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.

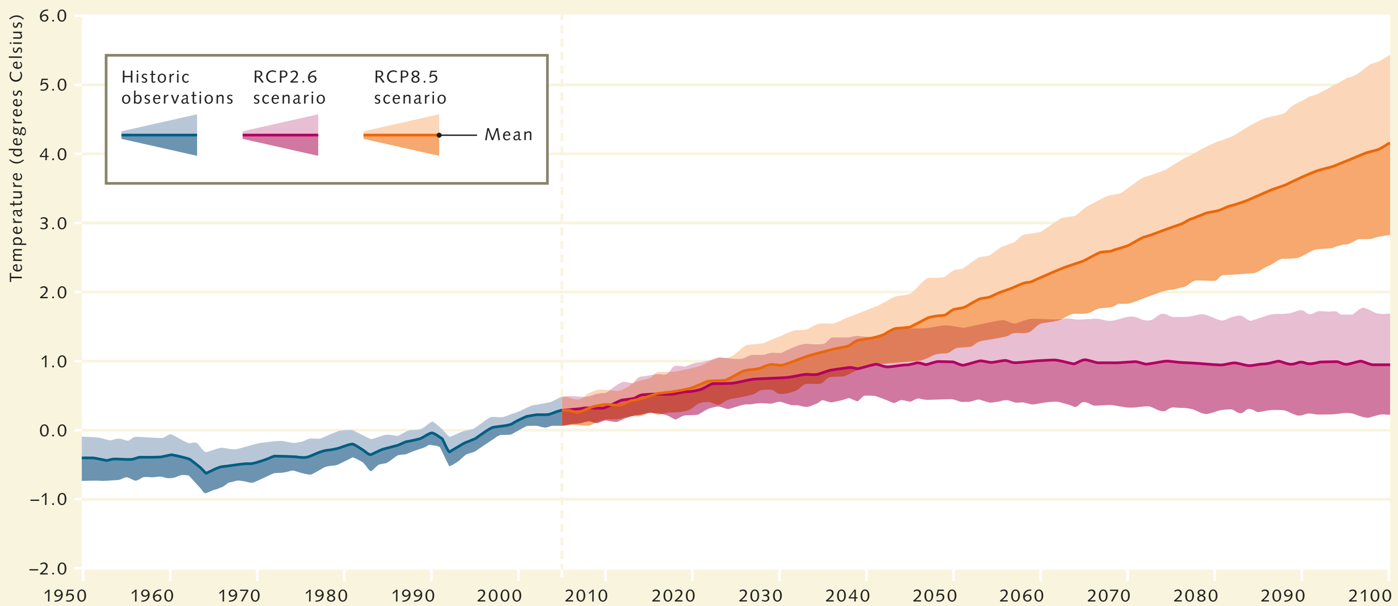
At the thermocline, a warm and less dense water layer rests over a colder water body of higher density. The thermocline thus functions like a barrier. The greater the temperature differential, the greater the difference in density and the more stable the thermocline. Ultimately hardly any oxygen-rich 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.



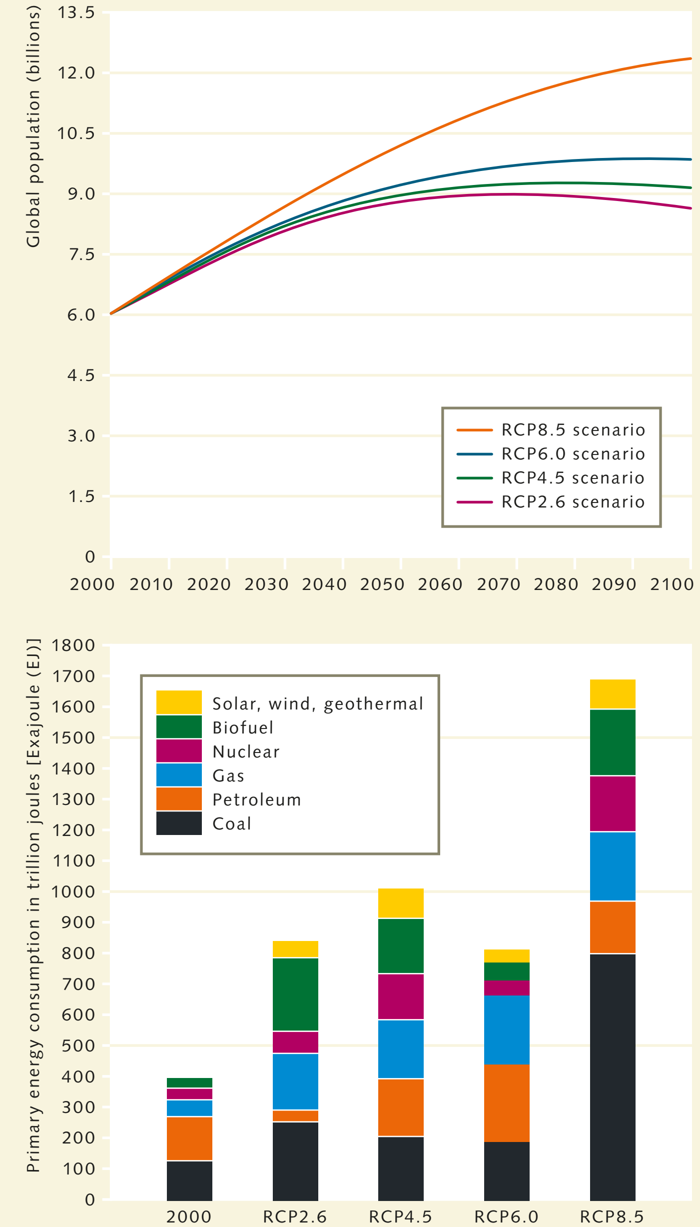
3.2 > The Earth's mean global temperature will definitely continue to rise – by more than 4 degrees Celsius relative to the 1986 to 2005 period under the RCP8.5 scenario. Only under the RCP2.6 scenario will it be possible to limit warming to below 2 degrees Celsius relative to pre-industrial levels.

