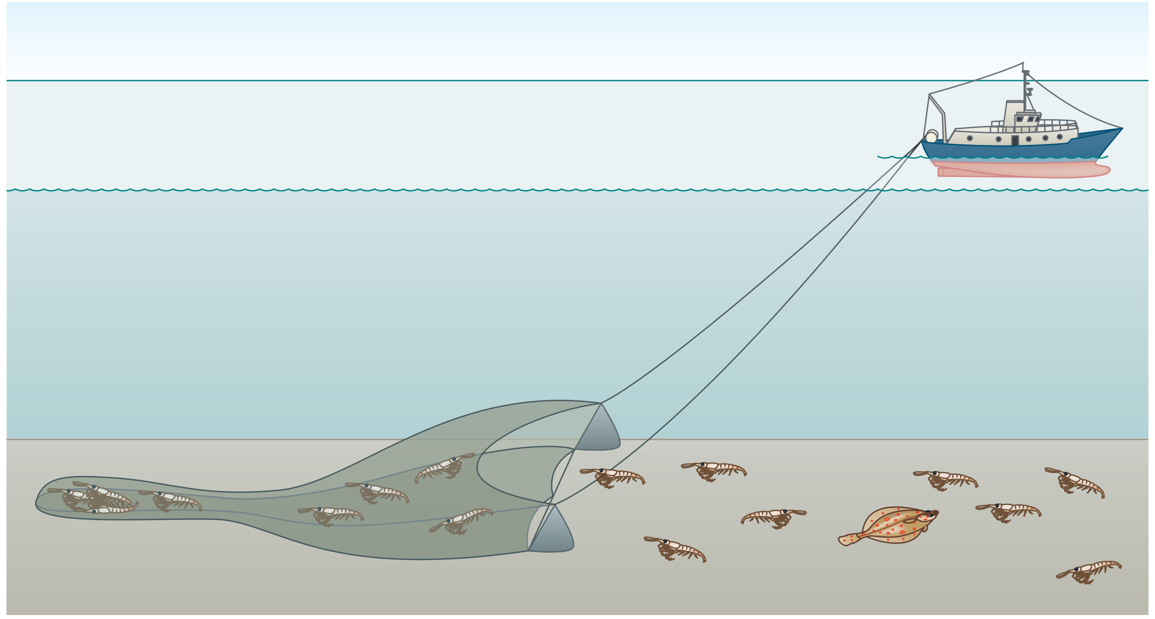
Just how strongly intensive fishing impacts on inshore marine areas can be illustrated by the example of the Belgian, German and Dutch North Sea coast where fishing has very strongly altered seafloor habitats over the last hundred years. In these habitats, flatfish species such as dab, plaice and sole that camouflage themselves by partially burying themselves in the soft seabed are caught with bag-like bottom trawls that are dragged across the sea floor on heavy metal frames. These beam trawls and the chains attached to them are designed to penetrate and basically plough up the top few centimetres of the soft seabed as they are towed along.

In the nineteenth and early twentieth century, flatfish were in many areas still caught using small rowing or sailing boats and correspondingly small beam trawls. However, with the introduction of larger, motorized vessels ever larger beam trawls came to be used in the North Sea. Due to their high weight and the attached chains they plough up the seafloor and crush many of the larger benthic organisms. Studies conducted in Belgium, Germany and the Netherlands have shown that this is the reason for the significant decline in larger, long-lived or sensitive benthic species observed since the middle of the last century. The sensitive organisms include the tiny moss animals, organisms that form delicate colonies on the seafloor, some of which resemble corals in shape.

Ocean quahog populations are also affected. This species of clam lives buried only a few centimetres deep in the ocean floor and their shells therefore are easily crushed by beam trawls. Normally, ocean quahog can grow to a size of more than 10 centimetres and live for up to 120 years. But as a result of intensive beam trawling they have been decimated in the inshore areas of the North Sea; with multiple beam trawl passes per year and area the populations are hardly given a chance to recover. Today the heavily fished areas are dominated by fast-growing bristle worms and small bivalves such as the tellinids which measure only 1 to 2 centimetres in size. Starfish and hermit crabs have also increased in abundance, both of which feed on the remains of the organisms killed by beam trawls. Hermit crabs are protected from beam trawls as they reside in thick-walled empty seashells. Starfish survive as they are relatively robust; if any of their arms are severed by a beam trawl they can regenerate these arms and survive.



2.42 > The English port town of North Shields in 1904. At the beginning of the twentieth century North Sea fishing was still mostly carried out by means of sailing boats.



2.43 > Beam trawls are bottom trawling nets that are dragged along the seafloor on heavy metal frames. They kill many of the animals living on and in the seafloor.

The end of a clam paradise

Just how fishing can destroy an almost paradisic habitat, marine biologists were able to document using unique historic datasets for the Dogger Bank, a relatively shallow area in the North Sea. The Dogger Bank has only been used for fishing since the middle of the last century, primarily to catch sandeels to be processed into fishmeal. Thanks to a detailed study conducted by British researchers in the 1920s we have knowledge of the then pristine condition of this region. At the time, the scientists found extensive mussel banks on the Dogger Bank's seafloor that hosted a multitude of large bivalve species – the thick shelled trough shell *Spisula subtruncata* for example or its up to 6 centimetres long relative *Mactra stultorum*. Another frequent species was the common necklace shell, a predatory species feeding on the two trough shell species. Large numbers of moss animals and colourful sea anemones settled on the mussel banks, while many different crustaceans and fish species used this habitat as their hunting ground. As a result of the intensive sandeel fisheries the mussel banks have disappeared and have been replaced by monotonous sandy areas. Comparative studies conducted in recent years have shown that the two trough shell species now only occur as juveniles, if at all. They develop from larvae carried to the Dogger Bank by currents passing from other regions of the North Sea. Adult specimens have become very rare. Today the biocoenoses are dominated by small hardy species instead, such as small amphipods, small tellinids or brittle stars, a particular type of starfish with long thin arms.

The biocoenosis as a functional unit

In how far such changes should be considered acceptable or intolerable is a matter of perspective. While the loss of original biocoenoses is indeed regrettable, ecologists say that first and foremost it is primarily important for a habitat to continue to function as a whole. The term used by experts in this respect is biodiversity and ecosystem functioning (BEF), i.e. the functioning of a habitat including its potentially changing suit of species. One example of such a function is the cleaning function performed by bivalves as they draw seawater into their shells and filter it. Both small and large bivalves can perform this cleaning function. For the Dogger Bank this means that at present many small tellinids perform the cleaning function previously performed by the significantly larger trough shells of old. The cleaning function is not lost despite the fact that the habitat has changed significantly.

However, as recent studies conducted at the Dogger Bank have shown, the biocoenoses in the area are no longer impacted just by fishing alone but also by climate change. Species at home at more southerly latitudes are slowly migrating into cooler, more northern marine areas such as the North Sea. It remains uncertain how such migrations will impact on the area's diversity and ecosystem functioning.

Nutrients destabilize the ecosystem

Habitats lose their function when changes exceed stress limits. In many areas, one of today's major stressors is eutrophication, i.e. the enrichment of a water body with nutrients. These nutrients originate in wastewater contaminated with faecal matter or in the form of crop fertilizers applied to fields from where they reach rivers and are transported into the sea. Where there is an oversupply of nutrients, algal growth can be so rapid that it results in algal blooms. The more abundant the algae, the greater is the quantity of algae that die at some point, and the more intensive is their subsequent decomposition by oxygen-consuming microorganisms and therefore overall oxygen consumption. As a result, oxygen-deficient or oxygen-depleted zones can develop in coastal waters in which fish, crustaceans and molluscs can no longer survive.

For a number of decades now such zones have been observed in many places worldwide, for example on the west coast of India, in Chesapeake Bay on the eastern US

2.44 > Mussel graveyard in the Finnish Baltic Sea: Once the water's oxygen concentration had fallen below a critical threshold, the sand gapers emerged from the seafloor sediment in an attempt to reach fresh water. Due to the low oxygen concentrations they perished nonetheless.

seaboard and in the Gulf of Bohai on the east coast of China. The oxygen-depleted zones often develop at greater water depths where wind and waves cannot mix the water and enrich it with atmospheric oxygen. In recent years, these zones have been found on the German Baltic coast during the summer and also in inshore areas at depths of just a few metres. The lack of oxygen in shallow coastal areas is particularly problematic as it also kills benthic organisms the activities of which would normally contribute to the decomposition of nutrients in marine waters and would thus combat eutrophication. These organisms include bivalves and worms that live burrowed into the seafloor substrate into which they fan fresh water. The many passages increase the overall area available for benthic microorganisms to break down nitrogen compounds. But if these bivalves and worms die, this filter function is lost, resulting in a negative feedback loop in oxygen-deficient coastal areas: Oxygen-deficiency results in the soil organisms' death, which adversely impacts the substrates' cleaning function and in turn leads to a further deterioration in water quality.

Nutrient loads from aquaculture

While coastal waters in most countries are primarily impacted by nutrients from agricultural sources, intensive aquaculture exacerbates the problem of eutrophication in many regions. This is particularly true for China's coastal areas where aquaculture installations are lined up like pearls on a string, such as is the case on Hainan Island, a Special Economic Zone in China's tropical south and a destination for many domestic tourists.

With an area of 34,000 square kilometres, Hainan is larger than Sicily. It is the largest island of the People's Republic. A wide mangrove belt constitutes the natural coastal vegetation, followed on the seaward side by shallow sandy areas covered by seagrass meadows and, further seaward still, by extensive coral reefs. In recent years, this natural zonation of mangroves, seagrass and corals has, in part, been hugely altered as a result of the expansion of aquaculture. An entire biodiverse ecosystem was lost when the mangroves were cut down. Moreover, nutrients from aquaculture installations, primarily in the form of faeces and excess feed, can now flow directly into the sea. Where normally the mangroves would have taken up much of this nutrient load through their root system, the nutrients now directly enter the seagrass meadows. It is a known fact that under the influence of high nutrient loads small algae thrive that overgrow and ultimately kill the seagrass. Moreover, the oxygen-deficiency caused by eutrophication results in a drop in oxygen concentrations not only in the water column but also in the seafloor, creating conditions that lead to the production of toxic compounds in the sediment which can be lethal to seagrass. Studies are currently being undertaken to determine the extent to which the seagrass meadows in the Hainan area have already died off or may die off in the future.

Just how much of the nutrient load the seagrass meadows can absorb is another unanswered question. This capacity to take up nutrients is important for the survival of the coral reefs since the seagrass meadows function as a buffer between them and the land. Corals would be impacted by excess nutrients and particularly by the resultant excess algal growth and could die off. This is an additional threat to the coral reefs of Hainan which are already impacted by overfishing as well as cyanide and dynamite fishing, similar to the Spermonde Archipelago.

Coastal waters as sewage basins

Coastal waters are not only impacted by excess nutrients but also by untreated sewage and industrial effluent. While wastewater treatment technologies in industrial nations tend to be highly developed and remove a high proportion of pollutants from wastewater before it enters rivers or the sea, there are many regions in developing countries in which wastewater treatment is insufficient. According to the World Bank, in Africa only about 10 per cent of wastewater reaches treatment facilities. Studies have shown that in the Ghanaian capital Accra untreated wastewater is responsible for the bacterial and viral load of rivers and other watercourses serving as drinking water sources for the population. Frequent cases of diarrhoea are the result. Approximately one quarter of all deaths of children aged under five years in the greater Accra area are attributed to this problem. Moreover, there have been repeated cases of cholera.

In many regions there is not only the threat from pathogens but also the problem of pollutants that directly enter the sea via rivers or sewers. These pollutants include heavy metals, for example from mining or metal production, as well as numerous compounds originating in the chemical industry. Several environmental disasters have shown just how dangerous these substances can be. One such case is that of Minamata, a port town in western Japan. In the 1950s, a local factory discharged mercury-containing wastewater into the sea. The poison was first taken up by algae. Then the algae were consumed by fish the local people valued particularly highly as culinary fish. The mercury concentration in the fish was so high that more than 10,000 people suffered from mercury poisoning. Thousands of them died. Today this type of severe mercury poisoning is known as Minamata disease.

A lot more than a "dirty dozen"

According to the Organisation for Economic Co-operation and Development (OECD), around 100,000 different chemical substances are being produced worldwide; in Europe alone about 10,000 of these are produced in quantities of more than 10 tonnes per year. Up to 3 per cent of the global production is of concern; these environmentally relevant pollutants include, for example, compounds of lead, mercury and other heavy metals arising in the course of mining, in industrial manufacturing processes and when burning heating oil.

Persistent organic pollutants (POPs) are particularly critical. They are defined by the following problematic characteristics: They are persistent and toxic, they accumulate in living organisms and they can also volatize into the atmosphere and travel long distances. Since POPs are strongly resistant to breaking down in the environment they can continue to enter the food chain for many years.

A group of twelve particularly dangerous compounds of this nature, known as the "dirty dozen", were the first such substances to be banned worldwide under the Stockholm Convention. Polychlorinated biphenyls (PCBs) are among the twelve. Today a total of 24 substances are banned under the Convention.

Fighting fire with fire?

In 2007 the EU REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) entered into force in the European Union; it was adopted in order to improve the protection of human health and the environment from risks potentially posed by chemicals. The Regulation requires industrial companies manufacturing or using chemical substances to register these substances and provide evidence of their harmlessness. However, companies may put substances that have already been in the marketplace for some time to new uses without having to furnish any additional evidence.

Therefore, substances that are banned today on account of their toxicity may be replaced by established substances with similar characteristics. But these replacements may equally be of concern. Polybrominated diphenyl ethers (PBDEs) are an example of this problem. For a long time these bromium containing compounds were used as a flame retardant. Experts had found that PBDEs are persistent and carcinogenic, which is why they were banned some time ago. As an alternative, the industry then began to use Dechlorane Plus, an established substance originally used as an insecticide in the 1970s, the use of which in the outdoors had since been banned in the EU. Dechlorane Plus is persistent too and in water it attaches to suspended solids together with which it is primarily deposited in coastal sediments. Scientists have shown that eels in European coastal waters are contaminated with Dechlorane Plus.

This example highlights the weakness in common practice whereby banned substances may be replaced with established substances that are similarly problematic. As a consequence, discussions are underway as to whether Dechlorane Plus should also be banned internationally under the Stockholm Convention. Denmark has launched an initiative to this effect.

2.45 > For decades, mercury-containing wastewater had been pumped into the bay off the Japanese fishing town of Minamata. Making its way through the food chain, the poison was ultimately ingested by humans.

A ban on chemicals posing environmental hazards is normally preceded by years of discussions. Countries in which the relevant substances are produced or processed often oppose a ban. However, the Stockholm Convention contains a provision under which particularly hazardous POPs can be banned within a shorter timeframe if they are extremely bioaccumulative and extremely persistent. These substances are termed very P/very B (very persistent/very bioaccumulative).

The chemical compound PFOS (perfluorooctane sulfonate) is an example of substances of this kind. It was primarily used in the textile industry, for example in the manufacturing of breathable membranes for outdoor jackets. But it was also used in the paper industry for the production of stain, grease and water repellent papers used for example in fast-food packaging. In addition it was used for surface treatments for furniture, carpets and clothing. Because of the persistent nature of PFOS it has strongly accumulated in nature. It has been detected in water, soils, air and living organisms worldwide. Comparatively high concentrations can be found in the top links of the food chain, such as fish, seals, marine birds and polar bears and of course also in humans.

When it became obvious at the end of the last century that PFOS are among the vP/vB compounds, the substance was banned. The chemically closely related compound PFOA (perfluorooctanoic acid) was similarly taken off the market. A period of only five years passed between various groups of researchers providing evidence of the substance's potential hazardous nature and its ban. For other POPs that are not considered to be vP/vB this process can take up to 20 years.

Shifting problems

PFOS and PFOA primarily accumulate in the blood and liver. Following their ban, they were replaced by chemically closely related compounds in the perfluorocarbon group (PFCs) which includes PFOS and PFOA. The industry now uses PFCs that less strongly accumulate in the blood and liver and thus are less bioaccumulative. However, this poses a new problem: These PFCs are relatively well soluble in water. Studies have shown that concentrations of these water-soluble PFCs have increased strongly, especially in China's rivers and coastal waters. The introduction of new PFCs has therefore only shifted the environmental problem from bioaccumulation in organisms to elevated concentrations in the water.

Regardless of the type of pollutant, it has been shown that the concentrations of many problematic substances in rivers and coastal waters in the EU and the USA have declined in recent years. This is due in part to improved wastewater treatment technologies and the improved treatment of industrial effluents but it is also due to the fact that the production and processing of many chemicals has been shifted from western industrialized nations to countries such as China and India. Therefore it is hardly surprising that the situation has worsened in these countries even though, at least in part, modern wastewater treatment technology is being used.

But even modern technology is not capable of completely removing all contaminants from wastewater. Given that China produces particularly large quantities of chemicals, the quantity of pollutants entering the environment remains relevant, including the total amount of PFCs. Many estuarine coastal areas are contaminated by PFCs, for example the Yangtze River Delta in eastern China. This is where the PFCs are produced and used by several textile companies. Other rivers along China's east coast are also heavily polluted. The PFC concentration in the Xiaoqing River Delta, for example, is 2000 times as high as that found in the estuary of the Elbe River in Germany, a situation that is attributed first and foremost to the relocation of production to China. There has not yet been any in-depth research on the potential environmental impact of these high concentrations in the water or on the overall severity of this accumulation.

Surface mining poisons entire regions

Large-scale mining operations are another significant contributor to pollution in rivers and coastal waters. Mostly these involve the mining of economically interesting chemical elements such as iron, copper or gold. Since these elements do not occur naturally in their elemental form but are bound to other elements they must be separated and concentrated. The resultant mining waste is deposited either as dry waste in spoil heaps or together with partially toxic wastewater and sludges in basins or tailings ponds. Time and again such basins and pits fail, releasing into the environment the substances they contain.

There are also cases where wastewater is directly discharged into rivers, one example being the Ok Tedi mine in Papua New Guinea which has discharged directly into the Ok Tedi and Fly rivers since the 1980s. These rivers, together with their tributaries, form one of the largest tropical river systems worldwide. At times the inland mine discharged such vast quantities of sludge into the rivers that it deposited on the riverbanks, polluting not only the river water but also the surrounding environment with copper residues in particular. It is assumed that the decline of the river's fish populations is due to this contamination.

Similar environmental pollution is evident in the southwest Indian coastal region in the Panmana village area in the state of Kerala. Heavy-metal-rich placer deposits, mineral-rich sediments deposited over millions of years, have been mined here since 1922. The placer deposits were initially mined for metal. Since the 1980s, the interest has shifted to ilmenite, a titanium-iron oxide mineral. Ilmenite is the main source of the widely used whitener titanium dioxide, a pigment used in wall paints, automotive paint and toothpaste. Since 1984, ilmenite has been processed directly at a local factory. The resultant heavy metals are no longer used. Together with other chemical elements, the heavy metal-containing wastewater is discharged into storage basins which, however, have been leaking for more than a decade. During this time this leakage has slowly contaminated water wells and soils over an area of 16 square kilometres around the factory. The heavy metal concentrations in the area exceed international threshold values multiple times over. The contamination of soils and water not only result in plants dying in many places, but more and more people are suffering from excema and are getting cancer. Many of the local people have left their home region as a result.

Inland sludge spill contaminates the coast – the Rio Doce case

Even mines situated well inland can pollute coastal regions, as demonstrated by an iron ore mine located near the Brazilian town of Mariana 250 kilometres north of Rio de Janeiro. On 5 November 2015 a dam holding waste sludge from opencast iron mining burst, spawning a mud tsunami into the Rio Doce, a river that flows into the Atlantic Ocean. According to the United Nations Human Rights Council (UNHRC), approximately 50 million tonnes of iron ore sludge, roughly equating to the volume of 20,000 Olympic-size swimming pools, spilled downhill and buried the village of Bento Rodrigues located 5 kilometres away from the mine as well as large swathes of land. The red sludge wave traversed 600 kilometres of the Doce River before spilling into the Atlantic. Sixteen people lost their lives in the disaster.

Since the sludge was laced with high concentrations of heavy metals and other toxic substances, the affected areas around Bento Rodrigues are still inhabitable to this day and agricultural land use is impossible. The impacts of the pollutants on the affected Atlantic estuary are not yet known. There are fears that large quantities of pollutants have been deposited on the ocean floor. If marine animals ingest these with their feed, fishing will also be affected as fish and seafood would no longer be fit for sale.

2.46 > Environmental disaster in the Brazilian state of Espírito Santo: Toxic iron ore sludge spills from the Doce River into the ocean.

Mysterious marine litter

In recent years, scientists and the media have paid particularly strong attention to marine pollution caused by plastic waste, not least owing to the fact that this threat is often directly visible and the relationship between cause and effect is easily understood. Current discussions revolve around potential risks caused by the plastic debris and the question of how just much litter is floating around the oceans. Marine litter is categorized as follows:

- macroplastics are greater than 25 millimetres in size,
- mesoplastics are 5 to 25 millimetres in size,
- large microplastics are 1 to 5 millimetres in size,
- small microplastics measure from only a few micrometres up to 1 millimetre.

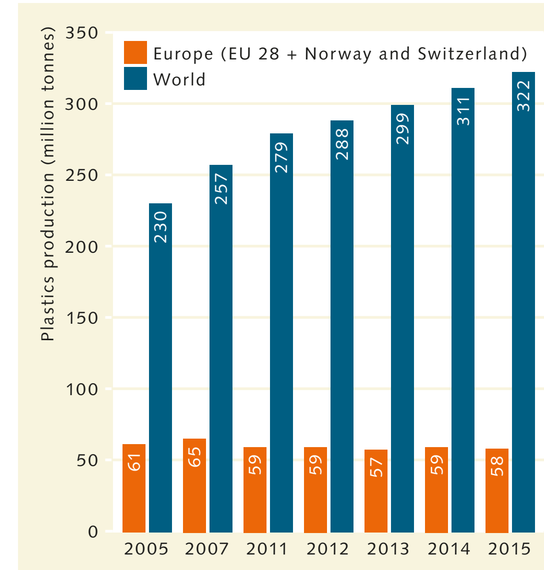
The impact this waste has on marine organisms depends on its size and nature. Macroplastics can become deadly traps for marine organisms. Discarded fishing nets for example can entrap marine turtles, leading to their death by asphyxiation. There is an on-going debate as to whether marine macroplastics and mesoplastics might be capable of not only killing some individuals but putting whole populations of marine animals at risk. A recent study has shown that presently as many as 90 per cent of all seabirds are already ingesting pieces of plastic. The degree to which different seabird species are at risk depends on their feeding behaviour.

For some time now investigations have been underway on the impacts of microplastics on marine life. In a laboratory experiment, mussels were exposed to high concentrations of microparticles. The particles were absorbed from the digestive tract into tissues where they triggered inflammatory responses. These experiments have been criticized for working with extremely high particle concentrations, i.e. significantly higher than the concentrations found in the oceans. For comparative purposes, similar experiments were conducted in which the mussels were kept in water with significantly lower particle concentrations, i.e. concentrations similar to those found in the North Sea. The mussels suffered no evident damage in these experiments.

2.47 > Heavy metal contamination is widespread in the soils in the village of Panmana in the Indian state of Kerala. Plants can hardly grow here anymore.

Waste beyond measure

In general, it is impossible to precisely measure and quantify the amount of litter present in the oceans. Nonetheless, in 2015 US American scientists attempted to come up with an estimate as part of a study. To this end, they looked at the production side and calculated that the 300 million tonnes of plastic materials produced worldwide every year result in the generation of 275 million tonnes of plastic litter, i.e. approximately 90 per cent of the production. For their study, the researchers had analysed the existing waste disposal infrastructure and recycling quotas in a range of countries. From this information they deduced that approximately 4.8 to 12.7 million tonnes of plastic litter end up in the oceans each year. While these figures have often been cited since their publication, criticism has been levelled at the study to the effect that production data in conjunction with information on waste recycling do not allow for conclusions as to the quantities of waste that ultimately end up in the oceans, given that litter finds its way into the marine environment through very different pathways: by way of rivers, through direct disposal into the oceans, or by being blown out to sea from landfill sites. It is impossible to quantify all these pathways. Owing to the fact that a major proportion of the plastic waste has sunk to greater depth where it can no longer be discovered, it is similarly impossible to quantify the amount of waste that has entered the oceans in the past.



2.48 > The amount of plastics produced worldwide has been increasing for years. It is reasonable to assume that the amount of plastic waste reaching the oceans has similarly increased. However, there are no reliable data.

Exaggerated estimates?

Many different sources contribute microplastics to the marine environment: the slow degradation or disintegration of larger plastic marine litter items under the influence of saltwater and UV sunlight, ship coatings, abrasion from plastic items and car tyres, and also plastic microbeads in scrubs. The difficulty in determining the overall quantities of microplastics is primarily due to the fact that different groups of researchers have thus far used different methods and devices to record and study microplastics. Some scientists extrapolated particle concentrations in water to cubic metres, others to square kilometres. Some stated the absolute number of particles found while others stated their weight in milligrams per kilogram. As a result, the comparability of figures is very limited at present. To remedy this situation an EU project is underway which aims to develop the first harmonized measurement standards. These will concern not only the way waterborne particles are counted but also their correct identification. For a long time researchers have tried to use microscopes to record the number of particles. However, this optical method overestimated the quantity of particles by up to 70 per cent as quartz sand was often misidentified as plastic. New devices that use infrared light and are capable of precisely identifying plastics are to avoid such errors in the future.

Tourism: recreation at the expense of coastal habitats

While the risk to coastal habitats posed by plastic litter is as yet largely unknown, the adverse impacts of tourism have been evident for years. The construction of hotels and roads, especially in highly popular holiday regions, has considerably altered many coastal landscapes. Wetlands have been drained and built over and beaches are visited by high numbers of people. The organisms dependent on the coastal strip, i.e. the immediate transition area between water and land, are strongly impacted by these developments. Many bird species, for example, depend on coastal wetlands such as lagoons or estuaries as breeding or resting areas. Seals similarly use the coastal strip for hunting or resting, and marine turtles need pristine sandy beaches on which they can bury their eggs. In some regions such sites have become very rare. At the beginning of the nineteenth century, many Mediterranean regions still hosted large populations of green sea turtles, loggerhead sea turtles and leatherback sea turtles. As a result of the transformation of natural sandy coastal areas into tourist resorts these species have almost completely disappeared. In the Mediterranean, green sea turtles can now only be found off Cyprus, loggerhead sea turtles have become limited to small areas off Greece and Turkey, and in exceptional cases leatherback sea turtles may still be found off Syria or Israel.

The transformation of natural coastal margins into tourist sites, some of which have taken on an urban character, also gives rise to other impacts on the coastal

2.49 > Intensive tourism can severely damage coral reefs – for example when holidaymakers carve graffiti into marine organisms.

environment. In many places, concrete walls and harbour infrastructure have been built for the purposes of coastal protection, as seafront esplanades or as marinas. Such developments have completely altered the habitats of many different aquatic organisms. Caves, refuges and feeding grounds were lost. Even where the seashore is primarily rocky, concrete buildings alter biocoenoses. The chemical composition of the surfaces of concrete structures differs from that of natural stone. Many marine organisms that attach to solid surfaces therefore avoid concrete structures, which tend to be significantly less species-rich overall as a result.

Great pressure on coral reefs

The gradual destruction of coastal habitats is caused not only by building development but also by intensive tourism use. Coral reefs are among the heavily frequented habitats. The impacts of intensive diving tourism were studied in greater detail at the Great Barrier Reef on Australia's East Coast. The reef was found to be subject to different types of destruction:

- In areas where boats set off, corals are destroyed by holidaymakers wading from shore to boats and back. Corals are completely destroyed in heavily frequented sections. Anchored pontoons, floating restaurants and bars etc. permanently shade out sections of reefs. Corals die off in such sections.
- Anchors that are carelessly dropped by pleasure boats or diving boats may directly destroy corals.
- Where fish are fed for observation purposes, inappropriate or spoilt feed may result in the spread of diseases on the reef. Moreover, feeding may attract large predatory fish that do not normally frequent the reef sites concerned, which in turn leads to a significant decline in certain fish species.
- Divers, and inexperienced divers in particular, come into contact with reef material and break off especially the finely branched corals.

While the Australian researchers emphasised that optimized local management could avoid all this damage, other experts argue that diving tourism on coral reefs is damaging as a matter of course, independent of the degree to which the tourists are informed and guided. They also emphasise that minor damage caused by diving tourism in conjunction with other stressors, such as an increase in water temperatures caused by climate change, can result in greater cumulative damage.

Conclusion

Immense performance, immense pressure

Humans have been closely associated with coastal ecosystems for millennia. They have used the coasts both as a source of food and a space for trading. Archaeological finds indicate that humans navigated coastal waters in simple boats as early as 6000 years BC, for example in the South China Sea and the eastern Mediterranean. Coasts have also always been the arena of countless conflicts among parties seeking to gain political or economic dominance in a given region.

Coasts deliver many different types of services that are generically termed ecosystem services. These include the "provisioning ecosystem services", i.e. the goods provided by the oceans such as fish or fossil resources. The "supporting ecosystem services" are of key importance. They include primary production, i.e. the production of biomass by algae through the process of photosynthesis. Primary production is in fact a precondition to marine life. In addition, there are "cultural ecosystem services" such as the coasts' spiritual significance and their vital role in tourism. "Regulating ecosystem services" are clearly of special importance with regard to environmental pollution caused by humans. These services primarily include the cleaning function performed by coastal waters, as they significantly contribute to the degradation of nutrients reaching the oceans from intensively used arable farmland or untreated sewage.

In many cases, humans are overexploiting coastal waters at present, thus preventing them from performing their ecosystem functions. If nutrient inputs into the oceans from agriculture or aquaculture are too high, these nutrients can no longer be eliminated. Watercourses suffer from eutrophication, resulting in the spread of oxygen-depleted zones. Moreover, industrial pollutants are a threat to coastal waters. The latter include heavy-metal-containing compounds as well as persistent chemical substances that accumulate in the food chain and cause illnesses such as cancer. Such substances include, for example, polyfluorinated compounds which have been used for years in common products such as outdoor clothing or cookware coatings.

Plastic litter is another type of pollution reaching the oceans through diverse pathways. Marine animals and seabirds ingest plastic particles and die as a result. Moreover, plastic litter breaks down into microscopically small fragments. These microplastics are now present throughout the world's oceans. Scientific studies are underway to determine the degree to which animals are ingesting and are at risk from microplastics.

Overfishing is doubtlessly one of the most significant problems currently faced in coastal waters. These waters are particularly productive, and are thus fished too intensively. Moreover, in many places fishing activities destroy seafloor habitats such as coral reefs.

Uncontrolled proliferation of settlements and the growth of coastal megacities are profoundly changing the coasts today and have led to the loss of important ecosystems such as floodplains, wetlands and mangroves. Moreover, sand extraction for building projects causes widespread damage to coastal areas. A particular threat to human society is arising from the gradual sinking of coastal metropolises. This subsidence is caused, in particular, by the pumping of groundwater for human consumption. Normally the groundwater functions as an abutment to the heavy mass of buildings above. Incidences of flooding are becoming ever more frequent as a result of urban subsidence. Rising sea levels in the wake of climate change may exacerbate this situation in future.

3 Climate change threats and natural hazards

> Climate change will have a twofold adverse impact on coastal ecosystems through warming and acidification. However, for humankind the greatest direct threat will come from sea-level rise which is likely to cause more frequent flooding in many regions in the future. As a result of ever denser coastal settlement, natural hazards may in future lead to catastrophes. Modern warning systems may help to limit the damage caused.

Climate change and the coasts

> Anthropogenic emissions of the greenhouse gas carbon dioxide and the associated global warming are resulting in gradual sea-level rise, with coastal areas being particularly affected. In addition, acidification and the warming marine waters will have far-reaching consequences for the communities of organisms that live in coastal ecosystems.

Unbridled carbon dioxide emissions

Coasts are adversely affected by many stressors. These include not only local construction or pollution. In addition, coasts are increasingly facing global threats from climate change – sea-level rise, ocean acidification and ocean warming. These trends are primarily due to the still unrestrained burning of the fossil fuels natural gas, petroleum and coal, which adds large quantities of the greenhouse gas carbon dioxide (CO_2) to the atmosphere. Since the beginning of the Industrial Revolution, the atmospheric CO_2 concentration has risen from 280 **parts per million (ppm)** in 1800 to a level of 400 ppm today. This increase has resulted in gradual climate change, with the attendant consequences.

Human-induced warming

As such, the greenhouse effect is a natural phenomenon which protects the planet against heat loss. Water vapour, carbon dioxide (CO_2) and other radiative-forcing trace gases in the atmosphere, such as methane (CH_4), allow short-wave radiation reaching the Earth from the sun to pass through the atmosphere. At the Earth's surface, this radiation is transformed into heat and largely radiated back to space at long wavelengths. Similar to the glass panels in a greenhouse, however, the gases prevent the long-wavelength heat radiation from escaping to space. The Earth heats up. By emitting large quantities of additional greenhouse gases, humans are amplifying this natural effect. CO_2, the source of which is the burning of natural gas, petroleum and coal, accounts for the biggest proportion of these additional gases. On the other hand, one of the sources of methane is intensive cattle farming; cattle belch methane as part of their digestion process. Methane is also produced as a result of wetland drainage and subsequent processes of decomposition.

Climate inertia

Due to the inertia that is inherent in our climate system, many impacts of human-induced global warming are slow to become apparent. Even if we managed to completely stop all carbon dioxide emissions today, near-surface air temperatures would continue to increase for at least another hundred years. The sea level would even continue to rise for several centuries. What is the cause of this? One factor is that due to slow deep sea warming the ocean waters are only gradually expanding. At the same time, the continental ice sheets in Greenland and the Antarctic probably react very slowly to atmospheric warming. As a result, the melting of the glaciers is a long drawn-out process that will continue for thousands of years.

Increasing ocean warming will substantially alter the conditions faced by many marine organisms. These processes are likely to result in sustained changes to the composition of the oceans' biotic communities (biocoenoses) and food webs. Such changes will be further amplified by ocean acidification, which effectively alters the chemistry of marine waters. This acidification is a result of the increasing uptake by seawater of carbon dioxide from the atmosphere. Simply put, when carbon dioxide dissolves in water it forms acid.

In recent years, the number of research projects investigating the impacts of climate change on the oceans has increased rapidly. Many of these studies primarily deal with the impacts on coasts and coastal waters. They also address the question of how far the impacts of ocean warming and ocean acidification are similar in coastal waters and the open sea, or whether they differ significantly between those two marine realms.

3.1 > In the ocean, a thermocline often forms between the warm surface water and cool water at greater depth. This distinct layer can be seen with the naked eye as the water's density changes with the temperature and certain particles concentrate at the thermocline as can be seen here off the Thai island of Ko Phangan.

OCEAN WARMING

Warmer water, increased stratification

While it is already possible to fairly accurately predict which coastal areas will be affected by a specific amount of sea-level rise, it is much harder to appraise the impacts of ocean warming. Enhanced stratification of ocean waters in future is however deemed a certainty. It will be more difficult for oxygen-rich layers at the water surface to mix with colder, deeper layers. This may result in a lack of oxygen at greater depths, as has already been observed in various marine regions of the world.

The stratification of waters is a natural process: during the summer months sea surface water warms up and forms a layer of water close to the surface that covers the heavier, colder deep water like a lid. The transition from the warm surface layer to the colder water below is quite abrupt, which is why the line separating warm and cold water is called the thermocline. These thermoclines range in thickness from only a few decimetres to many metres in different marine regions, with thermoclines in the open ocean with deep waters being considerably thicker than those in coastal areas.

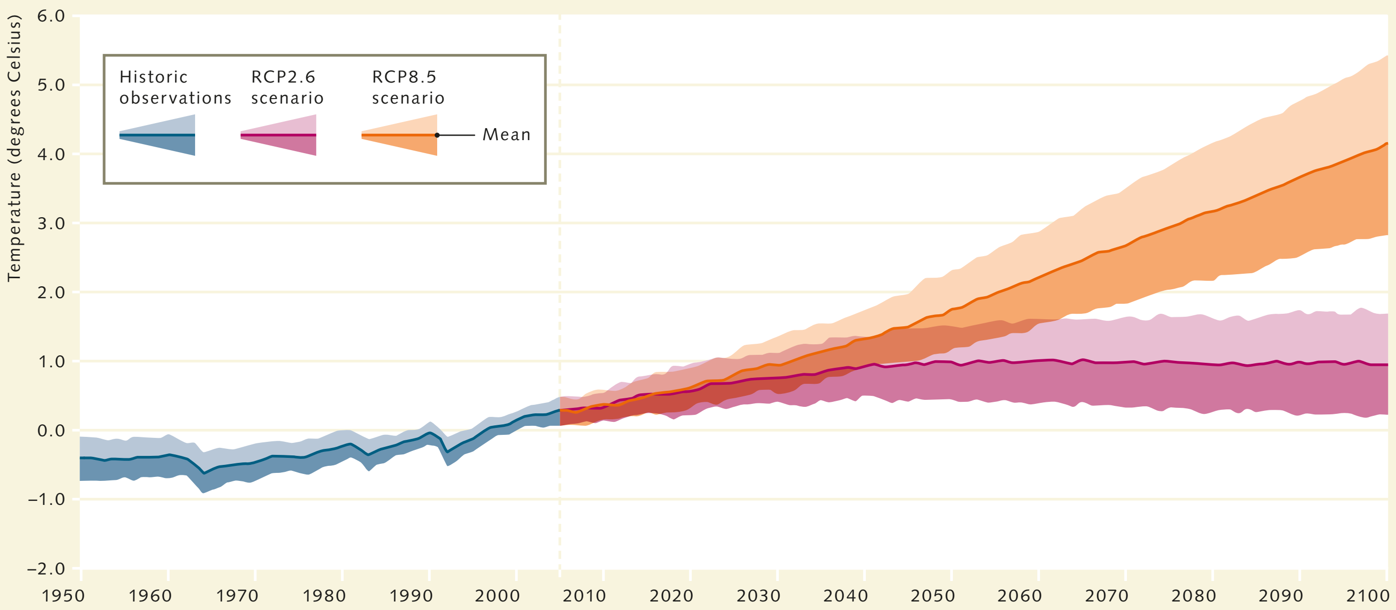
At the thermocline, a warm and less dense water layer rests over a colder water body of higher density. The thermocline thus functions like a barrier. The greater the temperature differential, the greater the difference in density and the more stable the thermocline. Ultimately hardly any oxygen-rich surface water can be mixed into deeper layers by means of wave motion, with the lack of light in the deep ocean also precluding oxygen production through photosynthesis. As the decomposition of organic material by microorganisms in the deeper water layers continuously consumes oxygen this is a serious issue which results in oxygen deficiency in the deeper layers of many coastal seas.

