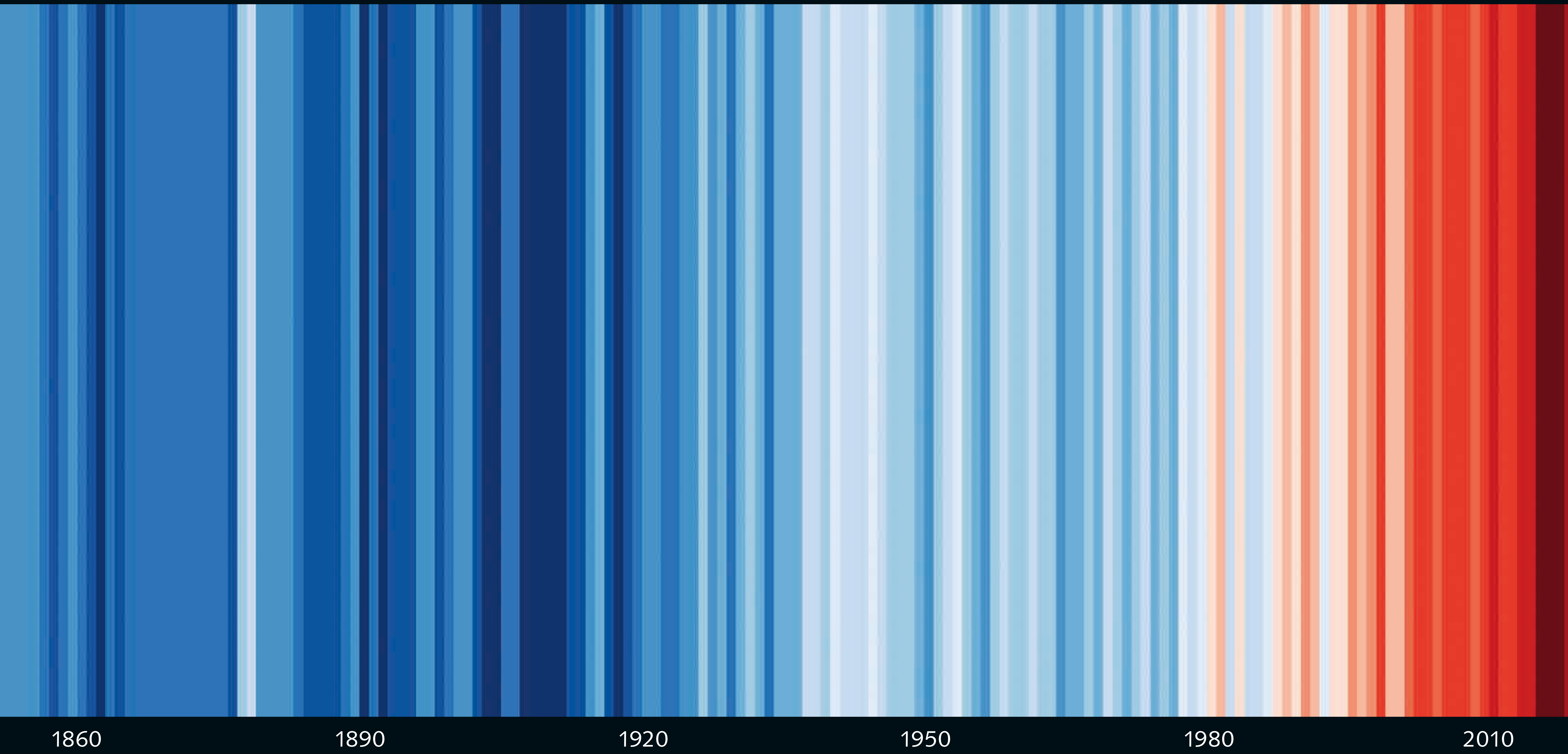
2 Oceans under climate change

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

Global Warming (1850 until 2020)