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:

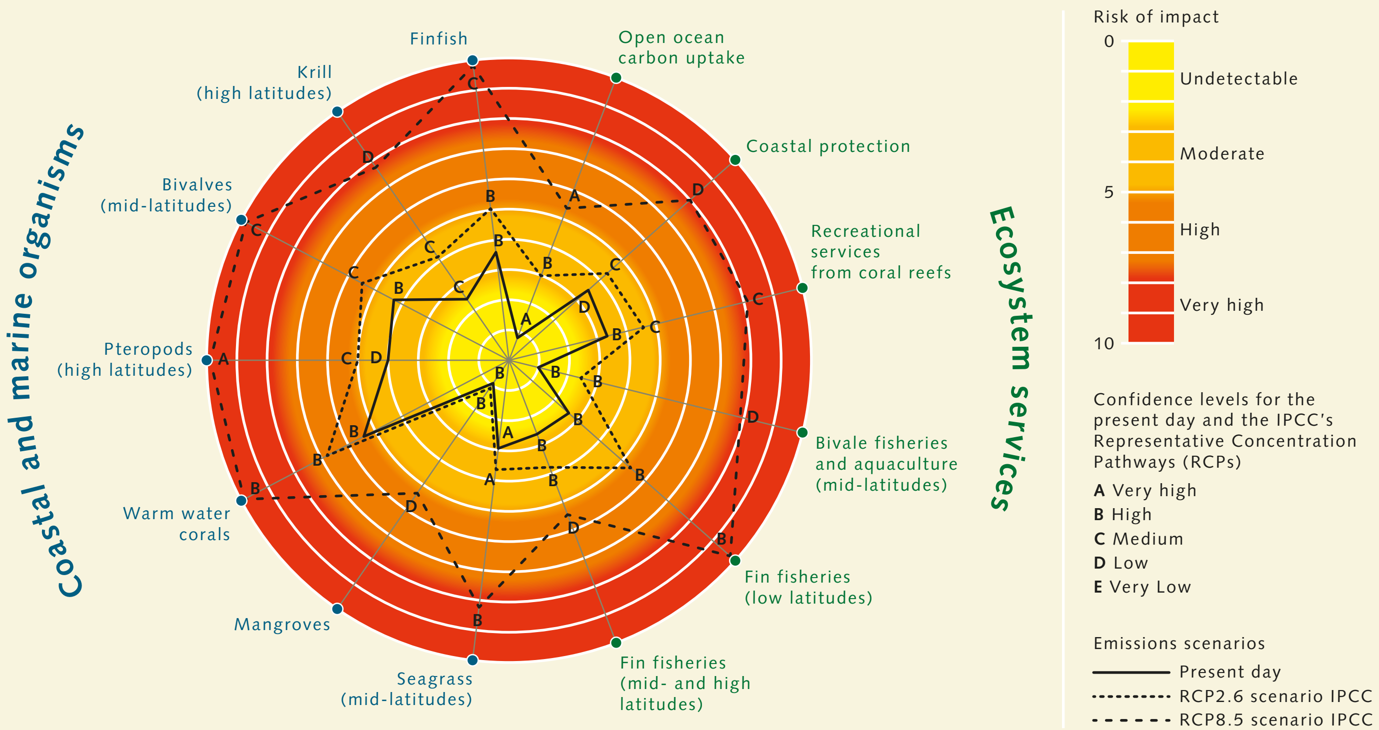
- very high likelihood,
- high likelihood,
- medium likelihood,
- low likelihood,
- very low likelihood.



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

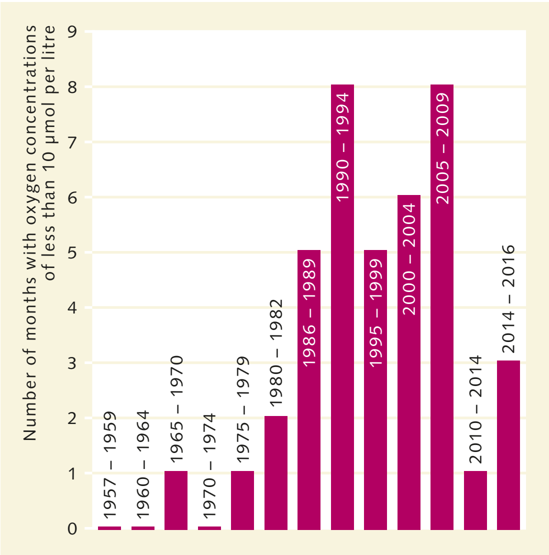
For the German Baltic Sea, scientists have detected the current specific impacts of ocean warming by analysing a unique time series, the data points of which go all the way back to 1957. The scientists regularly measure the water's temperature, nutrient and oxygen contents as well as other parameters 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 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.