The IPCC Scenarios

At this point in time, no one can say with certainty how strongly the climate will change in future, especially as the amount of carbon dioxide (CO_2) emitted from the burning of fossil fuels (natural gas, petroleum and coal) in years to come is an unknown quantity. The demand for fossil fuels in turn depends on population growth, future energy needs and the degree to which renewable energies will be used. Moreover, land use, such as the destruction of rainforests and their conversion to arable land, also has a significant impact on the atmospheric carbon dioxide balance.

As it is not possible to accurately predict these developments, the Intergovernmental Panel on Climate Change (IPCC) has adopted four different scenarios that differ in the projected atmospheric CO_2 concentrations in the year 2100. These sample scenarios are termed Representative Concentration Pathways (RCPs). Specifically, the IPCC calls these four trajectories RCP2.6, RCP4.5, RCP6.0, and RCP8.5, with the numerical values indicating the degree to which the different CO_2 concentrations in the year 2100 will have altered the Earth's energy balance. The IPCC expresses this change as "radiative forcing". Radiative forcing is a measure of the degree to which additional energy is reaching the Earth's surface over time. It is expressed as radiant flux and measured in Watts per square metre (W/m²). It generally describes the amount of energy reaching 1 square metre of the Earth's surface per second, for example from natural sunlight. While radiant flux provides a momentary value, radiative forcing describes the degree to which radiant flux changes over time. For its RCP scenarios the IPCC compares the projected radiant flux values for the year 2100 with the radiant flux in 1860, when systematic weather recording began. The difference between these values provides an estimate of radiative forcing as a multiple of the 1860 value.

The relatively optimistic RCP2.6 scenario predicts that in the year 2100 at 421 ppm the CO_2 concentration will be only a little higher than today. This level would represent a 2.6 fold increase in radiant flux compared to the 1860 level. This scenario is based on the assumption that the global population will increase from its current level of 7 billion to just under 9 billion people and, correspondingly, that global energy consumption will have doubled compared to the year 2000 level. Renewable energies will then be able to meet close to half of the global energy needs. In contrast, the extreme RCP8.5 scenario is based on the assumptions that greenhouse gas concentrations will increase to more than 900 ppm by 2100, that in the same time period the global population will increase to 12 billion people and that energy consumption will have roughly quadrupled compared to the year 2000, with the majority of the global energy needs being met by coal. The two other scenarios project developments in between the two extremes. The RCP4.5 scenario assumes a CO_2 concentration of 538 ppm, i.e. a 4.5-fold increase in radiant flux, while the RCP6.0 scenario assumes a CO_2 concentration of 670 ppm, i.e. a 6-fold increase in radiant flux.



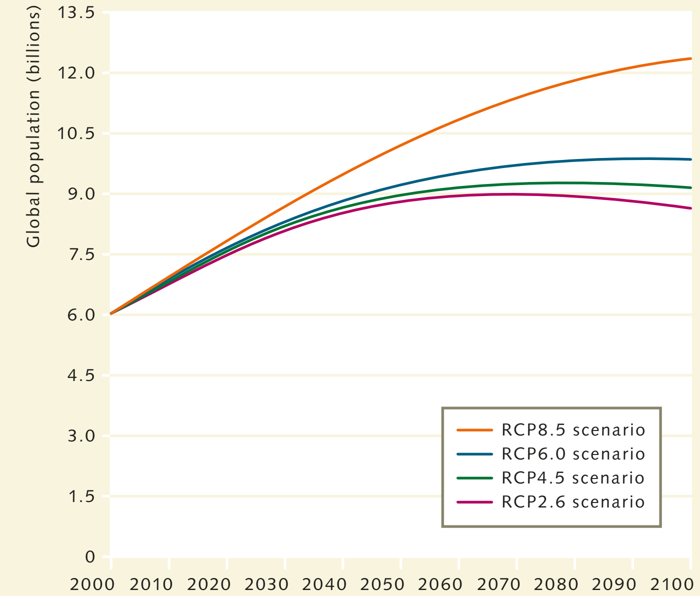
3.2 > The Earth's mean global temperature will definitely continue to rise – by more than 4 degrees Celsius relative to the 1986 to 2005 period under the RCP8.5 scenario. Only under the RCP2.6 scenario will it be possible to limit warming to below 2 degrees Celsius relative to pre-industrial levels.

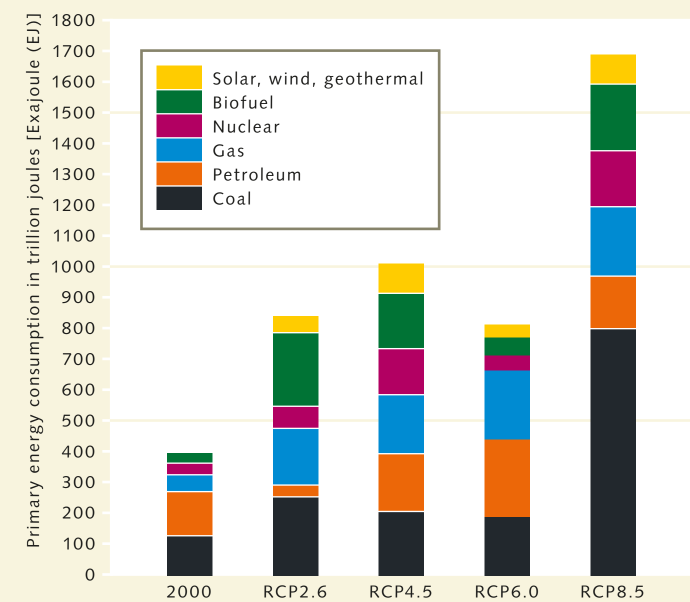
Gradual atmospheric warming is a direct outcome of the high level of CO_2 emissions and is followed by ocean warming. Due to its physicochemical properties, water can absorb large amounts of heat but warms up significantly more slowly in the process than the atmosphere. Thanks to this major capacity to absorb energy, the oceans act as a key global heat buffer which mitigates atmospheric warming.

The IPCC has found that the oceans have stored the major proportion of the energy accumulated between 1971 and 2010 as a result of human-induced global warming. Overall, the upper ocean (0 to 700 metres depth) stored 64 per cent and the lower ocean (700 to 2000 metres) stored 29 per cent of this energy. Three per cent contributed to ice melt and another 3 per cent contributed to the warming of the continental terrestrial surfaces, while only about 1 per cent contributed to atmospheric warming. If CO_2 emissions continue to rise it is highly probable that the oceans' deeper water layers will also gradually store some of this energy but the extent to which this will occur has not yet been clarified. For the upper ocean up to a depth of 700 metres, the moderate RCP2.6 scenario projects a global temperature increase by an average of 0.5 degrees Celsius by 2100. However, consideration must be given to the fact that different oceanic regions will experience different levels of warming depending on local conditions. In contrast, the pessimistic RCP8.5 scenario projects an increase of more than 3 degrees Celsius in the upper 700 metres of the global oceans by 2100. For some Arctic regions, RCP8.5 even predicts an increase in water temperatures by up to 5 degrees Celsius.

The scenarios also differ significantly in terms of the projected sea-level rise. The RCP2.6 scenario projects a sea-level rise of between 26 and 60 centimetres, while under the RCP8.5 scenario sea levels would rise by almost 100 centimetres. Overall, the current IPCC scenarios very clearly set out the specific impacts climate change will have on the oceans. The likelihood of certain impacts such as extreme storms or floods, however, can not yet be predicted precisely. Moreover, some impacts are more predictable than others. The degree of ocean acidification for example can be predicted by way of relatively simple chemical equations. In contrast, the degree to which cyclones will increase depends on a whole array of physical parameters. Therefore, the IPCC sets out its predictions for the occurrence of certain phenomena by likelihood, differentiating between the following categories:

- very high likelihood,
- high likelihood,
- medium likelihood,
- low likelihood,
- very low likelihood.

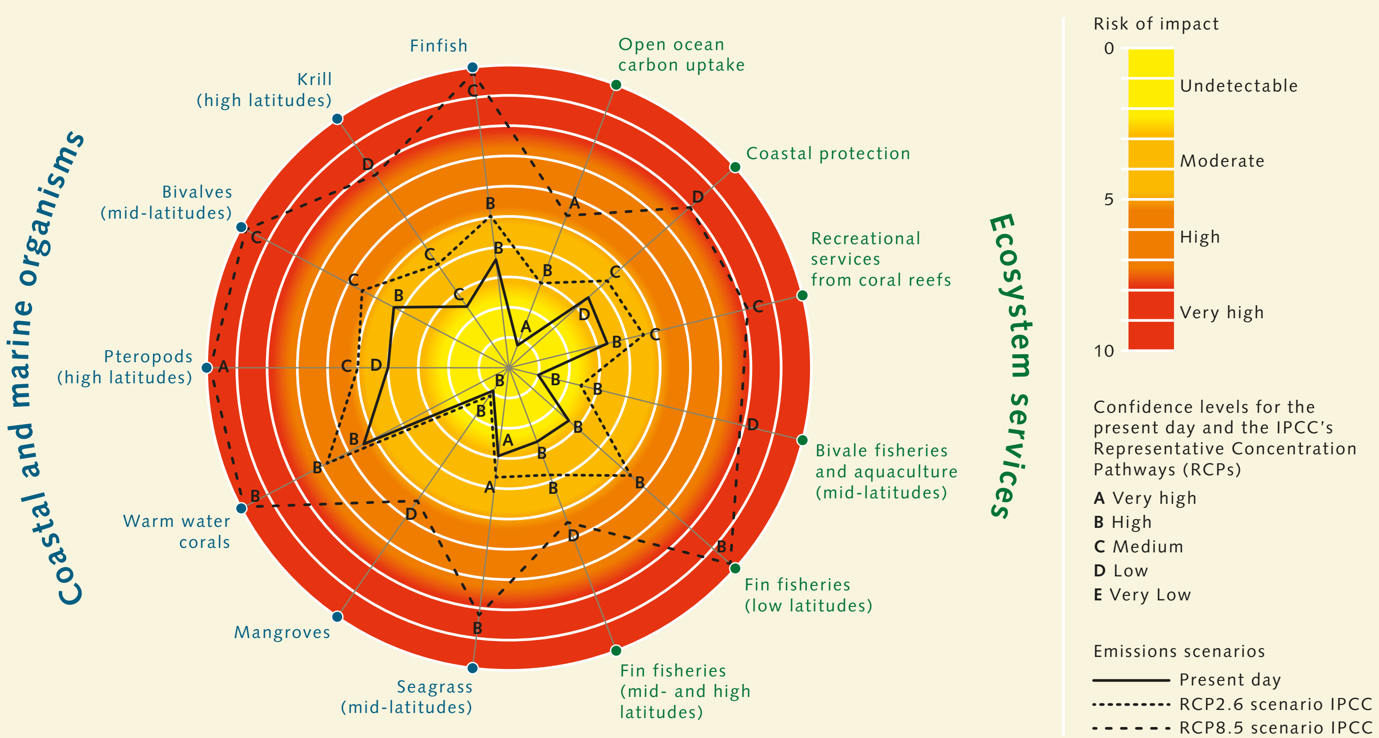




3.3 > The IPCC developed scenarios projecting climate change pathways based on a range of calculations. To this end, the IPCC more closely assessed causes and effects and found that the trajectory of climate change and the increase in average global temperatures are determined particularly by the trajectory of population growth and the associated increase in the consumption of fossil fuels. The RCP2.6 pathway is the most optimistic scenario and RCP8.5 the most pessimistic.

Emissions scenario	Representative Concentration Pathways (RCPs)	2100 CO_2 concentration (ppm)	Mean sea-level rise (m)		Emissions scenario	Mean sea-level rise (m)		
			2046–2065	2100		2200	2300	2500
low	2.6	421	0.24 (0.17–0.32)	0.44 (0.28–0.61)	low	0.35–0.72	0.41–0.85	0.50–1.02
medium	4.5	538	0.26 (0.19–0.33)	0.53 (0.36–0.71)	medium	0.26–1.09	0.27–1.51	0.18–2.32
high	6.0	670	0.25 (0.18–0.32)	0.55 (0.38–0.73)	(very) high	0.58–2.03	0.92–3.59	1.51–6.63
very high	8.5	936	0.29 (0.22–0.38)	0.74 (0.52–0.98)				

3.4 > For the period to 2100, the IPCC develops scenarios differing by their projected atmospheric CO_2 concentrations, which in turn depend on global population growth and associated energy consumption, among other factors. The highest sea-level rise is expected for the RCP8.5 scenario with the highest atmospheric CO_2 concentration. It is very difficult at present to predict post-2100 developments of the global population, energy consumption and other parameters. For the period after 2100, the IPCC therefore does not use the four nuanced RCP scenarios but three emissions scenarios. The high emissions scenario is however comparable to the RCP8.5 scenario as it is similarly premised on a high level of fossil fuel consumption. The high emissions scenario anticipates sea-level rise of up to 6.63 metres by the year 2500.



3.5 > Many organisms and ecosystem services of the oceans and of coastal waters in particular are highly at risk from climate change. The IPCC sets out different likelihoods of specific impacts occurring. The changes shown in the diagram need not necessarily mean that species will become extinct but they may result in changes in ecosystems as a result of the organisms in question migrating to other areas that still provide them with optimum conditions.

Today, ocean warming further exacerbates oxygen deficiency in deep waters. This is due to the fact that biochemical processes generally run faster at higher temperatures as the biochemical substances involved are more reactive. This is also true for the metabolism of bacteria. Bacteria decompose the remains of dead plankton that has sunken into greater ocean depths and use oxygen in the process. The higher the temperatures, the faster the bacterial metabolism and the more oxygen will be used up.

Unique measurements spanning six decades

For the German Baltic Sea, scientists have detected the current specific impacts of ocean warming by analysing a unique time series, the data points of which go all the way back to 1957. The scientists regularly measure the water's temperature, nutrient and oxygen contents as well as other parameters at the same location in the Eckernförde Bay. The data show that the water's nutrient content has decreased in recent years, very probably due to lower nutrient loads from terrestrial sources. Surprisingly, however, the deeper water layers are nonetheless affected by oxygen deficiency during the spring and summer months. At a depth of 25 metres, oxygen concentrations in the Eckernförde Bay have decreased significantly, with the lowest values found between May and September. At times oxygen is completely absent from the deep-water areas.

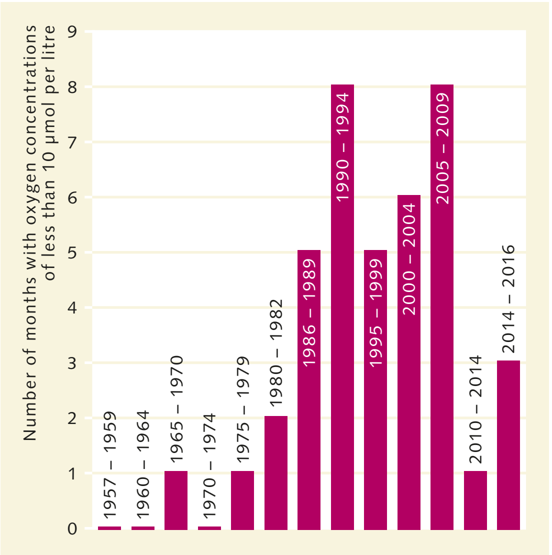
This is most likely caused by ocean warming which on the Baltic coast gives rise to two interconnected phenomena. Firstly the warming of the upper water layers results in a more pronounced thermocline which hampers oxygen transportation to greater depths during the summer months. Secondly this is accompanied by a biological phenomenon. Small filamentous algae that settle on macroalgae such as bladder wrack thrive particularly well in warmer waters. Normally such filamentous algae are grazed by small crustaceans. But when water temperatures increase, the crustaceans become more sluggish and hardly feed at all. This allows the filamentous algae to proliferate and ultimately overgrow the bladder wrack

3.6 > Scientists have regularly studied the water at a certain location in the Eckernförde Bay on the Baltic Sea coast since 1957. Nowadays they use modern water samplers that take water samples at different depths.

and other macroalgae. Bladder wrack, which is dependent on sunlight for photosynthesis, dies off, thus generating unnaturally large quantities of dead biomass which then sinks to deeper water layers where it is decomposed by bacteria. This increases the oxygen demand, with oxygen already being in short supply due to the more pronounced thermocline. These processes can give rise to oxygen-depleted zones, especially during July and August.

For several years now the scientists have observed a collapse of the biocoenoses in the water layers near the bottom of the Eckernförde Bay at the height of summer.

These observations in the Eckernförde Bay are congruent with measurements that have been analysed for



3.7 > In the Eckernförde Bay, the number of months per year in which the water at 25 metres of depth is oxygen-deficient has increased since the late 1950s. This is thought to be due to the warming of the Baltic Sea waters.

Cyanobacteria
Cyanobacteria are a group of bacteria that are able to photosynthesise. For this reason they were originally considered to be plants and were called blue-green algae. The term "blue" refers to the fact that some types of cyanobacteria contain the bluish plant pigment phycocyanin instead of the green plant pigment chlorophyll.

the entire Baltic Sea. US American weather satellites have been measuring Baltic Sea surface temperatures several times per day since 1990, thus building up a very good set of temperature data. These data show that the Baltic Sea surface temperature has increased by 0.6 degrees Celsius per decade since 1990. This figure is based on annual averages, as the Baltic Sea is subject to strong seasonal fluctuations and also displays clear regional differences. Over the study period of 27 years the surface temperature has therefore increased by 1.62 degrees Celsius. The increasing temperatures particularly favour the growth of cyanobacteria. In calm summer weather periods during which the water heats up particularly swiftly, these algae rise to the sea surface where they form mats, primarily in the central Baltic Sea. Winds can wash such algal mats onto the beaches. From the human point of view this is a problem because many species of cyanobacteria produce toxic substances. Overly rapid growth of cyanobacteria can result in toxic carpets of Harmful Algal Blooms (HABs). Swimming is prohibited in affected coastal areas. Moreover, HABs can poison marine animals such as fish, thus resulting in potentially significant losses for coastal fisheries.

Corals under heat stress

Tropical coral reefs are one of the coastal ecosystems particularly at risk from ocean warming. Not only are they sensitive to a rise in water temperatures, but in many areas they suffer additional pressures, particularly as a result of the pollution of coastal waters with toxic substances, nutrients and suspended solids. While globally only approximately 1.2 per cent of the continental shelves are covered by coral reefs, these reefs are enormously species-rich. It has been estimated that they host more than 1 million species of fish, bivalves, corals and bacteria.

Coral bleaching – a symbiosis is failing

Corals are marine animals in the *Cnidaria* phylum living in symbiosis with unicellular plants. These single-celled organisms, the zooxanthellae, reside in the tissue of corals. They are green-brown in colour and are able to photosynthesise. It is these organisms that provide corals with much of their colour. They also provide their hosts with sugars and in return they receive various nutrients. Coral bleaching occurs when this symbiosis fails and the zooxanthellae leave the corals, which as a result lose much of their colour. Recent research has been able to identify the various factors contributing to the failing of this symbiotic relationship. Ocean warming evidently plays a key role.

The optimum water temperature range for many tropical coral species is between 25 and 29 degrees Celsius. For many species, an increase of as little as 1 to 3 degrees Celsius can trigger bleaching. This appears to be caused by changes in the zooxanthellae's metabolism. At higher temperatures, many metabolic processes, such as photosynthesis, run faster and result in the production of increased amounts of cell-damaging radicals, i.e. aggressive molecules, a proportion of which enters the corals from the zooxanthellae. As soon as the corals register an increase in the production of radicals they trigger a protective reaction, expelling the zooxanthellae into the water column. Bleaching is therefore a mechanism protecting corals from cell damage.

3.8 > Surveys have shown that more than 70 per cent of the corals in Japan's largest coral reef, the 400 square kilometres Sekiseishoko reef, are affected by bleaching.

Coral bleaching is a natural and reversible phenomenon. Once the stressor abates, for example if water temperatures drop, the corals once again take up the zooxanthellae from the surrounding water into their tissues and recover. However, in many coral reefs bleaching now occurs much more frequently than in the past due to ocean warming in combination with other stressors. While in the past a reef may have experienced a bleaching event roughly once in twenty years, in many areas the phenomenon now tends to occur at intervals of only a few years, leaving the corals hardly any time to recover. Once the zooxanthellae have been expelled they can no longer provide the corals with sugars. The corals then begin to starve and weaken and become more susceptible to being attacked by pathogens such as bacteria.

Approximately 20 per cent of corals have been killed and a further 30 per cent are severely damaged as a result of ocean warming and other stressors. Moreover, a total of 60 per cent of all tropical coral reefs are locally at risk due to at least one of the following local aspects:

- overfishing;
- destructive fisheries practices that destroy the reef, such as anchored boats or nets;
- coastal development (construction);
- pollution of marine waters due to riverine inputs of pollutants or suspended solids;
- local pollution of marine waters due to direct inputs of wastewater along the coast or from merchant vessels and cruise ships as well as destruction resulting from bottom-contact by ferries or tourist vessels.

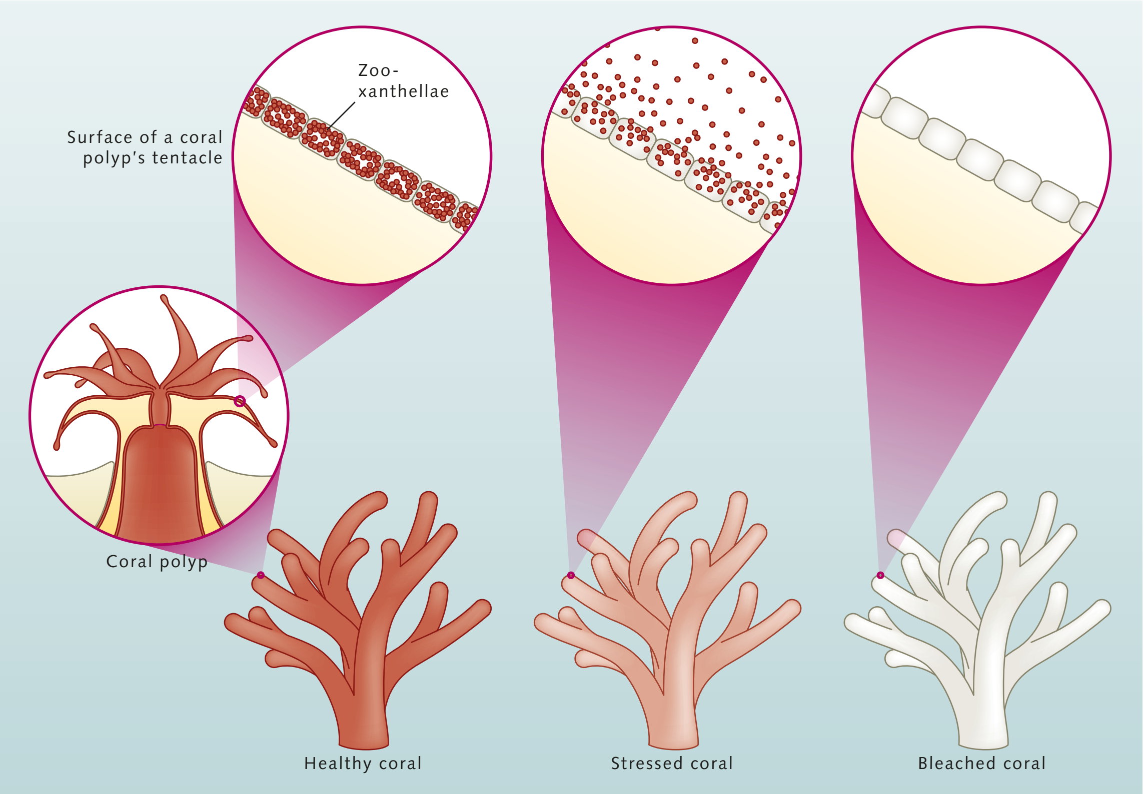
3.9 > Corals bleach when they come under stress – such as this stony coral in the Indonesian Raja Ampat Archipelago. The corals then expel the zooxanthellae, pigmented single-celled organisms with which they live in symbiosis.

Adaptation to warming

Fortunately corals can adapt to rising ocean temperatures to a certain extent. Recent studies have shown that some coral species selectively incorporate other species of zooxanthellae following a bleaching event. This form of adaptation is called adaptive bleaching. The corals appear to prefer species of zooxanthellae that only moderately increase their metabolism under conditions of rising water temperatures and thus produce fewer radicals. However, these zooxanthellae tend to have a lower metabolic rate which means they also produce less sugar. If in the course of the year temperatures drop again, this may put the corals at a disadvantage, as the zooxanthellae will then be less productive and provide lower quantities of sugar due to their lower metabolic rate. Research is currently underway into the consequences this may have. The insufficient supply of sugars might slow down the corals' growth. Moreover, adaptive bleaching has limits. If the water temperatures are constantly too high, the symbiosis may fail nevertheless, resulting in renewed bleaching. This may be due to the production of radicals in the zooxanthellae or to other metabolic processes that are as yet not fully understood.

In addition, eutrophication of coastal waters with nutrients from agricultural or aquacultural sources may contribute to the failure of the symbiosis. Nitrogen plays an important role in this context as it is a vital nutrient for zooxanthellae. If a lot of nitrogen is available, the zooxanthellae increase their metabolism and display strong growth. However, if in the course of this growth phosphorus, another important plant nutrient, is missing, problems may arise.

Phosphorus is an essential component of cell membranes. If it is in short supply during cell growth, insufficient amounts of phosphorus are integrated into the membranes, making them more permeable. As a result, increased amounts of free radicals can transfer from the zooxanthellae into the coral tissue, which in turn leads to the zooxanthellae being expelled, and to coral bleaching.



3.10 > Corals are basically colourless. Single-celled organisms (zooxanthellae) residing in the coral tissue are responsible for making them appear colourful. Zooxanthellae engage in photosynthesis and are of a greenish or reddish colour. If the coral comes under stress, for example due to elevated water temperatures or water pollution, it expels the zooxanthellae and bleaches as a result. Moreover, it now lacks the essential sugar compounds normally provided by the zooxanthellae. This weakens the coral.

Efforts are now underway to restore dead coral reefs. To this end, fragments of living corals are attached to the dead ones in the hope that they will grow and reproduce. Experts have also been searching for particularly stress-resistant coral species suited to these efforts. The Red Sea appears to host particularly robust species. Due to the seasonal variations in water temperatures – just over 20 degrees Celsius in winter and often more than 30 degrees Celsius in summer – many corals in this region are adapted to fluctuations in water temperature and would therefore be suitable for the restoration of damaged reefs. However, it is important to consider that there are several hundred species of corals worldwide. Experts consider that probably only very few species will be suitable for reef restoration efforts in that they are sufficiently robust to exist in other oceanic regions with other environmental conditions. Even if reef restoration for purposes of coastal protection was to be successful, the reef's species diversity will have been irretrievably lost upon its destruction.

Bleaching is not the only impact of ocean warming. There are numerous diseases that can cause corals to die. Bacterial infections in particular are on the increase, Acropora White Syndrome (AWS), for example, or the Black Band Disease (BBD), both of which quickly kill the Cnidaria upon infection. These diseases are therefore clearly more dangerous than bleaching, as the latter is reversible while the infections are generally lethal. These infectious diseases primarily affect reefs in the Caribbean where they can spread several metres in just a few days. It is thought that in such cases the corals are weakened by ocean warming and are not able to produce sufficient quantities of antibodies which would normally help them to keep the pathogens at bay.

Too warm for fish offspring

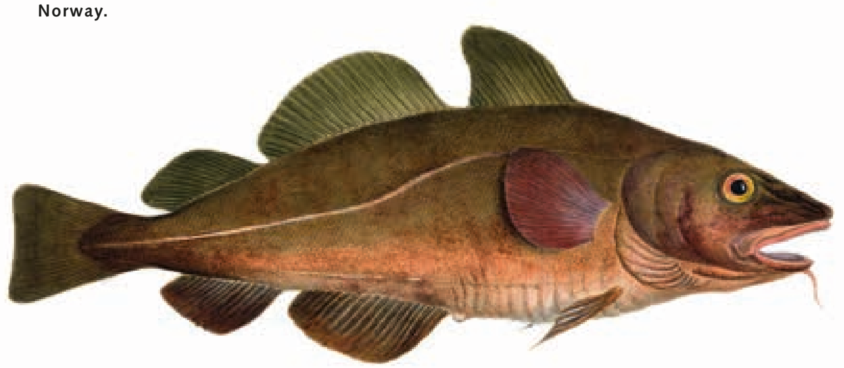
Marine organisms are adapted to limited temperature ranges. Changes in temperature can cause massive species shifts within the marine food web. The encroachment of marine organisms from warmer southern regions to cooler regions in the north has already been observed over a number of years. For many species, sensitivity to warming is somewhat variable through the individual life-cycle stages. The tolerance range of young developmental stages, particularly the egg and larva, is often very narrow and thus critical with regard to the impact of climate change on a particular species. This is the case for the codfish, native to the Northeast Atlantic and one of the most important food fishes worldwide. Cod spawn in the spring, with each fish releasing up to 5 million eggs in water temperatures between 3 and 7 degrees Celsius because embryo development in the eggs is most successful within this range. The most important spawning areas in the Northeast Atlantic are located near the coast of Norway around the Lofoten Islands, and in the Skagerrak and the Kattegat between Denmark, Norway and Sweden.

Past experiments have shown that the embryos of cod are highly sensitive to water acidification. Now, for the first time, studies are being carried out to determine how the added factor of ocean warming affects their development. Fertilized cod eggs are held at different water temperatures and acidities in aquariums until the fish larvae hatch. These simulate ocean conditions that could develop during this century. The results show that a temperature increase of around 3 degrees leads to the death of the eggs or to larval deformity. Embryos in the fish eggs appear to react sensitively to warmer water, particularly during the early stages of their development. The experiments also indicate that this situation is exacerbated when the acidity of the water is increased. The number of damaged or dead embryos then escalates by 20 to 30 per cent.

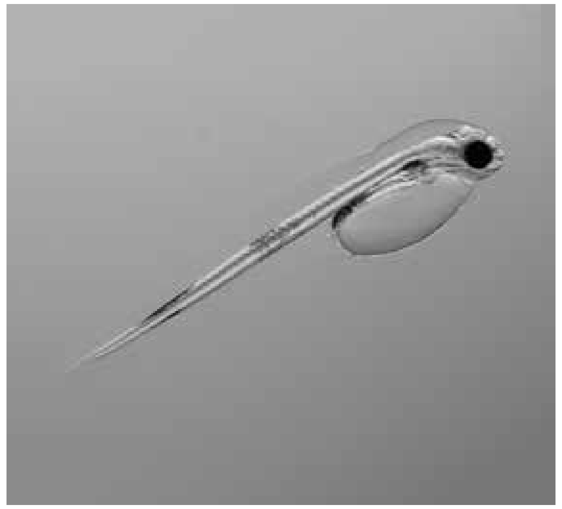
In addition, climate models are being applied to determine possible changes in the geographical distribution of the cod that could occur due to future warming and acidification of the ocean. Investigations are focussing on whether critical temperatures will be reached in the known spawning areas. The results of the studies are alarming. They suggest that up to 40 per cent fewer cod larvae will hatch along the Norwegian coast. This would very probably have severe consequences for the entire ecosystem and for the cod fishery in the Barents Sea to the north of Norway. For centuries this **stock** has ensured the livelihood of Norwegian and Russian fishermen who take in around 2 billion euros from the fishery each year. A collapse of the cod population is a potential catastrophe that would threaten the livelihoods of a majority of the human population in this region.

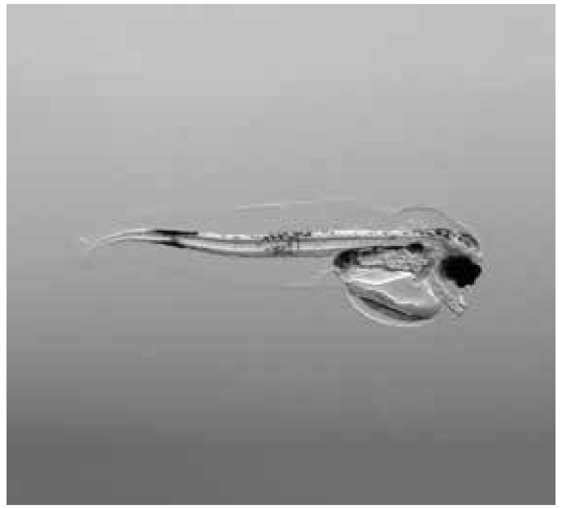
The total magnitude of the consequences of climate change on cod offspring, however, is difficult to assess. Cod release their eggs in open water. The eggs and subsequently hatched larvae are then transported by ocean currents into areas that provide optimal conditions for development of the young fish. If ocean warming causes a northward shift of the cod populations, they may end up spawning in marine areas with different current patterns. It is not known whether these will provide optimal conditions for development of the offspring.

According to current studies, not only the cod but also other marine organisms will migrate northward or become scarcer in the south. The coastal waters of Great Britain are thus expected to suffer huge losses in their fisheries. Investigations here are assessing how the fisheries for cod and sea bass, as well as cockles, scallops and mussels will develop. Together these five species presently account for around half of the total fish catch in Great Britain. The analyses, again, are based on the four RCP scenarios of the Intergovernmental Panel on Climate Change. According to the RCP2.6 scenario, by the end of this century a decline of around 30 per cent in the catch volumes of mussel species is expected, while under RCP8.5 the expected loss would be about 60 per cent. The regional situations, however, would differ somewhat for England, Northern Ireland, Scotland and Wales. For cod and sea bass, the expected changes would range from negligible to slight losses under scenario RCP2.6. If RCP8.5 proves to be the future reality, however, the volumes of cod and sea bass caught are likely to decrease by as much as 20 per cent by the year 2100. England, lying farthest to the south, would be especially hard-hit under this scenario. England, therefore, would have to look to other species to compensate for the losses, possibly to Mediterranean species that could spread northward with ocean warming.



3.11 > Economically, cod is one of the most important fish in the Northeast Atlantic. Ocean warming could create unfavourable growth conditions for the cod eggs and larvae. This could cause a significant decline in the large cod stocks north of Norway.





3.12 > On the left is a healthy cod larva, on the right a deformed one. This clearly illustrates the destructive impact of increased temperature and acidification on young life stages.

Hypersaline river deltas

Warming of the Earth due to human-induced amplification of the greenhouse effect can also have an indirect impact on the fish communities in coastal waters. This is illustrated by the situation in the Sine-Saloum Delta on the coast of the West African country of Senegal. Senegal is located in the transitional area between the dry Sahel zone to the north and the more humid tropical forest belt further to the south. Because precipitation in the Sahel has decreased considerably since the 1960s, only very limited amounts of fresh water now flow into the delta from the landward side. Consequently, salt water from the Atlantic has penetrated deeply into the delta. In the upper reaches of the tributaries, as a result of evaporation, salinity can be as much as three times the normal concentration of seawater. Fish species that can only survive in relatively low salinities have thus disappeared from the delta. These include, among others, the very popular food fish tilapia. Today, in its place, large areas of the delta are dominated by smaller herring-like fish such as bonga shad, which have a considerably lower market value than the tilapia. The total fishery yield is thus decreasing. In general, fewer fish species are found in the Sine-Saloum Delta than in comparable Western African deltas located in the humid tropical belt to the south that still have a strong input of river water.

Sudden mass proliferation after a half century

Not only can the composition of biotic communities in coastal seas change during the course of ocean warming through migratory shifts of species, but also through direct introduction – when organisms or larvae are transported unintentionally in the **ballast water** of ships or as incrustations on their hulls from one marine area to another. Non-native species can also be introduced into new

3.13 > The Australasian barnacle *Austrominius modestus* enjoys ideal living conditions in the North Sea thanks to an increasingly mild climate. On the island of Sylt it has almost completely supplanted the native species *Semibalanus balanoides*.

areas when organisms are released or escape from an aquarium. This introduction of new animal species (neozoons) and new plant species (neophytes) is also known as bioinvasion.

Some introduced organisms are able to establish themselves and proliferate in their new environment. If conditions are favourable they can even supplant native species and thus significantly alter the habitat. There is now evidence that ocean warming can also contribute to such a change, as illustrated by the example of *Austrominius modestus*. This Australasian barnacle species was probably introduced into British waters in the 1940s by warships or sea planes from Australia and spread from there across the entire North Sea. It was first observed on the German island of Sylt in 1955. It was also able to propagate there, but for several decades it occurred only in very low numbers. The native Sylt barnacle species *Semibalanus balanoides* and *Balanus crenatus* predominated. This relationship was reversed in 2007 with the first massive proliferation of the Australasian barnacle.

Barnacles in the area around Sylt preferentially colonize on mussel beds. In 2007, the mussels were predominantly covered for the first time by young Australasian barnacles. The barnacle population density was 70,000 individuals per square metre. For comparison, in 1997 there were just 70 individuals of this species per square metre. The reason for the sudden enormous increase is presumably related to the changing climate through the preceding years. For some time there had been a general trend toward warmer summers and milder winters. For example, the average air temperature on Sylt between April and August today is 2 degrees higher than it was in 1950. Now, decades after its initial introduction, the Australasian barnacle is evidently living under ideal conditions for mass proliferation.

Heavy encrustation of their shells by the Australasian barnacle is not a problem for the mussels. This example illustrates, however, how rapidly a massive proliferation of invasive species can occur. When the invasive species supplant or even prey on the native species, an ecosystem can be degraded quickly and severely.

OCEAN ACIDIFICATION

Carbon dioxide alters the pH value of water

While global warming as a result of human activity has been a topic of intensive discussion within scientific and public circles for several decades, acidification of the oceans has been largely ignored. It was only a decade ago that researchers first began to point out that increasing CO_2 in the atmosphere is accompanied by significant changes in the chemistry of ocean water.

Chemists determine the acidity of a liquid based on its pH value, whereby a more acidic liquid has a lower pH value. The pH scale ranges from 0 (very acidic) to 14 (very alkaline). A value of 7 is considered to be neutral and marks the transition from acidic to alkaline. Since the beginning of the Industrial Revolution near the middle of the eighteenth century, the average pH value of the oceans has dropped from 8.2 to 8.1. Strictly speaking, with a value of around 8 ocean water is a weak base and not an acid. But because the pH value of seawater is shifting toward the acidic side of the scale with continuing CO_2 absorption, this development is nevertheless considered to represent an acidification of the water. By the year 2100 the present pH value of 8.1 could decrease by an additional 0.3 to 0.4 units. This may sound like an insignificantly small change, but not when one considers that pH is measured on a logarithmic scale. This means that it is mathematically compressed. So, in fact, even with this small numeric change, the ocean would then be 2 to 2.5 times as acidic as it was in the year 1860. The cold Arctic and Antarctic waters are especially impacted by acidification. Because CO_2 dissolves more easily in cold water, these marine regions acidify more readily than warmer regions.