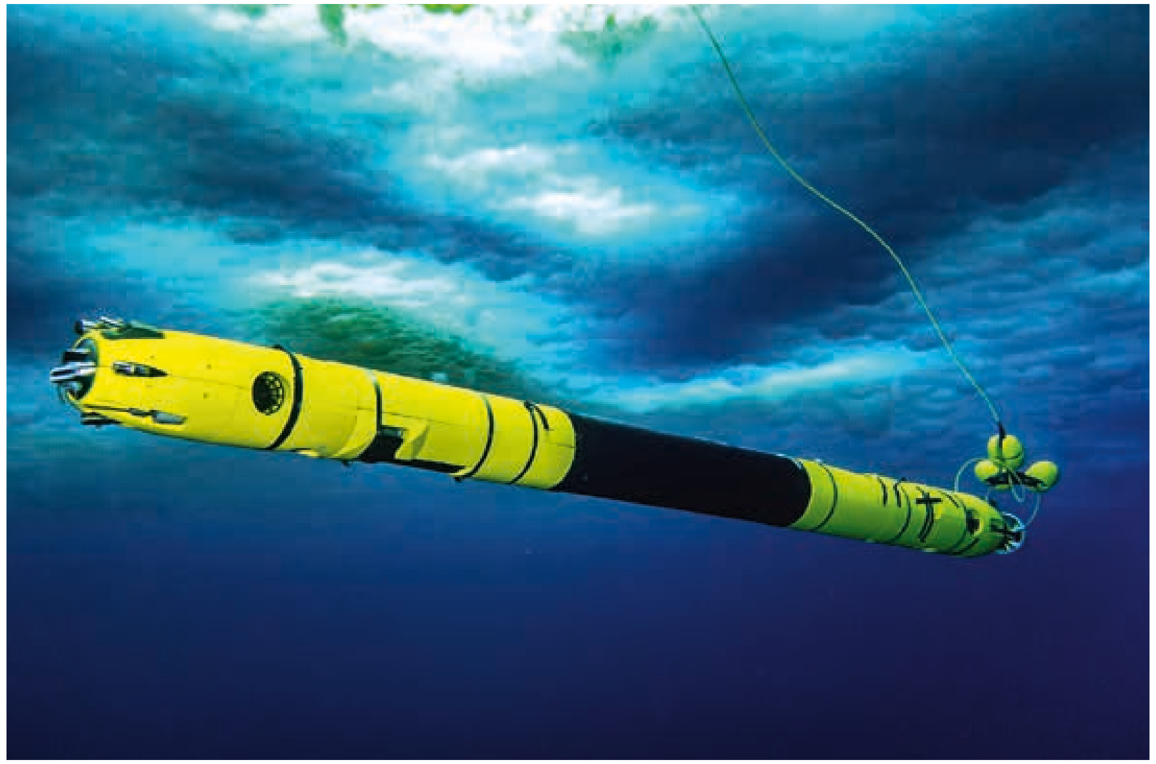
The fatal consequences of heat

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

Old role, new attention to detail

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

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



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

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

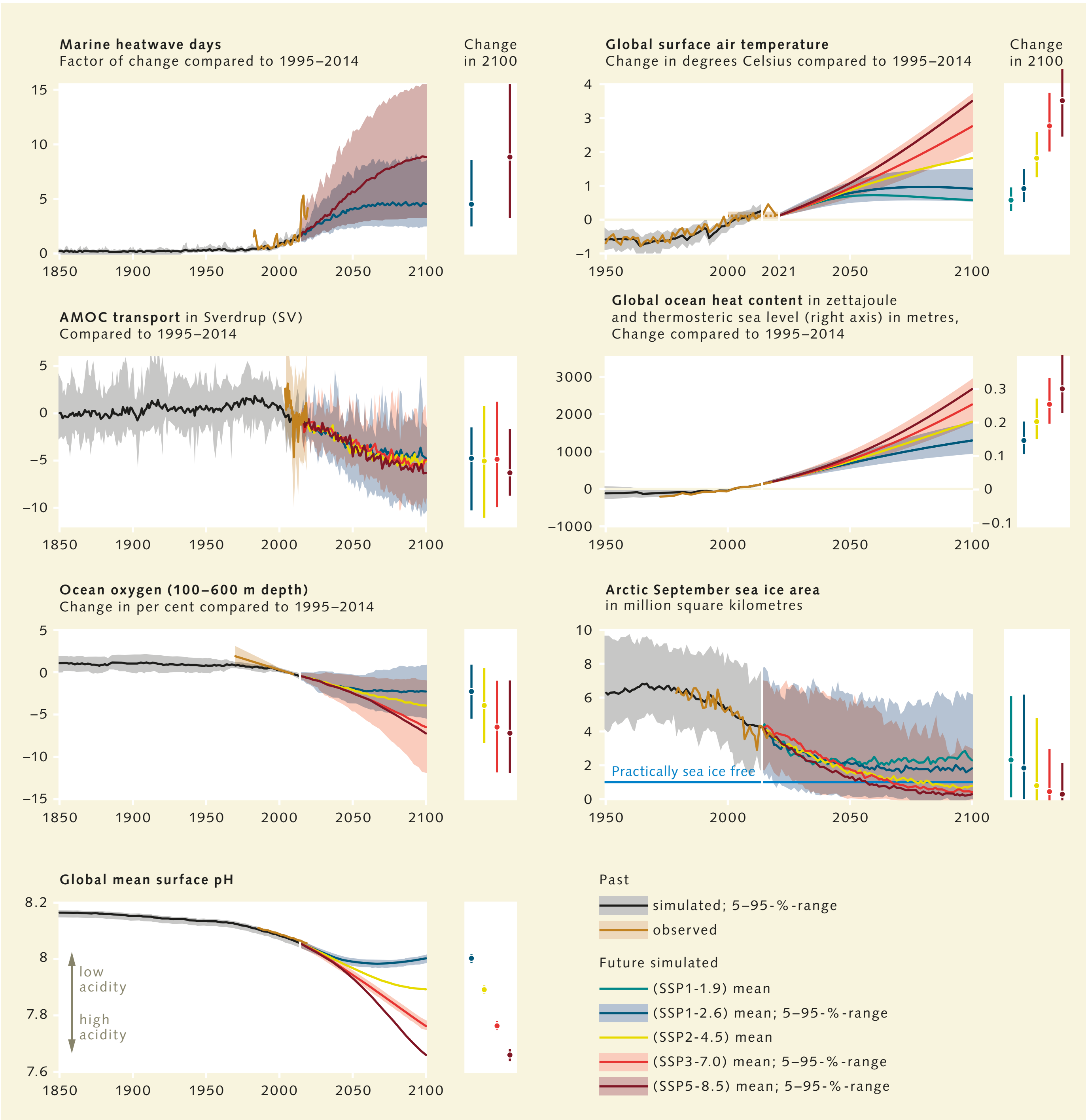
Also contributing to our better understanding of the role of the ocean in the climate system, however, are a plethora of historical, mostly handwritten