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.

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.

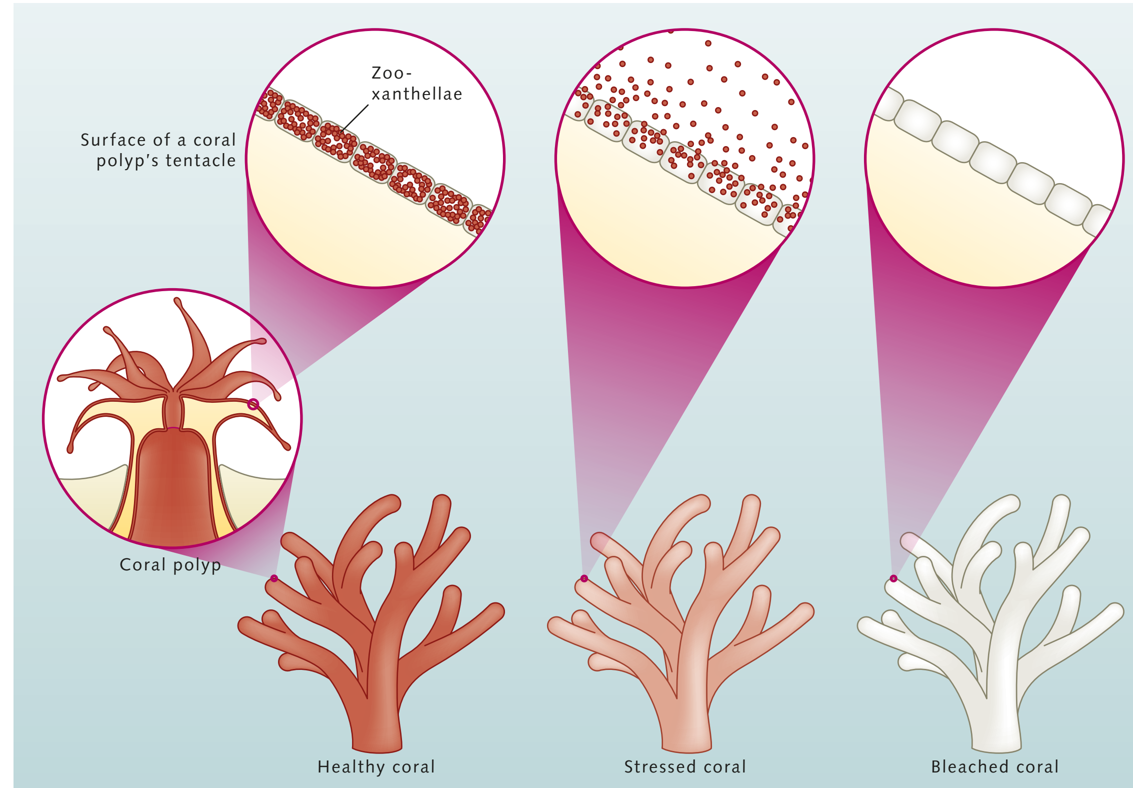
3.9 > Corals bleach when they come under stress – such as this stony coral in the Indonesian Raja Ampat Archipelago. The corals then expel the zooxanthellae, pigmented single-celled organisms with which they live in symbiosis.

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, insuffi-



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.

cient 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.

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

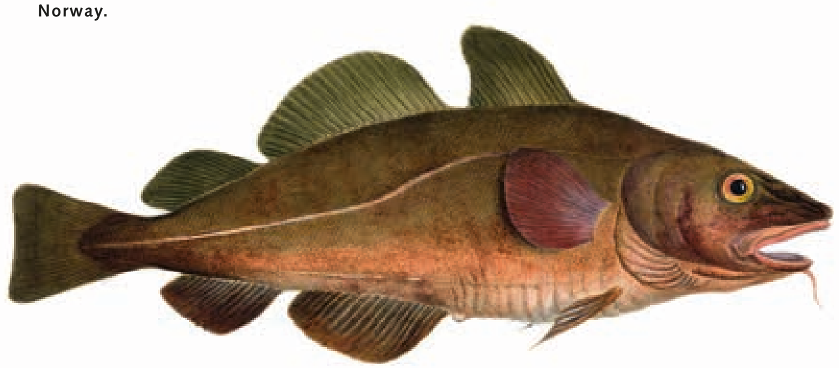
Marine organisms are adapted to limited temperature ranges. Changes in temperature can cause massive species shifts within the marine food web. The encroachment of marine organisms from warmer southern regions to cooler regions in the north has already been observed over a number of years. For many species, 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.