For the high seas and non-coastal regions, the trend of continued acidification, which is already well documented, can be reliably predicted for the future because relatively constant conditions prevail here in terms of water chemistry. On the other hand, it is more difficult to determine how CO_2 will affect coastal waters. Water chemistry near the coasts is strongly influenced by substances brought in from landward areas, particularly carbonate anions and bicarbonate (hydrogencarbonate) ions, which are the fundamental components of numerous minerals. As the rocks are weathered by rain, these materials are washed through rivers into the coastal waters. They are also the major component of lime, which is applied, for example, to neutralize acidic soils. Large amounts of carbonate anions and bicarbonate ions entering the coastal waters can have a buffering effect on the acidification. The term alkalinity is used as a measure for this buffering property.

Complex interactions between the land and coastal seas

Interactions between the land and coastal seas have been intensively studied in the Baltic Sea. It is considered to be an inland sea because it is surrounded by land and has only a single narrow outlet to the North Sea, and thus to the Northeast Atlantic. An analysis carried out over the past 20 years indicates that, depending on the season and area of the Baltic Sea, the input of carbonates from the land either partially or totally compensated for the acidification – as a function of alkalinity in the water.

The alkalinity, in turn, is dependent upon many different factors, including the amount of precipitation on land. When rainfall is stronger, weathering of the rocks is more intensive, so that more carbonate and bicarbonate ions are carried to the rivers. Alkalinity is also increased in the rivers and the sea as a result of the liming of farmland in agricultural areas around the Baltic Sea.

Most climate studies for northwest Europe assume that climate change will be accompanied by increased precipitation because warming of the atmosphere will enhance evaporation at the sea surface. The prevailing winds in northwest Europe will then bring in more moisture from the North Atlantic. If precipitation increases, more water will flow from the land into the sea, thus bringing more alkalinity into the sea. Acidification in the area of the Baltic Sea could therefore be partially or totally buffered in the future because of its geographical position and the strong influx of water from the land. With an increase in precipitation, of course, more alkalinity would also be

Alkalinity
The acidity (pH value) of a liquid such as seawater can be changed by adding alkalinity – by introducing a high-alkaline liquid, for example. This buffers the acidity and is referred to as the acid-binding capacity. The degree of alkalinity, and thus the acid-binding capacity, is determined by the content of carbonate anions and bicarbonate ions, which have an alkaline effect and thus counteract the acidity. Carbonate anions and bicarbonate ions have a high affinity for hydrogen ions, which generally make liquids acidic. They buffer the acidity by capturing a certain portion of the hydrogen ions.

How acute is coastal water acidification?

Carbon dioxide (CO_2) gas contained in the atmosphere is easily dissolved in water. This is well known in the form of sparkling water products into which CO_2 has been dissolved under pressure. In the dissolution process the CO_2 reacts with the water molecules (H_2O). When it is absorbed from the atmosphere carbon dioxide is in part transformed – into carbonic acid (H_2CO_3), hydrogencarbonate ions (HCO_3^-) and carbonate anions (CO_3^{2-}). The transformation is illustrated in three equations:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3$$

$$H_2CO_3 \longleftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \longleftrightarrow H^+ + CO_3^{2-}$$

Together, all of the chemical species in water that derive from CO_2, comprising carbon dioxide, carbonic acid, hydrogencarbonate ions and carbonate ions, make up what is known as dissolved inorganic carbon (DIC).

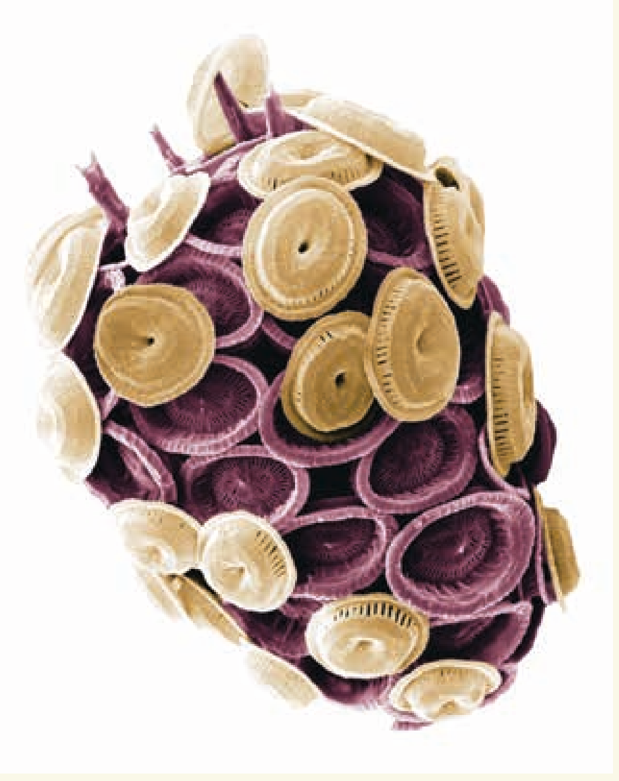
The various forms of DIC can transform into one another through the chemical reactions described in the equations.

This CO_2 equilibrium system controls the content of free hydrogen ions (H^+) in seawater and thus the pH value, which is a measure of the amount of free hydrogen ions in a liquid. The "p" stands for potential and "H" for the Latin word Hydrogenium (hydrogen). The reaction of carbon dioxide in seawater proceeds summarily as follows: First, the carbon dioxide reacts with water to form carbonic acid. An H^+ ion then splits off the carbonic acid, forming a hydrogencarbonate ion. This hydrogencarbonate ion can then, in the next step, lose another H^+ ion to form carbonate.

Considering the first and second equations, which are coupled with each other in water, it is clear that when more CO_2 is absorbed in the water, more H^+ ions are produced, making the water gradually more acidic. If more alkalinity is added to the system in the form of hydrogencarbonate ions and carbonate anions, however, hydrogen ions are captured, so that the pH value increases and the water becomes more alkaline.

Alkalinity in the water basically has a double function. For one, it influences the pH value through reactions with the H^+ ions. For another, it is fundamentally crucial in enabling calcite-producing marine organisms such as corals, clams, snails and many planktonic organisms to secrete their shells and carapaces. For this, the creatures remove carbonate anions and calcium ions (Ca^{2+}) out of the water to produce calcium carbonate ($CaCO_3$), which is also an important component of human bones.

The more carbonate ions there are in the water, the easier it is for the animals to produce calcium carbonate. Because ocean acidification leads to a long-term reduction in the concentration of carbonate anions in the water, the ability of marine organisms to form shells and skeletons is likewise reduced. In extreme cases, when very little carbonate is available in the water, acidification of the water can even lead to the dissolution of calcite shells and skeletons.



3.14 > The microscopically small coccolithophorids (calcareous algae) form an exoskeleton of calcium carbonate plates. Over millions of years the plates of dead coccolithophorids have accumulated on the sea floor to form thick carbonate layers. The white cliffs of Dover are also composed of these plates.

introduced into the Northeast Atlantic. But in the small, inland Baltic Sea, the impact would be recognizable much more quickly than in the open ocean with its significantly greater volumes of water.

Withstanding acidification?

In recent years many studies have been undertaken to investigate how marine organisms react to acidification. Pictures of calcareous algae, called coccolithophorids, showing the calcareous plates slowly dissolving with decreasing pH values have become familiar. The studies, based on laboratory experiments, consistently supported the conclusion that large numbers of organisms could perish under conditions of increasing acidification, and some species could become extinct. Now, however, some contrasting results have been obtained which show that this may not necessarily be the case. It has been shown, for example, that certain groups of organisms apparently have the ability to adapt to the acidification. Experiments on the coccolithophorid species *Emiliania huxleyi* have shown that after about 500 generations a certain degree of resistance is developed and calcite formation improves again in more acidic seawater. Because *Emiliania* reproduces rapidly, the 500th generation is achieved after about six months. Ongoing investigations are attempting to discover what kinds of metabolic changes are at the root of this adaptation to acidification.

Interesting field studies in this context were carried out off the Swedish Baltic Sea coast, investigating how phytoplankton, the base of the marine food web, reacts to acidification. Here, over a six-month period, CO_2 gas was introduced into Baltic Sea water so that it corresponded approximately to a level that would be produced if the present CO_2 content of the atmosphere were doubled. Amazingly, only minor changes in the plankton associations could be recognized at specific times in their development when compared to seawater without CO_2 introduced. The increased CO_2 had a slightly negative effect on some groups of organisms in the plankton community and a slightly beneficial effect on others. The researchers propose that many of the organisms are able to tolerate lower pH values because of the natural fluctuations of pH in the Baltic Sea due to alkalinity.

Meta-analyses, however, in which the results of several hundred publications were analysed and integrated, indicate that there are still organisms in other coastal regions that definitely react to acidification, especially in marine regions where the chemical conditions of the water are fairly constant. Besides many areas in the open ocean, these are primarily coastal waters in hot and dry regions where no rivers flow into the sea. The marine organisms most strongly impacted are those that form calcareous shells or skeletons. It is evident that carbonate formation by corals, clams and snails, depending on the group studied, is reduced by 22 to 39 per cent in acidified water. Changes are also seen in the growth of organisms. Taking all carbonate-forming marine organisms together, it can be shown that on average they are up to 17 per cent smaller than those living in water with normal pH values.

Lower species diversity in coral reefs

Studies by Australian researchers illustrate how increased acidification affects coral reefs in Papua New Guinea. In these areas, CO_2 escapes from the sea floor through volcanic vents, producing a natural acidification of the seawater. Coral colonies have developed here that are able to cope with the increased CO_2 content of the water and relatively low pH values. The area can be seen as a kind of field laboratory for anticipating ocean acidification. The closer the corals are to the CO_2 sources, the more acidic the water. Thus, depending on the distance to the source, conditions are found that could be prevalent globally in the ocean 20, 50 or 100 years from now. Here, instead of the delicate, branching stony corals, which react especially sensitively to acidification, the robust and plump *Porites* corals with an outward appearance similar to cauliflower are more common. Overall species diversity in these reef areas is significantly lower than in areas with normal pH values. In water with a pH value of 7.7, which could actually be reached by the year 2100, the living conditions are so unfavourable that even the *Porites* corals can no longer grow.

Winners and losers in ocean acidification

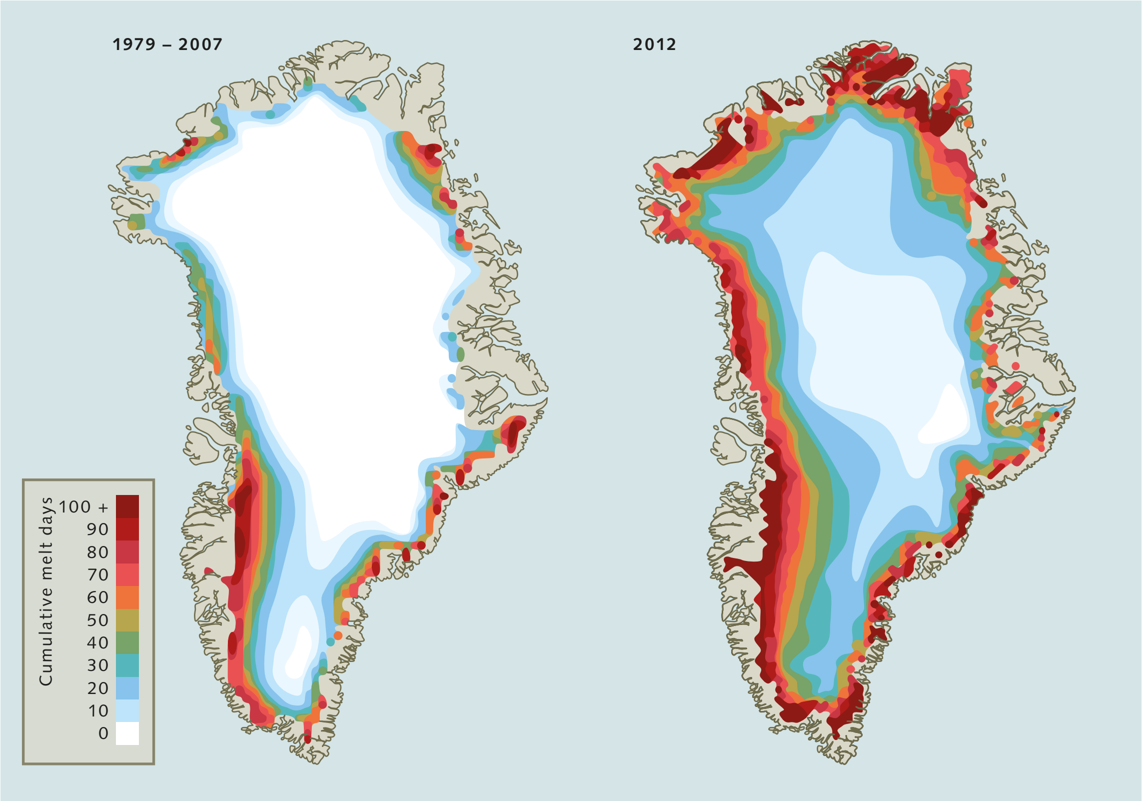
While calcareous organisms are at a disadvantage, the cyanobacteria, previously called blue-green algae, may possibly be among the winners. Very much like plants, cyanobacteria require CO_2 to produce sugar with the help of photosynthesis. They can thus carry out metabolic processes that concentrate CO_2 in their body and make it available for photosynthesis. But these Carbon Concentrating Mechanisms (CCMs) consume energy. If there is abundant ambient CO_2 available, the strain on the CCMs is lightened and cyanobacteria and plants can save energy. This energy can then be used to enhance growth. The ancestors of today's cyanobacteria existed as early as 2 billion years ago, at a time when the Earth's atmosphere contained abundant carbon dioxide and sparse oxygen. Cyanobacteria living today are therefore still well adapted to high CO_2 concentrations and low pH values in the water.

SEA-LEVEL RISE

Imminent danger for coastal residents

Residents of many coastal regions will probably notice the impacts of climate change primarily in the form of sea-level rise, because it will cause a great loss of land in the form of residential areas, industrial and economic centres, and farmland. Furthermore, due to the rising sea level, storm floods today surge to higher levels. It should be noted that not only human-induced global warming influences the level of the water, but that natural processes also play a part. Generally a distinction is made here between:

- eustatic, climatically induced, globally acting causes that lead to an increase in the water volume in the oceans, such as rising sea level when ice melts after a glacial period;



3.15 > Scientists expect that, with global warming, thawing of the Greenland ice sheet will intensify in the future. Particularly acute melting was observed in the year 2012. Due to exceptionally mild air temperatures in this year, thawing on the surface of the glaciers persisted for many more days over large parts of the island than the annual average of the years from 1979 to 2007.

3.16 > Melting of the Greenland glaciers during the summer months, as seen here near the town of Qaanaaq, is a natural process. For the past several years, however, the thawing of the ice masses appears to be intensifying.

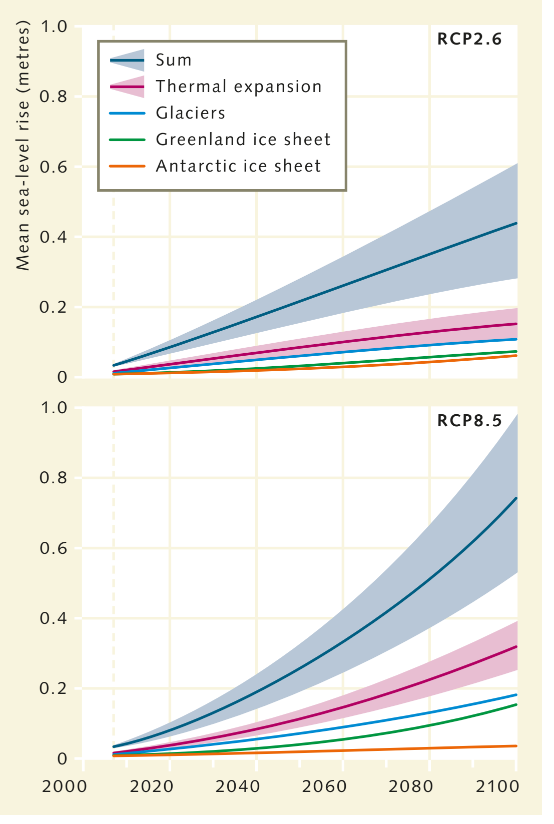
- isostatic, primarily tectonically controlled causes that have an essentially regional impact. These include the subsidence or uplift of land masses that occurs with the alternation of cold and warm periods. The immense weight of ice sheets formed during the ice ages causes the Earth's crust to sink in certain regions, resulting in a sea-level rise relative to the land. When the ice thaws, the land mass begin to rebound, or uplift, again, a phenomenon that can still be observed in the Scandinavian region today.

Over millions of years the height of sea level can fluctuate by more than 200 metres. But it can also change significantly within relatively short time periods. Changes of around 10 metres can occur within a few centuries. After the last glacial period, around 15,000 years ago, temperatures on the Earth began to rise strongly again, and since that time sea level has risen by around 125 metres. At first the rise was relatively rapid. This phase lasted until around 6000 years ago. For a long period of time after that, sea level varied only slightly with fluctuations of a few centimetres per century. Compared to the relatively minor changes during the past 6000 years, however, the rise has now started to accelerate again. Between 1880 and 2009 sea level rose by 21 centimetres, fairly weakly through the first half of the twentieth century but with increasing speed during more recent decades. Since 1990 sea level has risen annually by about 3 millimetres. The following factors are presently contributing to sea-level rise:

- 15 to 50 per cent is due to the expansion of seawater as a result of temperature increase;
- 25 to 45 per cent to the melting of mountain glaciers outside the polar regions;
- 15 to 40 per cent to the melting of the ice sheets on Greenland and in the Antarctic.

A question of location

For the coasts, sea-level rise is surely the gravest consequence of climate change, but in this century it will not lead to permanent flooding of coastal areas like an overflowing basin. Furthermore, sea-level rise does not affect all coasts to the same degree. The climate scenarios of the Intergovernmental Panel on Climate Change (IPCC) usually refer to a global average sea-level rise. But regionally, in fact, there will be large differences in sea-level rise relative to the land surface. So today a differentiation is recognized between the global sea level, regional sea level and local sea level.



3.17 > Sea level is presently rising by an average of around 3 millimetres each year. Whether the rate escalates or becomes weaker depends on how much the greenhouse effect increases in the future.

Different regions, different sea level

Regional sea level is mainly determined by regional conditions, such as the uplift or subsidence of land masses or changes in regional wind and ocean-current patterns. For example, on the Pacific coast of South America the El Niño climate phenomenon causes a deviation in sea level of up to 40 centimetres from the normal average level. El Niño occurs at irregular intervals every 3 to 10 years in the Pacific between Indonesia and Peru, when the surface ocean currents reverse due to a weakening of the prevailing **trade winds**. Normally the strong trade winds drive the surface water from the Pacific coast of South America out into the open sea. During El Niño events, however, the trade wind is weaker and water piled up in the West Pacific swashes back toward America. The effect of this current reversal can then be observed in the water level at the coast.

The thick continental glaciers in Greenland and the Antarctic also have a large regional influence. The masses of these glaciers are so great that the gravitational force is stronger there than in other marine regions. The physical principal that bodies with greater mass have a stronger gravitational attraction applies here. Seawater is thus more strongly attracted in the vicinity of the glaciers, so that sea levels around Greenland and the Antarctic are a few decimetres higher than the global average. With the melting of the glaciers as a response to climate change, however, the glacial mass will decrease, and in the coming centuries Greenland and the Antarctic will likely experience a regionally falling sea level while the average global level rises each year.

Regional sea levels are also influenced by other phenomena. These include, for example, the present-day uplift of Scandinavia or other areas that were covered by ice in the past. During the last glacial period several thousand years ago the large ice load depressed the Earth's crust down into the mantle. As the ice thawed the land mass began to rebound and is still now rising relative to the sea, which is observed on the coasts as a fall in sea level. The uplift today amounts to several millimetres each year.

Homemade sea-level rise

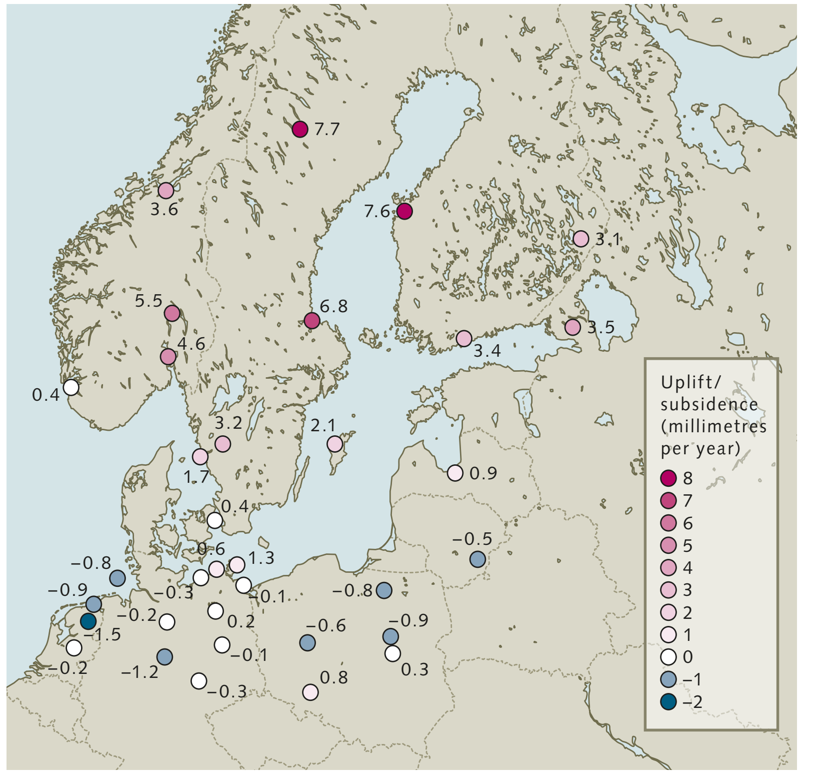
Local changes in sea level often result from the construction of high-rise buildings or the extraction of groundwater for drinking water (see Chapter 2). River deltas, on the other hand, subside under their own weight. In many places today the construction of dams prevents adequate compensation for this subsidence due to the reduced amount of new sediment being transported in by the rivers. With rising sea level many delta regions will likely be more frequently flooded in the future.

For the 33 large delta regions of the world, it is presently assumed that the surface area threatened by flooding due to sea-level rise will increase by around 50 per cent by the year 2100.

More than 6 metres in 500 years?

Regardless of the present state of local and regional sea-level rise, failure to significantly curb the emission of greenhouse gases will result in a substantial rise in the average global sea level during this century and beyond. If the Earth's population and its energy consumption increases greatly, as illustrated by scenario RCP8.5, average sea level could rise more than 6 metres by the year 2500. This would be exacerbated by additional threats to

3.18 > Since the melting of ice-age glaciers the Scandinavian land mass has been rising. This motion continues even today. Northern Germany, on the other hand, is sinking. The boundary runs approximately along a line from southern Denmark to the island of Rügen.



the coasts as were summarized in the latest report of the Intergovernmental Panel on Climate Change. The report finds that the following consequences can very probably be expected during this century:

- an increase in wind speeds and precipitation during tropical cyclones, which will likely lead to more flooding and damage, whereby the heavy flow of rainwater from the land and high ocean water levels caused by strong winds occur concurrently;
- higher storm-flood surges. The average surge of storm floods today is already higher than it was 100 years ago;
- higher extreme water levels due to higher wind speeds. Subsiding coastal regions are especially hard-hit;
- stronger erosion of the coasts as a result of more frequent flooding and surging waves breaking higher than normal on the beach.

Sinking beaches and wetlands

Many natural coastal habitats will be destroyed irretrievably through permanent flooding and erosion, or will shift inland. This loss of land is already happening today. On the coasts of northern Alaska and Siberia, for example, the permafrost soil is breaking off in many places at a rate of several metres a year. The reason for this is milder and longer summers. In addition, large expanses of sea ice are melting, allowing the wind to create stronger waves, which can then, in turn, easily erode the thawing soil on the shore. Beaches and dunes have also been more strongly eroded on many coasts in recent years, such as those along the east coast of the USA. Scientists attribute this to stronger winds and higher-surging storm floods.

Many of the world's coasts are characterized by wetlands, salt marshes, or seagrass growth in shallow waters. These are vital habitats for many organisms, including specialized plants and insects, birds that stop to rest and breed, or for fish. Many of these areas have already been destroyed by construction or pollution of the coastal waters. Due to rising sea level, combined with higher-surging floods and strong winds, these areas are severely threatened by erosion. Salt marshes, for example, are more strongly eroded on the water side. With higher water surges in the future, new salt-marsh areas could possibly form further inland. This will only be possible, however, in locations where the hinterland is not protected by dikes and cut off from the salt marshes on the sea side. Where the salt marshes have no room to retreat they will be lost as a valuable habitat as erosion increases. The same is true in many regions for wetlands or shallow-water seagrass. Because seagrass can only take root in relatively sheltered, shallow-water areas with low wave activity, many populations will be battered and destroyed by stronger currents or waves.

Can corals keep pace?

With regard to the consequences of sea-level rise for coastal habitats, the fate of coral reefs appears to be not yet sealed. Current studies on Indonesian coral reefs, for example, indicate that they can react quite flexibly to rising or falling sea level. Tropical stony corals live in shallow coastal waters suffused with light because their symbionts, the zooxanthellae, need sufficient light for photosynthesis, which is not available below certain depths. If sea level rises the deeper water layers become darker. As the studies show, however, the corals are able to keep pace with the water by growing the reef vertically at the same rate that the water rises. New corals colonize at the top while the corals at greater depths die.

Studies on ancient coral reefs show that corals were also apparently able to cope with the intermittent, very rapid sea-level rises after the last glacial period. There were phases during which sea level rose at rates up to 40 millimetres per year – 13 times more rapidly than today. If even more CO_2 is emitted in the future, with the growing world population and increasing energy consumption, the rate of sea-level rise could increase to as much as 15 millimetres per year by the end of this century. It is conceivable that the corals would be able to keep up with that rate. This observation, however, requires qualification. Due to acidification and the warming of coastal waters, corals are already highly stressed in many regions to the extent that carbonate formation and growth are seriously hampered. It is not yet known whether the corals can keep up with rising sea level under these conditions. Current studies in the USA indicate that coral reefs that are under pressure from stressors such as destructive fishery, disease or water pollution cannot always grow fast enough, and in fact, on the contrary, are even being eroded by breaking waves. In field studies, the present-day state of reefs in Hawaii, off Florida, and in the American Virgin Islands in the Caribbean were compared with their condition in the 1930s, 1960s and 1980s. The comparisons revealed that the reefs have been eroded by 9 to 80 centimetres since the 1930s. The researchers were only able to find actively growing reefs in protected areas or on especially secluded segments of the coasts.

Densely populated coasts, heavy losses

In its most recently published report the Intergovernmental Panel on Climate Change compiled the results of many scientific publications on the consequences of climate change for populated coastal areas. The results indicate the extent to which livelihoods will be lost. Furthermore, they present an estimate of the financial burden that can be expected in terms of how much coastal protection will cost in the future. It is evident that with the continuing population influx to coastal regions, increasing numbers of people are threatened by extremely intense high-water events. The economic damages will be enormous. Many could lose their homes and property, or even their lives by drowning, drinking polluted water or by epidemics.

Estimates are now available for the numbers of people who will be affected by a 100-year flood, i.e. a flood which is statistically likely to occur on the average every 100 years. In the year 2010 around 270 million coastal residents were at risk globally. In 2050 it will be up to 350 million and in 2100 between 500 and 550 million, based on world population estimates of 9.7 and 11 to 12 billion, respectively. The flooding in 2100, according to the estimates, would likely result in losses of up to 9.3 per cent of the global gross domestic product. Up to 71 billion US dollars would have to be allocated in order to prevent this. Such coastal protection measures are critically needed because even isolated events can cause immense damage.

The extent of damage that can result is illustrated by the destruction caused in 2005 by Hurricane Katrina in the Gulf of Mexico and in 2012 by Hurricane Sandy on the east coast of the USA. US researchers estimate that Katrina caused damage totalling around 150 billion US dollars in the most severely affected states of Louisiana and Mississippi. Hurricane Sandy also caused huge damage in 2012 on the highly developed east coast. Sandy made landfall near New York City, causing damage of up to 50 billion US dollars within a few hours.

With the strength of hurricanes and higher-surging waters in the future, the damage could be even significantly greater if appropriately designed coastal protection systems are not erected. It has been estimated for the US coast of the Gulf of Mexico that, with an average rise in global sea level of 1 metre, along the 750 kilometre stretch between the coastal cities of Mobile and Houston about one-third of all streets would be permanently flooded and 70 per cent of all harbours would be practically useless.

Without massive investments in coastal protection many other coastal regions and cities worldwide will be similarly threatened by flooding. The Intergovernmental Panel on Climate Change notes that the greatest population influx to coastal regions today is occurring in developing countries and newly industrialized countries where coastal protection measures are less well developed. These primarily include India and China, but also Vietnam, Bangladesh and Indonesia, where especially severe losses from high-water levels can be expected. Because protection measures in the form of dikes or dams are rare, it is anticipated that more people with drown in storm floods in coastal regions in the future. Furthermore, the lack of coastal protection will lead to great economic losses, which the weak national economies will scarcely be able to compensate for.

Coping with natural hazards

> Coastal areas are at risk from natural events such as tsunamis and landslides. For the habitats and people within their range these events can have devastating consequences. Efforts are under way today to mitigate the dangers through various early warning systems. But nature remains unpredictable.

Learning lessons from disasters

While humans, through the emission of greenhouse gases, bear some measure of responsibility for sea-level rise, ocean warming and acidification, the coasts are also exposed to a number of natural threats as well. These include earthquakes, landslides, tsunamis and volcanic eruptions, as well as natural climate phenomena, particularly the Pacific climate anomaly known as El Niño. Although humans have no direct influence on the occurrence of such events, a variety of technological solutions have been developed to protect coastal communities as far as possible and to minimize damage to property. Many lessons have been learned from past disasters, as evidenced by modern disaster preparedness schemes for tsunamis.

Tsunamis are especially large waves that can travel for thousands of kilometres across the sea. As they approach a coast they are slowed down by the shallow water, which causes them to rise up many metres in height. Up to 70 per cent of all tsunamis are triggered by earthquakes, mostly in the sea. Other causes include volcanic eruptions or landslides, in which large amounts of sand, rocks or sediments surge downslope like an avalanche. The more material that is set in motion or the faster it moves, the more energy the resulting tsunami possesses.

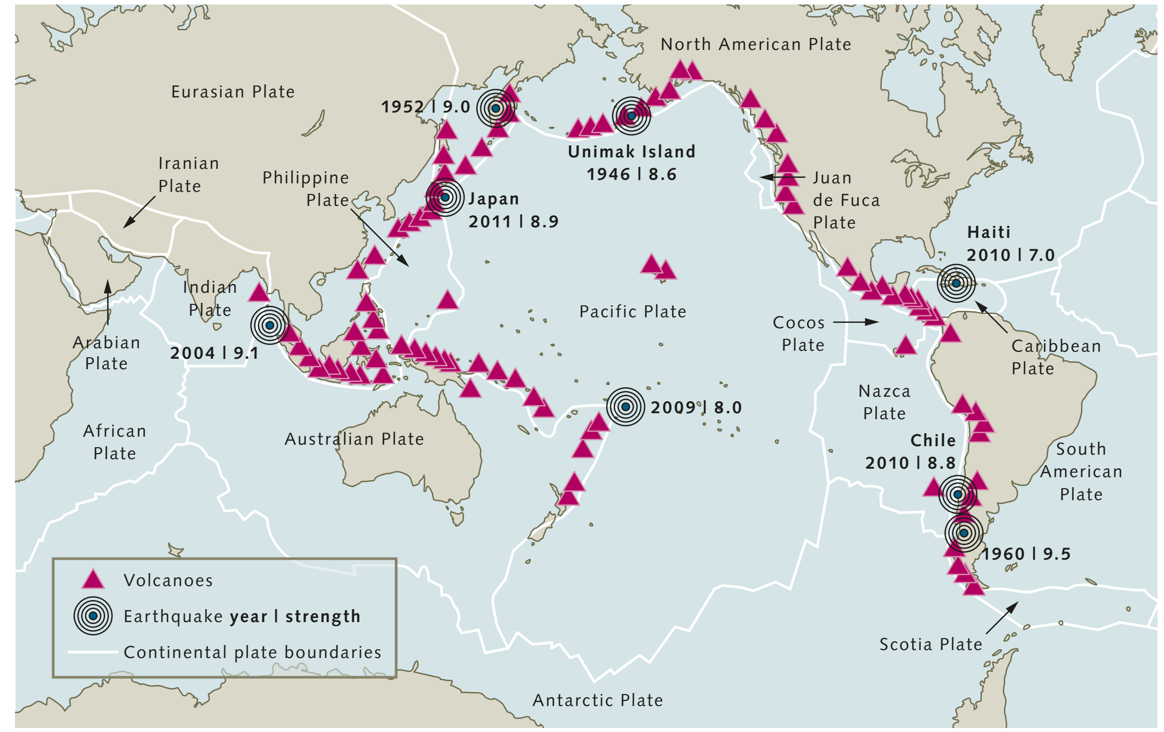
3.19 > It was one of the most devastating natural disasters in the history of Europe. When the earth shook on 1 November 1755 in Lisbon, tens of thousands of people died beneath the rubble of buildings, in the fire storm, and in the floods of a tsunami.

Catastrophes out of the blue

For a long time people in coastal areas were simply at the mercy of tsunamis because they came with no warning at all. A tsunami on 1 November 1755 caught the people of Lisbon, Portugal's capital city, completely unprepared. On that day, about 200 kilometres to the west of the Strait of Gibraltar, a powerful submarine earthquake occurred that was so violent it destroyed most of the city. To add to the devastation, it triggered an enormous tsunami that flooded large areas of the city around 40 minutes after the earthquake. According to various estimates, between 30,000 and 100,000 people lost their lives due to the earthquake and tsunami in the Portuguese capital alone. Other cities and villages on the Portuguese and the Moroccan coasts were also devastated. Even on the other side of the Atlantic, in the Caribbean Islands, the tsunami caused damage to harbour structures and boats.

Especially high-risk regions

Regions in the Pacific are especially threatened by tsunamis because of the tectonic plate boundaries that run parallel to the coasts and are often characterized by heavy seismic and volcanic activity. This is why the term "Ring of Fire" is used to describe these regions. In the western Pacific they include the coasts of the Philippines, Indonesia, Japan and Russia, while in the east large segments of the coasts of North and South America make up the ring.



3.20 > The Ring of Fire circling the Pacific. The coastlines run parallel to plate boundaries, where many earthquakes originate. These may often be followed by tsunamis.

Many sites within the Ring of Fire have repeatedly experienced strong earthquakes throughout history that have also triggered large tsunamis.

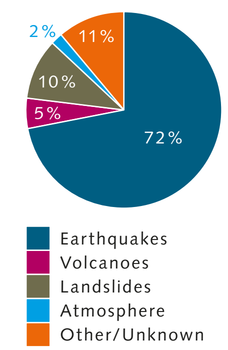
Japan also lies on the Ring of Fire. Because multiple plate boundaries meet here, the country has frequently been shaken by strong earthquakes. Likewise, numerous giant waves have occurred in this area throughout the past, and the phenomenon received its name there long ago. The term "tsunami" is of Japanese origin and derives from the words "tsu" (harbour) and "nami" (wave). The term tells us that the waves are especially destructive to harbour cities.

Development of the Japanese tsunami warning system

It was a long time before people began to understand how to interpret the initial warning signs. On 15 June 1896, a tsunami with a wave height of 38 metres hit the northeast coast of Japan. Around 20,000 people died. It was unusual that the earthquake preceding it was only weakly felt on the Japanese coast, but still produced such a powerful tsunami. This led to a debate in Japan over the origin of this enormous wave. Some specialists attributed the tsunami to submarine landslides. Although the causes remained unclear, the ensuing discussion led to an increased awareness of tsunamis in Japan.

Among the citizens of Japan, the perception generally spread that earthquakes were an important warning sign for possible tsunamis. The general rule was accepted that "When the ground shakes it's time to evacuate". In 1933 a tsunami hit the northeast coast of Japan, again following closely after an earthquake. This time the population was better prepared and many saved themselves by escaping to higher ground. Still, around 3000 people lost their lives.

In 1941 Japan became the first country in the world to implement a tsunami warning system – at the meteorological station at Sendai, a large city on the east coast. A seismometer was permanently installed there that could be used to estimate the strength and approximate distance of earthquakes. From then on tsunami warnings were announced on the radio, and police stations were informed



3.21 > Tsunamis can have different causes, but earthquakes are the most important triggers.

The origins of tsunamis

Tsunami waves originate with the occurrence of a forceful vertical motion that causes the water column to fall or rise suddenly, comparable to the wave that is formed when a hand is plunged abruptly into water. Tsunamis are most commonly triggered by earthquakes that result from the motion of continental plates. If the continental plates simply slide horizontally against one another without one being thrust above the other, however, the overlying water column does not receive the strong vertical impulse necessary to create such a wave. But if the plates rise or fall relative to one another, the water surface is correspondingly lifted or lowered, thus producing a tsunami. These kinds of motions occur most commonly in the vicinity of subduction zones, where one continental plate is thrust beneath another.