weather records (ships logs, marine weather reports, etc.) that have now been digitized and fill some of the gaps in long-term observation series. Progress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

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

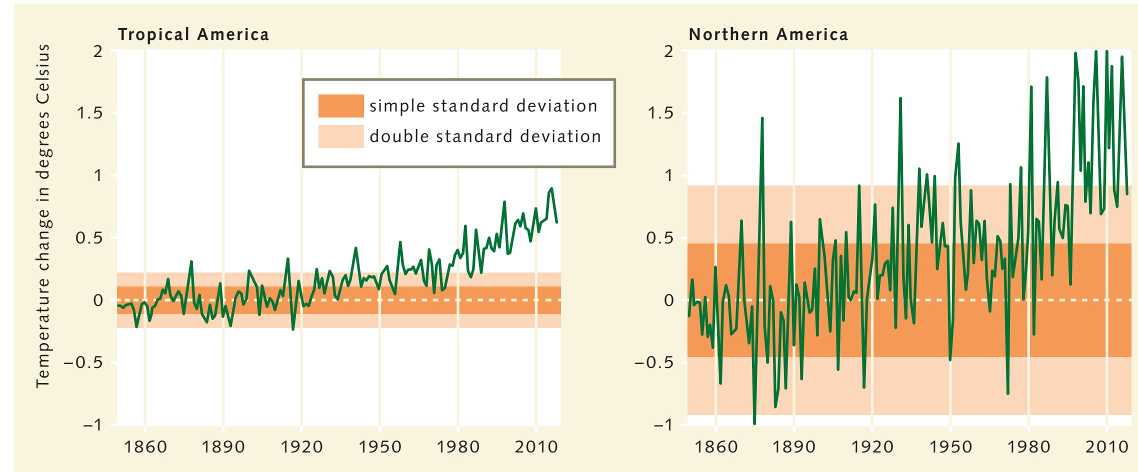
2.2 > The Thwaites Glacier is one of the fastest flowing ice streams in West Antarctica. It transports ice from a region as large as the US state of Florida toward the sea. Its melting ice masses alone are responsible for four per cent of the current sea-level rise.