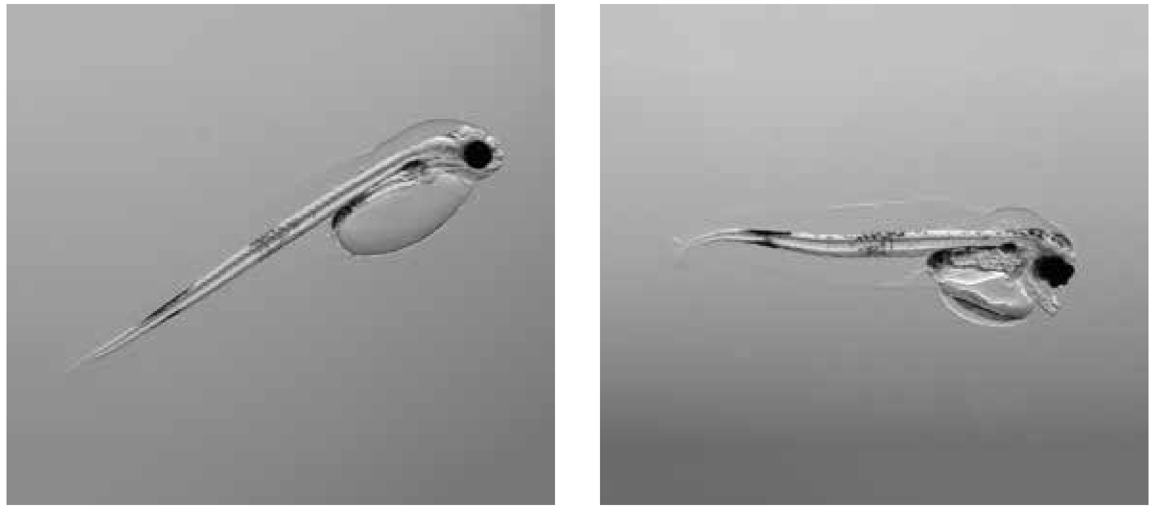
In addition, climate models are being applied to determine possible changes in the geographical distribution of the cod that could occur due to future warming and acidification of the ocean. Investigations are focussing on whether critical temperatures will be reached in the known spawning areas. The 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

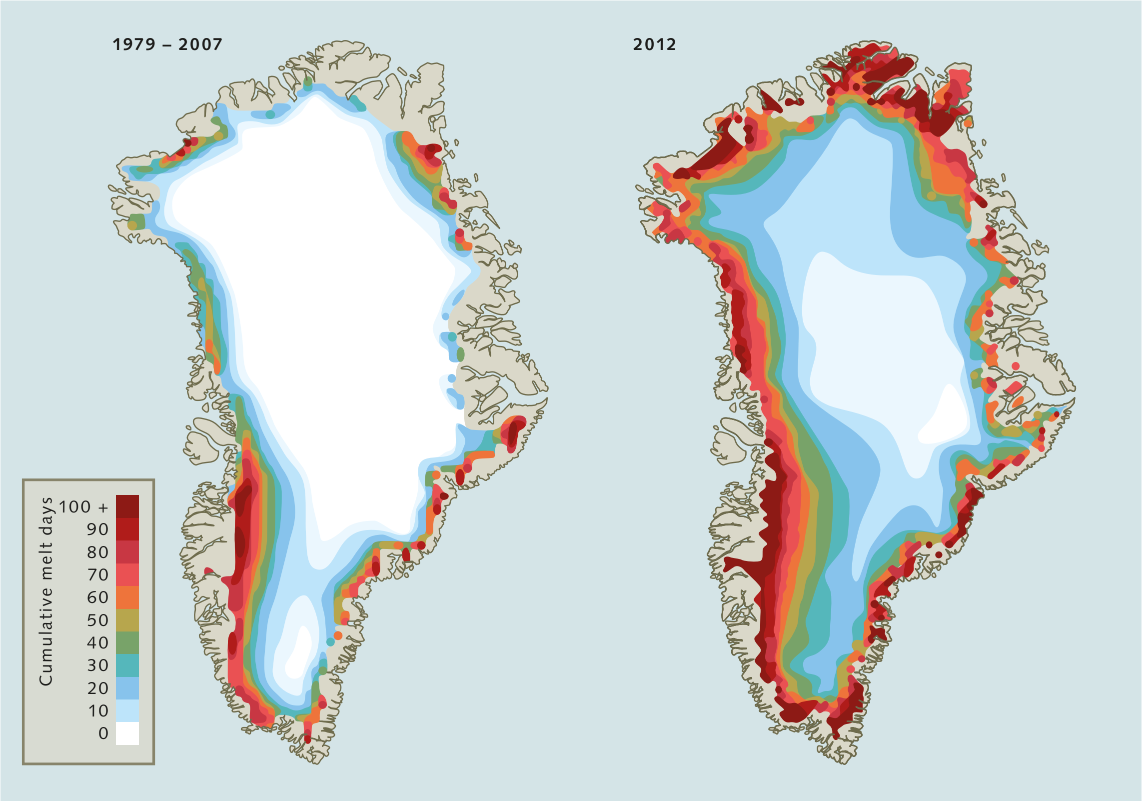
While calcareous organisms are at a disadvantage, the cyanobacteria, previously called blue-green algae, may possibly be among the winners. Very much like plants, cyanobacteria require CO_2 to produce sugar with the help of photosynthesis. They can thus carry out metabolic processes that concentrate 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.