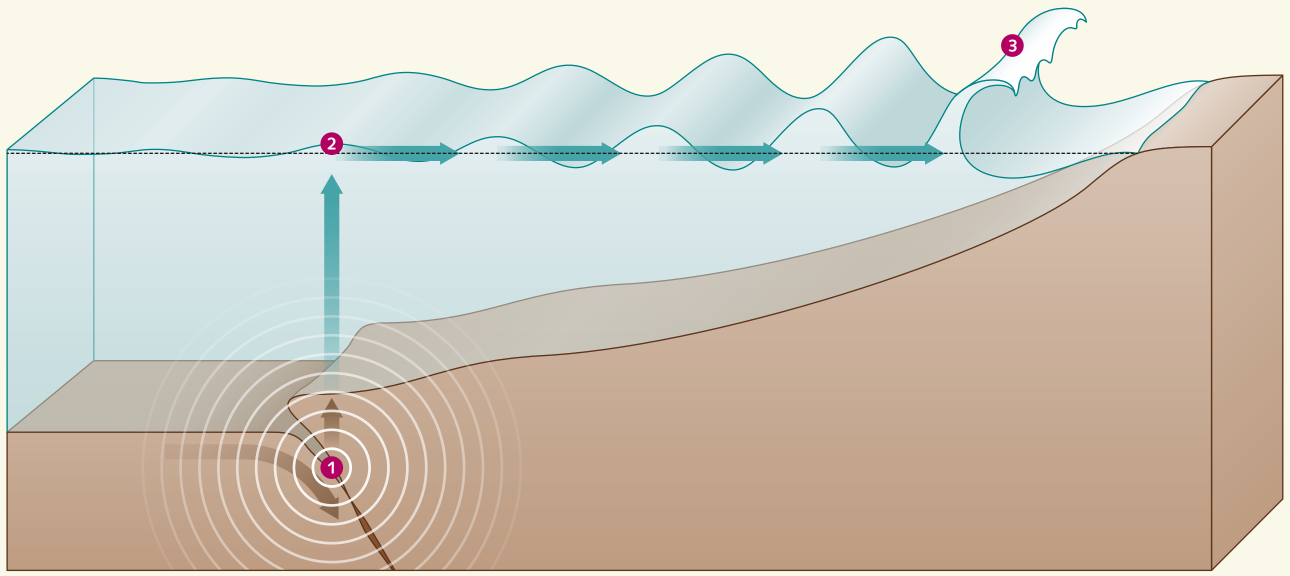
Formation of a tsunami, therefore, does not depend necessarily on the intensity of an earthquake. There have been earthquakes measured with magnitudes of 8 or 9 that did not trigger tsunamis. By contrast, relatively weak earthquakes have been known to produce large tsunamis.

Sophisticated computer models are now being applied in attempts to better understand the special characteristics of earthquakes that are particularly relevant to the development of tsunamis.

Unlike waves at the water surface, which are produced by wind, a tsunami wave involves motion through the entire water column continuously from the site of its origin. At great depths it can propagate unimpeded, and at a water depth of 5000 metres can attain speeds of up to 800 kilometres per hour. The character of its propagation can be described with some confidence using mathematical-physical wave models.

But when the wave encounters a continental slope or the shore, its progress is slowed, causing it to rise up vertically. How the tsunami develops from this point on depends upon the shape of the coast, and is much more difficult to describe mathematically. It is therefore almost impossible to accurately predict the wave height when it strikes land.

Before a tsunami hits a coast, the water there initially retreats. This sequence of retreating water and surging surf can also be observed in the normal wave motion on a beach, whereby this motion is, of course, significantly smaller.



3.22 > Tsunamis often originate when continental plates in the ocean crust shift downward or upward during an earthquake.

3.23 > A tsunami hit the coast of Hawaii on 1 April 1946. The triggering event was an earthquake that occurred 4000 kilometres away near the Aleutian Islands. It took 4.5 hours for the tsunami to travel from the site of its origin to Hawaii, where it took the lives of 159 people.

in the affected regions. As a rule, it took 20 minutes from assessment of the earthquake data until a tsunami warning was given.

In the following years more seismometers were installed in various other regions and finally, in 1952, the Japan Meteorological Agency (JMA) implemented a nation-wide tsunami warning system. By 1999, increasingly technologically advanced seismometers had been installed that constantly improved the speed and quality of determinations of the intensity and location of earthquakes. Tsunami warnings could ultimately be announced within 3 minutes after an earthquake. But in spite of the use of mathematical simulation models, it was not possible from the earthquake data alone to reliably determine the size of the tsunami to be expected. After the tragedy of 11 March 2011, the tsunami warning system in Japan was finally significantly improved. On this day, off the coast of the northeast Japanese region of Tōhoku, a strong submarine earthquake occurred. Around 16,000 people died in the quake and the great wave it produced.

As a consequence, sensors were installed on the sea floor off the Japanese coast that could recognize a tsunami wave passing overhead based on discernable changes in pressure. Thanks to the deployment of these additional sensors, the ability to determine the path of a tsunami and estimate the size of the wave expected to hit land has been greatly improved.

Development of the tsunami warning system in the USA

Not only in Japan but also in the USA, efforts to develop a warning system began relatively early. In the Aleutian Islands, which extend from the coast of Alaska far out into the Pacific, a strong earthquake occurred in 1946 and triggered a large tsunami. The wave was so enormous that it completely destroyed a steel-reinforced concrete lighthouse that stood atop a 12-metre-high cliff on the Aleutian Island of Unimak.

4.5 hours later the tsunami reached the Hawaiian Island group 4000 kilometres away. It hit the inhabitants with no advance warning, because the earthquake was not felt here at all. The waves were up to 16 metres high and in some locations the water penetrated a thousand

Earthquake intensity
The intensity of an earthquake is determined on the basis of a moment magnitude scale. The scale ends at a value of 10.6. This maximum intensity is reached when the Earth's crust breaks completely apart in the area of the earthquake. Theoretically it is not possible for an earthquake to release more energy than this. The structure of the scale is logarithmic. This means that the strength of the earthquake increases exponentially with the scale value. One point on the scale is equivalent to an increase in energy of about 30 times. For the purpose of visualization, the seismic energy of an earthquake can be compared to the explosive power of TNT. The energy of an earthquake with a magnitude of 5 is equal to about 475 tonnes of TNT; that of a magnitude 6 earthquake is equal to about 15,000 tonnes of TNT.

metres inland. 159 people died. The tsunami was also felt on the northwest coast of the USA. The waves here were only about 2 metres high, but there was still some damage to boats in a number of harbours.

After this experience, US officials established a tsunami warning centre in 1949 near Honolulu, Hawaii. Similar to the system in Japan, their method was based on identifying earthquakes and calculating the travel time of a potential tsunami. If a partner country reported an earthquake, the centre would calculate the travel time of a possible tsunami wave to its arrival on the coast of the USA.

International cooperation emerges

For a long time Japan only generated warnings for its own coast, while the system in the United States rapidly developed into an international warning centre for the entire Pacific realm. The impetus for this international cooperation was an earthquake that struck near the large city of Valdiva in Chile on 22 May 1960. The Earth's crust ruptured on land in Chile from north to south over a length of 1000 kilometres. This included the jarring movement by 20 metres toward the west of a 200-kilometre-wide block situated between the continental margin and the Andes. This triggered an enormous tsunami wave that caused immense damage nearby, particularly on the coast of Chile, and then spread westward across the entire Pacific.

Hawaii experienced 10-metre waves, while the more distant east coast of Japan was subjected to 5-metre waves. Because other countries in the Pacific and island nations in particular were impacted, UNESCO (United Nations Educational, Scientific and Cultural Organization), beginning in 1960, strongly pushed for the implementation of a Pacific-wide warning system. The Intergovernmental Oceanographic Commission (IOC), established by UNESCO after the earthquake in Chile, was responsible for the international cooperation. The IOC member states decided to integrate the system with the existing warning centre in Hawaii. It began operations in 1965 as the Pacific Tsunami Warning Center (PTWC). The PTWC still coordinates tsunami warning and prediction for the entire Pacific realm on behalf of the USA's National Oceanic and Atmospheric Administration (NOAA).

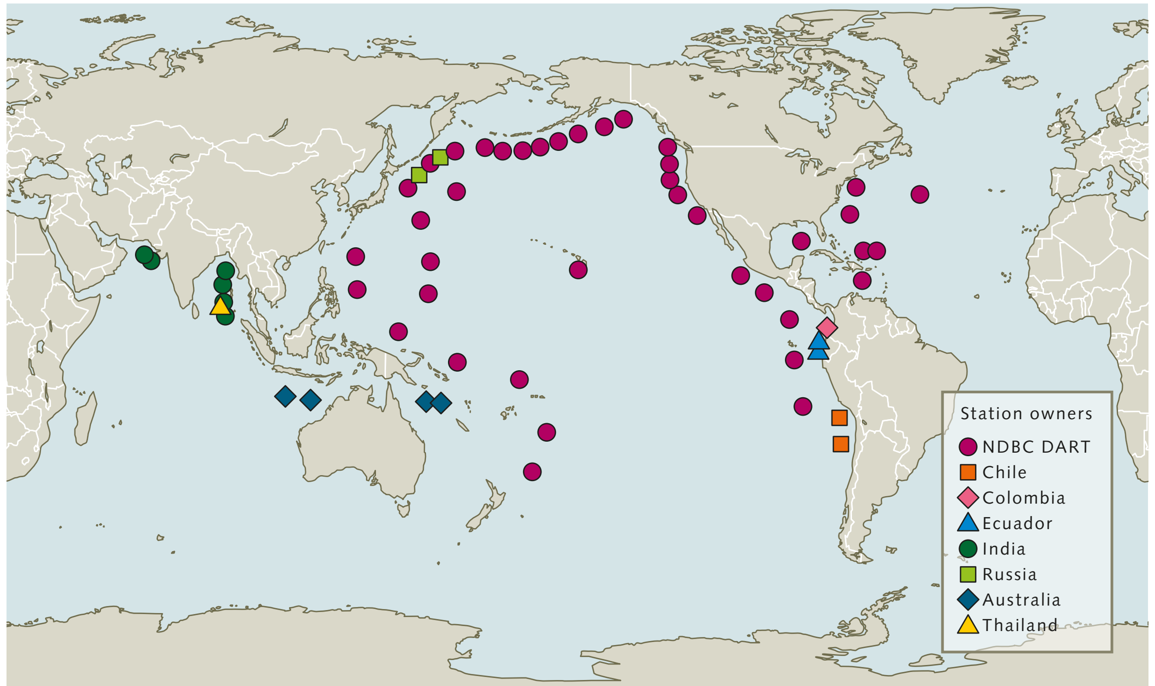
As in Japan, the accuracy of tsunami prediction was limited in the beginning. The warning system essentially consisted of member states informing each other by telephone whenever an earthquake was recorded. Aided by the seismographic information and travel-time maps, calculations could then be made to determine whether and when a possible tsunami could hit land. This information was augmented by water-level measurements in various coastal areas. But predictions still remained uncertain.

75 per cent of all tsunami warnings were false alarms, which often led to expensive evacuation measures. In 1986 an alarm led to the evacuation of Waikiki, a district of Honolulu. Many public buildings in this part of the city had to be vacated. Although waves arrived at the beach at the expected time, they were only slightly larger than the normal surf. Officials in Hawaii estimate that the interruption of normal business as a result of the false alarm caused losses equivalent to 41 million US dollars. This was followed by considerable criticism of the efforts of the PTWC tsunami warning centre.

In 1987, therefore, NOAA decided to install a completely new warning system that delivers tsunami data in real time. This consisted of pressure sensors on the sea floor that send data to buoys at the surface through an acoustic signal. The buoys then transmit the data via a satellite connection to the PTWC. The advantage of this is that the system directly measures the strength of the tsunami wave, providing a reliable indication of its magnitude and behaviour at landfall. It therefore complements very well the classic seismographic earthquake measurements.

This buoy system is known in the USA as DART (Deep-ocean Assessment and Reporting of Tsunamis). It is operated by the National Data Buoy Center (NDBC) of NOAA and continues to be upgraded even today. Australia, Chile, Colombia, Ecuador, India, Russia and Thailand are now also using these kinds of buoys. Japan developed its own buoy system, but is gradually giving

3.24 > The earthquake off the east coast of Japan on 11 March 2011 lasted around 5 minutes. It triggered a tsunami that devastated broad areas of northeast Japan and also breached the seawall of the Fukushima I nuclear power plant.



3.25 > Since the 1980s a tsunami warning system of buoys has been installed around the Pacific that receive signals from pressure sensors on the sea floor. These sensors detect tsunami waves.

this up in favour of pressure sensors connected by cables. In the Pacific and adjacent marine regions today, more than 50 buoys have been installed that can be used by the PTWC.

A tsunami alters global awareness

The cooperation among many countries around the world today in the field of tsunami warning is, to a large extent, a consequence of the catastrophic tsunami that occurred on the morning of 26 December 2004 in the Indian Ocean. At 7:58 a.m. there was a submarine earthquake with a magnitude of 9.1. It was centred about 85 kilometres off the northwest coast of the Indonesian island of Sumatra on the Sunda Arc, and triggered several seismic shocks and severe tsunamis that struck the coasts of 16 countries around the Indian Ocean.

The Sunda Arc is a 6000-kilometre-long subduction zone that runs along the coast of Sumatra, extending from Myanmar in the north, through and beyond the Indonesian Island of Java in the south. At the Sunda Arc the Indo-Australian Plate is thrust beneath the Sunda and Burma Plates, which is why this region frequently experiences earthquakes and strong volcanic activity. The coast of the island of Sumatra, the island of Sri Lanka located to the west of the epicentre, and the Indian coast were especially hard-hit because of their proximity to the Sunda Arc. The northern coastal districts of the large Indonesian city of Banda Aceh on Sumatra were completely destroyed. In all, 235,000 people lost their lives, 170,000 in Indonesia alone. 1.7 million people lost their houses and dwellings.

It was disastrous that, in contrast to the region covered by the PTWC, hardly any of the affected countries had established tsunami catastrophe protection programmes. Because the victims also included many tourists, the event had an immediate and huge international impact. Measured by the number of victims, the tsunami was the greatest natural disaster ever for Sweden; for Germany it was the largest since 1945. More Germans died in this catastrophe than in the flooding of Hamburg in 1962. A total of 13.5 billion US dollars were raised worldwide to assist with reconstruction in the disaster area.

The tsunami of 2004 drastically altered public perception. After this momentous event the world immediately

developed a heightened awareness of this natural hazard. At their annual meeting in June 2005, member states of the IOC called for the establishment of new international warning networks for the Indian Ocean based on the model of the PTWC. As a further consequence, appropriate warning centres were established under the auspices of the IOC:

- The Caribbean and Adjacent Regions Early Warning System (CARIBE EWS),
- The Indian Ocean Tsunami Warning System (IOTWS),
- The North-Eastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System (NEAMTWS).

The Indonesian warning system – constructed from scratch

After the tsunami of 2004, there were intense international efforts to install a reliable warning system in the Indian Ocean. In especially hard-hit Indonesia, particularly with German assistance, a dense network of survey stations was built: the Indonesian Tsunami Early Warning System (InaTEWS), which is part of the IOTWS system for the entire Indian Ocean.

Unexpected problems arose right away, at the beginning of the installation. Like in the Pacific, plans for the InaTEWS also included incorporation of some DART buoys. These, however, were repeatedly damaged by vandalism or carelessness; batteries were removed or the technical mechanisms destroyed because fishermen frequently used the DART buoys for mooring. It was therefore decided that a combination of other sensors would be installed exclusively on land in Indonesia. This had the additional advantage of avoiding the expensive maintenance costs of equipment at sea.

The system presently includes a network of 160 broadband seismometers that were installed along the coast and precisely record the waves of an earthquake in real time. Additionally, around 50 survey stations record the water elevation to recognize anomalous changes in sea level. About 30 GPS stations were also established on land. This concept is based on the fact that continental plates shift

3.26 > The devastated coastal strip of Banda Aceh (left, 2005) was rebuilt (right). One of the towers of the new warning system, outfitted with a siren, can be seen in the right-hand picture.

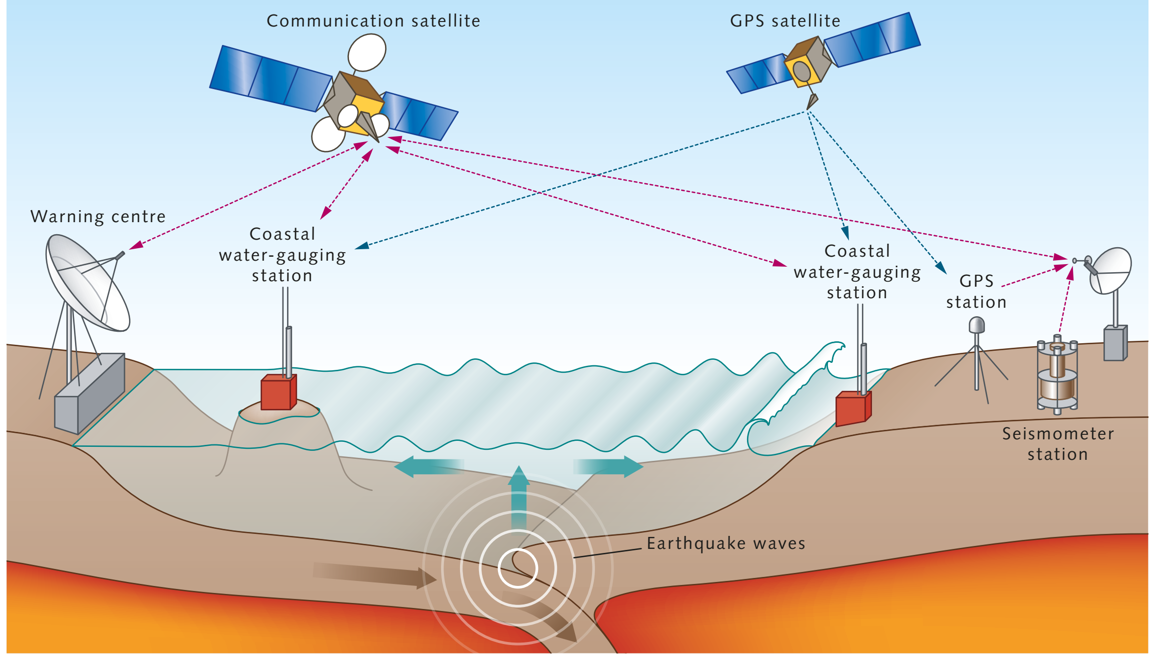
during an earthquake and the GPS sensors can detect this motion. The reliability of prediction is increased significantly by the combination of these three types of sensors, because the information from a single sensor type alone is not sufficient to conclude the formation of a tsunami.

Mathematical models have been developed that can statistically evaluate the sensor data within a few seconds and, with the help of simulations, determine whether a tsunami will be triggered and its impact on land. The sensor data are processed in detail by two models. One models the formation of the tsunami while the other integrates the phases of propagation through the sea and flooding on land. Within a matter of seconds the sensor data are compared with a multitude of previously calculated possible tsunami scenarios. This means that in the case of a catastrophe the time-consuming calculations of probable pathways no longer need to be made. Only now, with this comparison to multiple scenarios, is it possible to make quick and quite reliable predictions accompanied by assessments of statistical uncertainty. All things considered, with the InaTEWS system an alarm can now be sent out within five minutes for the entire Sunda Arc region.

Preparing for the next waves

Not only must warning systems be constantly improved, increased investments in protection measures also have to be made in regions at risk from tsunamis. The IOC is responsible for coordinating this tsunami protection worldwide. It relies largely on educational efforts to teach people to recognize the warning signs of a tsunami and to practice the correct behaviour in the event of a disaster. In many countries, therefore, emergency drills are regularly carried out under the direction of the IOC during which both the warning system is tested and evacuation procedures are taught.

Furthermore, the IOC sponsors the construction of tsunami protection systems. In recent years these have mostly been installed in Indonesia. They include warning sirens, flood-resistant structures built on sturdy stilts that people can escape to, or escape routes that lead quickly to the hills or higher areas of the cities that people can run to. Preliminary evacuation drills have shown, however, that congestion quickly builds up, preventing large numbers of people from making a rapid escape to safe areas. In view of this, the IOC recommends for Indonesia the construction of more flood-resistant buildings in areas directly threatened by tsunamis.



3.27 > The tsunami warning system for the Indian Ocean, developed with significant input from German researchers, is composed of measurement stations located exclusively on land. It includes 30 GPS stations, 160 broadband seismometers and 50 gauging stations to record the water level.

The IOC also endeavours to promote a general awareness of the danger. The tsunami of 2004 clearly showed that the majority of people in the affected countries were completely unaware of the existence of the tsunami phenomenon before the catastrophe occurred. Only on a few islands in the Indian Ocean has the danger of tsunamis been understood and remembered over many decades.

Keeping the memory alive

The island of Simeulue, located 150 kilometres west of Sumatra, is an example. Although the island was struck hard by the tsunami only seven people died. The rest of the inhabitants, still a significant number of around 70,000 people, were able to save themselves by escaping to higher elevations. This was only possible because the people had kept alive the memory of a tsunami that occurred in 1907. The elders referred to this event as "Smong" in their language, and in their traditional stories described very accurately the three phases of tsunami development: the vibrations of an earthquake, retreat of the water, and the approach of the flood wave. The inhabitants of the island were therefore prepared when the tsunami came. They reacted appropriately and most survived.

Threat of tsunamis in the Mediterranean

Similar to the situation off Indonesia, continental plate margins are also located throughout the Mediterranean Sea, and are likewise the sites of frequent earthquakes and active volcanism. Furthermore, the Mediterranean Sea is comparatively small so that, like in the Sunda Arc, a tsunami can reach land within just a few minutes. Second only to the Pacific region, the Mediterranean Sea is considered to be the area most threatened by tsunamis worldwide. The consequences of a tsunami there can be especially devastating because the Mediterranean is a very popular vacation region where hundreds of thousands of visitors go to enjoy the beaches and bathing.

Italy is a good example of a tectonically very active region. At a subduction zone there an extension of the African Plate, the Apulian spur, thrusts beneath the Eurasian Plate to the north. This subduction zone runs lengthwise from north to south through Italy, curves westward in the south and continues further through Algeria and Tunisia. Because of this geological configuration, Italy is repeatedly subjected to large quakes. The intense earthquake in Messina on 28 December 1908 is well known. It almost completely destroyed this Sicilian city as well as the Calabrian cities of Reggio Calabria and Palmi. It also triggered a tsunami that caused further damage. Estimates of the total number of deaths in the region range from 72,000 to 110,000 people.

The difficulty in forecasting tsunamis in the Mediterranean Sea

Although the North-Eastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System (NEAMTWS) has been in operation since 2005, it is still not possible today to accurately determine how great the risk actually is for tsunamis in the various marine areas of the Mediterranean Sea. In recent years, as part of a European cooperative project, investigations using mathematical models were carried out to determine how tsunamis interact with the sea floor in the Mediterranean and how the complex shapes of the Mediterranean coastlines, with the many offshore islands, deep-cutting embayments and differences in water depth, affect their propagation. The results are now being evaluated, and should help to identify areas that are at especially high risk, in order to install protective facilities such as escape routes or seawalls in those areas. There has been some criticism that cooperation among countries bordering on the Mediterranean is not adequate, even though the NEAMTWS is in place. The countries do inform each other in the event of danger, and they carry out joint emergency drills and communication tests. But Portugal, France, Greece, Turkey and Italy each develop their own scenarios and models.

At the UNESCO level, efforts are now being made to promote a better exchange of information among the countries in the future, because when multiple models are compared with one another the quality of prediction is significantly improved. If the conclusions are all similar, then the confidence that the tsunami will behave precisely in that manner is greater. If the conclusions are conflicting, however, or significantly different from one another, then the uncertainty is greater and it would be prudent to collect additional information.

Earthquakes – a dual threat for the coasts

Not only do earthquakes trigger tsunamis on the coasts, they themselves can cause extensive destruction. This was illustrated by the earthquake that occurred in 2003 a few kilometres off the coast of Algeria. Of the more than 2000 people who died, most lost their lives in collapsed buildings. The earthquake gave rise to a weak tsunami that travelled northward. Just an hour later it reached the Balearic Islands, where it damaged boats and cars but no people were injured. The problem is that the buildings in Algeria were not designed to withstand earthquakes and thus collapsed. There are many other coastal areas in the Mediterranean that are at greater risk from earthquakes because the buildings are not built to withstand them.

The coastal city of Istanbul is of particular interest in geoscience research. The city lies on the western extension of a continental fracture zone, the North Anatolia Fault, and is considered to be at very high risk. Based on seismographic measurements on the fault, an earthquake with a potential magnitude of up to 7.5 has been expected for quite some time. Such an earthquake would probably have catastrophic consequences because many buildings in the Istanbul metropolitan area were not constructed to withstand an earthquake. According to a study by the United Nations up to 50,000 deaths could be expected. In Japan it has been shown that earthquake-proof buildings can be constructed. There, even tall office buildings have been able to survive quakes with intensities greater than 8. The buildings are designed to be relatively elastic so that they can absorb the shock.

Landslides – spatially limited and unpredictable

Danger to the coasts also exists in the form of landslides. These originate on the flanks of slopes when large amounts of debris or sediment break loose and plunge into deep water. Landslides can occur on land or on underwater slopes where the material can be transported to great depths. This can result in various hazards for the populations. For one, in the landslides on land people can be buried and residential areas can be destroyed. For another, when it plunges into the sea, the impulse transferred to the water by the slumping of the material could produce a tsunami.

In contrast to earthquakes, which can be precisely recorded and analysed today by modern seismometers, many landslides occur completely unnoticed because they are relatively limited in areal extent. While earthquakes originate along tectonic faults of up to 1000 kilometres in length and are observable on a very large scale, slope collapse, as a rule, usually only occurs at a scale of up to a few dozen kilometres. They therefore produce only comparatively minor tremors.

Although landslides have been intensively researched for a number of years, there are still many unanswered questions. When or where they may occur is not predictable, so direct observations or measurements are almost impossible. Even though it cannot be stated with certainty why a slope has slumped at a specific time, we do have a fundamental understanding of the factors that can lead to landslides. These include:

- Earthquakes that can mobilize the material;
- Gas seeps on the sea floor that destabilize the material;
- Storms producing powerful wave action that break material loose;
- Undercutting of steep cliffs by erosion, for instance by currents over long periods of time;
- Changes in the **pore pressure** in the sediments;
- Volcanic activity that causes entire flanks of volcanic islands to collapse and fall into the sea.

Worldwide, research on landslides has intensified since the turn of the century. One reason for this is the tsunami that occurred on 17 July 1998 in northern Papua New Guinea. On that day there was an earthquake on the coast followed 20 minutes later by the flood wave. It destroyed three coastal villages and killed 2200 people. Soon afterward, because of the severity of the tsunami, the coastal region was intensively investigated. The studies revealed that on the slope off the coast, in a 4-kilometre-wide area, sediments had slumped downward by about 1000 metres. This sudden collapse probably led to a vertical motion of the water column. The waves triggered by the motion were strong enough to cause destruction along a 30-kilometre-wide segment of the coast.

As a consequence of this event, debate intensified regarding the frequency of such landslides and the kinds of hazards they pose. Many coastal regions were investigated using research ships and surveyed with geophysical instruments – including the multibeam echo sounder, which scans the bottom with acoustic waves. The acoustic waves are transmitted from the ship in a fan shape so that a wide strip of the sea floor is recorded. The time required by the acoustic waves reflected from the sea floor to return and be recorded by the ship varies depending on the depth of the sea floor. From the differences in travel time, an elevation profile of the sea floor is calculated on which the evidence of landslides can be clearly seen because, like an avalanche, they leave deep scars in the sediment. The Mediterranean Sea, for example, which is characterized by steep slopes in many locations, has now been almost completely mapped. The depth profiles have been stored in large databases. These document numerous past landslides whose traces have been discovered with the help of the modern instruments.

An area of the Norwegian Sea in the North Atlantic has also been thoroughly studied. There, on the continental slope off Norway on the southern Vøring Plateau – called “Storegga” (the great edge) in Norwegian – one of the largest slumps known today, called the Storegga Slide, occurred 8200 years ago. At that time a 5600 cubic kilometre block of the Norwegian shelf edge slumped off. This impulse triggered a tsunami in the North Sea that attained a height of 20 metres at landfall on the coast of the Shetland Islands. Researchers were able to conclude this based on deposits at the corresponding elevation.

3.28 > 8200 years ago, off the west Norwegian coast, one of the largest landslides known today occurred. At that time a large piece of the Norwegian shelf edge slumped off and plunged several hundred kilometres out into the Atlantic.

Repeated massive collapses

It is now known that there are some coasts where, over the course of time, landslides have occurred repeatedly. Off the coast of the West African country of Mauritania, for example, there are areas where multiple old and young slides overlap. This region is known as the Mauritania Slide Complex. Through coring and analysis of the various sub-bottom layers, it has been discovered that the oldest slide deposits are around 20,000 years old, whereby the individual events apparently occurred at intervals of a few thousand years. Compared to the billions of years of Earth history, that is a short period of time. In the Gulf of Mexico off the coast of the USA, in the Ursa Basin, a flank was discovered on which slides have occurred in the past at a frequency of about one every 5000 years. Further research will be necessary, however, in order to estimate the global average frequency of landslide occurrences.

Efforts have also been underway for a number of years to resolve the possible wave heights of tsunamis triggered in this manner, and their destructive potential. Useful evidence toward this goal is provided by deposits on coasts that have been struck by tsunamis in the past. Noteworthy in this respect is the example of the volcanic Cape Verde island of Fogo, which rises out of the water with a diameter of around 30 kilometres. Based on deposits on

3.29 > Landslides can trigger megatsunamis with heights exceeding 100 metres. When the flank of the Cape Verde island of Fogo plunged into the sea 73,000 years ago, a tsunami wave was formed that heaved water at the coast of the neighbouring island of Santiago to a height of 270 metres.

the sea floor, it has been discovered that around one-third of this volcanic cone slumped into the sea about 73,000 years ago. The material that was mobilized had a volume of about 500 cubic kilometres, which is equivalent to a block five kilometres high with an area equal to that of the german city of Osnabrück. This mass motion produced a powerful impulse that forced the water at the shore of the neighbouring island of Santiago, 40 kilometres away, to a height of 270 metres. Tsunamis like this, with wave heights of greater than 100 metres, are referred to as megatsunamis.

Understanding the distance effect

Researchers are currently investigating how far waves initiated by landslides can travel. Because they are relatively small events compared to submarine earthquake waves, the impacts of landslides are more local in nature. But waves triggered by them can reach very great heights. It is unknown, for example, whether the landslide on Fogo caused any damage on the coasts of Africa or America because it is difficult to find any traces there of a tsunami that happened 73,000 years ago. It is generally assumed, however, that tsunamis triggered by landslides do not have the kind of long-distance destructive effect that the earthquake of 2004 had. But even when landslides do not trigger a tsunami they can still be destructive. There have already been many cases where submarine landslides have severed telecommunication cables, which then led to expensive repair work. There has also been some discussion of the potential dangers to oil pipelines and drilling platforms that have been installed on slopes.

There are also known cases of landslides being triggered by human activity, such as the slide at Nice on 16 October 1979. About two kilometres off the coast of Nice the sea floor falls steeply parallel to the shoreline. In 1979 a harbour jetty was built outward like a finger pointing into the sea. The construction activity and especially the immense weight of the breakwater structure itself eventually caused the slope to cave and slump downward, taking the new harbour with it. Shortly afterward a tsunami reached the area around Nice with a height of three metres, but it subsided again relatively quickly. Still, several people died.

El Niño – climate fluctuation with major consequences

Another natural phenomenon that can impact coastal habitats is the El Niño climate event, which occurs irregularly every three to ten years in the tropical Pacific. It arises when the atmospheric pressure relationship between the western Pacific and the central Pacific is reversed, leading to large-scale directional changes in the prevailing winds and surface-ocean currents. As a result, it greatly changes the spatial distribution and intensity of precipitation over land and thus, to a similar degree, the living conditions for coastal human populations and marine organisms. There are natural climate fluctuations in other marine regions of the Earth that occur with a certain rhythm. But El Niño is considered to be the largest in the world and the one with the most severe consequences.

The phenomenon is especially dreaded by the fishermen on the coasts of Chile, Ecuador and Peru because El Niño can lead to a decrease in the volume of their catch. Because of the upwelling of nutrient-rich deep water, the Pacific coast of South America is normally very productive. Plankton grows here in large amounts, providing the fish with abundant food. There are especially large stocks of anchovies here, as well as other species of fish.

When the ocean current reverses during an El Niño event, warm, nutrient-poor water from the equatorial region flows toward the coast of South America. The upwelling process is interrupted, the influx of nutrients is stopped and plankton growth declines, thus inhibiting the production of anchovies. These are replaced by tropical fish species that migrate in with the warm water. Because the incoming water is very oxygen-rich, it is beneficial to the bottom fauna, and a number of invertebrate animal species that are important for the fisheries can thrive under these conditions. For example, during the two strongest El Niño events of the past century, in the years 1983/84 and 1997/98, the populations of scallops and

How El Niño forms

The formation of the El Niño climate phenomenon has been a puzzle for many years, and even today it is not completely understood. Today it is known that an El Niño event is related to two important atmospheric circulation systems: Hadley Circulation and Walker Circulation. The Hadley Circulation is like a rolling drum of air currents that circulate worldwide in the tropical latitudes. Because the sun is high in the sky all year round in the tropics, air masses are warmed there, then rise and flow northward and southward toward the poles. The circulation is completed when air masses in the lower layers of the atmosphere flow back toward the equator, there to rise again. The circular motion occurs because the upper-level air flowing poleward from the equator gradually cools down and sinks again near the Northern and Southern Tropics, at around 23 degrees of latitude. This circulation was named after the man who discovered it, the English physicist George Hadley. Because the Earth is rotating, the sinking air masses flowing back toward the equator are deflected to the west, so that the surface winds in the northern hemisphere come from the northeast (northeasterly trade winds) and in the southern hemisphere from the southeast (southeasterly trade winds). These steady winds push the surface waters of the tropical Pacific toward the west, away from the coast of South America. This constant westward forcing results in a sea level in the West Pacific off South East Asia that is up to 60 centimetres higher than that off the western coast of South America.

Replacing the surface water pushed westward away from the South American coast by the trade winds, cold, nutrient-rich water from below flows upward to the surface. This phenomenon is called upwelling. This water is also forced to the west, forming a cold tongue of water extending out into the Pacific. But as it moves westward it is constantly heating up, until the water masses finally reach a temperature of around 30 degrees Celsius off the South East Asian coast. Because of the heat, large amounts of the water evaporate off South East Asia, forming intense cloudiness and resulting in the development of a warm tropical rainforest climate.

The other circulation system, the Walker Circulation, only occurs in the Pacific. It flows in an east-west direction, at right angles to the Hadley Circulation. This circulation, named after its discoverer, the English physicist Gilbert Walker, is driven by atmospheric pressure differences between the western and central Pacific.

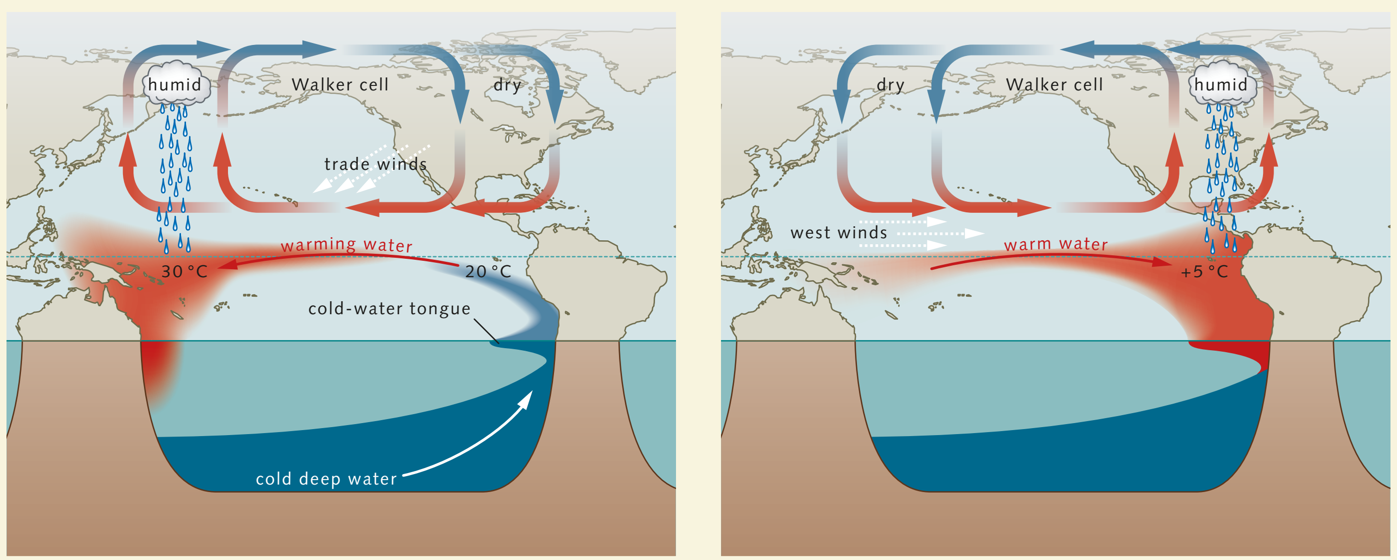
As a rule, there is a stable low-pressure system above the western Pacific near South East Asia and a high-pressure system in the central Pacific. This results in a constant westward flow of the air masses from the area of high pressure to the area of low pressure. Warm humid air rises here, forming clouds over South East Asia and leading to rainfall. At higher altitudes this air then flows directly eastward, oblique to the Hadley Circulation. Above the South American continent the air descends and flows westward again. Because its humidity has been lost over South East Asia through the heavy rainfall, the air that descends to the western coast of South America is very dry. Due to the combined components of Walker Circulation and Hadley Circulation, there is a strong prevailing wind toward the west in the lower layers of the atmosphere, which maintains the stable coastal upwelling system.

During an El Niño event there is a significant change in the relative atmospheric pressures: above South East Asia the pressure increases and in the central Pacific it drops. The prevailing winds weaken, decreasing the water transport from east to west. The changing air pressures ultimately progress to the extent that the east-west relationship is reversed. A high-pressure system forms over South East Asia and a low-pressure system over the central Pacific. The westward-blowing winds weaken significantly, and the wind direction can even be reversed. As a result, the warm surface water then flows from South East Asia toward South America. This often produces unusually heavy precipitation on the dry west coast of South America. In spite of intense research, the reason for this reversal in atmospheric pressure is still unknown.