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

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



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



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

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

Beyond all doubt

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

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

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

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

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

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

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

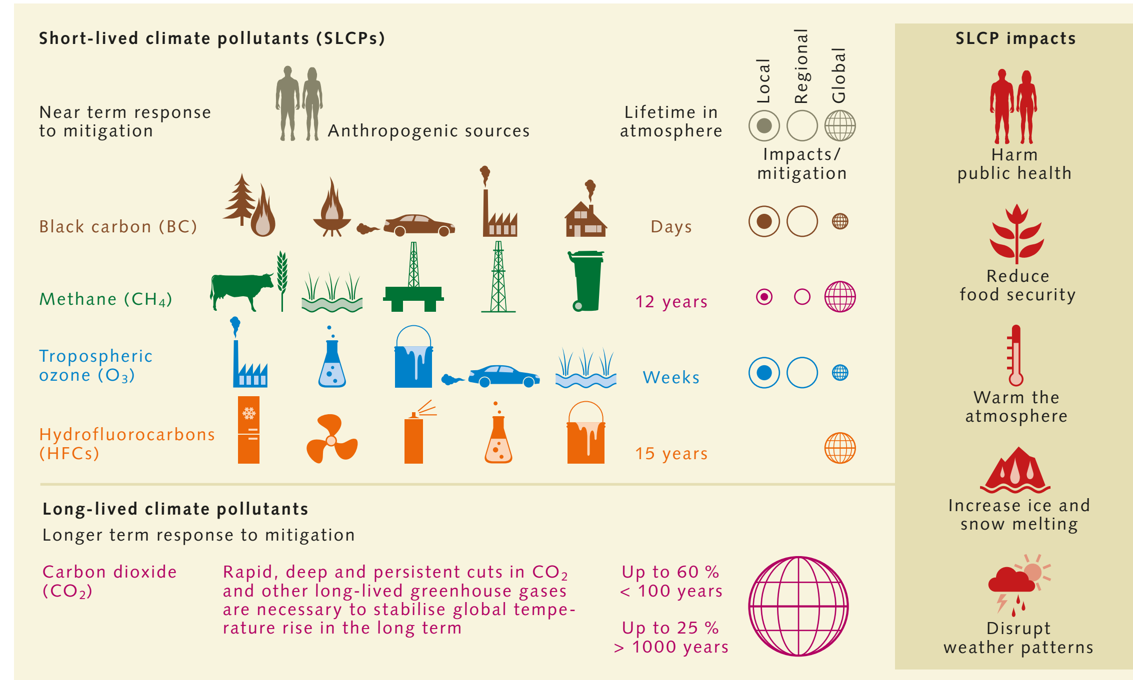
Humans are primarily responsible for these changes. This statement can be made beyond any doubt today. Important natural climate factors such as the brightness of the sun or the cooling effects of large volcanic eruptions fade into relative insignificance in view of the effects of human activity on Earth.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

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

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

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

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



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

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

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

The world ocean as a heat repository

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

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

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

Methane – the unexpected rise of "younger brother"