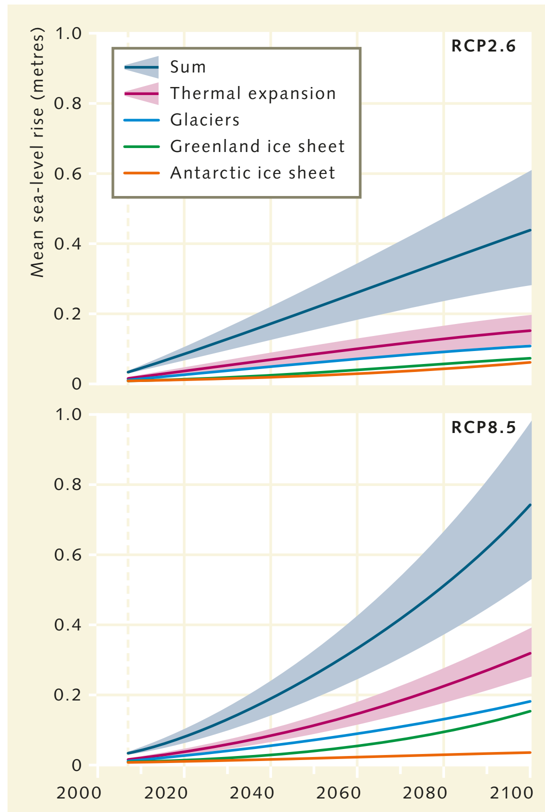
- isostatic, primarily tectonically controlled causes that have an essentially regional impact. These include the subsidence or uplift of land masses that occurs with the alternation of cold and warm periods. The immense weight of ice sheets formed during the ice ages causes the Earth's crust to sink 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 over-



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.

flowing 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.

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.

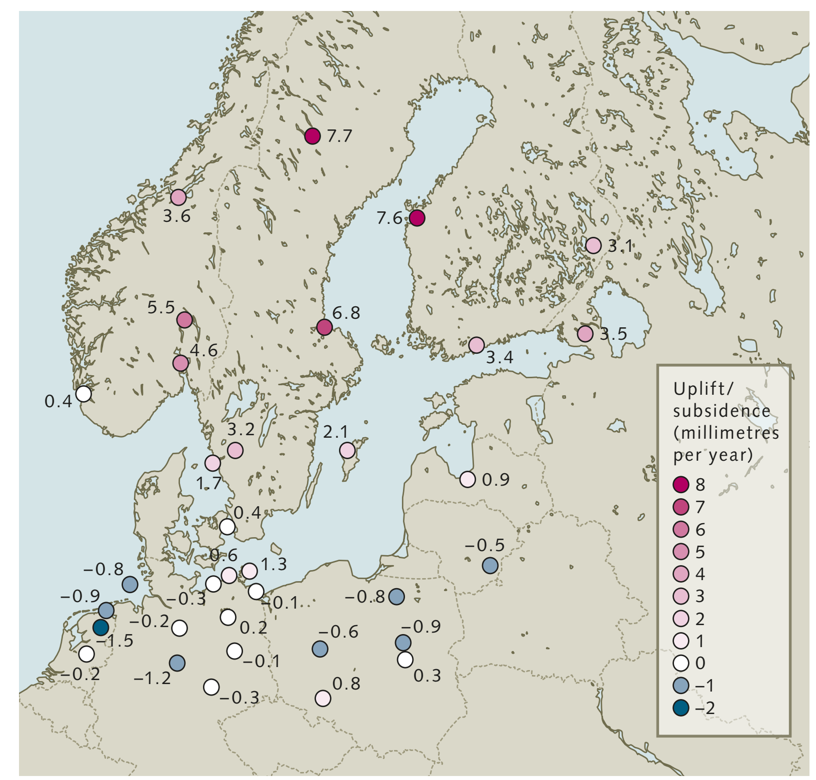
Homemade sea-level rise

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.

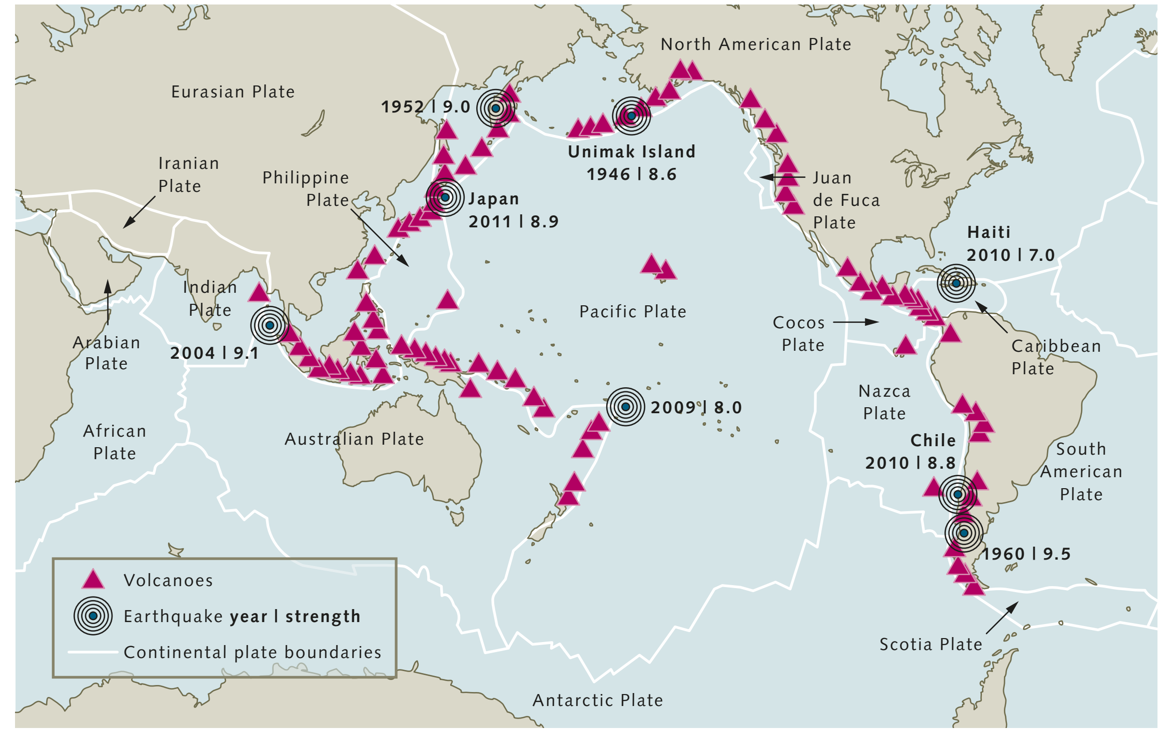
3.19 > It was one of the most devastating natural disasters in the history of Europe. When the earth shook on 1 November 1755 in Lisbon, tens of thousands of people died beneath the rubble of buildings, in the fire storm, and in the floods of a tsunami.