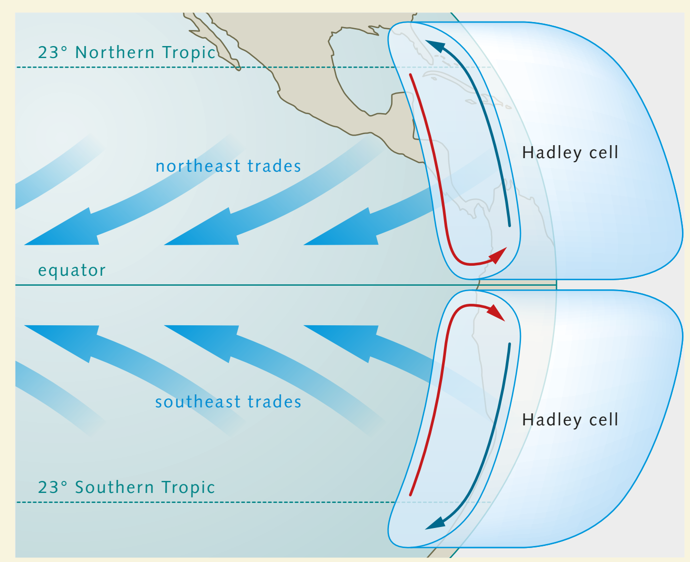
The name "El Niño" is Spanish for "the child" and refers to the infant Jesus. It originates from South American fishermen who have long known that El Niño reaches its peak around Christmas time. Today scientists refer to the phenomenon as ENSO, which stands for El Niño southern oscillation. This highlights the fact that the phenomenon occurs in the south and is driven by the oscillation of atmospheric pressure between the east and west. An El Niño event can last for more than twelve months.

Besides El Niño, there is another deviation from the normal atmospheric pressure regime in the Pacific called "La Niña" ("the girl"). During a La Niña event the normal atmospheric pressure difference becomes more pronounced. Thus, the pressure in the western Pacific low-pressure system falls even further and it increases even more in the central Pacific. In this extreme situation, the winds blowing toward the west increase in strength, which also increases the transport of water from South America toward South East Asia.

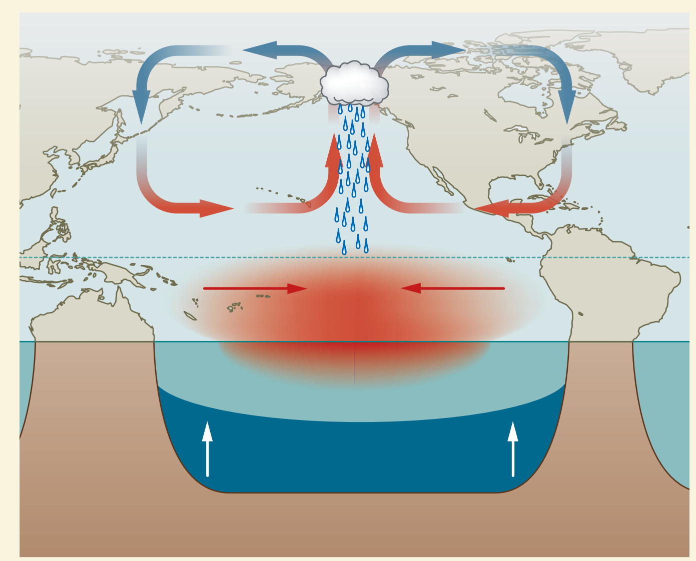
Today it is known that in addition to El Niño and La Niña, there are other variations of this phenomenon. There are El Niño events that do not encompass the entire Pacific. In these cases, the air-pressure relationship between the western and central Pacific changes, but the warm water does not extend as far as South America. Japanese scientists published an article in 2004 in which they described this unusual El Niño variant. According to their work, the air pressures over the Pacific change as follows: a low-pressure system develops in the central Pacific; at the same time high-pressure systems form in both the eastern and western Pacific, so the wind flows from both directions toward the low-pressure area in the central Pacific, where the warm air then rises and forms clouds. These rain down in the central Pacific. The Japanese researchers called this form "Modoki", a Japanese phrase that follows and qualifies the noun. It means "similar, but different". This variant has since been referred to by experts as El Niño Modoki.



3.30 > Steady trade winds normally force water from the coast of South America out into the Pacific. This causes cold, nutrient-rich deep water to rise off the coast of South America. During an El Niño event the winds become weaker and warm water flows toward America.



3.31 > The Hadley Circulation is a drum-like air circulation pattern that operates in the tropics and moves air between the equator and the Northern and Southern Tropics.



3.32 > During the rare phenomenon known as El Niño Modoki, the wind blows from the west and east toward the low-pressure area in the central Pacific.

3.33 > Peru is a major supplier of anchovies. During El Niño events the catch sizes can fall drastically.

octopuses exploded. In both cases the El Niño phases lasted for several months and brought strong rainfall and high water temperatures to South America. The anchovy stocks, however, fell drastically. Many of them starved, while others were able to concentrate in the remaining cold-water cells, but they were easy prey there for the industrial fisheries. As a result of the El Niño of 1983/84 the anchovy fishery off Peru ultimately collapsed completely. Lessons were learned from that mistake, and in 1997/98 the fishing pressure during El Niño was drastically reduced. The yield dropped from the previous average of 12 million tonnes per year to a mere 2 million tonnes, but by the following year the catch sizes had already begun to increase again.

Heavy rainfall over South America

El Niño events are also known to produce prolonged heavy rainfall on the west coast of South America. The most recent example is an El Niño event that brought flooding and landslides in February and March 2017, especially to Peru, and resulted in the declaration of a state of emergency in more than 800 of the approximately 1800 districts of Peru. Nationwide more than 70,000 people were left homeless and suffered heavy loss of possessions. A hundred people died. In addition, the voluminous rains led to a freshening of the coastal waters. The salinity of the seawater was reduced in some locations to a quarter of the normal level. Hardest hit by this were the scallop farmers, much of whose crops died in the low-salinity water.

How far the impact of a strong El Niño extends is still not precisely known today. It is believed that El Niño can also alter climate outside the Pacific for periods of several months. The following consequences can be attributed to El Niño with a relatively high degree of probability:

- an increase in tropical storm activity in the eastern North Pacific;
- a decrease in hurricane activity in the Atlantic Ocean and a corresponding aridity in the Caribbean and Central America, increased precipitation in the southern USA and in eastern Africa, but also drought in northeast Brazil.

The explanation for these long-range effects is presently being studied.

El Niño Modoki events can also have serious consequences for coastal habitats, even though they do not directly involve the entire Pacific. Extensive climatic changes in various regions have been attributed to one such event that occurred in 2015, including severe negative consequences such as flooding in southeast India and Paraguay as well as droughts in Ethiopia and southern Africa, but also positive effects such as milder winter temperatures in the USA and fewer hurricanes over the Atlantic. It is not certain whether all of these effects can in fact be ascribed to this El Niño Modoki event. It is fairly conclusive that the 2015 event led to particularly heavy coral bleaching in the Great Barrier Reef on Australia's northeast coast. There had already been a number of coral bleaching episodes on the reef since the beginning of the millennium, so that some reef segments were already vulnerable. The El Niño Modoki led to further warming of the water, subjecting the corals to additional stress and causing bleaching in large areas of the reef. Even today, many of these areas have still not recovered from the bleaching.

Conclusion

Climate change and natural hazards threaten the coasts

The intensity of the impact of climate change on coastal habitats depends to a large extent on the levels of carbon dioxide (CO_2) in the Earth's atmosphere. The direct consequence of heavy CO_2 emission is a gradual warming of the atmosphere, which causes a warming of the surface water, and that, in turn, inhibits its mixing with the underlying cooler and denser water.

This then reduces the amount of oxygen-rich water being introduced into the deep layers, which can result in an oxygen deficiency. It is difficult for animals such as crabs, clams or fish to survive in such areas.

Tropical coral species are also affected by the warming. It is presently believed that around 20 per cent have been irretrievably lost through warming and other stress factors such as marine pollution, and at least another 30 per cent severely impaired.

In other marine organisms it is often the eggs and larvae that react sensitively to ocean warming. For the Northeast Atlantic cod it can mean an early death. Yields in the economically important cod fishery could fall drastically in the Barents Sea in the future.

Another consequence of climate change is acidification of the oceans. This is due to the increasing dissolution of CO_2, which produces acid. Marine organisms that secrete calcareous shells or form skeletons are most severely affected by this. In corals, clams and snails, the calcite formation declines by 22 to 39 per cent in acidified water, depending on the animal group in question. On the other hand, studies now indicate that some marine organisms can cope with acidification over the course of several generations.

For humankind, climate change represents a hazard as a result of the sea-level rise that it causes. Since 1990, sea levels have been rising annually by around 3 millimetres; this rate will likely accelerate with sustained CO_2 emission levels. By the year 2100 it is expected that global sea level will have risen by an average of up to 1 metre.

In addition to the consequences of climate change, there are also a number of natural hazards that impact the coasts. These include earthquakes, landslides and tsunamis, as well as natural climatic phenomena. Although humans have no influence on the occurrence of such events, a number of technical solutions have been developed to protect coastal populations as far as possible.

There have been many cases where lessons were learned from disasters such as tsunamis, which are usually triggered by earthquakes. While Japan and the USA have had warning systems operating since the middle of last century, they were first installed in the Indian Ocean region after the tsunami of 2004.

Tsunamis can also be triggered by landslides. These are generated when large volumes of sand or sediment break off on slopes and plunge into deeper water. As a rule, such local events do not have the long-distance consequences of a tsunami wave initiated by an earthquake. Extreme wave heights of over 100 metres are possible, however.

Coastal habitats can also be affected by the El Niño climate phenomenon, which occurs every three to ten years in the tropical Pacific. It can lead to severe aridity in South East Asia and torrential rainfall in South America.

In addition, water temperatures in the Pacific change, causing a collapse of the large fish stocks off South America. The losses by fisheries are extensive.

4 Improving coastal protection

> If the coast is to be conserved as habitat, it has to be protected. This not only entails prudent management of coastal areas, taking all stakeholder groups into consideration, but also maintaining a catalogue of effective coastal protection measures that can be adapted as sea level rises. Worldwide there are examples which give cause for hope. One challenge that remains is that of creating homelands in new places for the coastal dwellers that lose their homes because of climate change.

The art of coastal management

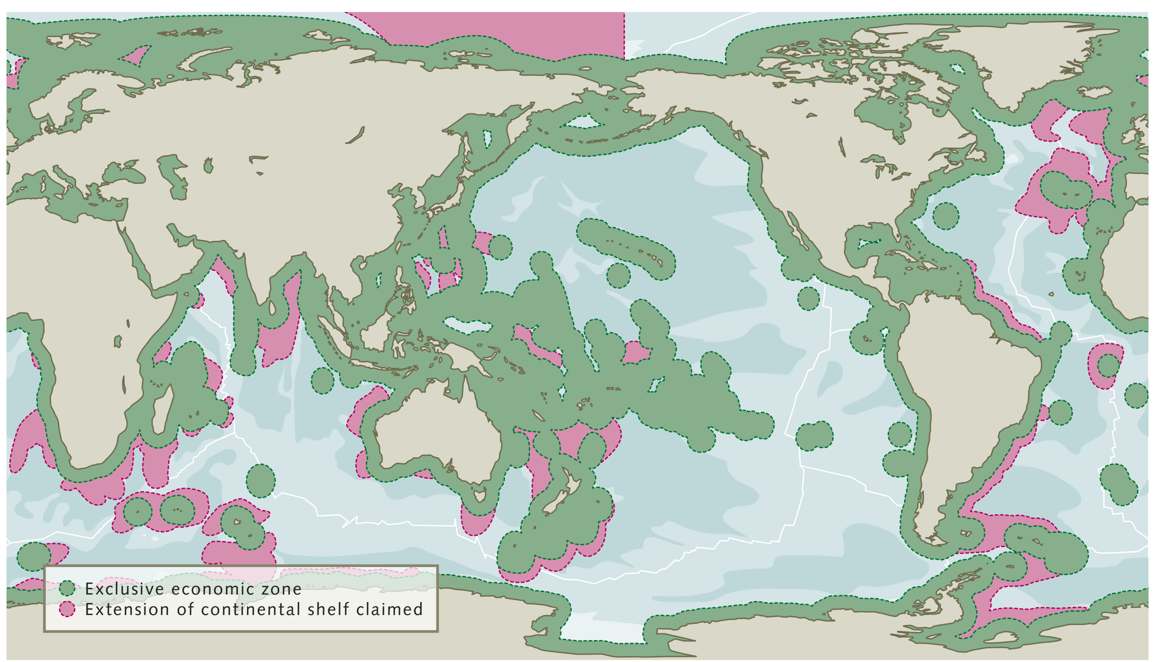
> Divergent interests give rise to conflicts time and time again in the course of comprehensive coastal protection. However, if all stakeholder groups can agree on a sustainable management plan, this often generates considerable benefits for all.

The significance of coasts – a question of perspective

The world's coasts are diverse. Some are popular as holiday destinations and have remained almost unspoilt. Others, located on important shipping routes, have been heavily developed industrially. Then there are coastal regions that are significant for small-scale fisheries. These supply large quantities of fish from which millions of people earn their living; on the other hand, they are often used as a natural water-purification plant for the effluents of a growing coastal population. The significance of the coasts in traditional or indeed religious respects varies greatly from culture to culture. And whether a region or a country considers the coasts as significant at all depends on all kinds of factors, but is most obviously reflected in active political measures for their protection.

International ground rules for the world's coastal areas

Anyone who is permitted to use a coastal area in any way today is subject to clear international regulations through the United Nations Convention on the Law of the Sea (UNCLOS) which was adopted at the UN Conference on the Law of the Sea of 1982 and entered force in 1994 after arduous negotiations. It sets out the ground rules for all uses of the ocean, such as shipping, fishing, natural gas and oil drilling and environmental protection. The provisions of UNCLOS apply to all states and as a general principle in all zones of the ocean. Nevertheless, it must be noted that different bodies are responsible for the implementation of the law in each of the various oceanic zones. Distinctions are made between the following coastal and marine zones:



4.1 > Coastal states have exclusive rights within their exclusive economic zones (EEZ) to exploit marine resources such as fish. If certain conditions are satisfied they can even extend their EEZ to include part of the continental shelf.

4.2 > The Banc d'Arguin National Park is an area of tidal mudflats and lagoons on the coast of the West African state of Mauritania. The national park is an important over-wintering site for migratory birds which feed there to build up their fat reserves for the long flight ahead.

TERRITORIAL SEA: The territorial sea is the 12-nautical-mile zone. It belongs to a state's sovereign territory. Activities in this zone are governed by the legislation of the individual states. However, legislation must conform to the internationally agreed rules if the state has ratified UNCLOS.

EXCLUSIVE ECONOMIC ZONE (EEZ): This extends from the outer edge of the territorial sea to 200 nautical miles (approximately 370 kilometres) offshore. Therefore the EEZ is also called the 200-nautical-mile zone. Included within the EEZ are the sea floor and the water column. Unlike the territorial sea, the EEZ is not part of a state's sovereign territory. Nevertheless, within its own EEZ the coastal state alone may extract resources such as petroleum and natural gas, mineral resources, and of course fish stocks. Other nations may only use the resources if the relevant coastal state consents. Resource extraction in the EEZ is subject to the coastal state's legislation, which in turn must be in line with the international rules laid out in UNCLOS. For other uses of the ocean, particularly shipping, the freedom of the high seas applies equally within the EEZ.

CONTINENTAL SHELF: The continental shelf is the gently or steeply sloping sea floor off the coast, which is a natural geological extension of the mainland. The term has both a legal and a geological definition. In the legal sense it denotes the area that extends to 200 nautical miles beyond the coastline, while in the geological sense, the term is synonymous with the shelf. The shelf referred to is the shallow, near-coastal section of the sea floor. The shelf slopes away gently to an average depth of 130 metres, and is adjoined by the continental slope which slopes more steeply up to 90 degrees. The continental shelf is of special economic interest because among other resources, large quantities of natural gas and oil can be found there. In many parts of the world there are regions where there is geological evidence of an outer continental shelf that begins within the exclusive economic zone and continues beyond the 200-nautical-mile limit, thus enlarging the coastal state's sphere of influence. Such evidence must be submitted scientifically to the Commission on the Limits of the Continental Shelf (CLCS) in New York, and accepted by that body. This outer continental shelf which goes beyond the EEZ can then be extended up to a line at a maximum of 350 nautical miles off the coast. Alternatively a state can claim a marine area up to 100 nautical miles past the 2500-metre-depth line as an extension of the continental shelf past the limits of the EEZ, and in some cases even beyond that.

HIGH SEAS: Adjoining the EEZ are the high seas, which no national government may claim for itself alone; they are available to be used by all countries. Nevertheless, the use of resources in the high seas is regulated. Fisheries, for instance, are regulated by Regional Fisheries Management Organizations (RFMOs) which, among other issues, specify maximum catch sizes for fish species. In contrast, the International Seabed Authority (ISA) is the sole body that supervises the use and distribution of seabed resources. It is responsible for all mineral resources on the sea floor. These are defined in the Convention on the Law of the Sea as common heritage of mankind.

National-level regulations

Whereas UNCLOS sets out clear international regulations on the use of the various marine zones and thereby defines whom the ocean or the coastal waters belong to, the management of the 12-nautical-mile zone is the sole province of the coastal state concerned. Consequently the administrative details are regulated differently from one nation to another (and, in federal countries, sometimes even from one federal state to another). For the management of coastal waters this means a considerable need for coordination between different authorities.

How many different authorities can be involved in coastal administration can be exemplified by the administration of the German North Sea coast, which borders onto the German states of Lower Saxony, Schleswig-Holstein and Hamburg. In Lower Saxony alone the responsibility for the coastal sea is shared between the following authorities or bodies:

- Water and Shipping Authorities: These are subordinate to the Federal Ministry of Transport and Digital Infrastructure and are responsible for the safety of shipping in the coastal sea and on the federal waterways of the rivers Elbe, Weser and Ems, which are under the control of the German federal government. Among their tasks are the siting and servicing of navigational aids and the maintenance of bank reinforcements as well as locks and weirs along the federal waterways. Responsibility for nature conservation along the banks of the federal waterways rests with the subordinate nature conservation authorities of the district authorities, provided that these areas are not part of a national park or a biosphere reserve.
- Lower Saxony Ministry for the Environment, Energy and Climate Protection: The ministry is responsible for the natural areas along the coast that have biosphere reserve status. Biosphere reserves are model regions initiated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) with the aim of achieving sustainable development in environmental, economic and social respects.
- Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (NLWKN): This agency is subordinate to the Lower Saxony Ministry for the Environment, Energy and Climate Protection and is responsible for coastal defences on the islands belonging to Lower Saxony; the authority cooperates closely with the dike associations. In addition, the NLWKN is responsible for nature conservation in part of the dike forelands – in the salt meadows for example.
- National Park Administration: It is subordinate to the Lower Saxony Ministry for the Environment, Energy and Climate Protection and is responsible for the Lower Saxony Wadden Sea National Park, and beyond this, for the dike forelands located within the bounds of the national park.
- Main Dike Associations: These are public-law bodies which are responsible for the safety of the dikes that defend the full length of the mainland coast. The dike associations have a long tradition, going back several hundred years in some cases. They were founded by the residents of the different coastal municipalities and to this day consist largely of a voluntary workforce. The president of a dike association bears the title of "dike reeve" (Deichgraf). In the 1960s several dike associations were merged, leaving a total of 22 Main Dike Associations controlling and improving the dikes along the Lower Saxony coastline.
- Lower nature conservation authorities: These are subordinate to the respective districts and are responsible for natural areas along the coastline that are not part of the national parks.

Even just the example of Lower Saxony shows what a proliferation of responsibilities there can be in one German federal state. In Hamburg and Schleswig-Holstein, by comparison, there are differences of detail in the regulations and the official structures. This diversity is explained in large part by Germany's federalist system, but is also an example of how the management of an entire coastal area can only function when there is clear coordination and division of work between the different authorities. For example, over the years it can be deemed a success that the German Wadden Sea as a whole has been designated as a protected national park in spite of the disparate responsibilities across federal state boundaries. Beyond this, the responsibility for infrastructures of supraregional importance such as the federal waterways rests with a single body – the Federal Ministry of Transport and Digital Infrastructure. However, experts also emphasise that the division into different authorities can have advantages. They point out that within the different authorities there are large numbers of experts who possess important detailed and specialist knowledge, be it on coastal defences or nature conservation or regarding waterway safety.

Many demands – many conflicts

Coasts have many functions and provide many ecosystem services – such as fish, navigable waterways, tourism and

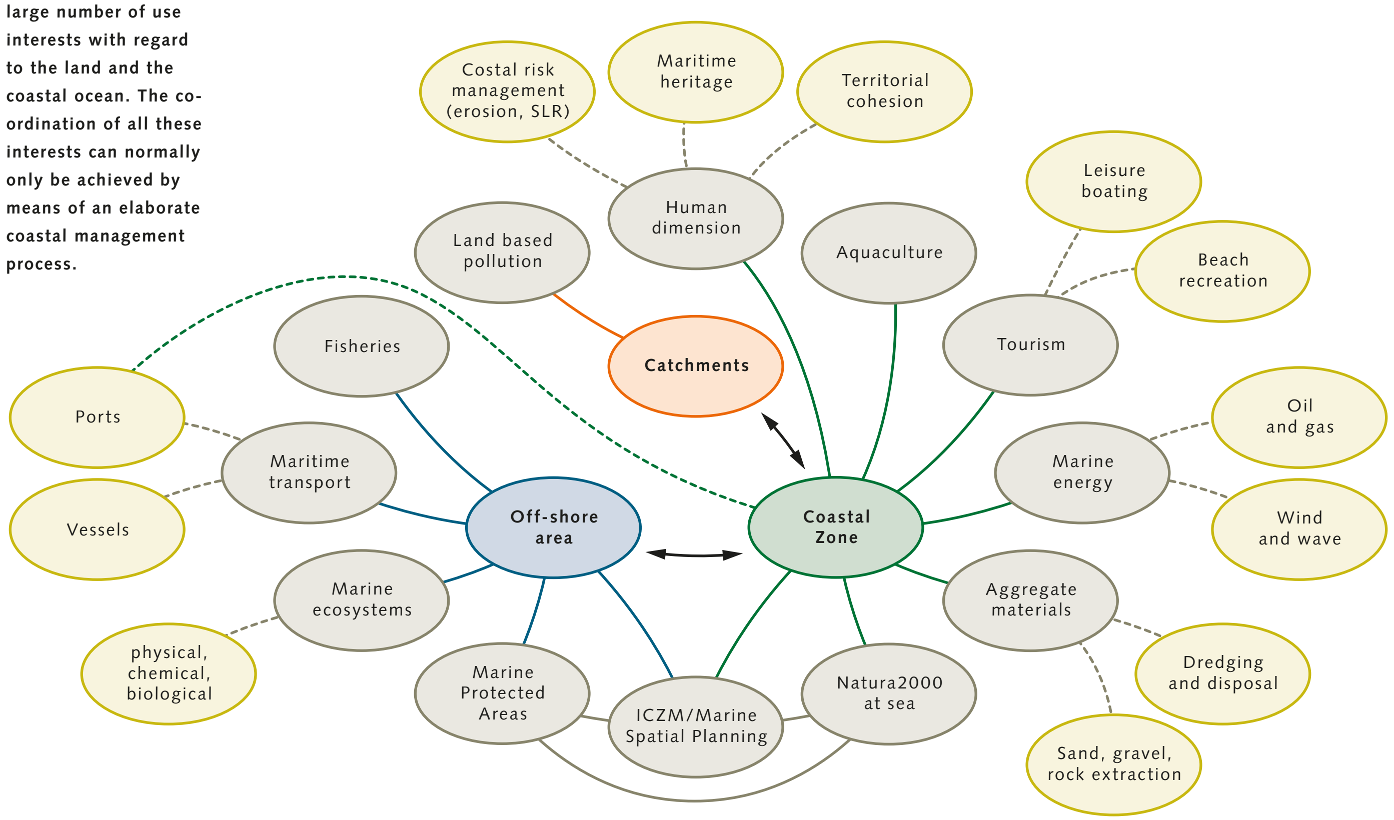
4.3 > Responsibility for the maintenance and safety of federal waterways like the river Elbe, pictured here, rests with the Federal Ministry of Transport and Digital Infrastructure, whereas the dikes protecting the hinterland are cared for by dike associations.

recreation, or space for agriculture and construction projects. That is to say, countless activities are concentrated on the relatively slender strip between land and sea in densely settled or heavily used coastal regions – which automatically results in a plethora of responsible authorities.

This plurality can easily lead to conflicts if there is not sufficient coordination between the respective authorities or among the different stakeholder groups generally. For example, human use often comes into conflict with nature conservation aspects. In China the desire for economic development led to substantial pollution of coastal areas. In order to catch up with the high economic standards of the West as fast as possible, often very little attention was paid to environmental aspects. Today there is growing resistance to such a one-sided focus among the Chinese population, and it is being realized that goal conflicts have surfaced which can only be resolved by rising above the mere satisfaction of particular interests. Not just in China but in many other regions worldwide, such stringently sectoral approaches are preventing efficient protection of coastal habitats or sustainable use. The situation is even more difficult if coastal habitats extend beyond national borders, as the Wadden Sea does, for example, in Germany, the Netherlands and Denmark. Here an effective coastal management scheme is only possible in international cooperation.

All parties around the table

An appropriate concept for the sustainable and comprehensive management of coasts was presented for the first time in 1992 during the United Nations Conference on Environment and Development in Rio de Janeiro: Integrated Coastal Zone Management (ICZM), the aim of which is sustainable development of coastal zones and which seeks to reconcile all aspects of coastal development. To this day many countries and international communities – for example, the European Union – have made ICZM the guideline for planning future coastal development, defined as follows: "Integrated Coastal Zone Management seeks, over the long term, to balance the benefits from economic development and human uses of the Coastal Zone, the benefits from protecting, preserving and restoring Coastal Zones, the benefits from minimizing loss of human life and property, and the benefits from public access to and enjoyment of the Coastal Zone, all within the limits set by natural dynamics and carrying capacity." Although ICZM is acknowledged today as a tool for future coastal zone management, coordination of the particular interests of the different stakeholder groups remains the greatest challenge.



4.4 > Many coastal areas are subject to a large number of use interests with regard to the land and the coastal ocean. The coordination of all these interests can normally only be achieved by means of an elaborate coastal management process.

According to the Food and Agriculture Organization of the United Nations (FAO), nowadays there are a series of causal factors that result in the exploitation or degradation of coastal habitats rather than their sustainable use. These include:

- large business enterprises geared towards quick profits, which exploit or destroy resources and which conflict with the interests of the coastal population;
- a shortage of serious governmental follow-up measures for the support and implementation of nature conservation programmes;
- low awareness among local people and policy-makers about a form of management that relies on sustainable resource use;
- poverty which is exacerbated by the increasing scarcity of resources, damage to habitats and fish breeding grounds and a lack of alternative livelihoods;
- strong population growth.

Good management delivers benefits

This conflict potential can be defused, the FAO notes, if all these aspects are taken into consideration as part of an integrated coastal zone management scheme, and ICZM programmes, once drafted, are actually implemented in full. According to the FAO approach, ICZM programmes can benefit countries or individual coastal regions in the following ways:

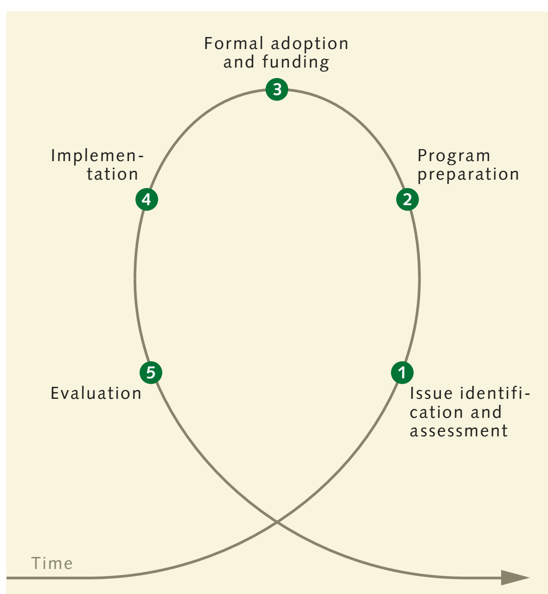
- Facilitating sustainable economic growth based on natural resources;
- Conserving natural habitats and species;
- Controlling pollution and the alteration of shorelands and beach fronts;
- Controlling possible pollution in watersheds that drain into the coastal region;
- Controlling excavation, mining and other construction impacts on coral reefs and on the near-coastal sea floor generally;
- Sustainable use of overused resources so that these can recover, such as fish stocks and other marine organisms;
- Providing mechanisms and tools for equitable and sustainable resource allocation among the various stakeholder groups;
- Quicker and more focused implementation of projects by involving all stakeholder groups, because this averts later disputes that might delay a project;
- Avoiding damage to the marine environment or marine resources.

Furthermore, a comprehensive ICZM programme today must address more than just the immediate shorelands and coastal waters but also the multifarious relationships between the coast and the hinterland – be it for the creation of sales markets for new, sustainably harvested products, or with regard to preventing land-based pollution of coastal waters. The FAO emphasises that this list represents the ideal form of ICZM and that in today's world not all the goals of ICZM projects will be achieved in every case. Nevertheless, the ICZM idea has gained traction in many places.

Depending on the number of use interests, an Integrated Coastal Zone Management process can vary in its complexity. If only individual or a handful of user groups are involved, the overall process is generally more streamlined. This may be the case in coastal regions of developing countries, for instance, where artisanal fishery is the main feature and few other types of use exist. In the meantime, successful examples exist from which much can be learned.

Optimization through quality control

Regular monitoring of whether certain measures have resulted in a set objective is of crucial importance for a successful ICZM process. This also means that ICZM is not a one-off project but a cyclical process in which results are continually reviewed and assessed. Thus it is also possible to adapt the ICZM process little by little to new conditions and optimize it. An ICZM cycle begins with an analysis of the situation and assessment of the problems. This is followed by the drafting of an action plan that takes account of all the issues. Next, the action plan is formally approved by all parties involved. A prerequisite for this, however, is that financing is pledged for the complete set of measures from the action plan. This is followed by the implementation phase. Once the measures defined in the action plan have been implemented, an evaluation takes place which assesses the measures to determine their impact. If further problems or new difficulties arise, the action plan must be refined. This completes the cycle.



4.5 > Ideally an ICZM process takes place in cycles, during which measures are planned, implemented and then evaluated. If optimization is found to be needed, the next cycle begins with the planning of new measures.

Depending on the scale of an ICZM process, the duration of a cycle may vary. Best-practice examples show that one cycle of an ICZM project on a national scale, from situation analysis to evaluation, takes around eight to twelve years. If the process only encompasses a certain coastal region or a single coastal town, one cycle lasts around three to four years on average.

Bringing local people on board

Depending on the situation in the given location, various stakeholder groups must be involved in the ICZM process. The following successful examples will make this clear.

In the year 2000 the Locally-Managed Marine Area Network (LMMA) was founded in the Indo-Pacific region, the marine region that encompasses the Indian Ocean and the Western Pacific. This network was first instigated by the work of non-governmental organizations and individual, well-networked scientists, and could ultimately be established in the region. Its objective is to protect coastal waters by making use of them sustainably and prudently – for example, if fishers switch from destructive dynamite fishery to gentler methods of catching fish. The LMMA idea was born from the insight that marine protected areas (MPAs) that are defined at high political level are often not accepted by the population because they can massively curtail their rights. In concrete cases the population was completely prohibited from fishing in MPAs, which could not be reconciled with the local people's traditional customs. The local people resisted the prohibition on use, which undermined marine protection in the areas concerned from the very start. In the meantime many village communities in different countries now belong to the LMMA network, and have regular opportunities to engage with each other at regional, national and international workshops. The supreme objective of the LMMA is marine protection.

It differs from the idea of MPAs in that grassroots groups are given a voice during the planning phase and take charge of sustainable management in their locality themselves. Thus, all stakeholder groups are involved in the planning: village communities, associations of land-

4.6 > A self-painted sign for a self-administered protected area. The ocean around the island of Vanua Levu, which belongs to Fiji, was declared a locally managed marine area (LMMA) in a comprehensive management process. Here the local fishers themselves ensure sustainable use of the fish and seafood.

owners, nature conservationists, representatives of regional or national authorities who live locally, with scientists on hand to provide advice and backup.

The problems are similar in many coastal areas of the Indo-Pacific region. In many places the marine biotic communities and natural resources are being harmed by overfishing, by destructive fisheries such as dynamite and cyanide fishery, by pollution or by industrial activities on land. The coral reefs in the region suffer additional degradation from being trampled by tourists and damaged by anchors or by the removal of corals for sale as souvenirs. It is important that the local population can retain its sovereignty through the LMMA process by participating in deciding, in consultation with other stakeholder groups, which fishery methods they should use in future. Also as part of the planning process, alternative activities need to be developed whereby local people can secure their incomes in future. Compliance with the agreed rules is overseen either by local chiefs, traditionally organized village communities or else the local coastal fishery authorities. As a rule, some territory is also defined during the LMMA planning process where a complete prohibition on use applies, which guarantees that stocks of the marine organisms subject to use can recover. In this respect the LMMA idea certainly comes close to the principle of the MPAs. In summary, the LMMA approach pursues the following objectives:

- Improved quality of the marine habitat (coral cover, sea grass, mangroves);
- Increased fish population, and hence improved reproduction of fishes and higher fish biomass;
- Increased incomes resulting from the use of marine resources;
- Enhanced capacity of the local population to manage their resources;
- Stronger sense of environmental stewardship and community cohesion.

The long road to the Wadden Sea World Natural Heritage site

How complex and laborious it can be to reconcile opposing positions and achieve sustainable use of a coastal area is exemplified by the North West European Wadden Sea, which was granted World Natural Heritage status by UNESCO (United Nations Educational, Scientific and Cultural Organization) in 2009. This area of tidal mudflats, the world's largest, is around 500 kilometres long and extends across large parts of the Dutch, German and Danish North Sea coasts. Today, with its World Natural Heritage status, it is recognized internationally as an ecological region of special aesthetic quality and of particular significance as a breeding ground for the fish of the North Sea and millions of breeding and resting birds. Several million holidaymakers currently visit this region every year.

It took almost 50 years for protected status to be achieved. Interestingly, this was accomplished despite the fact that each of the coastal states pursued the protection of this transboundary ecological region through their own national legislation rather than through trilateral treaties. Moreover, this example shows that initial resistance can be overcome, in this case thanks mainly to the enduring commitment of individual protagonists and nature conservation organizations over many years.

A severe storm surge affected the Netherlands in 1953 and Germany in 1962. In both cases, the dikes along the North Sea coast were breached in many places. Some 1800 people died in the Netherlands in 1953 and more than 300 in Germany in 1962. In the following years, dikes were reinforced in many places and the shorelines straightened by damming bays. In the Netherlands and Germany there was also discussion of large-scale solutions – constructing dikes around major areas of the Wadden Sea. The intention behind this was not merely to protect the land from further floods; additional plans were made to put the newly reclaimed land areas to industrial and agricultural uses. In the 1960s the Wadden Sea was considered by all three countries as a backward region that required economic development. To this end, initially a series of nuclear power stations was to be constructed in the enclosed areas, which would then be likely to attract other industrial enterprises. The construction of an airport was also proposed.

4.7 > In 1972 fishers in the Netherlands protested against the damming of the Eastern Scheldt estuary.

The first critiques of these plans were voiced in 1965 in the Netherlands where activists published letters of protest in the daily press. Out of this solitary act of resistance, the first nature conservation organization came into being that was dedicated wholly to the protection of the Wadden Sea, the Landelijke Vereniging tot Behoud van de Waddenzee (Association for protection of the Wadden Sea). At about the same time, the Royal Dutch Academy of Sciences had commissioned a group of younger scientists with a first systematic survey of data on the Wadden Sea's ecology. Although the significance of the habitat for fish breeding and bird life was known, very little else about the ecosystem was understood. Strong advocates from the scientific world thus stood shoulder to shoulder with nature conservationists. Even then, the scientists were emphasising the significance of the Wadden Sea as a transboundary habitat which needed to be protected by means of international agreements. In Germany, too, the first groups emerged in the 1960s, cooperated with their Dutch partners and were very early in calling for the establishment of a Wadden Sea National Park. But little notice was taken of them at the time. In Denmark, on the other hand, there was no lobby worth mentioning at first, which was partly due to the fact that the Wadden Sea only accounted for a relatively small proportion of the total coastline of around 7000 kilometres and its importance was barely perceived.

The fact that in the following years the Wadden Sea still came to be perceived as an ecological region of transnational importance was due to the adoption of the international Ramsar Convention for the protection of wetlands such as peatlands, marshes, salt meadows, swamps and tidal mudflats. It had been drafted at the instigation of UNESCO and the non-governmental IUCN (International Union for Conservation of Nature and Natural Resources) and was adopted on 2 February 1971 in the Iranian city of Ramsar. Although the Convention was not binding in international law, it did engender a signal effect. Most wetlands until then had been treated as a land reserved for future economic use. The Convention for the first time officially underscored on the policy level the international importance of wetlands, especially for waterfowl and migratory birds.

In 1974, the new left-wing liberal government of the Netherlands abandoned most of the construction and economic projects planned for the Wadden Sea in the previous years, and the nature conservation organizations never tired of proclaiming the Wadden Sea's importance as an ecological region, particularly for the population at large. In Germany, meanwhile, nature conservation associations set up information centres along the North Sea coast in which tourists were informed about the ecology of the Wadden Sea by means of talks and guided tours of the tidal mudflats. But politically there was no letting go of the idea of making industrial and agricultural use of the Wadden Sea and strengthening coastal protection by means of dike construction.

In Denmark at this time, Danish researchers also started to advocate protection of the habitat in their country.

Finally, in the early 1980s, the overall environmental policy situation in Europe began to undergo a distinct change. In view of pollution due to the discharge of industrial wastes and the high effluent loads in the rivers Rhine, Elbe, Humber and Thames, there was a growing perception of the North Sea, and the Wadden Sea along with it, as threatened habitat. This was also reflected in the intensive media reporting on the theme.

In Germany the issue of North Sea pollution definitively reached the top of the political agenda in 1980 after the German Advisory Council on the Environment had published an alarming report about the worrying condition of the North Sea and marine pollution generally. In the Netherlands, the conservation of the Wadden Sea ecological region was now integrated into an overall regional-planning concept as a government policy objective. The Dutch government took this step to try and strengthen trilateral cooperation, stressing the significance of the "indivisibility of the international tidal mudflats region". It sought to codify a statute for the Wadden Sea region which should transcend national borders and regulate common administrative objectives and cooperation with Denmark and Germany.

Closer cooperation with the neighbouring countries Germany and Denmark did not initially come about, however, because these countries wanted to continue managing the Wadden Sea according to their own rules. Furthermore, the idea of the Wadden Sea as a unified ecological region collided with the prevailing attitude in Denmark and Germany of unrestrained national sovereignty in their own territorial waters. In 1982 the three countries signed the Joint Declaration, a trilateral declaration of intent, but it was not binding: for example, Denmark retained the right to continue hunting seals in the Danish Wadden Sea while the Netherlands resolved to protect them.