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

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

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

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

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

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

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

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

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

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

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

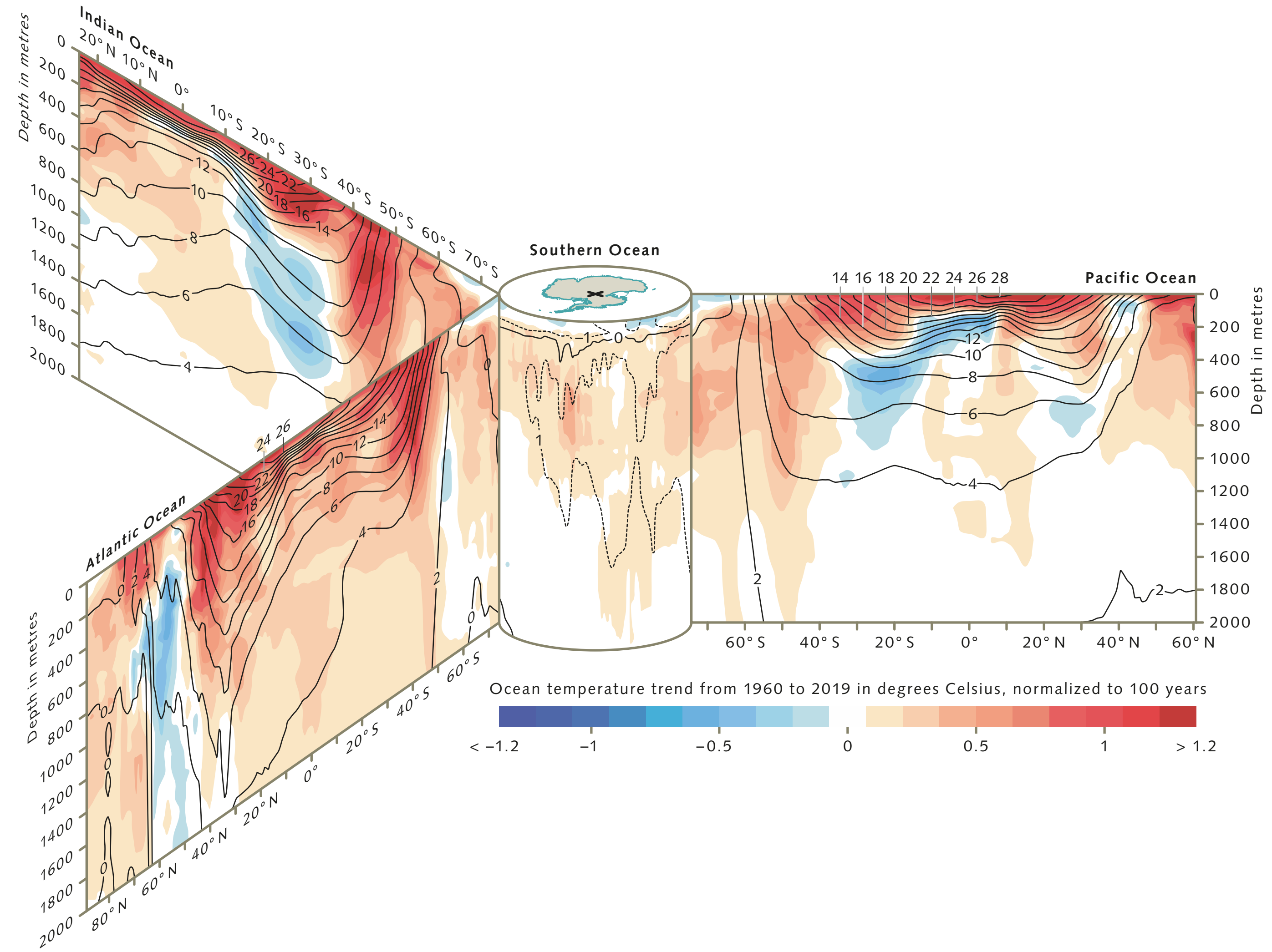
In this case, the ocean releases its heat energy back into the atmosphere and causes air temperatures to rise, especially in the temperate and higher latitudes. The time frame in which this occurs is difficult to predict. Once it is absorbed, the heat in the ocean can significantly influence the Earth's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