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.

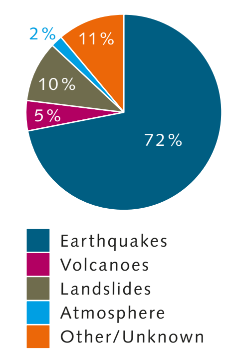
Japan also lies on the Ring of Fire. Because multiple plate boundaries meet here, the country has frequently been shaken by strong earthquakes. Likewise, numerous giant waves have occurred in this area throughout the past, and the phenomenon received its name there long ago. The term "tsunami" is of 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.

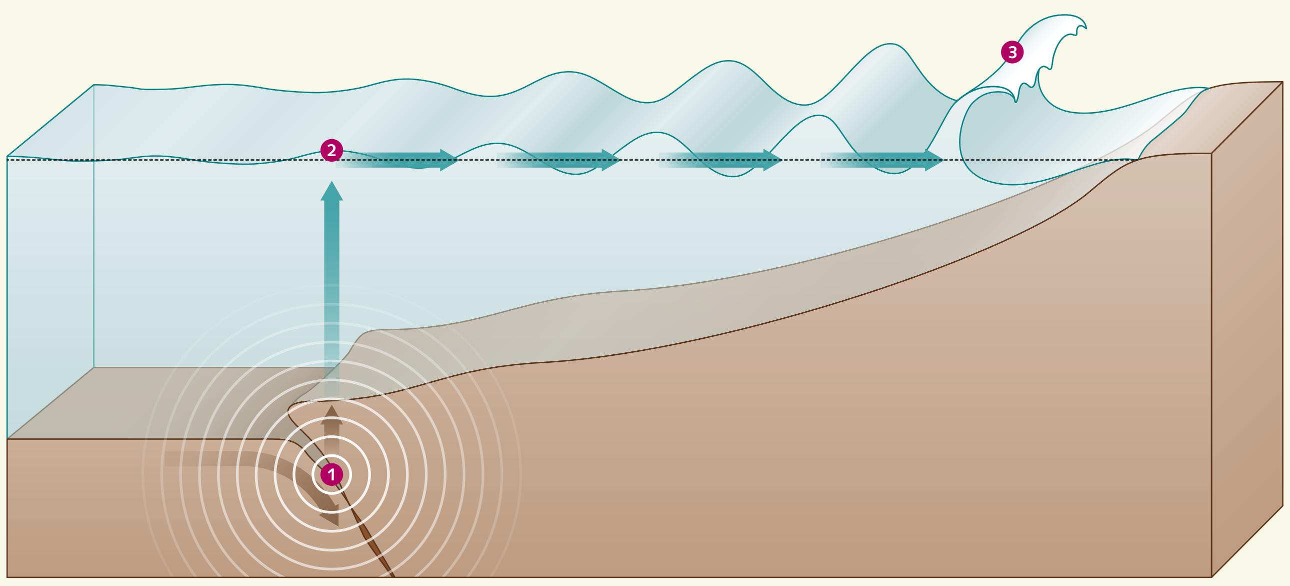
But when the wave encounters a continental slope or the shore, its progress is slowed, causing it to rise up vertically. How the tsunami develops from this point on depends upon the shape of the coast, and is much more difficult to describe mathematically. It is therefore almost impossible to accurately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

1 Through a vertical motion of the continental plates a pressure impulse is produced in the water column.

2 The impulse propagates as a tsunami through the ocean.

3 When the wave nears the shore, it is slowed down and rises vertically.



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 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.

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.

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).