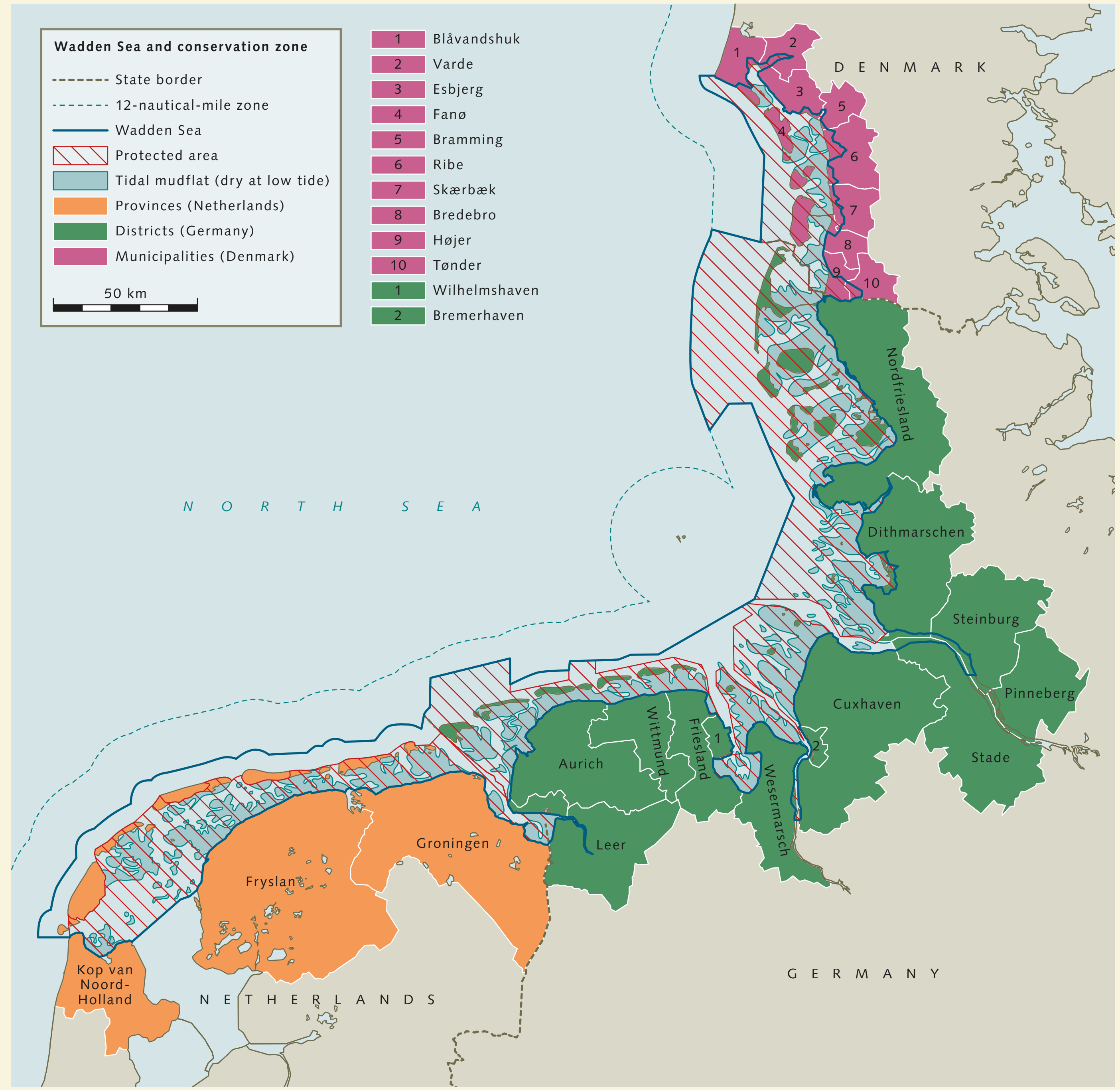
Nevertheless, progress began to be made from the mid-1980s. The Netherlands decided to protect areas of its Wadden Sea by barring them from agricultural, industrial or tourist uses or designating them as protected natural areas. Germany, on the other hand, embraced the idea of national parks, which had been discussed repeatedly since the 1970s and which have the highest protection status that can be conferred on an ecological region in Germany. Since the decision to establish a national park is a regional government matter, three German federal states designated three different national parks in succession – in the state of Schleswig-Holstein in 1985, in Lower Saxony in 1986, and a small section belonging to the city of Hamburg and located in the Elbe estuary in 1990. That did not amount to a solution to all problems, however.

Schleswig-Holstein was the main focus of criticism. The nature conservation organizations complained that oil drilling had been approved in the direct vicinity of the national park boundary. Furthermore, bird hunting as well as mussel fishery continued to be allowed on a limited scale. Denmark, for its part, did not initially consider it necessary to protect the Wadden Sea in its entirety. The establishment of a large-scale protected area would have entailed a prohibition on hunting for waterfowl or seals, for example.

A strengthening and internationalization of cooperation was only achieved at the renewed initiative of nature conservation associations from the three coastal countries. At their urging, the trilateral Wadden Sea Secretariat in Wilhelmshaven was finally founded in 1987. Over the years it has succeeded in establishing itself as a coordinating body that acts in a policy advisory capacity. Today it is financed jointly by all three countries. It coordinates research, public relations work and environmental monitoring programmes – for example, the control of invasive species – and organizes Trilateral Wadden Sea Conferences which take place every three to five years.

In the view of experts, it would be wrong to talk about an ideal integrated coastal zone management programme in relation to the Wadden Sea because of the divergent national regulations that apply. So far that has remained a goal for the future. While the existence of the Wadden Sea Secretariat means that a state-supported organization exists and the recognition as a World Natural Heritage site by UNESCO has further advanced the perception of the Wadden Sea as a transnational entity, there are no legally binding standards of any kind attached to this status. However, World Natural Heritage status has international charisma and finally induced Denmark, whose tidal mudflats were not initially included in the World Natural Heritage listing, to designate them as a national park. Having been brought up to the same protection status as had been achieved in Germany, in 2014 the Danish section of the Wadden Sea was then accordingly recognized as World Natural Heritage.

4.8 > In 1985 the Wadden Sea in Schleswig-Holstein was declared a national park. Despite this there was strong criticism to begin with because controversial coastal protection measures were still being carried out, such as the locking of the Nordstrand Bight with a dike formed from sand using hydraulic filling.



4.9 > Although the Wadden Sea in its entirety is a World Natural Heritage site, the responsibilities for this habitat are distributed among several countries. The area extends across three nations and is administered by a variety of regional authorities within these states.

Since the various village communities in coastal regions are now connected with each other via the network, best-practice solutions can easily be passed on. Since the year 2000 a series of LMMA projects have been carried out successfully – including in Indonesia, Papua New Guinea, and the Philippines, on the Solomon Islands archipelago and on the islands of Fiji, Pohnpei and Palau. Since the individual regions are often small, however, some national governments are not highly motivated to allocate ministry or civil service resources to support this type of engagement. Since coastal areas are significant for the local people's food supply, in certain cases in-situ projects are most likely to be initiated by non-governmental organizations.

Sustainable management in China: combining conservation and use

A range of comparable projects are taking place around the world which, while they do not designate themselves LMMAs or conform to that specification in every detail, nevertheless all have the same objectives, namely that local people are granted a kind of ownership over the marine resources and that these resources are managed by the community. China, for instance, has been trying for some years to reconcile the conservation and use of marine areas. Here as elsewhere, experience has shown that rigidly defined marine protected areas (MPAs) are not accepted and hence tend to be ignored. For that reason, since 2005 China has been designating what are known as special marine protected areas (SMPAs), in which zones are opened up seasonally for different uses such as fishery or tourism. Other zones in turn are barred from any kind of use.

A study has recently been undertaken to assess how effective this system is. To that end, interviews were carried out with advocates and critics of the SMPAs policy. The findings show that SMPAs can be considered as a complement to standard MPAs but are no substitute for them. Depending on the situation, either complete protection of a marine area or an SMPA solution might be appropriate. What clearly emerges is that consultation of the different interests during planning distinctly reduces conflict and boosts acceptance of the conservation zones within the SMPAs. Critical remarks have been voiced that so far there has been no scientific backup research to analyse whether the protection objectives are being achieved. One reason for this is the failure to fund such scientific work. An evidence-based evaluation as specified for ICZM processes, for example, first needs to be firmly anchored in the Chinese SMPAs concept. Overall, the current study finds that the SMPAs concept is assessed as a worthwhile tool for marine conservation in China, and one that is likely to continue to gain in significance in future.

Nature conservation and tourism – (not) in conflict

For the protection of coastal habitats it is indispensable to restrict certain forms of use. For example, the problem with tourism is that often precisely the most valuable and near-natural habitats exert a special attraction for holidaymakers because of their original character: there may be extensive dunes and beaches, or wetlands that are inviting to bathers or of special interest to birdwatchers because of their species diversity. Drawing the boundaries between zones used for tourism and the protected areas is difficult in this situation. This explains why in many European coastal regions, two environmental directives have led to an especially large number of conflicts between authorities, conservation organizations and other stakeholder groups: the Birds Directive of 1979, the purpose of which is to conserve wild species of birds, and the Habitats Directive of 1992, aimed at the conservation of various natural habitats together with the wild animals and plants living in them. When these directives were adopted, every EU member state was obliged to transpose these provisions into national law and to designate corresponding protected areas in its own country.

Findings of a study on conflicts between tourism and nature conservation in coastal areas of Germany that are especially popular among tourists suggest the following conclusions: conflicts arise mainly when the parties to the conflict were not in dialogue prior to the designation of protected areas. Where protected areas were simply imposed by the responsible authorities and the population was faced with a fait accompli, this led to great resistance not only among tourists but also among tradespeople, retailers and farmers.

One of the criticisms from tradespeople and from tourism associations was that the designation of conservation areas creates the necessity to steer tourist flows, which requires a major effort, particularly in large-scale protected areas. Paths through the protected areas must be fenced on either side and car parks set up at the margins.

There is also criticism that in many places, during the first phase of designation of the area, members of the public are not adequately notified, informed, and hence taken seriously. The approach taken by many administrations, merely to have focused on the EU directives without having communicated the advantages and opportunities, was seen as a particular mistake. Consequently there was a widespread public perception of being affected by measures imposed from the top-down without having any influence. For the future, the study therefore suggests the following measures:

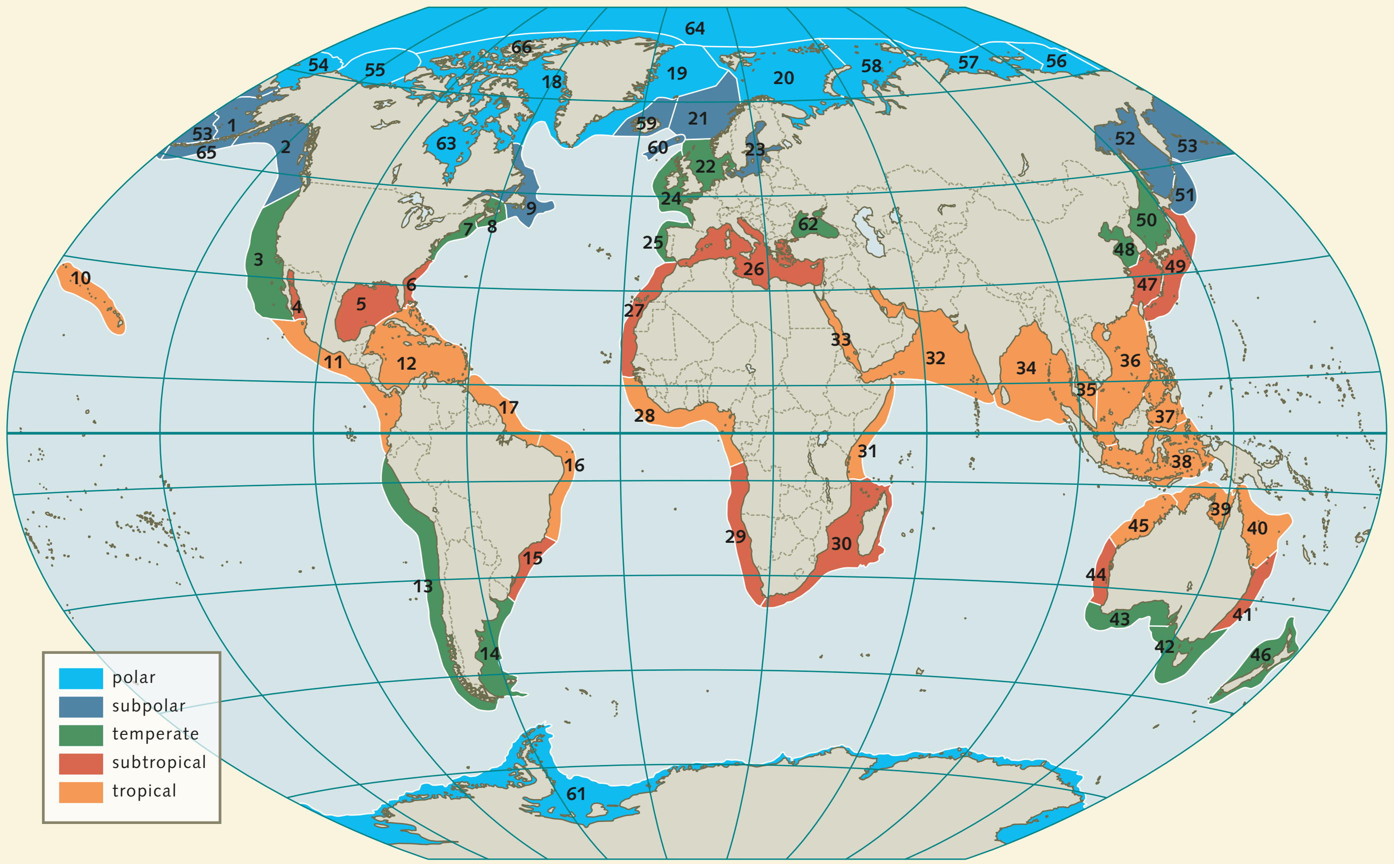
- Negotiations and consultations with the responsible organizations in each case (tour operators, municipalities, sporting associations) in order to develop common solutions, for example coordinating the scheduling of guided hikes, designating car parks or moorings for boats and canoes;
- Well thought-through action plans for visitor information and education, particularly by maintaining a comprehensive network of rangers and information centres and by means of information boards;
- Communication of the quality of an area on the basis of existing natural assets and the need for protection with the perspective of developing new business models, such as ecotourism.

The recipe for success: involving citizens from the outset

A successful example of an ICZM process in the tourism sector is presented by the coastal defence measures that were undertaken in the two German Baltic Sea municipalities of Scharbeutz and Timmendorfer Strand between 1999 and 2011, after a study had shown that these were severely threatened by flooding. Both municipalities are densely settled and intensively used for tourism as holiday destinations. A feature of these locations is a long shoreline promenade providing open access to the Baltic Sea and following a course between a parade of shops and small businesses on one side and the beach on the other. Both places are located in a bay in which the water level can rise significantly in the event of a strong easterly wind. An economic valuation analysis found that at water levels of more than 3 metres above mean sea level, severe flooding can occur. This would pose a threat to up to 6000 people and material assets of more than 3.4 billion euros. The municipalities therefore decided to construct a coastal defence dike with financial support from the district authority and the Federal State of Schleswig-Holstein. The local community put up resistance right from the start because it was feared that such an embankment would destroy the aesthetics of the promenade, which could ultimately damage the tourist trade. For this reason the population's involvement was sought in subsequent planning – firstly via information material which explained the issues at length, and secondly through participation in public meetings, where more than 50 people from the local population and the administration discussed various solutions which ranged from dispensing with coastal defences altogether to the maximum-intervention solution of constructing the dike.

A combined solution emerged from this participatory process: a flood abatement scheme that would be tastefully adapted to the local circumstances. By refraining from constructing the dike, it was possible to retain the character of the promenade completely. While the structural works were in progress, public tours of the construction site were held fortnightly on a Saturday in order to inform people about the current progress of the works and address unanswered questions.

A significant measure of success was that the scheme delivered altogether more aesthetic coastal defences. In one section, for example, it was decided not to fell trees



1. East Bering Sea
2. Gulf of Alaska
3. California Current
4. Gulf of California
5. Gulf of Mexico
6. Southeast U.S. Continental Shelf
7. Northeast U.S. Continental Shelf
8. Scotian Shelf
9. Newfoundland-Labrador Shelf
10. Insular Pacific-Hawaiian
11. Pacific Central-American Coastal
12. Caribbean Sea
13. Humboldt Current
14. Patagonian Shelf
15. South Brazil Shelf
16. East Brazil Shelf
17. North Brazil Shelf
18. West Greenland Shelf
19. East Greenland Shelf
20. Barents Sea
21. Norwegian Shelf
22. North Sea
23. Baltic Sea
24. Celtic-Biscay Shelf
25. Iberian Coastal
26. Mediterranean Sea
27. Canary Current
28. Guinea Current
29. Benguela Current
30. Agulhas Current
31. Somali Coastal Current
32. Arabian Sea
33. Red Sea
34. Bay of Bengal
35. Gulf of Thailand
36. South China Sea
37. Sulu-Celebes Sea
38. Indonesian Sea
39. North Australian Shelf
40. Northeast Australian Shelf/ Great Barrier Reef
41. East-Central Australian Shelf
42. Southeast Australian Shelf
43. Southwest Australian Shelf
44. West-Central Australian Shelf
45. Northwest Australian Shelf
46. New Zealand Shelf
47. East China Sea
48. Yellow Sea
49. Kuroshio Current
50. Sea of Japan
51. Oyashio Current
52. Okhotsk Sea
53. West Bering Sea
54. Chukchi Sea
55. Beaufort Sea
56. East Siberian Sea
57. Laptev Sea
58. Kara Sea
59. Iceland Shelf
60. Faroe Plateau
61. Antarctic
62. Black Sea
63. Hudson Bay
64. Arctic Ocean
65. Aleutian Islands
66. Canadian High Arctic and North Greenland

4.10 > The near-coastal areas of the world's oceans have been classed into 66 large, transnational marine ecosystems, known as the large marine ecosystems (LMEs). It is hoped that this approach will enable better cooperation among nations on international marine conservation.

and instead a steep storm-beach was installed, with additional breach protection in the form of an unobtrusive wall about half a metre high. A recreational footpath now runs between the low wall and the row of trees. Overall this approach succeeded in gaining a high level of acceptance of the coastal protection scheme, which now even enriches the visual appearance of the promenade thanks to the high quality of project execution.

The concept of large marine ecosystems

ICZM always becomes a particular challenge when coastal areas and habitats are so large that they extend to several countries. Comprehensive protection of these areas is only possible if the countries cooperate on such matters as marine pollution or the management of fish stocks. In the 1990s, researchers at the US National Oceanic and Atmospheric Administration (NOAA) therefore developed the concept of large marine ecosystems (LMEs). Under this system, today the Earth's near-coastal marine areas are classed into 66 LMEs, each of which is distinguished by a typical flora and fauna. LMEs are defined along coasts and extend to the continental slope, the part of the sea floor where the continental shelf drops steeply into the deep ocean. The main difficulty is that for successful coastal zone management it is necessary to realize transboundary cooperation on different levels. Firstly, the individual states must consent to high-level cooperation between national governments. Secondly, the responsible sectoral authorities and the local administration must be involved to ensure that the local coastal population can actually be included in the transboundary cooperation. The conservation of larger fish stocks, for example, is only feasible if the new rules for sustainable fishery are put into practice by all fishers and authorities throughout the LME.

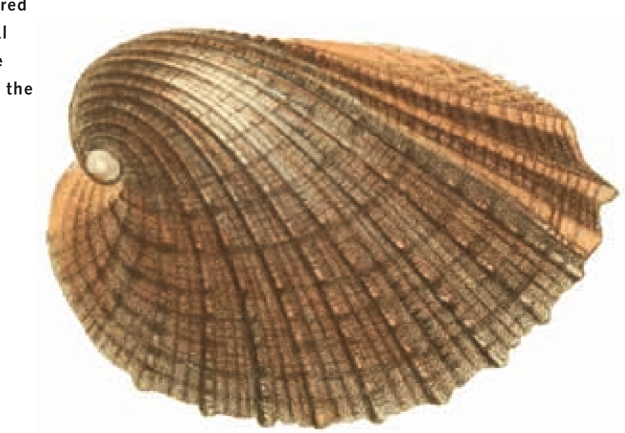
With the support of the World Bank, the Global Environment Facility (GEF, an international institution for the financing of environmental protection projects) and the United Nations Environment Programme (UNEP), efforts are being made principally in developing and newly industrializing countries to improve international cooperation over the protection of the LMEs. Researchers and politicians as well as members of the general public from neighbouring nations meet up at workshops and conferences. Since economic aspects such as marine oil drilling often take priority over conservation of the environment, the concept of the LMEs is aimed at providing a counterbalance and creating awareness within the countries of the ocean as habitat.

A fledgling network for protection of the Bay of Bengal

One example of successful cooperation is the Bay of Bengal Large Marine Ecosystem (BOBLME), within which the coastal states of the Bay of Bengal to the east of India work together: Bangladesh, India, Indonesia, Malaysia, the Maldives, Myanmar, Sri Lanka and Thailand. Within this area, the BOBLME project was launched in 2010 for a planned five-year term. Its aim was to manage fish stocks more effectively in order to tackle overfishing, and additionally to combat marine pollution. A comprehensive analysis of the local situation was the first item on the agenda. The many different local, regional and national responsibilities had to be clarified and joint work priorities defined. These in turn depended on the hardships or needs reported by the people in the given localities. For example, fishery is administered by different authorities in every nation, sometimes by fishery offices and sometimes by economic authorities, so it was first necessary to locate the relevant contact partners, who were then put in touch with one another at international conferences and workshops. A further objective of the project was to survey the status of the various fish populations. In this respect there was a large gap in knowledge because in many countries it had been some long time since research ships had last undertaken regular estimates of fish populations. In Myanmar, for example, no such census had been carried out for the last 30 years. With support from a Norwegian research ship, population estimates were carried out for the entire bay. Thanks to these estimates, for the first time a management recommendation could be made for the region to ensure sustainable catches of the economically important Indian mackerel and Hilsa herring. In order to be able to monitor fish populations and the state of the marine environment in future, scientific working groups were also formed with researchers from all coastal states so that they could cooperate in future on matters relating to fish population statistics, the monitoring of marine pollution and on ecological studies in the Bay of Bengal. In addition, the working groups compiled best-practice solutions for sustainable fishing in the region and will attend local workshops and present these methods to other fishers, who will adopt them. In 2015 the BOBLME project came to an end. Since then gradual introduction and implementation of the fishery practices and management recommendations developed during the project term have continued in every country.

Conservation through regional self-governance

For the sustainable use of coastal areas, it can be sufficient for a single affected group of users to change its behaviour. For instance, this is true of artisanal fishery in various coastal regions, which can be practised under new management methods in such a way as to make prudent use of fish stocks. One example is the Chilean loco fishery. Locos are sea snails of the species *Concholepas concholepas*, the very popular Chilean abalone, which are harvested from the sea floor along the coast by divers. Fishery biologists refer to fisheries like these as "S fisheries", a term derived from the categories "small-scale fisheries", "sedentary stock" and "spatially structured". Spatially structured means that a number of geographically separated populations exist at various sites within one region. The danger with S fisheries is that these populations will be overfished locally.



4.11 > The mollusc *Concholepas concholepas* is a popular shellfish in Chile. To harvest them, geographically delimited fishery territories administered by individual local cooperatives were established along the Chilean coast.

In the past that is precisely what happened in Chile. Once one population had been harvested to exhaustion, the fisher-divers moved on to the next area. This led to conflicts with the resident fisher-divers in each new location, because it increased pressure on the population in their locality. At the end of the 1980s, loco stocks had shrunk to the extent that loco fishery was in crisis along the whole of the coast. Many fishers lost their livelihoods. The Chilean government therefore instituted a new management system in 1991, whereby spatially delimited fishery territories along the coast and corresponding locality-based cooperatives of fisher-divers were established. The cooperatives based in the area were thus granted exclusive rights of use as well as self-governance. These areas with territorial use rights are called Management and Exploitation Areas for Benthic Resources (MEABR), or in Spanish, Áreas de Manejo y Explotación de Recursos Bentónicos (AMERB). Another phrase in general use is MEABR management. Internationally this type of local management is referred to as territorial use rights in fisheries (TURFs).

This territorial fishery use right was only granted if the fisher-divers organized themselves into cooperatives and then, with support from experts, drew up a management plan for future prudent use of the loco population in a certain territory – for instance with regard to the maximum daily quotas for permitted extraction from the marine area. These quotas were then allocated among the individual members of the cooperative. Fisher-divers from other coastal areas and cooperatives were excluded from extraction in this area. As an additional benefit of organizing themselves into cooperatives, the fishers found themselves in a better negotiating position vis à vis middlemen. Most of the fisher-divers previously used to fish for locos and sell on their catch alone, whereas now they could collectively negotiate a price for the shellfish.

The loco stocks did indeed recover, which was a successful result for MEABR management. Subsequently the principle went on to be adopted for other fisheries in

4.12 > A fish market in Bangladesh. Hilsa herrings are the main product on sale, and are especially popular here in the Bay of Bengal region. After years of overfishing an international project has finally succeeded in developing a responsible fishery management regime for the entire Gulf.

4.13 > In future, the breeding of algae could become established in many parts of the Indian Ocean and in the Pacific as an alternative to fishing. Algae breeding has the advantage of low costs because very little is required in the way of equipment and materials.

Chile. Today around 45 benthic organisms, which include bivalves and molluscs but also algae, are fished according to MEABR management plans.

But not in every case was this kind of management successful. Sometimes populations have collapsed and the carefully designed MEABR strategy has become redundant. A notable reason for this has generally been that the population dynamics of certain organisms had not been sufficiently researched, and thus overfishing could still occur on the basis of mistaken estimates.

Alternatives to fishery

One strategy of ICZM projects today in developing and newly industrializing countries consists of developing alternative income-earning opportunities locally with the coastal population. In regions dominated by fishery, this can help to take the pressure off overfished stocks or overused marine habitats. An example in the Philippines and in Indonesia are projects in which the breeding of marine algae (seaweed) on long ropes was established as an alternative to destructive fishing with dynamite and cyanide. Algae breeding has the advantage of low costs because very little is required in the way of equipment and materials. Moreover, there is a growing global demand for algae, the majority of which is used for the production of carrageenan, a substance extracted from algae that is used in the food industry as a setting and thickening agent. The projects show that while algae production cannot replace fishing, in some places it led to a reduction of the quantities caught so that pressure on the ecosystem did indeed diminish. In other places fishing continued at the same intensity despite algae breeding. Not in every case could the local population be sufficiently convinced of the significance of resource conservation. Experts therefore emphasise that one sole alternative source of income is not always enough. Ideally it should be possible to present a certain plurality of alternatives in ICZM projects of this kind.

Too many cooks impede development assistance

For successful integrated coastal zone management in developing and newly industrializing countries it is essential to integrate all national and local stakeholder groups into the management process, but that is not all: consultation is also necessary between the various international and regional organizations for development assistance. That is by no means always the case. There are regions in which different organizations are active in neighbouring localities, sometimes even with the same priorities, without conferring with or knowing about each other. This gives rise to several drawbacks: Firstly, it is not possible to share the use of resources such as infrastructure, offices or vehicles. Furthermore, when different development assistance organizations pursue their projects in isolation from one another or fail to coordinate with development priorities locally, it precludes the possibility of comprehensive integrated management whereby, for example, the drinking water supply, agriculture and coastal protection are monitored simultaneously. In unfavourable cases, results are achieved that are unsustainable or even counterproductive. To counteract these aspects and to increase the effectiveness of development assistance as a whole, in 2005 the OECD therefore adopted the Paris Declaration on Aid Effectiveness. This Paris Declaration pursues five essential objectives in total:

- Ownership: The partner countries, not the donor countries, exercise coordination and responsibility for every development process.
- Alignment: Donors adapt their strategies and processes to those of partner countries and use existing institutions of the cooperation countries or the partner organizations.
- Harmonization: Donors coordinate and harmonize their programmes and procedures among themselves.
- Managing for results: Donors have their results measured in terms of the effects of their development policy action, such as reducing the illiteracy rate, and not their financial input, such as 10 million euros for new schools.
- Mutual accountability: Donor and cooperation countries are jointly accountable to the public and their parliaments for their development policy actions and their progress.

Since 2012 these objectives, slightly modified in part, have been steered and further pursued via the Global Partnership for Effective Development Cooperation.

Kiribati leads by good example

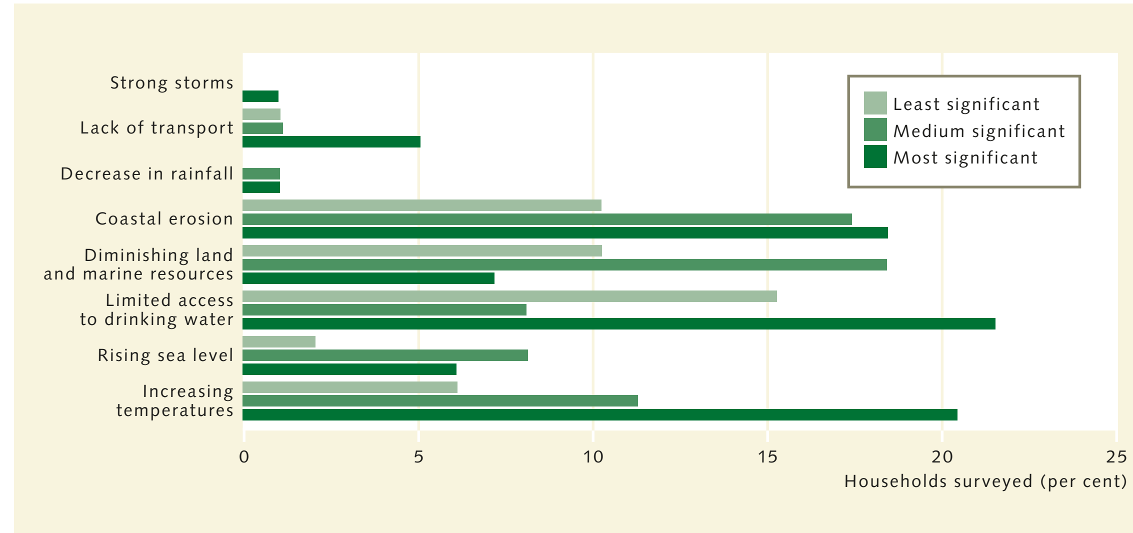
Today the principles of the Paris Declaration are also being subsumed into integrated coastal zone management. An example is the Pacific island-state of Kiribati which comprises over 30 islands. The expanse of the island-state is vast. From west to east the nation extends over around 4500 kilometres, which is roughly equivalent to the distance from the west coast to the east coast of the USA. The people of Kiribati do not see themselves as inhabitants of a tiny island-state by any means, but as inhabitants of a large oceanic state boasting a tradition as seafarers in the Pacific going back thousands of years. Over the years many development assistance projects have been implemented but in many cases they did little to coordinate efforts with each other or to align their activities with national development objectives. In accordance with the Paris Declaration, the government therefore decided to require greater cooperation between the individual development projects and that these should also take their guidance from national and local priorities. To this end, a strategy called the “whole-of-island approach” was introduced on Kiribati a few years ago. In this way the state and several international development organizations have now agreed to implement projects jointly, paying attention not just to sub-aspects but always to a whole island in each case with all its problems and challenges. This means that individual aspects – such as coastal protection or agriculture – are not considered in isolation from each other, but that solutions are developed for all domains of life at once and articulated in a development plan for the given island. What this contains in detail are measures promoting sustainable education, fishery, infrastructure, coastal protection, agriculture, energy, water supply and health. At the same time consideration is given to how the population can adapt to climate change.

Kiribati together with development assistance organizations wants to carry out analyses on all islands gradually in the next few years. Known as Integrated Vulnerability Assessments, these will be used to inquire into the population's needs and study the impacts of climate change. Under a whole-of-island approach as with any typical ICZM process, cooperation with local people plays a decisive role, since this is the only way of ensuring that measures are implemented which people actually need and accept.

Taking the initiative on the island of Abaiang

On each of Kiribati's islands there is a council of elders consisting of members delegated from every village. The council of elders is the first port of call for cooperation. As a first step the staff of the development assistance organizations accompanied by representatives of the various responsible ministries from the capital of Kiribati, South Tarawa, visit the islands in order to carry out interviews. In doing so they take pains to ensure that it is not just the all-male council of elders who have their say. Individual interviews are also held to survey the needs and opinions of all other groups within the population – and particularly of the women and young people. The results are aggregated into a representative profile of opinions on how the inhabitants imagine their future in ten or 20 years' time. Talks are also held with representatives of the different local institutions such as the church or the police. The first

4.14 > The island state of Kiribati is endeavouring to protect its low-lying atolls from the ocean, partly with solid sea walls. But in many cases storm surges destroy the structures, as seen here off the capital, South Tarawa.



4.15 > For the island of Abaiang climate change is already a reality. According to a survey, the most obvious signs noticed by the inhabitants are freshwater scarcity, higher temperatures and erosion of the shoreline.

island on which the whole-of-island approach is currently being put into practice is the island of Abaiang. With 5500 inhabitants it is relatively populous. A vulnerability analysis has recently been carried out. One urgent issue is the question of a reliable water supply because the islands of Kiribati possess very small water reserves in the form of freshwater lenses located in the subsurface and recharged solely by rainwater. If too much water is extracted or rainfalls fail to materialize, but also if the sea level rises, salt water seeps in from the ocean and the water lenses become oversalinated. The freshwater lenses are subject to additional pollution caused by livestock or by fertilizers and crop protection products from nearby arable farms. To address these problems, water management on Abaiang is currently being improved. Furthermore, arable farming is now practised at a sufficient distance from the freshwater lenses.

Another issue is the avoidance or disposal of waste. Traditionally the island's waste, which used to be entirely organic, was deposited into the sea and transported away by the tide. In view of growing fractions of inorganic and toxic waste, this practice leads to considerable pollution of the ocean and environment and can result in substantial contamination especially of the freshwater lenses. Since the inhabitants obtain their drinking water from wells, the majority of which are heavily contaminated with germs, there are frequent cases of diarrhoea infections which mainly put children at risk. It has therefore been decided in accordance with the wishes of Abaiang's inhabitants that a better sanitation infrastructure will now be built. Currently a similar analysis is being carried out for a second island.

Furthermore, certain challenges are the same for all the islands of Kiribati. Apart from water supply and sanitation, these consist primarily of coastal protection, overfishing and declining yields in agriculture. Added to that is climate change, which strongly influences and considerably amplifies all these aspects. Today cumulative droughts are occurring on some of Kiribati's islands, leading to water scarcity and creating difficulties for farmers. Since there is not a vast amount of agriculture on the islands in any case due to their relatively infertile soils, shortages in the food supply are likely to ensue. The plan is therefore to practice alternative farming methods on the islands in future and to pilot the production of different fruits. During the process, care will be taken from the outset to ensure that the local population sets itself realistic goals. In this way the ministry representatives clearly communicate that the management process cannot fulfil gratuitous demands to increase prosperity dramatically. It is hoped that this will prevent the arousal of unrealistically high expectations.

Coping with rising sea levels

> Dikes, walls and barriers protect coasts from flooding. Yet sea-level rise calls for novel solutions that take account of ongoing natural impacts and can gradually adjust to the rising water. Even with these, some coasts will become uninhabitable in the future. For those who are affected new homes need to be located now, for they will become climate refugees.

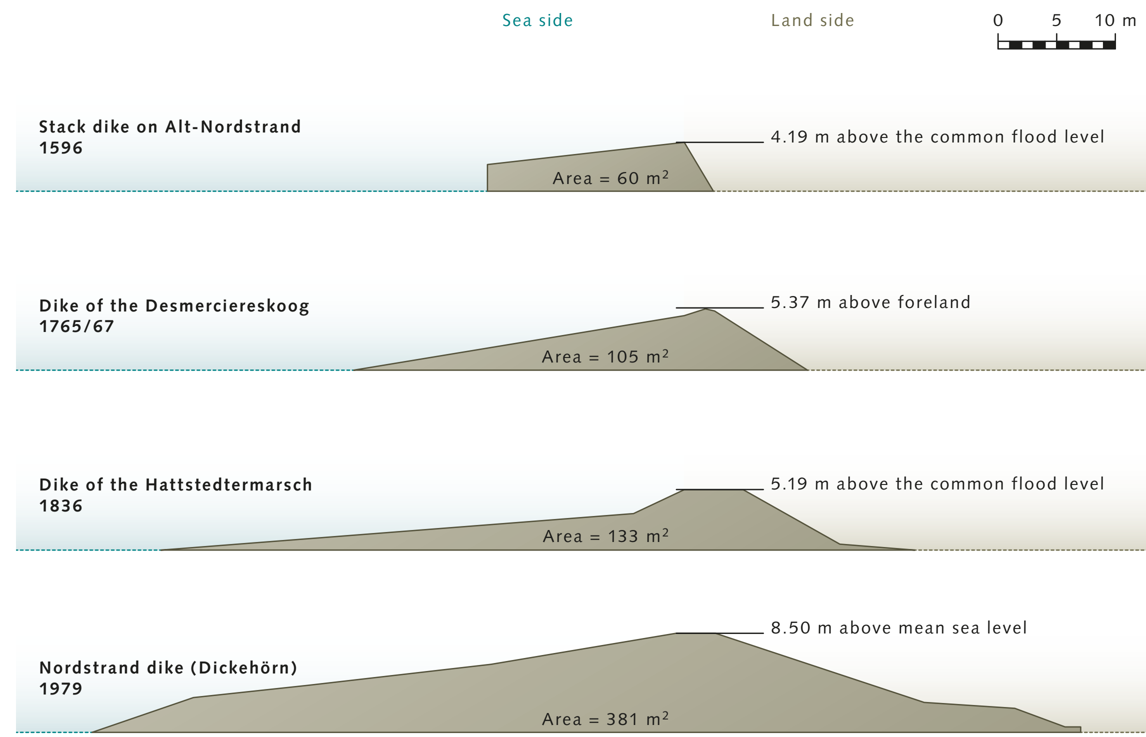
The development of modern sea dikes

Coastal populations have always been threatened by flooding. Although fairly helpless against such events at first, over time they learned to build protective structures against storm floods. In some countries buildings were built on stilts, so that water could flow freely underneath, while in other places houses were built on man-made earthen hills. As early as the twelveth century, ring dikes were already being built in northwest Europe for the protection of individual settlements. Through time, the design of dikes changed. In the early sixteenth century the dikes in many places consisted of two-metre-high walls of timbers, backed and stabilized by an earthen wall. But because these kinds of dikes were heavily battered by the surf, the vertical form was soon abandoned in favour of an elongated slope and flatter profile, where the wave energy of the storm floods could be absorbed more gradually. In the mid-eighteenth century, these dikes often had a height of around five metres. Although the gradually sloping profile proved to be effective, water would still spill over the top during high-surging floods. This would wash out material on the back side until the dam collapsed. The trend thus developed toward the construction of increasingly higher dikes with even flatter slopes. Today, the large sea dikes in northwest Europe have heights of around nine metres. They have low slope ratios of at most 1:6, and are around 100 metres wide at the base. These can withstand even high storm-flood surges. But with climate change and its accompanying rise of sea level, coastal inhabitants are facing new challenges.