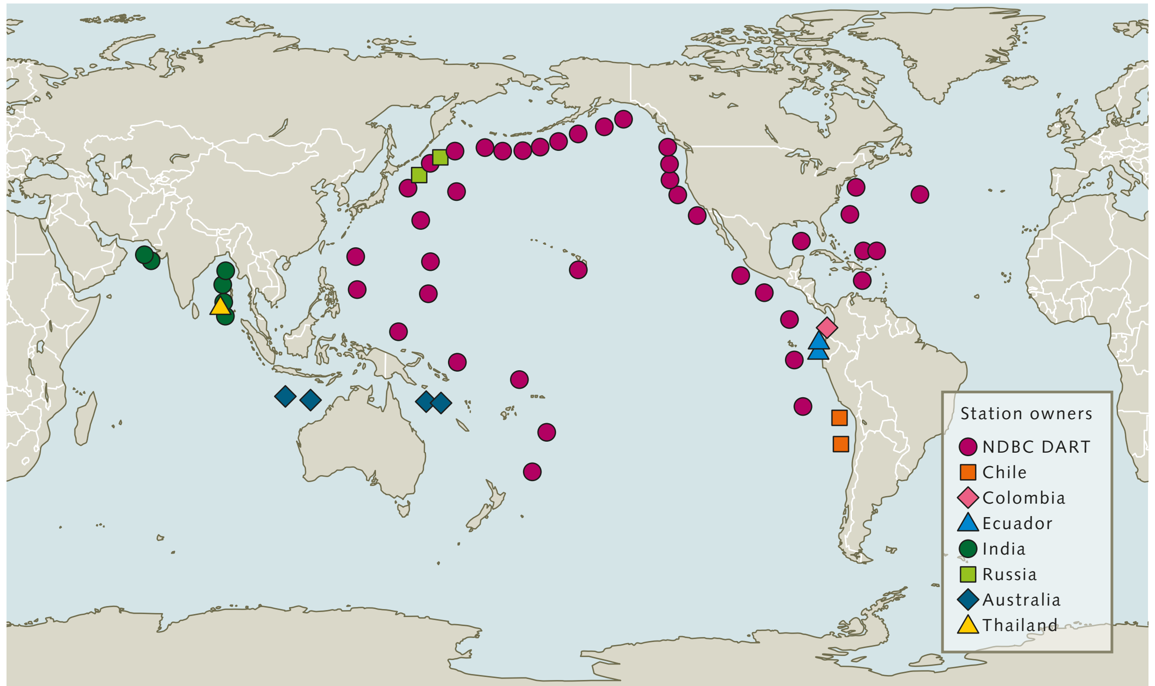
As in Japan, the accuracy of tsunami prediction was limited in the beginning. The warning system essentially consisted of member states informing each other by telephone whenever an earthquake was recorded. Aided by the seismographic information and travel-time maps, calculations could then be made to 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.

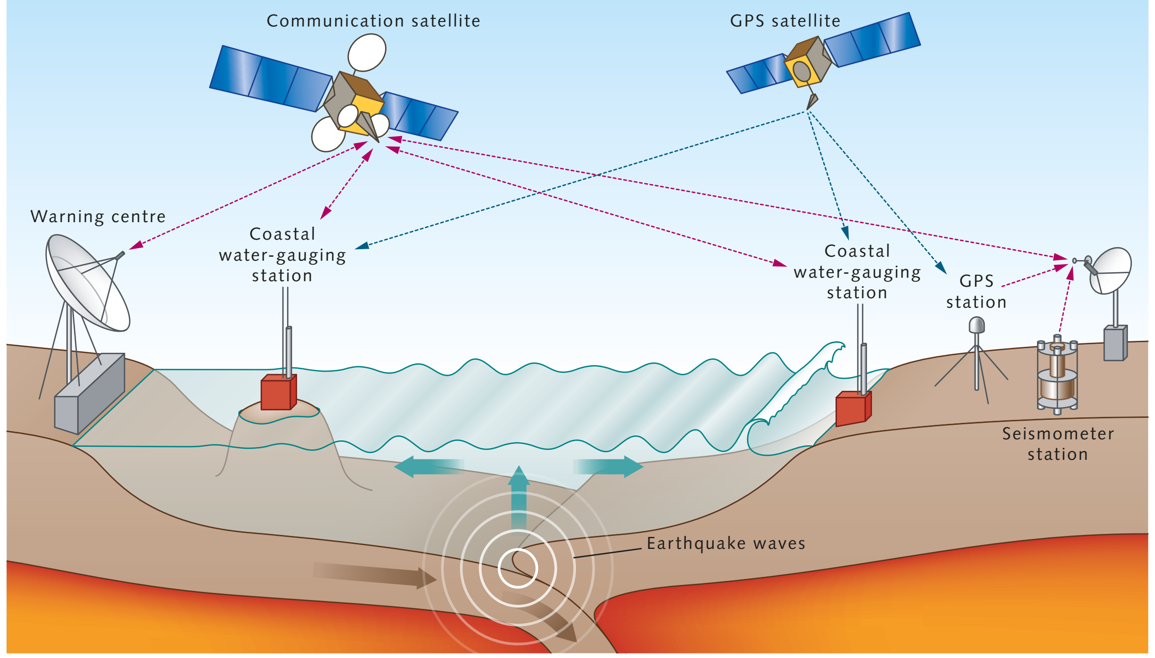
during an earthquake and the GPS sensors can detect this motion. The reliability of prediction is increased significantly by the combination of these three types of sensors, because the information from a single sensor type alone is not sufficient to conclude the formation of a tsunami.

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.