4.16 > For several centuries the people in the Netherlands relied on "stack dikes" (Ger. – Stackdeiche) to protect the region around Amsterdam, as shown in this illustration of the Zuiderzee in 1702. These were repeatedly damaged during heavy storm surges.

Climate change as a new challenge to coastal protection

If sea level should rise by one metre by the end of the century, and even by several metres thereafter, today's tried and tested coastal protection systems will no longer be adequate. They will have to be upgraded in many places. No one knows, however, how strongly or rapidly climate change and sea-level rise will progress. In contrast to past centuries, when it was sufficient for engineers to design structures that were suitable for the existing conditions, precisely this question arises now in the face of climate change: What conditions will exist in the future? Coastal protection will have to account for diverse probabilities and consider the various scenarios of the IPCC (Intergovernmental Panel on Climate Change) in the planning and construction of protection systems.



4.17 > Through time, the profile of dikes on the North Sea coast of Schleswig-Holstein changed. There was a trend away from the steep structures to a long and much lower gradient, so that the storm-flood wave energy could gradually run out over a longer distance.

Staying a step ahead of sea-level rise

A fundamental question for coastal engineers is how high or strong coastal defence structures should be designed today. Because the future global progression of sea-level rise is uncertain, and a more rapid advance than the global average is expected in some regions, it would be prudent to incorporate flexibility into coastal protection designs for the future. An adaptive pathways approach is now being promoted. This involves the planning of coastal protection measures adapted to the short-term consequences of change, and not rigidly committed to an uncertain assessment scenario to the end of the century. In this way it may be possible to keep pace with the rising water. A large barrier that closes off a river mouth during storm floods has to be completely rebuilt when it no longer provides sufficient protection as a result of rising sea level. The initial investment would thus be completely lost. It is more sensible to plan for smaller measures that build upon one another. Coastal protection is therefore now facing a paradigm shift. While the axiom of preserving a coastline through the use of large immobile structures was considered valid in the past, the adaptive pathways design approach introduces an array of different concepts and measures, including the selective opening of dikes and the creation of emergency flood plains, or "polders". Specialists today distinguish the following conventional and adaptive protection principles:

Conventional coastal protection

- Resistance: Planning and construction of coastal protection measures at a large economic cost, which are designed for today's extreme events such as 100-year floods. This approach represents the classical method for designing coastal protection systems. The disadvantage is that extensive damage can result if these systems do fail, as in the breaking of a dike.
- Static robustness: Planning and carrying out coastal defence measures that are already designed for the worst-case climate scenario for today. This principle has clear disadvantages. For one, enormous invest-

4.18 > Preparations are ongoing in the Netherlands for future flooding: Engineers have designed floating residences like these in Maasbommel. The amphibious houses are anchored to posts and can respond flexibly to high water.

ments would have to be made today. For another, the construction would be planned according to the present-day knowledge of climate change. This entails the danger that the protection measures will not be adequate if climate change becomes more intense than expected.

Adaptive coastal protection

- Resilience: Planning and construction of coastal protection structures that are designed so that their failure does not result in losses and severe damage to infrastructures, buildings or ecosystems, and allows rapid recovery or restoration. This could be achieved, for example, by building floating houses. Another possibility would be to build elevated streets and railways on the tops of dams. This would limit the extent of damage. Ideally, damage would be completely avoided.
- Dynamic robustness: Coastal protection structures are implemented in succession, to a degree that is based on the latest available knowledge about the development of climate change. This principle is based on a "no-regret" strategy. This refers to measures that would have societal benefits even when the extent of climate change turns out to be greater or less than what was expected, and that do not entail irreparable damage if false assumptions were made in the scenarios. One example of a "no-regret" measure is the creation of a "polder" that serves not only for coastal protection, but at the same time can function as a local recreation area or nature conservation area – and thus has an additional societal or ecological value. The disadvantage of this approach is that, in contrast to the concept of static robustness, the coastal protection is not fabricated in a short time by a single measure, but has to be repeatedly evaluated and expanded over a long time period by supplemental and complementary measures. It thus requires long-term and constantly adaptive planning, as well as a management system that can function over time periods of many decades and even has a planning horizon of a full century.

London leads by example

The larger bulk of coastal protection measures worldwide today are carried out according to the conventional resistance principle, but in a number of countries initial concepts are being developed that follow the adaptive pathways approach. An ongoing example is the protection of the Thames estuary in England. To protect London from flooding during storm surges, a large flood barrier, the Thames Barrier, was put into operation in 1984. It consists of large movable flood gates that are closed during storm tides and prevent the surge of high water from the sea from reaching the city. At the beginning of this century, because of concerns that the existing barrier will not be able to resist the higher storm tides expected in the future, debate began about whether it should be replaced by a new and even larger barrier further downstream within the estuary of the Thames. The ramifications for the population of London and the expected extent of damage if the barrier were to fail would be immense. The storm floods as a consequence of climate change and sea-level rise could indeed exceed the capacity of the existing Thames Barrier. They would acutely threaten 1.25 million people who live and work in the high-risk flood areas, as well as 500,000 dwellings, 40,000 commercial and industrial properties, important government buildings, 400 schools and 16 hospitals.

Coastal protection road map for the future

The construction of the new barrier in the Thames, which would cost up to five billion pounds, was rejected as an exclusive solution. Instead, in cooperation with scientists, the authorities created a kind of road map for future coastal protection that provides for various measures to be realized with continuing and accelerated sea-level rise, which is commensurate with the adaptive pathways approach. The Thames Estuary 2100 Plan presents a catalogue of measures, and provides clear options in dealing adequately with the risk situation at any given time, in spite of great uncertainties about the progression of climate change. Additionally, the financial burden that would result from

Polder
The term "polder" originally comes from the Dutch, signifying a piece of land that is protected from high water by dikes. In the context of coastal protection, "polder" designates areas that are purposely allowed to flood in order to diminish the crest of a flood wave.

construction of a new barrier will be avoided for as long as possible. In this developmental plan, detailed critical points in time by which decisions must be made regarding planned future measures were identified, and by which times the measures must be carried out. Furthermore, and in agreement with the surrounding counties, it was decided which measures should be carried out on various segments of the river between London and the North Sea. In chronological order, the measures include:

Option 1: Classical defence systems
- Increase height of existing systems (sea walls, dikes, etc.);
- For old systems that need to be replaced, build the new structures higher;
- Design new defence systems so that they are more easily repaired, replaced, or raised.

Option 2: Create floodplain areas
- Create target areas for flooding – for this purpose four large areas have already been identified in the estuarine area of the Thames.

Option 3: New barrier
- Construction of a new barrier, for which possible sites have already been identified and the legal framework already established, so that if it becomes necessary construction can be started quickly without the need for elaborate negotiations.

Option 4: Massive barrier
- Construction of a barrier that, in contrast to the existing one, is always closed, in order to permanently hold back the water under higher sea level conditions. This barrier will include locks for ship traffic.

The Netherlands under pressure

Because large portions of the country lie below sea level, the Netherlands and the Dutch-Belgian border region, which lies in the shallow estuarine area of the Scheldt River, are at risk in the future. Sea-level rise and the processes it triggers present a dual threat for this region. For one, it is feared that the higher storm floods associated with rising sea level will damage or spill over the dikes and protective structures. For another, with climate change, an increase in precipitation is expected for Western Europe, so inland rivers could overflow their banks more frequently. When both processes occur together – higher water levels at the coast and strong rainfall inland – the river water is no longer able to flow into the sea, so it swells and backs up in the inland regions.

Around nine million people live in the low-lying areas of the Netherlands. In addition, there is a high concentration of economic assets, comprising infrastructure as well as business and industry. The city of Rotterdam, for example, incorporating Europe's largest harbour, presently lies an average of two metres below **mean sea level**. For many years now, these low-lying areas have been protected by massive structures such as dikes, dams or flood walls. Additionally, since the 1950s flood-defence systems comprising large barriers have been installed that seal off many former bays and rivers from the North Sea, either permanently or during storm surges. In order to upgrade this system to adapt to sea-level rise, expenditures have been calculated for the Netherlands of up to 1.6 billion euros annually to 2050. According to present estimates, if the massive coastal defence installations should fail in spite of these investments, and the region be flooded, the resulting losses could be as high as 3700 billion euros.

Making room for water

In view of the enormous costs for maintenance of coastal defence structures and the enormous risk that a failure of coastal protection installations entails, an additional strategy has been followed in the Netherlands since 2012 with the "Ruimte voor de Rivier" project (room for the river). While many river channels have already been highly altered by dikes and barriers, more than 30 separate measures will be carried out on the Maas (Meuse), Rhine and Waal Rivers in the Netherlands by the end of the project in 2019.

4.19 > Steel colossus against storm floods: after a devastating flood, often referred to as the Dutch flood disaster of 1953, dikes and barriers began to be built to defend most of the river mouths in the Netherlands. This is an image of the Maeslant Storm Barrier, which protects a part of the Rhine estuary and the harbour of Rotterdam.

These include:

- Widening river beds so they can hold more water;
- Deepening of rivers;
- New construction of separate canals that will relieve the main river and provide a substantial creative landscape element for new residential areas, which would be built at the same time;
- Relocation of dikes and creation of wide polders, in order to give the high water more room.

With these measures, the "Ruimte voor de Rivier" project also fits rather well with the concepts of the "Building with Nature" initiative, which was jointly initiated in recent years by Dutch coastal protection experts, engineering agencies, government offices, and researchers, and has already been implemented through a number of pilot projects. "Building with Nature" means that coastal and high-water protection measures are designed to conform to the natural conditions, while at the same time offering new locations for the development of natural areas. An example is the relocation of dikes for the creation of flood polders where species-rich wetlands can develop. The "Building with Nature" concept expands on conventional coastal defence systems, which could more appropriately be described as "building IN nature". With the conventional measures, rigid artificial structures are imposed on the landscape, looking like foreign objects and often tending to slice through natural spaces.

Major project on the Scheldt estuary

One of the first major projects to adopt the "Building with Nature" concept is the creation of a number of polders along both the Belgian and Dutch sides of the Scheldt estuary. This involves flattening all of the old dike lines to make lower overflow dikes, and moving the position of the new dike back to form a polder. The polder is bounded on the river side by the overflow dike, which only allows water to spill over at times of high water. In addition, the water level in the polder is regulated by a sluice built into the overflow dike. The purpose of the low overflow dike is to keep water in the polder to sustain wetland habitats. The polders will have a total area of 40 square kilometres. In case of high water they can take on large volumes of

4.20 > New polders are being built on the Scheldt estuary. The existing levee (A) is lowered to function as an overflow dike. The water level within the polder is regulated through a sluice (B) in order to form a wetland area (C). A new ring dike (D), located behind the original location, protects against high water surge.

additional water and protect against flooding in the hinterland in the future.

On around 60 per cent of the polder area wetland areas should develop naturally and will serve, among other things, as breeding grounds for birds. The first polder was created in 2006. The project is to be completed by 2030. The total costs will be around 600 million euros. Compared to this, the high-water damages that would result if the polders were not built would be significantly higher. These could be as much as one billion euros annually throughout the period to 2100.

Different coasts, different measures

As Belgian and Dutch experts point out, "Building with Nature" is possible in river estuaries and deltas as well as on sandy coasts. The latter are primarily impacted by erosion, which during the course of climate change could intensify through more frequent or higher storm floods. If buildings are present, they could be damaged or even destroyed over time. Many sandy coasts are therefore protected by massive structures. These include stone groynes in particular, which stretch from the shore out into the sea like long fingers, and considerably reduce current strength on the shore. These groynes prevent the erosion of material from the coasts during periods of strong wave activity. But this creates another problem when the primary current direction is parallel to the coast. Normally in this situation, sediment removed from one site is subsequently deposited at another location farther along the shore. It is then available to protect the sandy coast at another site. If this natural sediment transport is inhibited by groynes, other segments of the coast can be strongly eroded because the normal replenishment process is interrupted. The construction of groynes can thus lead to a deficiency of sediment somewhere else and to a gradual loss of beaches and protective dunes.

Artificial island as sediment contributor

On many coasts worldwide, beaches need to be restored by artificial filling after the storm season. This usually involves pumping sand from deeper sea-bottom areas through a pipeline onto the land, or transporting sand in with ships. This periodic filling with sand is an accepted, but laborious and expensive coastal protection measure. In the areas of sand removal and sand fill, biological communities can also be disturbed. Within the framework of the "Building with Nature" initiative, therefore, a pilot project was begun to find a different way to solve the erosion problem on a 17-kilometre-long strip of coastline in the Netherlands. To this end, a hook-shaped peninsula was filled in with a volume of 21 million cubic metres of material. This is enough sand to cover 60 football fields to a height of 50 metres. The artificial island functions as a natural sand repository that will be gradually worn away over several decades by waves, tidal currents and wind, thus providing long-term delivery of fresh sediment to the beaches on the 17-kilometre segment of coast to compensate for erosion there. This measure not only saves the construction of new massive groynes, but also the annual hydraulic filling at many sites along the coast. Thanks to this one-time filling action, it is possible to avoid repeated long-term disturbances of the ecosystem by annual sand removal.

In the Mississippi Delta, off the coast of the US state of Louisiana, natural coastal protection measures of even larger dimensions are planned. The delta is heavily impacted by flooding and erosion because the amount of sediments

4.21 > Since 2013, sand from the Mississippi River at New Orleans has been pumped through a pipe for a distance of over 20 kilometres into the delta. Sand banks are created on which many square kilometres of salt marsh can develop. These, in turn, act as natural coastal protection.

being supplied to the delta has been severely curtailed by reservoir dams along the river. In a major project that includes more than 100 separate measures, the delta should begin to grow again and the danger of flooding be reduced.

Since 2013, for example, sand has been transported out to the delta through a pipeline more than 20 kilometres long. This sand is retrieved from the bed of the Mississippi by dredgers and pumped directly from the ships into the pipeline. Ecologically important sandbanks are created where salt marshes many square kilometres in size will develop in the coming decades and act as a natural protection for the coast. In practical terms, this should protect towns south of New Orleans from flooding. At other sites along the Louisiana coastline dunes are presently being replenished and beaches broadened by dredging.

Shellfish protect coasts

Another ecosystem-based coastal protection measure that is being employed in Louisiana, in the Netherlands, and in other coastal areas is the creation of oyster beds off the coast. These act as natural breakwaters that absorb a large portion of the energy from storm-flood waves before they reach the shore. The advantage of oyster beds is that they sustain themselves because young shellfish larvae colonize every year. Artificial breakwaters, by contrast, have to be periodically maintained and improved. In many cases, for the colonization of oyster beds wire baskets with empty shells are placed on the sea floor. These shells provide the free-swimming larvae with a firm substrate on which they can colonize and grow to mature animals. Because new larvae settle year after year, a reef is created over time.

The ecosystem-based approach – a trend with a future

The Dutch "Building with Nature" concept is now being adopted by many countries as a model for semi-natural protection from storm floods on the coasts and high waters inland. A common phrase heard in international discourse today is ecosystem-based coastal defence. In Germany, for example, as a major pilot project, a dike has been relocated on the Elbe River in south Hamburg to create the Kreetsand polder. This polder will protect the surrounding area from flooding by high inland waters that occur as a result of sustained rainfall. This project is notable because in Germany, as well as many other countries, there are still strong reservations toward ecosystem-based coastal protection, in spite of the large projects in the Netherlands. This is mainly because specialists still have relatively limited experience with these alternative measures. There is also still too little knowledge about the effectiveness of the protection and its performance over time. In addition, there are no established standards for the construction and maintenance of ecosystem-based alternatives. Thus, more trust is still placed in the classical coastal defence approach with its rigid protective structures. Moreover, our knowledge about the design and construction of classical coastal defence systems such as dikes and barriers has grown significantly over many decades. We have learned from flood catastrophes how these structures have to be designed in order to provide adequate protection even during heavy storm surges.

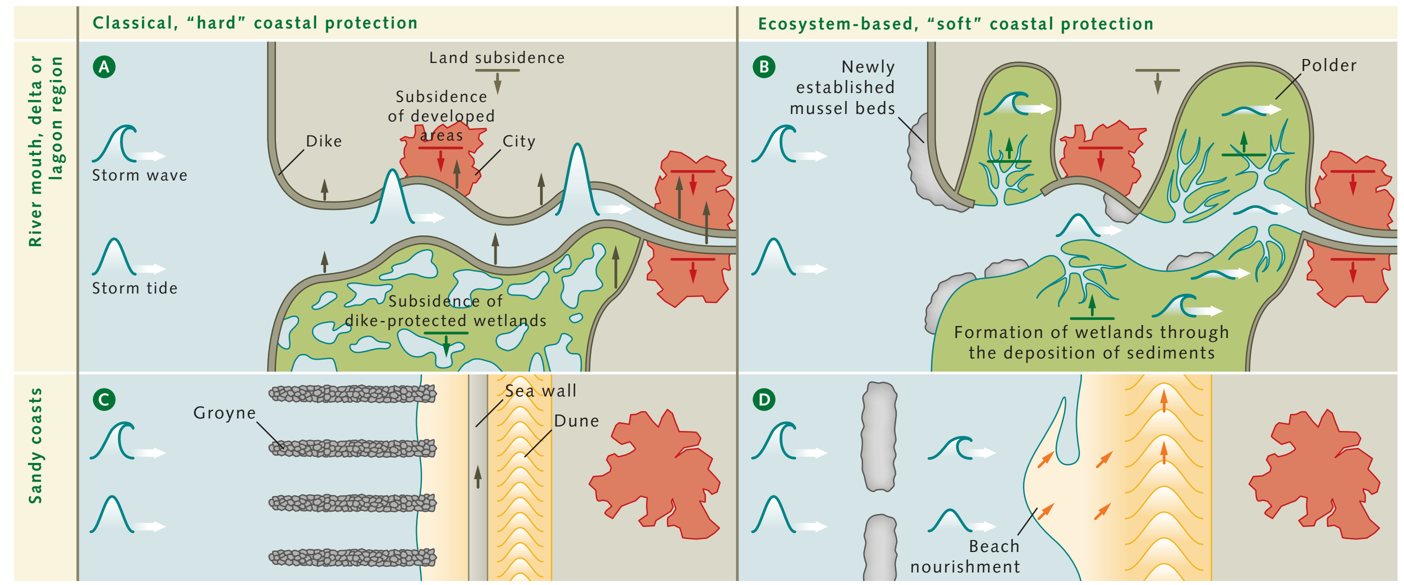
Practical test of alternative coastal protection

In order to better assess the efficacy of ecosystem-based solutions in practice, a number of test projects are currently underway. On the Indonesian island of Bali, for example, an ecosystem-based structure is being directly compared to a conventional rigid coastal defence structure. Bali is a popular vacation spot for tourists around the world largely because of its wide beaches and clear water. Preservation of the beauty and unspoiled nature of the coasts is thus very important both economically and socially.

The purpose of the project is to protect a stretch of coastline on the south side of Bali that is being affected by erosion. Strong wave action here carries large amounts of sediment away, and there is a lack of fresh sediment because the region is surrounded by rocky peninsulas that prevent the transport of sediment. In cooperation with coastal engineers from Europe, local agencies and the local population will compare the performance of a new protective structure made of bamboo poles and coconut-fibre mats with that of a recently built protective wall almost two metres high. Because it is known from other segments of Bali's coast that rigid walls can actually increase erosion by altering the surf and wave activity, it is desirable to find out whether construction using natural materials is more suitable for protecting the beach from further breakdown by heavy surf. The structure consists of a series of bamboo poles, behind which the coconut-fibre mats are rolled out on the beach. To prevent them from washing away, the mats behind the poles are buried and then planted with small seedlings of a native dune grass, which form a dense network of roots over time and stabilize the structure.

This kind of direct comparison between a classical and an ecosystem-based construction with regard to their performance and effectiveness is new for the island of Bali. Because the bamboo and coconut-fibre construction has only recently been completed no information has yet been gathered regarding its effectiveness. Should the protection by bamboo and coconut-fibre mats prove to be effective, however, it would have the following advantages:

- Cost saving: In the past, specialists and labourers had to be flown to Bali for the construction of conventional coastal defence structures made of concrete. This resulted in high costs. Construction using bamboo and coconut fibres is less expensive than a concrete structure.
- Local expertise: In the past there has been a lack of local specialists to periodically test and maintain the concrete structures, which is why they are defective in many places. Local people help, however, in constructing the systems of bamboo poles and coconut-fibre mats. They then have the knowledge and ability to provide upkeep and maintenance on the systems.
- Use of native and renewable resources: Bamboo and coconut fibres are traditional, renewable materials that can be obtained locally. Long-distance transport is avoided.
- Creation of employment: Local employment is expanded through the construction and maintenance of the natural coastal protection systems.
- Identification with coastal protection: Because the local people themselves construct the protective structures, they have a more direct relationship to the structure and a feeling of responsibility for its preservation. When the construction is carried out by foreign companies, subsequent maintenance of the structures is often neglected.



4.22 > While dikes or other man-made structures based on classical coastal defence concepts have to be raised to keep pace with climate change, ecosystem-based coastal protection utilizes the full natural potential of the coastal environment. Instead of setting forced limits on the water with increasingly higher dikes (A), polders can be built in estuarine areas to make more room for the sea (B). Instead of defence by groynes and sea walls (C), sandy coasts can be protected in the future through the creation of depots by artificial filling (D), which can provide the coastal areas with sand over several decades.

Now a significant number of other projects worldwide representing “soft” ecosystem-based coastal protection have been carried out or are at the planning stage. Ecosystem-based coastal protection specialists recommend that new projects first be tested within smaller pilot projects and that their suitability and impacts be assessed by interdisciplinary teams comprising engineers, landscape planners and social scientists. It is particularly important to assess in advance the extent to which the local inhabitants accept the coastal protection. In the creation of polders, for example, the owners and occupants of the areas need to be involved. If the pilot projects are successful, then the new ideas can be scaled up gradually into larger projects.

Eelgrass – a plant with potential

One new idea for coastal protection that is to be realized as pilot projects in the coming years is the establishment of eelgrass beds. Eelgrass grows tall and prolifically, and in this respect is similar to grasses growing on land. Furthermore – in contrast to seaweed, which usually attaches to firm substrates – it produces roots that help it to withstand strong wave activity and to protect the sediments from damage and gradual erosion. While coral reefs and mangroves have long been recognized as natural breakwaters, the importance of eelgrass beds for coastal protection has only been recognized in recent years, primarily as a result of their disappearance from many coastal regions. The causes for this include water pollution and, in areas of heavy fertilizer use, high rates of algal growth, which leads to a cloudiness of the water. In areas where eelgrass has been lost, increased erosion of the sediments is often observed today. New colonization by eelgrass then becomes improbable. Seedlings can no longer get a foothold because the currents are too strong in the barren areas.

An international research team of coastal engineers, geoecologists and material scientists is therefore working on methods to facilitate the settlement of eelgrass. They are developing synthetic mats of artificial seagrass that they plan to lay out on the sea floor in the future. The artificial seagrass should reduce water currents sufficiently to allow the eelgrass seedlings to take root again. In addition, these mats are so loosely woven that the sea floor beneath them is not hermetically sealed off, so no other native organisms are harmed. While material scientists are developing a suitable synthetic composition for application in seawater, the engineers carry out experiments in a water channel at a college lab. These experiments will make it possible for the first time to quantify how efficient the damping effect of eelgrass beds can be with regard to coastal protection. A further aim is to determine how fast eelgrass seedlings can colonize.

Salt marsh and dike in a wave flume

As with the eelgrass concept, there are several other ecosystem-based coastal protection approaches being considered today whose levels of effectiveness have not yet been accurately determined. This quantification is important in order to be able to assess the extent to which they will be able to supplement or even replace classical coastal defence methods in the future. Salt marshes, for example, which are located in front of the dikes at many locations along the North Sea coast, are known to slow down approaching waves during storm floods. To what extent this occurs, however, is not precisely known. So far it has not been possible to measure how effective the protective properties of heavily vegetated salt marshes are when the blades of grass are broken by the force of the waves. To make the necessary measurements, an actual patch of salt marsh from the Wadden Sea was recently removed and exposed to a strong surf in a 300-metre-long wave flume. The experiment revealed that the baffling effect was only negligibly reduced when the blades broke.

4.23 > Accurate measurements to determine how well a salt marsh with high-growth vegetation could reduce wave energy were made for the first time in a wave flume.

There is a general rule in coastal protection, even today, that the turf on dikes should be kept short as possible through sheep grazing. For one reason, the ground is compacted by the treading hooves, so that the dikes do not weaken during flooding. For another, the grazing inhibits the tall growth of herbaceous plants. Strong waves could otherwise more easily rip out clusters of plants, creating holes in the dike that would then be enlarged by the wave action. In extreme cases this could lead to a breach in the dike.

For the first time coastal engineers are investigating the extent to which dikes can be seeded with various flowering plants in order to create diverse grassland biotopes. For this purpose, a dike replica of actual size is now being built in a wave tank and will be planted with various combinations of wild flowers. Storm floods will then be simulated to find out which combination forms a dense network of roots that stabilizes the turf, and which wild flowers can tolerate constant flooding by salt water.

A synthesis of old and new

More of these kinds of investigations will be necessary before ecosystem-based measures can receive wide acceptance as alternatives in coastal protection. Irrespective of this, the challenges that confront us with rising sea level in the future will have to be met with a combination of ecosystem-based and classical coastal protection methods. In the Netherlands and Germany, for example, it will not be possible to completely dispense with the use of dikes.

However, it is also evident that channelized estuaries cannot be sufficiently protected in the future by dikes alone. This has been shown through mathematical models produced by a team of Australian, German and US American researchers, which computed how wave dynamics change when the water surges higher due to sea-level rise. Under the assumption that the tidal flats will not grow proportionately to keep up with the rise of sea level, they found that the waves become higher not only by a measure equal to the amount of sea-level rise, rather their height will increase disproportionately. This is because friction with the bottom is reduced when the water level is higher. The baffling effect of the bottom is thus likewise reduced.

4.24 > Breakwaters known as reef balls. The spheres distributed by a US American non-governmental organization are deployed for coastal protection. At the same time they help to form productive submarine habitats.

It is unsettling that this phenomenon already begins to become apparent when sea level is only a few centimetres higher. Because of this effect, waves could surge up to 56 per cent higher. This effect has so far not been taken into account in calculating the height of coastal protection structures. Presently only the amount by which sea level is predicted to rise in the future has been factored into the construction planning as a margin of safety.

Spheres that slow the wave surge

In contrast to groynes, which are built outward from the shore into the sea, breakwaters are elongate submerged structures that run parallel to the coast. They prevent the breakers from hitting the coast with unchecked strength, thus protecting beaches and promenades, for example. Today, they are typically made of massive concrete blocks or large stones in the water that otherwise have no further function. However, modules called reef balls have been in use for quite a long time and provide an ecosystem-based alternative. Hollow concrete spheres about one metre wide, made by a US American non-governmental organization, have numerous openings and not only reduce the wave energy, but at the same time provide shelter for fish and many other marine organisms. They are submerged beneath several metres of water and are ideal for organisms that colonize on firm substrates, such as mussels, sea anemones or sponges. Over time a densely settled underwater habitat is formed. Reef balls have also been set out in Germany, for example in the Bay of Kiel.

Is ecosystem-based coastal protection worth it?

Intact coral reefs and mangrove forests provide coastal protection at no cost, but other ecosystem-based measures can incur quite high expenditures, as demonstrated by the polder project in the Scheldt estuary. This then brings up the question of not only how reliable and effective ecosystem-based solutions are, but also how expensive they are and how high the costs are compared to classical coastal defence measures.

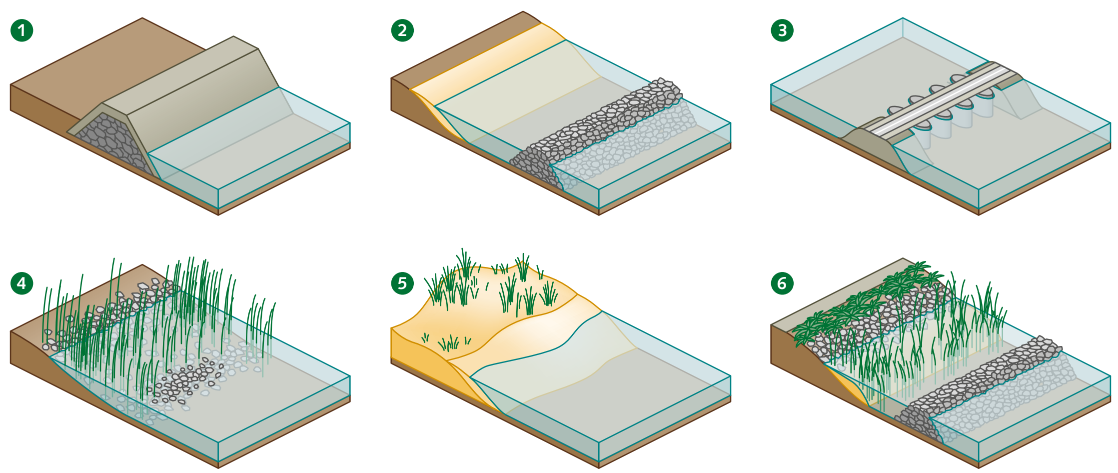
In a complex study, a team of international researchers analysed for the first time 52 coastal protection projects in which mangroves and salt marshes were planted or coral reefs were restored by introducing young corals. Eelgrass beds were also considered in the study. For one, they investigated how great the potential in the areas was for absorbing wave energy, and, for another, how high the project costs were compared to rigid defence measures. In a comparison of all projects, depending on the local situation, the various habitats decreased wave height as follows:

- Coral reefs by 54 to 81 per cent,
- Salt marshes by 62 to 79 per cent,
- Eelgrass beds by 25 to 45 per cent,
- Mangroves by 25 to 37 per cent.

It should be noted that the mangrove areas of the projects studied were only between 800 and 1500 metres wide. Mangrove forests that are many kilometres wide, however, can actually suppress waves at storm tide by 100 per cent before they reach the shore.

The salt marshes that were analysed, on the other hand, had widths from 100 to 2800 metres. The scientists point out, however, that in the creation of salt marshes one must take into account not only the width of the field but also the height of the vegetation. According to this study the cushioning effect in salt marshes is greatest when the vegetation height reaches up to just below the water surface.

For coral reefs, it was revealed that these have the greatest damping effect when they are at least twice as long



4.25 > Besides the classical coastal defence methods such as dikes (1), breakwaters (2), and barriers in river estuaries (3), ecosystem-based measures are being increasingly implemented today. These include the creation of man-made marshes (4) that collect fresh sediment, sand-fill areas (5) that promote the formation of sands and dunes along the coasts, and the installation of coastlines in harmony with nature (6) where species-rich green belts can develop behind structures that serve as breakwaters.

4.26 > The harbour of the British town of Cowes on the Isle of Wight is protected by massive breakwaters. Their construction is significantly more expensive than the creation of natural protection in the form of a salt marsh or eelgrass beds would be. Whether ecosystem-based coastal protection measures can actually be realized, however, largely depends on the form and use of a coastal area.

4.27 > In the Dutch resort town of Katwijk aan Zee, a parking garage was built parallel to the shore road and then covered with sand to create a high artificial dune.

as the incoming wave, and their tops lie at a depth of not greater than half the height of the wave.

Because there were no numbers for comparison for coral reefs and eelgrass beds, the cost analysis of the projects was limited to mangroves and salt marshes. For the latter, the study showed a clear cost advantage compared to conventional coastal defence in the form of breakwaters, and with the same damping effect. For the mangrove project, the study indicated that these can be three to five times cheaper than the construction of breakwaters. The salt marsh projects, which were primarily carried out in Europe and the USA, are either equal in cost or as much as three times cheaper than classical breakwaters, depending on the location. The differences are primarily due to the fact that the costs for breakwater construction increase disproportionately with water depth.

In addition to the cost factor, the creation of mangroves and salt marshes also has the advantage that both of these habitats can grow naturally with rising sea level. Frequent flooding transports more sediment into the areas, so the bottom surface is elevated and coastal protection remains in place. Breakwaters, by contrast, lose their protective effectiveness as sea level rises.

Limitations of the ecosystem-based approach

Ecosystem-based coastal protection solutions are not suitable for all kinds of coasts. A critical exclusion criterion is the large area required for many of the solutions. The installation of polders or mangrove areas of sufficient size is impossible in the vicinity of heavily developed coastal areas or harbours. In these cases the shore could be protected by installing artificial reefs or eelgrass beds in front of the dikes. In deeper waters, however, these measures are also ineffective and the only remaining option is the rigid classical coastal defence that simply offers resistance. With rising sea level these kinds of structures have to be designed with sufficient height.

In the Netherlands, for aesthetic purposes, dikes and flood walls are planned in combination with other functions to make them, to some extent, multi-purpose structures that are integrated into the townscape but retain an aspect of coastal defence. An example is the construction of parking decks within segments of dikes or dunes, whereby the massive wall is on the sea side and serves as coastal defence, and is additionally protected by a dike or dune in front. Streets or promenades could then be built along the top of the dike. A project of this kind has been realized in the Dutch resort of Katwijk aan Zee, where a parking deck built parallel to the coast was then covered with sand and planted with typical dune vegetation. Thus, a high artificial dune was created that protects the town and is integrated harmoniously with the natural landscape.

Confronting the inevitable

Even if conventional and ecosystem-based measures are combined for effective coastal protection in the future, not all of the coasts in the world can be protected if sea level rises by several metres in the coming centuries. There is no question that people will be forced to abandon certain areas because they will be permanently flooded or uninhabitable due to frequent flooding. To begin with, this fate will befall some island nations in the South Pacific, because some of these already lie less than one metre above sea level. The governments of these island nations are now already facing the question of how the withdrawal of citizens can be organized so that the island populations can gain a foothold in a new country and achieve the same standard of living that they had in their lost homeland.

In this regard, the efforts of the government of the West Pacific island nation of Kiribati are noteworthy. On the one hand, they are continuing to promote coastal protection measures for as long as possible, especially to protect economically important facilities like the airport. But in view of the early indications of sea-level rise, such as more frequent storm floods, increasing coastal erosion and saltwater intrusion into the freshwater lenses, preparations are already being made for a future emigration.

The government of Kiribati constantly points out, on an international level, that they do not want their citizens to be considered as helpless climate refugees, rather that they are a nation combatting the results of climate change, which they are not responsible for and to which their contributions have been negligible.

Orderly retreat instead of hopeless flight

Under the motto of “migration with dignity” the former president of Kiribati, Anote Tong, initiated an emigration strategy that should enable the population to gradually build a new life in another country before the islands become uninhabitable and the approximately 100,000 inhabitants of Kiribati become homeless refugees. Together with other Pacific island nations, a strong call has been made for climate justice and support from the industrial countries – in particular, the plea to those countries is that they should offer employment perspectives to citizens of the island nations as well as permanent resident status. This outspoken pressure has led to an increase in public awareness in recent years of the hazards faced by the Pacific island nations. Nevertheless, support by the industrial countries leaves much to be desired, including by the closely neighbouring countries Australia and New Zealand. New Zealand, for example, has launched a job programme that would accommodate workers from the Pacific island nations. But New Zealand officials do not want this to be perceived as a climate relief programme. Furthermore, the number of immigrants accepted is very low. From Kiribati, based on a lottery procedure, only 75 families are allowed to immigrate each year. If the immigrants make an effort to find employment they are given permanent resident status. Beyond this, New Zealand has been offering the inhabitants of Kiribati seasonal employment in agricultural jobs since 2007. Although permanent residency permits have resulted from these measures in some cases, it certainly cannot be viewed as a broad-based climate relief programme so far. Kiribati and other island nations are calling for unambiguous assurances from the industrial nations.

While other industrial nations have so far shown even less willingness to assure rights of residency to the inhabitants of island nations threatened by sea-level rise, there is a remarkable degree of solidarity among the Pacific island nations themselves. The island nation of Fiji, for

4.28 > The inhabitants of Nukunonu island in the South Pacific do not want to be seen as climate victims, but as warriors struggling against a rising sea level. According to a UN report, the atoll, which belongs to the island group of Tokelau, could be submerged in the twenty-first century.

instance, has sold Kiribati around 24 hectares of land. Many of Fiji's islands are higher in elevation than those of Kiribati, so they will be less impacted in the future by sea-level rise. Initially this area, which is located on Fiji's second-largest island, Vanua Levu, will be used for agricultural purposes. Kiribati wants to plant food here when their own agricultural areas are lost to flooding. If parts of the Kiribati Islands become completely uninhabitable in the future, the affected Kiribati natives will be able to settle on this land. The president of Fiji has given a public verbal promise of this.

One advantage of this settlement policy is that the emigrants from Kiribati will find living conditions on Vanua Levu similar to those in their homeland. The willingness of the Fiji government to accept refugees is even more remarkable considering that some of the Fiji islands themselves will be affected by flooding like Kiribati. Fiji will therefore also have to cope with the resettlement of internally displaced persons. According to present plans, these people will also settle for the most part on Vanua Levu.

New homeland for millions of people?

The example of Kiribati illustrates that it is possible for people, with advance planning, to leave threatened coastal areas in time to be able to build a new livelihood with dignity in another location. Critics, however, raise the concern that there must be assurances that not only a well-educated minority, but the entire population will have the opportunity to emigrate. It is also uncertain to what extent the example of Kiribati can be applied to other countries. The approximately 100,000 inhabitants of Kiribati may be completely taken in by other countries. By contrast, many millions of other people living in areas threatened by flooding, in Bangladesh for example, cannot readily be absorbed by the densely populated neighbouring countries. Many experts are therefore calling for higher levels of international solidarity with respect to the impacts of sea-level rise, particularly on the part of industrial nations.

An initial positive step in this direction is the Nansen Initiative, launched jointly by Norway and Switzerland in 2011 and named after the first High Commissioner for Refugees of the former League of Nations, Fridtjof Nansen. The work of the Initiative consists of advising various nations regarding the problems of climate refugees and involving political representatives of the industrial nations as well as those of the developing and emerging countries, which are usually the ones most affected, in the consultation process. Above all, the aim is to mediate among the countries – those from which the people are fleeing and those that are potential destinations for the refugees. The Initiative is active worldwide, both in inland areas where, for example, people are escaping from drought, as well as on the coasts. In the past it has initiated large consultation meetings in various regions, where the public authorities and affected people sat together at one table. The Nansen Initiative has now been renamed as the Platform on Disaster Displacement. This body continues the work of the Initiative, and is supported by governmental institutions such as the Swiss Confederation and the Department of Foreign Affairs of the Federal Republic of Germany, among others.

Conclusion

Together for conscientious use and better protection

Sustainable use of the coasts can only be achieved if the various interests of diverse users are brought into accord. To begin with, internationally, responsibility is explicitly regulated through the United Nations Convention on the Law of the Sea (UNCLOS). This establishes the concept of territorial waters, which are considered the sovereign territory of a country. Extending beyond this is the Exclusive Economic Zone (EEZ), within which the state has the exclusive right to exploit natural resources such as oil and fish, although it is not part of the sovereign territory of the state. How a nation uses its coastal areas, however, is its own decision.

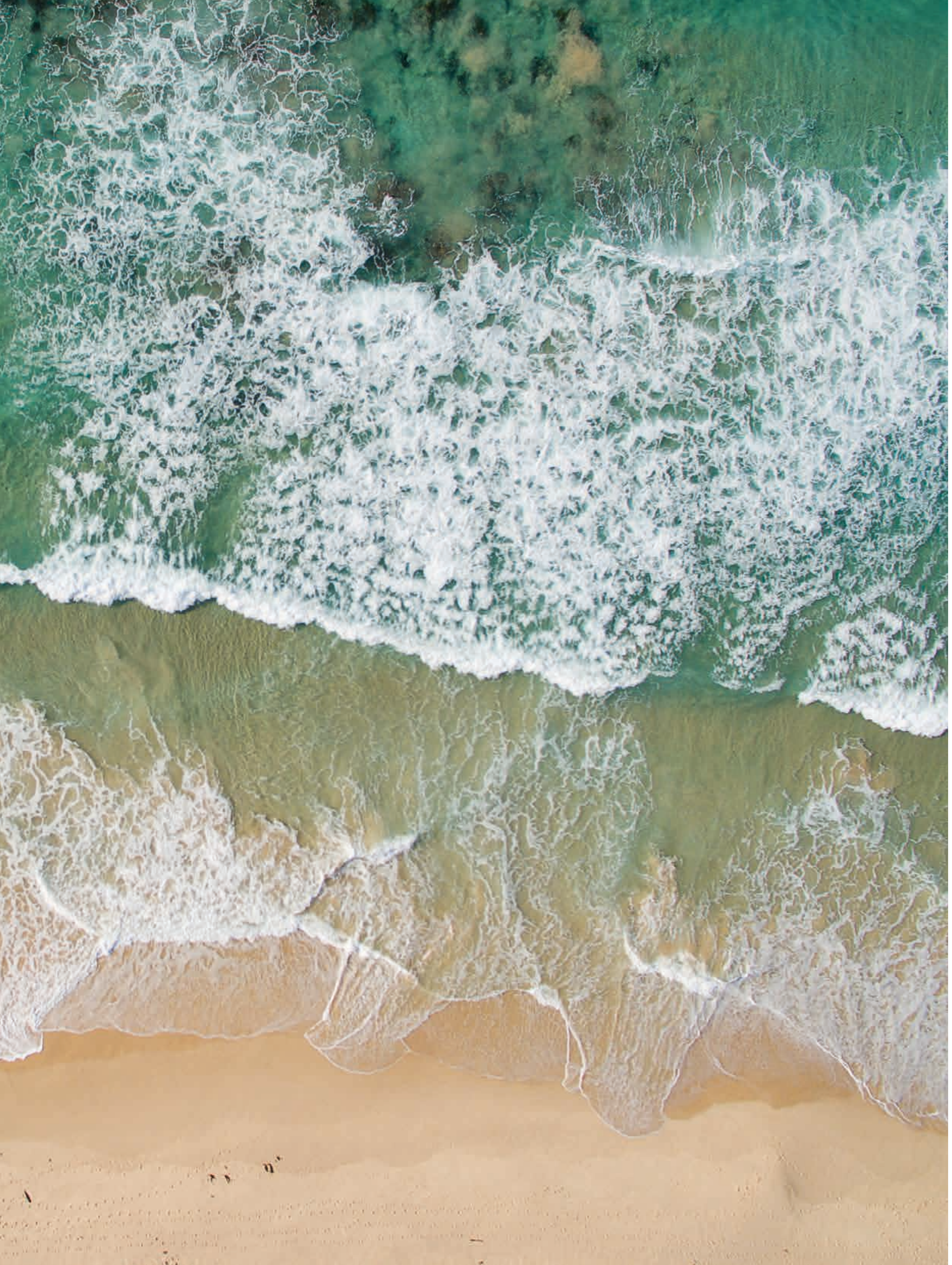
In order to avoid conflicts of interest, Integrated Coastal Zone Management (ICZM) aims to achieve sustainable development of coastal zones. ICZM has succeeded in some cases in preventing conflict between nature conservation and tourism, and in realizing sustainable coastal fisheries.

Where important coastal areas extend across national boundaries, additional international coordination is necessary. For this purpose the concept of Large Marine Ecosystems (LMEs) was developed, which has already led to a number of positive achievements. For example, states bordering on the LME in the Bay of Bengal were able to agree measures to control overfishing and pollution of the sea.

Successful coastal zone management in the future will have to include effective protection from rising sea level. While the previous strategy was to protect the coasts in part with strong and rigid structures like dikes or barriers, there is now a move away from this paradigm. This is especially because the consequences of future climate change cannot be predicted accurately. Coastal protection measures must therefore be planned more flexibly. Adaptive coastal protection is a promising alternative that provides for a number of different measures that build upon one another, and that are adapted to the advance of sea level in planning and design. These can include raising the elevation of dikes with the help of protective walls or creating new flood-plain areas called polders, into which flood waters can be diverted. One of the first large adaptive projects to be initiated is for the protection of the Thames estuary near London. Adaptive coastal protection also entails building settlements in such a way that they are not susceptible to damage by high waters – perhaps by the construction of floating houses.

While coastal protection in the past has often meant creating large structures cutting across coastal areas, coastal engineers are now calling increasingly for a philosophy of "Building with Nature". This involves using the natural potential of the coasts, for example by promoting the colonization of oyster reefs or eelgrass beds, or by constructing polders where high-diversity salt marshes can develop. Despite the many encouraging examples of alternatives, however, coastal protection programmes around the world remain quite conservative because generally accepted standards or regulations for ecosystem-based measures are still absent and their effectiveness in many cases has yet to be demonstrated. This lack of knowledge needs to be remedied quickly.

In spite of all measures, it will not be possible to preserve all of the world's coasts in the face of rising sea level. The governments of island nations are thus already preparing for an orderly retreat, for instance through education programmes that make their populations attractive for employment abroad. It is hoped that this may put the people who could soon be climate refugees in a position to build new livelihoods in other countries.



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Coasts – A Vital Habitat Under Pressure

Coasts are a special habitat. They are the transitional zone between land and sea, are influenced by both spheres, and are extraordinarily polymorphous. Whereas Brittany's northern French coastline is rocky and gouged by innumerable inlets, the high dunes of the Namib Desert on the coast of Namibia extend panoramically to meet the Atlantic, while differently again, the low-lying coast of Siberia consists of permafrost, i.e. ground frozen to a depth of several metres.

The variety of coastal landscapes is matched by the diversity of services they render to humankind. They provide important transport routes and industrial sites; they are favoured destinations for recreation and tourism, and they are sources of mineral and fossil resources. For that reason, coasts have always been especially popular sites for human settlement. The populations of many coastal areas have been growing for decades. According to United Nations estimates, around 2.8 billion people today live within 100 kilometres of the coast. Of the world's 20 megacities, i.e. cities with more than 10 million inhabitants, 13 are in near-coastal locations. It is widely expected that the urbanization of coastal areas will continue to advance in the next few years. It is estimated that in 2060 around 1.4 billion people will be living in low elevation coastal zones at elevations of no more than 10 metres above sea level.

In relation to terrestrial land mass as a whole, coasts are ultimately just a narrow strip where the land meets the sea. When people colonize this coastal strip, in many cases they give no thought to the fact that it is subject to constant natural change – and that over the course of time these changes can also destroy areas of human settlement. Changes of this kind happen on different time scales: those caused by plate tectonics occur over millions of years, permanently changing the form of the Earth's surface and the continents; temperatures swing between glacial and interglacial periods on a cycle lasting tens of thousands of years – while changes in recent centuries have largely come about due to the impacts of human settlement. Over relatively short periods of geological time, it is mainly fluctuations in sea level that dramatically affect the morphology of the coasts.

During glacial periods, large volumes of water are sequestered on land in the form of ice and snow. The sea level is lowered because very little water flows back from the land into the ocean. During the last glacial period around 20,000 years ago, it was around 120 metres lower than it is today. Many areas that are submerged today were dry land during that period, and the land mass protruding above the waterline was a total of 20 million square kilometres larger than it is today. For around 6000 years the sea level has barely changed. Due to human-induced global warming, however, for the last several decades it has begun to rise more markedly once again, by an average of 3 millimetres per year at the last count. There is an impending risk that entire island nations or low-lying coastal areas will be inundated in future – in Bangladesh, for example, which lies only slightly above the present-day sea level.

Depending on coastal morphology, widely diverse habitats have developed over time. Where rivers carry large quantities of nutrients and sediment into coastal waters, today – depending on climatic conditions and the prevailing currents – there are expansive river deltas with wide sand-

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banks, tidal mudflats or salt marshes. Such coastal areas are often especially productive and abundant in fish, thanks to the heavy discharge of nutrients. One of the rivers that carry particularly high levels of sediment into the sea is the Mississippi, around the mouth of which a large delta has developed. The record-holder is the Ganges, though: every year it carries around 3.2 billion tonnes of material into the sea. In contrast, other shorelines are more barren and rocky, like the limestone coast of Croatia from which very few nutrients find their way into the sea. Likewise, tropical coral reefs are found mainly at sites where nutrients and sediment barely flow into the sea from the land.

Today the coastal areas of the world are intensively used. They supply the bulk of the world's wild-caught fish. In fact, 90 per cent of global fishery takes place in coastal waters. Another use of great economic significance is the drilling of natural gas and oil in coastal areas. Although the bulk of both resources is still extracted onshore, the proportion coming from the sea (offshore gas and oil) is substantial. Currently offshore oil accounts for about 40 per cent and offshore gas for about 30 per cent of total global extraction.

In the past few years, coastal waters have become increasingly attractive sites for the harnessing of wind energy to generate electricity. The number of offshore wind turbines has increased markedly, and by the end of 2015 the combined capacity of all the offshore wind turbines in operation worldwide was at least 12,000 megawatts, which roughly equates to the capacity of 24 nuclear reactors. Another resource supplied by coasts are mineral raw materials, particularly sand and gravel, which are used in concrete manufacturing, as filling sand on building sites, or for hydraulic filling to create new port or industrial sites on the coast. The largest sand-mining area is located on the coast of Morocco. Dunes are being excavated and removed on a massive scale with wheel loaders, so that the coast in some regions resembles a lunar landscape.

In many places, human use of the coasts is exceeding their carrying capacity. The sources of pressure on these habitats are multifarious. High levels of nutrients are discharged into the sea from untreated effluents, from intensively fertilized agricultural lands or from aquaculture. This leads to eutrophication and to severe algal blooms. Pollutants from industrial processes that seep into coastal waters also pose a threat. These include heavy-metal compounds or persistent chemical substances that accumulate in the food chain and can give rise to illnesses like cancer. An example of these are polyfluorinated compounds, which have been in use for years now for everyday products like outdoor clothing or pan coatings. Likewise, the plastic waste that finds its way into the sea by many different routes raises a problem that is currently a matter of serious debate. Marine animals and seabirds swallow pieces of this plastic and die. Furthermore, the plastic decays into microscopically small fragments, microplastics, which are now in evidence in all the world's oceans. Scientific studies are currently investigating to what extent animals ingest them and how dangerous they are. Global plastics production has been increasing for years. Between 2005 and 2015 alone it rose by over 90 million tonnes, from 230 to more than 320 million tonnes.

Since coastal waters are especially productive, they are fished intensively, which has led to the overfishing of many stocks. Furthermore, seabed habitats – such as coral reefs – in many locations are being destroyed by fisheries. In some regions that are rich in corals, intensive fishing also means that other marine organisms are gradually overfished. If one species disappears, the next is hunted. Because of unsustainable fisheries, the coral reef habitats are becoming impoverished over time. This threatens the very foundation of many people's livelihoods.

Under particular pressure today are the coastal megacities with more than 10 million inhabitants. The distinctive feature of these regions is their high density of population and construction. There is a need to supply many people simultaneously with fresh water, food and electricity, which imposes major demands upon infrastructure, logistics and waste management. Because people from poorer rural regions inland are constantly moving to the coastal megacities in search of work or training, these metropolitan centres will continue to grow in future – above all in Africa, South America and Southeast Asia. Urban sprawl resulting from this growth blights the landscape. Natural areas such as floodplains, mangrove forests or salt meadows can very rapidly be lost. Regional species of fauna and flora are threatened with extinction. Added to this, the destruction of mangroves which normally act as natural wave-breakers means that many sections of coast are now particularly at risk of inundation. Flooding has been further exacerbated in some megacities by the fact that these densely built-up urban areas are slowly subsiding. This is largely caused by groundwater abstraction to obtain drinking water. Groundwater normally acts as a natural abutment that counterbalances the weight of built-up areas bearing down on the substrate. Compaction of the ground is another factor that contributes to subsidence. Currently the world's fastest subsiding city is the Indonesian capital, Jakarta, the centre of which is sinking by around 10 centimetres each year.

Added to these problems caused locally or regionally by human activities in coastal areas are those which are driven by the global phenomenon of climate change: ocean warming, ocean acidification and sea-level rise. How severely these consequences of climate change will affect coastal habitats depends to a great extent on how much carbon dioxide (CO_2) is released into the Earth's atmosphere in future. The direct consequence of high CO_2 emissions is gradual warming of the atmosphere and the ensuing warming of water, particularly at the ocean surface, which cannot then mix so easily with the cooler and heavier water layers beneath. As a result, the water that sinks to deeper levels is less oxygen-rich, which can lead to a shortage of oxygen in the deep ocean. In areas where this has occurred, it becomes virtually impossible for higher animals like crabs, bivalves or fish to survive. Warming also affects tropical coral species. At present it is assumed that around 20 per cent of tropical coral reefs face irreversible destruction and at least another 30 per cent severe degradation due to warming and other stress factors like marine pollution. In other marine organisms, it is primarily eggs and larvae that react sensitively to the warming of the water. In the Atlantic cod, for example, it leads to embryonic mortality. Model cal-

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culations show that this could cause a drastic decline in catches for the cod fishery in the Barents Sea north of Norway.

Another consequence of climate change is acidification of the oceans. This occurs because of increasing atmospheric carbon dioxide dissolving into the seawater and forming acid, to express a complex process in simplified terms. The marine organisms principally affected are those that form calcareous shells or skeletons. In corals, bivalves and snails, in acidified water this calcification process declines by 22 to 39 per cent depending on the animal group being studied. On the other hand, studies have meanwhile been published which show that a few marine organisms are highly capable of adapting to acidification over the course of several generations. Today it is impossible to predict with accuracy how severe the future consequences of acidification will be.

A direct danger for people is the rise in sea level caused by climate change. Currently the sea level is rising by around 3 millimetres per year, but this will accelerate if greenhouse gases continue to be emitted in large quantities by burning fossil fuels. Since the trend cannot be predicted with precision, the Intergovernmental Panel on Climate Change (IPCC) works on the basis of four scenarios, each of which makes different assumptions about how high the CO_2 concentration in the Earth's atmosphere might be in future. According to the extreme scenario, by the end of this century the sea level could rise globally by around 1 metre. By the year 2500 a rise by more than 6 metres is far from inconceivable. Under these conditions, coastal protection will increasingly become a task of vital importance for human survival.

Over the centuries, societies have managed to adapt to storm surges and flooding and to develop appropriate sea defence structures. However, the future trajectory of sea-level rise is impossible to predict exactly. Coastal protection must therefore become more flexible so that despite this uncertainty, people and material assets can be protected. Whereas in the past people relied on rigid coastal protection in the form of dikes and barriers, in future they might increasingly transition to an adaptive approach to coastal protection, which provides for a range of successive measures and is augmented as the sea level grows progressively higher. What is crucial is that the various interventions are planned well in advance and structured in the form of a roadmap so that it is possible to keep abreast of sea-level rise at all times. Large-scale projects of this kind already exist in the Netherlands, and a catalogue of measures for adaptive coastal protection has been developed to protect London and the Thames estuary. Beyond this, coastal engineers are increasingly urging a policy of "building with nature". This involves utilizing the potential of the coasts themselves – perhaps by establishing oyster reefs or eelgrass beds, or by constructing polders in which species-rich salt meadows can develop. It is now also acknowledged that people must learn to live with the rising water – perhaps by constructing floating houses. Furthermore, coastal protection can be combined with other functions and, at the same time, executed in a near-natural form. In the Netherlands, for example, multi-storey car parks have already been built along the coast, and subsequently covered with sand and overplanted to create artificial protective dunes. Nevertheless, despite all measures, it will be impossible to save all the world's coasts in future. The governments of island nations such as Kiribati are therefore already trying to make preparations for an orderly retreat – with efforts such as education programmes that put the population in a position to be attractive candidates for foreign labour markets. This would give people the option of building a new livelihood in other countries in preference to becoming destitute climate refugees.

Added to all the pressures caused by human overuse and warming of the climate, coasts are exposed to natural hazards such as earthquakes, landslides or tsunamis. Of course these threats have always existed, but because the coasts are more densely settled today than ever, the scale of any damage is significantly greater. Therefore efforts are now being made to protect people from these hazards of nature by means of sophisticated early warning systems. Particularly the USA and Japan have taken on a pioneering role in this respect since the middle of the last century. The severe tsunamis of 2004 in the Indian Ocean and 2011 in Japan brought about an even stronger emphasis on tsunami research and early warning, so that today effective warning systems are in place in all the most vulnerable marine regions. But there can never be 100 per cent protection.

The world's coasts are threatened from many directions – but the greatest threat today is posed by human overuse. This raises the question of how it may be possible in future to achieve prudent coastal management and to pre-emptively avoid conflicts over use arising from competing interests. An important approach for solving these problems is Integrated Coastal Zone Management (ICZM), of which there are already plenty of successful examples at regional level. For instance, there have been ICZM processes in which conflicts between nature conservation and tourism were successfully avoided or sustainable coastal fisheries established. There have been cases in which authorities placed marine areas under protection without involving the indigenous local fishers in the decision-making process. Many of the affected fishers, for their part, refused to accept the bans on fishing in their territories and continued to fish. In ICZM processes, in contrast, the fishers are given a voice and can also contribute their own proposals.

For example, in the Indo-Pacific region, protected areas were established in which fishing is only permitted in certain sectors or is organized sustainably by the local fishers themselves in what are known as locally managed marine areas. Where important coastal areas extend beyond national borders, international agreements also become necessary, like those covering the large marine ecosystems (LMEs), extensive near-coastal areas of the ocean, each of which is distinguished by its own typical flora and fauna. By way of an example, the coastal communities of the LME in the Bay of Bengal succeeded in adopting joint measures to combat overfishing and marine pollution.

Last but not least, the world's coasts also play a special role in cultural and aesthetic respects. They are places of recreation and important travel destinations. To this day, coasts not only have a direct use but also a spiritual value for many people and cultures. A purely economic view of coasts and the ecosystem services cannot therefore always do justice to the true significance of the coasts.

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 in the body of the review, making them easy to identify.

Abrasion: the mechanical wear or removal of rocks in the surf zone. A variety of mechanisms contribute to abrasion. Soft rocks can be worn away by the wave energy alone. Harder rocks can be abraded by loose material such as sand that is transported to the shore with the surf. Another type is weather abrasion, which is the washing out of rocks by rain or frost wedging. The latter is a term for the phenomenon whereby water that has penetrated into cracks expands upon freezing, and causes the rock to chip or flake.

Amphibious: Plants and animals that can live both in water and on land are called amphibious. The term comes from the Greek *amphi* (two-sided, double) and *bios* (life).

Ballast water: water pumped into special ballast water tanks in the hull to stabilize ships. Ballast water is transported over long distances primarily by cargo vessels. The organisms contained in the water, such as algae, larvae or bacteria, can easily cross great ocean expanses in this way. If they establish themselves in a new habitat they can displace native species.

Benthic: Organisms living on the bottom of a water body are called benthic.

Earth history: an object of research in the field of geology. It encompasses the period of time from the origin of the Earth up to the geological present.

Human history: the time period spanning the origin and evolution of the genus Homo in Africa up to the present. Archaeology provides knowledge of the early development phases through the investigation of past remains.

Ice shelves: are large platforms of ice that float on the ocean but are still connected to the ice on land. Ice shelves can be hundreds of metres thick. They often form when glaciers flow from the land into the sea.

Mean sea level, Normalnull: Normalnull (NN) is a reference datum for the standardization of elevation measurements in Germany, Switzerland and Austria. It is equivalent to the elevation of the mean sea level. Normalnull is also the reference used for designating elevations of buildings or mountains. It was originally derived from the Amsterdam Ordnance Datum (Normaal Amsterdams Peil – NAP) that has been used conventionally in the Netherlands since the nineteenth century, and was at that time equivalent to the average water level of the Zuiderzee, a marine inlet that lay largely in the area of the present-day IJsselmeer.

Parts per million (ppm): The expression parts per million (ppm) is used to designate one-millionth of a substance. 1 ppm of a substance thus represents a concentration of 1:1,000,000 parts.

Pore pressure: the pressure of the water that exists between the particles within a sediment body. Because water cannot be compressed, pore pressure increases when fresh sediment is deposited atop older sediment layers.

Rare-earth metals: a group of 17 metals that are located adjacent to one another in the periodic table of the elements and have similar chemical properties. The unusual name comes from the fact that in the past these metals were mined from minerals ("earths") that were thought to be very rare. In fact, however, many of the rare-earth metals are relatively abundant in the Earth's crust. But large deposits with high concentrations are not common. The largest occurrences are found in China and Mongolia. Rare-earth metals are used in many key technologies. Among other uses, they are needed for permanent magnets in magnetic resonance tomography (MRT) and in wind turbine generators, as well as for the production of storage batteries, LEDs and plasma displays.

Rated capacity: the maximum output at which energy-driven equipment can run over extended periods without being damaged or subjected to a decreased lifespan. The nominal power rating is always specified for motors and generators. In every-day application, technical equipment usually runs below the rating, generally in order to extend its lifetime. It is not uncommon, however, for wind turbine generators to reach their rated capacity on very windy days.

Stock: A stock is a self-sustaining population of a fish species that occurs within a limited marine region. As a rule, the different stocks of a fish species are so far isolated geographically from one another that the individuals of one stock do not mix with those of another, even though they belong to the same species.

Trades/trade winds: winds that blow steadily in the tropics and are thus a driving force of marine currents. The trade winds prevail between around 23 degrees latitude north and south of the equator. The northeast trades occur in the northern hemisphere and the southeast trades in the southern hemisphere. The direction of the trade winds is primarily controlled by the deflective force of the Coriolis effect.

Abbreviations

ABS Australian Bureau of Statistics

AMERB Áreas de Manejo y Explotación de Recursos Bentónicos; Management and Exploitation Areas for Benthic Resources

BOBLME Bay of Bengal Large Marine Ecosystem

BEF Biodiversity and Ecosystem Functioning

CARIBE EWS Caribbean and Adjacent Regions Early Warning System

Cosco China Ocean Shipping (Group) Company

DART Deep-ocean Assessment and Reporting of Tsunamis

EU European Union

EEZ Exclusive economic zone

FAO Food and Agriculture Organization of the United Nations

GAO Government Accountability Office

GEF Global Environment Facility

HSDRRS Hurricane and Storm Damage Risk Reduction System

IMTA Integrated Multi-Trophic Aquaculture

ICZM Integrated Coastal Zone Management

IPCC Intergovernmental Panel on Climate Change

ISA International Seabed Authority

IOC Intergovernmental Oceanographic Commission

IOTWS Indian Ocean Tsunami Warning System

InaTEWS Indonesian Tsunami Early Warning System

IUCN International Union for Conservation of Nature and Natural Resources

Jabodetabek A conurbation comprising the cities of Jakarta, Bogor, Depok, Tangerang and Bekasi

JMA Japan Meteorological Agency

LECZ Low Elevation Coastal Zone

LME Large Marine Ecosystem

LMMA Locally-Managed Marine Area Network

MEABR Management and Exploitation Areas for Benthic Resources

MPA Marine Protected Area

NEAMTWS North-Eastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System

NLWKN Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency

OECD Organisation for Economic Co-operation and Development

NOAA National Oceanic and Atmospheric Administration

PBDE Polybrominated diphenyl ethers

PCB Polychlorinated biphenyls

PFCs Perfluorocarbon compounds

PFOA Perfluorooctanoic acid

PFOS Perfluorooctane sulfonate

POPs Persistent organic pollutants

ppm parts per million

PTWC Pacific Tsunami Warning Center

REACH Registration, Evaluation, Authorisation and Restriction of Chemicals

RFMO Regional Fisheries Management Organisation

SMPAs Special Marine Protected Areas

TURFs Territorial Use Rights in Fisheries

UNCLOS United Nations Convention on the Law of the Sea

UNCTAD United Nations Conference on Trade and Development

UNEP United Nations Environment Programme

UNESCO United Nations Educational, Scientific and Cultural Organization

UNHCR United Nations Human Rights Council

UNWTO United Nations World Tourism Organization

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Contributors

Many experts have contributed their specialized knowledge to the compilation of the World Ocean Review in 2017. These included, in particular, scientists working in one of the member institutions of the German Marine Research Consortium (KDM) and the Cluster of Excellence "The Future Ocean".

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Prof. Dr. Ulrich Bathmann, director and biological oceanographer at the Leibniz Institute for Baltic Sea Research (IOW) in Warnemünde, professor of Earth System research at the University of Rostock, and spokesman for the Leibniz ScienceCampus Phosphorus Research. His research deals with coastal-sea topics, the naturally and anthropogenically induced changes of processes in the coastal seas and their impacts on society. He is a member of numerous national and international working groups, and is Chair of the German Marine Research Consortium (KDM). Furthermore, he is a member of the Executive Board of the Leibniz Association and a member of the German section of the Intergovernmental Oceanographic Commission (IOC).

Prof. Dr. Jörn Behrens, mathematician with emphasis on applied mathematics at the University of Hamburg. He earned his PhD at the University of Bremen and qualified as professor at the Technical University of Munich. He has developed numerical methods for atmospheric and oceanic simulations. In 2006 he took on the leadership position for tsunami modelling at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), where he and his working group developed the simulation components for the German-Indonesian Tsunami Early Warning System (GITEWS). In 2009 he accepted a position at the University of Hamburg. There, he is a member of the Center for Earth System Research and Sustainability (CEN – Centrum für Erdsystemforschung und Nachhaltigkeit). As co-chair of a UNESCO working group for hazard assessment and modelling within the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS), he played a leading role in 2016 in working toward the accreditation of tsunami warning centres in France and Italy.

Flemming Dahlke, marine biologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). His PhD investigations address the influence of climate change on the distribution of important fish species in the Arctic Ocean. His focus here is on the assessment of climatic risks related to the preservation of favourable breeding areas using physiologically based predictive models.

Prof. Dr. Ralf Ebinghaus, chemist at the Institute for Coastal Research at the Helmholtz Centre Geesthacht (HZG). He heads the Department of Environmental Chemistry there and teaches as professor (h. c.) at the Leuphana University of Lüneburg. His research directions include detection, transport and gas-water exchange of especially long-lived chemical substances in near-coastal, marine and polar environments. Ebinghaus is editor of the journal *Environmental Chemistry* and co-editor of the journals *Chemosphere* and *Atmospheric Chemistry and Physics*. He is a member of the Pool of Experts for the World Ocean Assessment of the United Nations.

Dr. Werner Ekau, fisheries biologist at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. His work focuses on population dynamics and the adaptations of different life stages to a changing environment. In projects such as GENUS (Geochemistry and Ecology of the Namibian Upwelling System) and AWA (Ecosystem Approach to the management of fisheries and the marine environment in West African waters), he investigates the influence of hypoxia and salinization of estuaries on reproductive ability in fish of the herring family. He is also director of the German operations centre of the International Ocean Institute (IOI).

Prof. Dr. Kay-Christian Emeis, geoscientist in the field of biogeochemistry at the University of Hamburg and concurrently leader of the Institute for Coastal Research at the Helmholtz Centre Geesthacht (HZG). His scientific interest is the elucidation of material cycles in the ocean and investigating the influence of human activity on coastal ecosystems. He earned his PhD in Hamburg and then worked at Texas A&M University and Woods Hole Oceanographic Institution in the USA, followed by periods at the University of Kiel, the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), and the University of Greifswald. He has now returned to Hamburg.

Dr. Sebastian Ferse, ecologist at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. His research work combines natural and social science approaches and deals with the ecology and human use of tropical coral reefs. He is concerned with the management, biodiversity and resilience of reef systems. Further aspects of his work include ecosystem functions and services, reef restoration, livelihood strategies, and small-scale fisheries, as well as participative management of tropical coastal areas. A central focus of his research is related to Indonesia, where he has been working for around 15 years.

Daniel Gerecke, geographer and consultant for the German international development organisation Gesellschaft für Internationale Zusammenarbeit (GIZ) in the regional programme "Coping with climate change in the Pacific island region". He is responsible for programme activities in the area of policy advice and adaptation to climate change in Kiribati, and also leads the programme components on climate change and education in the island nations of Fiji, Kiribati, Samoa and Vanuatu.

Prof. Dr. Anna-Katharina Hornidge, sociologist and development scientist, professor at the University of Bremen and leader of the Social Sciences department as well as the working group for development sociology and sociology of knowledge at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. Her research fields encompass the theory of science and innovation research with regard to environmental/marine issues, as well as adaptation research in development contexts. The aim of her working group is to further expand the marine social sciences relating to the theory of science and futures studies.

PD Dr. Tim Jennerjahn, biogeochemist and leader of the Ecological Biogeochemistry working group at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. He has been studying the reactions of tropical coastal ecosystems to climate-related and human-induced environmental changes for many years. He has led interdisciplinary research groups in China, Indonesia, India and Brazil, and has participated in numerous expeditions on both land and sea. He is chief editor of the international professional journal *Estuarine, Coastal and Shelf Science*. Jennerjahn also teaches at the University of Bremen.

Prof. Dr. Silja Klepp, professor for human geography in coastal and marine regions at Kiel University and member of the Cluster of Excellence "The Future Ocean". Her current research in the Central Pacific addresses the themes of climate change, climate-change adaptation and migration. She integrates post-colonial perspectives and critical theories in the research field of climate-change adaptation. Other focuses include the cultural and social consequences of climate change, flight and migration, and the EU border regime. Silja Klepp works primarily in Fiji and Kiribati, as well as in the Mediterranean Sea region.

Dr. Lotta Clara Kluger, marine ecologist at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen. She focuses on participative, ecosystem-based coastal and resource management and the diverse implications of aquaculture. She works within interdisciplinary projects in various South American countries on ecological and socioeconomic issues with the aim of promoting the sustainability of small fisheries.

Prof. Dr. Sebastian Krastel, marine geophysicist at the Institute of Geosciences at Kiel University and a member of the Cluster of Excellence "The Future Ocean". He studies sedimentation processes on the continental slopes and their associated natural hazards. For this he primarily employs acoustic methods to analyse the sea floor and its underlying layers.

Dr. Lasse Marohn, fisheries biologist at the Thünen Institute of Fisheries Ecology in Hamburg. His interest is in the stock management and biology of the European eel and other diadromous migrating fish species. An additional focus of his work is investigating the consequences of dynamic environmental conditions and anthropogenic influences on the migratory behaviour and habitat preferences of fish.

Dr. Barbara Neumann, geographer in the Ocean Governance project at the Institute for Advanced Sustainability Studies (IASS – Institut für transformative Nachhaltigkeitsforschung) in Potsdam, and until recently a member of the Cluster of Excellence "The Future Ocean" in Kiel and research associate at the Geographical Institute of Kiel University. She works in the field of human environmental research and is particularly interested in the analysis and assessment of human-environment and land-sea interactions in the coastal realm. Among other things, she is currently working on the implementation of Sustainability Goal number 14 of the UN 2030 Agenda, dealing with the conservation and sustainable use of the oceans and marine resources, the underlying sustainability concepts, and the resultant challenges for ocean and coastal governance.

Dr. Hanna Sabaß, portfolio manager and consultant in the regional GIZ programme "Coping with climate change in the Pacific island region". She is a geographer and has been working for over ten years for the GIZ in the areas of disaster preparedness, climate-change adaptation, rural regional development and environmental education. Until 2015 she played a significant role in the development of the "Whole of Island Approach" and in the coordination of the implementation partners on Kiribati. She has lived and worked in Fiji since 2011, from where regional projects are implemented in 15 Pacific island nations.

Prof. Dr. Torsten Schlurmann, coastal engineer and Managing Director of the Ludwig-Franzius Institute for Hydraulic, Estuarine and Coastal Engineering at the Leibniz University Hannover. Concurrently, he heads the "Coasts" research centre with the large research apparatus, the Great Wave Flume (GWK – Großer Wellenkanal). After his graduate studies, PhD, and post-doctoral (habilitation) qualification in civil engineering, he assisted at the United Nations University in the implementation of a tsunami early warning system in the Indian Ocean. In 2007 he accepted a W3 professorship in Hannover. His major areas of research involve surveying and modelling of the processes involved in estuarine and coastal engineering, particularly in the areas of coastal protection and risk management, harbour planning and maintenance, and the testing and development of maritime technologies, particularly those related to offshore wind energy. In recent years he has been especially engaged with the integral proactive approach of "Building with Nature".

Dr. Daniela Storch, integrative ecophysiologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. Her expertise is the ecophysiology of marine animals and their various developmental stages. She leads various projects in which she, along with her staff and colleagues, investigates which life stages are most sensitive, how adaptive these life stages are to environmental changes, and the degree to which the distributions and biodiversity of marine animals are influenced by these life stages.

Dr. Nicola Wannicke, microbiologist at the Leibniz Institute for Plasma Science and Technology (INP Greifswald). She studies the interactions between cold atmospheric plasma and plants. Until recently she worked at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) in the working group on the marine nitrogen cycle where she studied the impacts of ocean acidification on cyanobacteria. In addition, she investigated the changes in growth rate and nitrogen fixation in typical Baltic Sea species such as *Nodularia spumigena* as well as their generation of toxic substances.

Dr. Ralf Weisse, meteorologist and head of the Coastal Climate department at the Institute for Coastal Research at the Helmholtz Centre Geesthacht (HZG). His research interests deal with marine climate and its variability. His specific areas include storms, storm surges, wave motion and regional sea-level changes and their effects.

Prof. Dr. Christian Wild, leader of the marine ecology group and the working groups on marine ecology and coral reef ecology at the Department of Biology and Chemistry of the University of Bremen. Prior to this he was a contact person for coral reef topics at UNESCO in Paris, and worked as group leader for early career scientists at the LMU in Munich. His most important project for the future is the organization of the International Coral Reef Symposium in Bremen for the first time, in the summer of 2020.

Dr. Anna-Katharina Wöbse, environmental historian and research associate at the Institute for Biology Didactics of the Justus Liebig University in Gießen. She studies questions regarding the relationships between humans and nature, international environmental diplomacy, and the visualization and medialization of natural and environmental conflicts. Her current research project is to bring into closer focus the history of European wetlands, from the Wadden Sea and the North Sea to the Camargue.

Prof. Dr. Matthias Wolff, fisheries ecologist at the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen and professor of marine synecology at the University of Bremen. After completion of his PhD at Kiel University in 1985 he established the fisheries biology programme at Universidad Católica del Norte (Chile), and subsequently was instrumental in the establishment of the ZMT in Bremen. Here he developed the first international and interdisciplinary master's study programme of the University of Bremen (International Studies in Aquatic Tropical Ecology, ISATEC), with its orientation to the management of tropical coastal systems. From 2007 to 2010 he worked as scientific director of the marine department of the Charles Darwin Station on the Galapagos Islands. His primary research themes are in the areas of population dynamics and fisheries of aquatic resources and in the trophic modelling of coastal ecosystems.

Prof. Dr. Hans-Peter Ziemek, biologist at the Institute for Biology Didactics of the Justus Liebig University in Gießen. His research interest is the history of the region on the west coast of Schleswig-Holstein and behavioural patterns of the people there. In cooperation with the Foundation for Nature Conservation (Königswinter) he investigates in particular the origins of sustainability conservation concepts and works on their further development with consideration of climate change.

Partners

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 200 scientists from seven faculties of the Christian-Albrechts-University of Kiel (CAU), the GEOMAR Helmholtz Centre for Ocean Research in Kiel, the Institute for World Economy (IfW) and the Muthesius University of Fine Arts.

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

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

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

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Managing Director of maribus gGmbH

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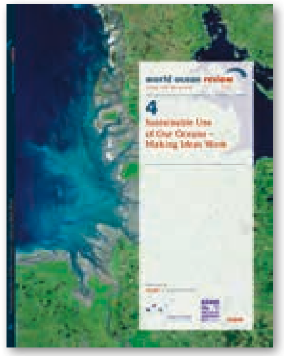

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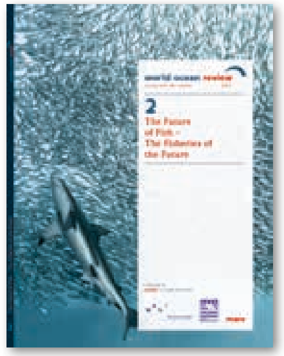

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