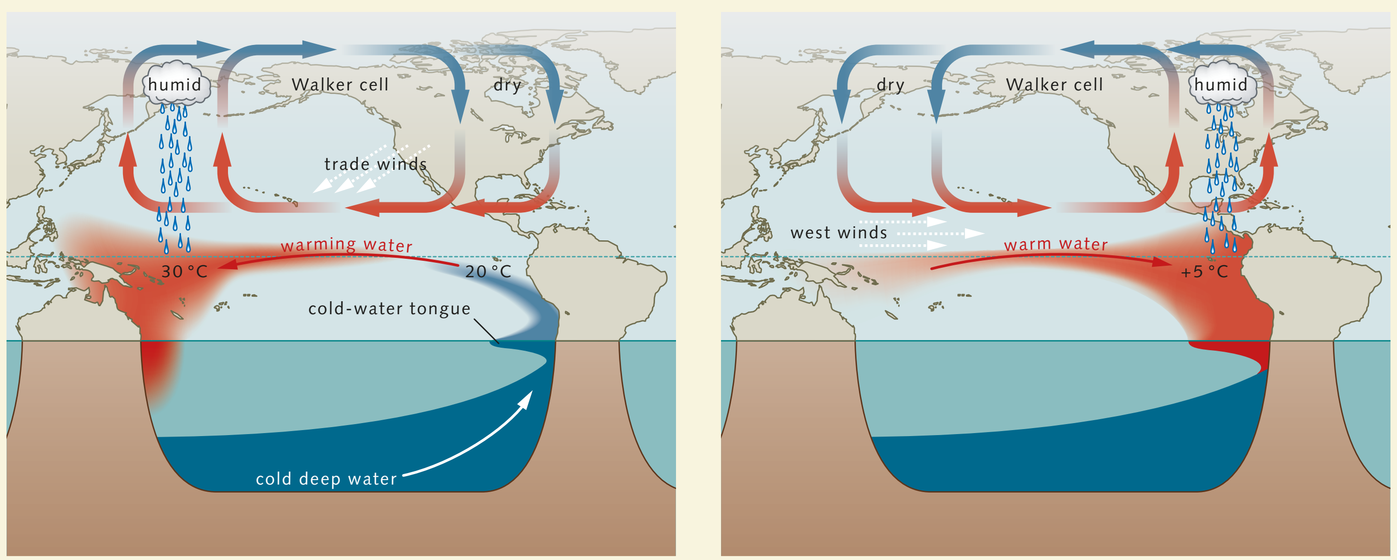
As a rule, there is a stable low-pressure system above the western Pacific near South East Asia and a high-pressure system in the central Pacific. This results in a constant westward flow of the air masses from the area of high pressure to the area of low pressure. Warm humid air rises here, forming 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.

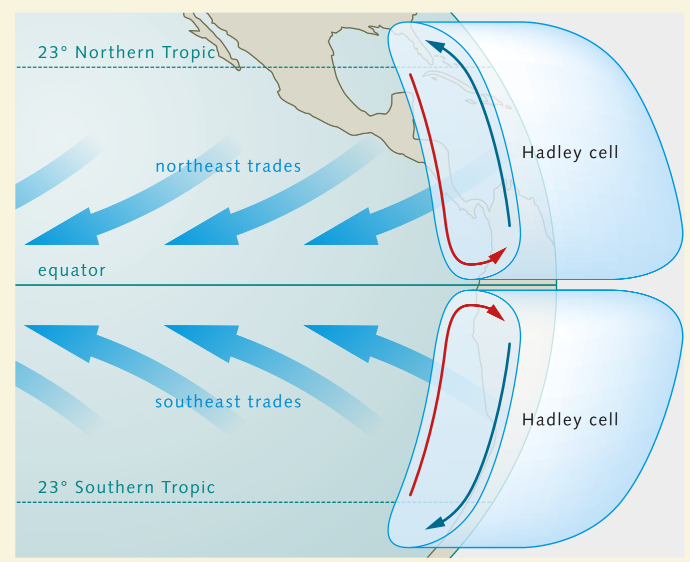
The name "El Niño" is Spanish for "the child" and refers to the infant Jesus. It originates from South American fishermen who have long known that El Niño reaches its peak around Christmas time. Today scientists refer to the phenomenon as ENSO, which stands for El Niño southern oscillation. This highlights 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.

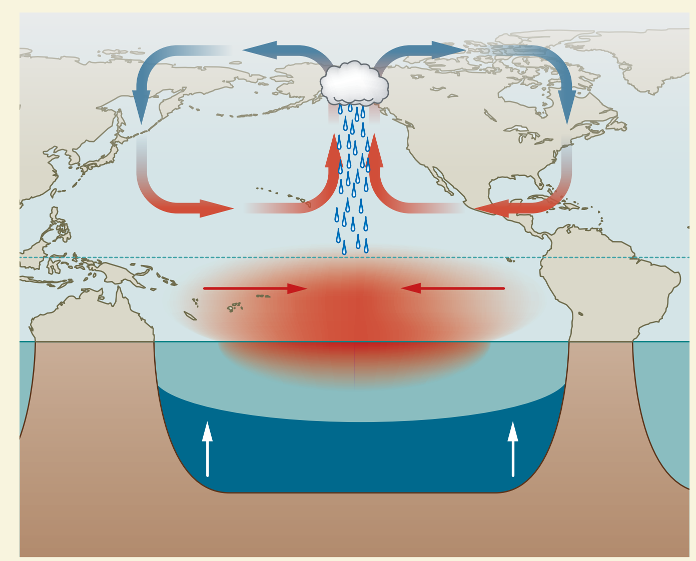
Today it is known that in addition to El Niño and La Niña, there are other variations of this phenomenon. There are El Niño events that do not encompass the entire Pacific. In these cases, the air-pressure relationship between the western and central Pacific changes, but the warm water does not extend 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.