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

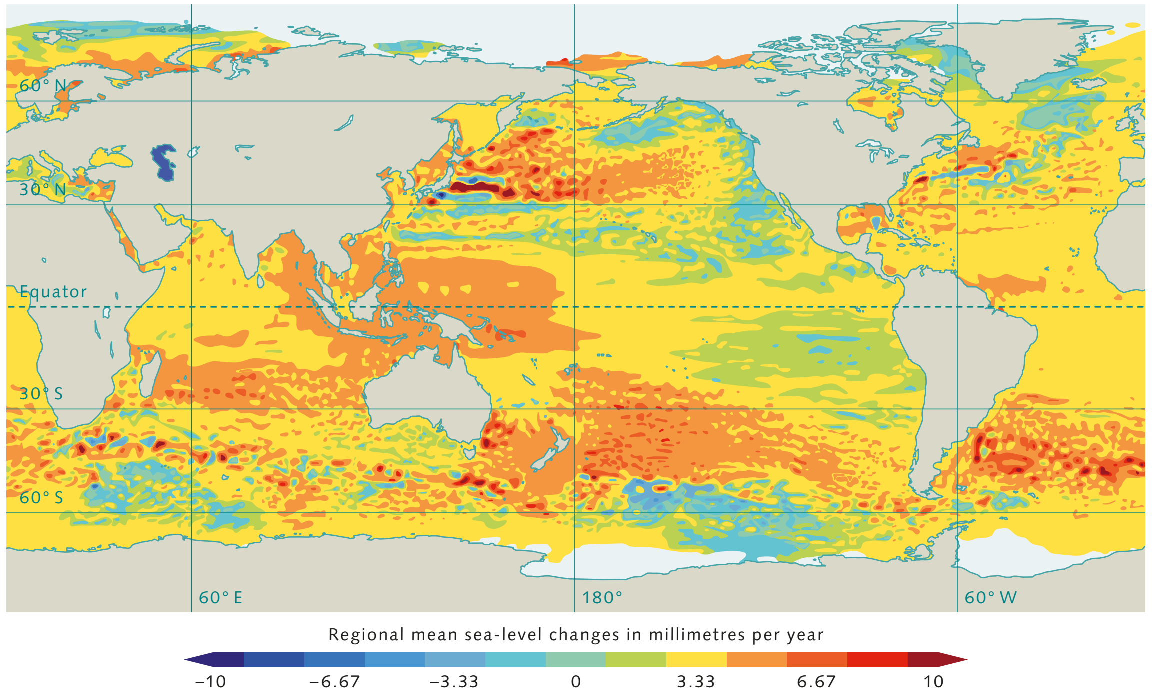
Temperature increases at great depths

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

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



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



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

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

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

Life-threatening consequences

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

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

Rising water level with no end in sight

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

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

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

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

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

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

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

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

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

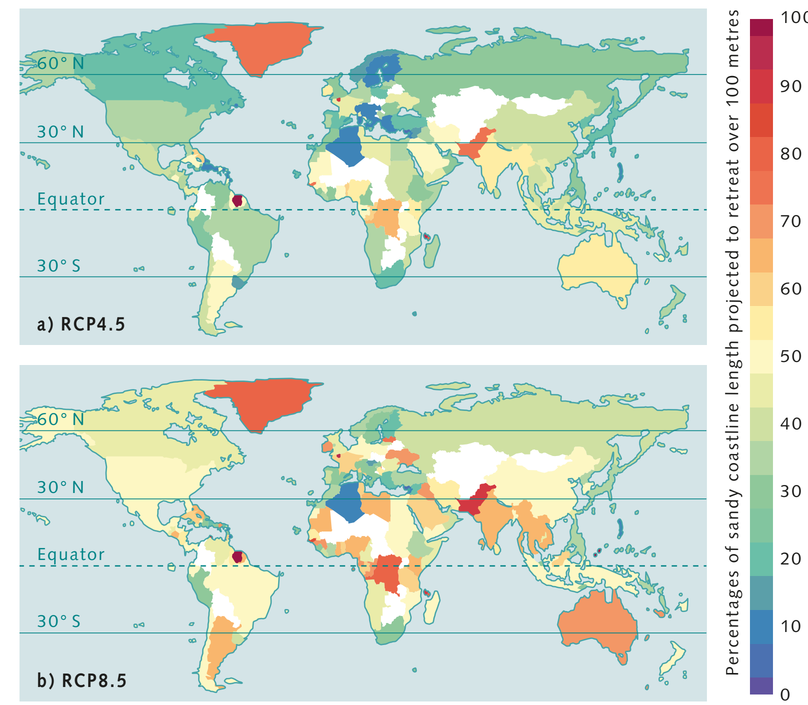
As water levels rise, the danger of flooding becomes greater, especially in coastal regions that are less than ten metres above sea level. Statistically, many of these, in the past, were hit by exceptional flooding events related to storm and spring tides or extremely high waves only once every 100 years.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

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

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

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

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



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

Oceans running out of oxygen

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

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

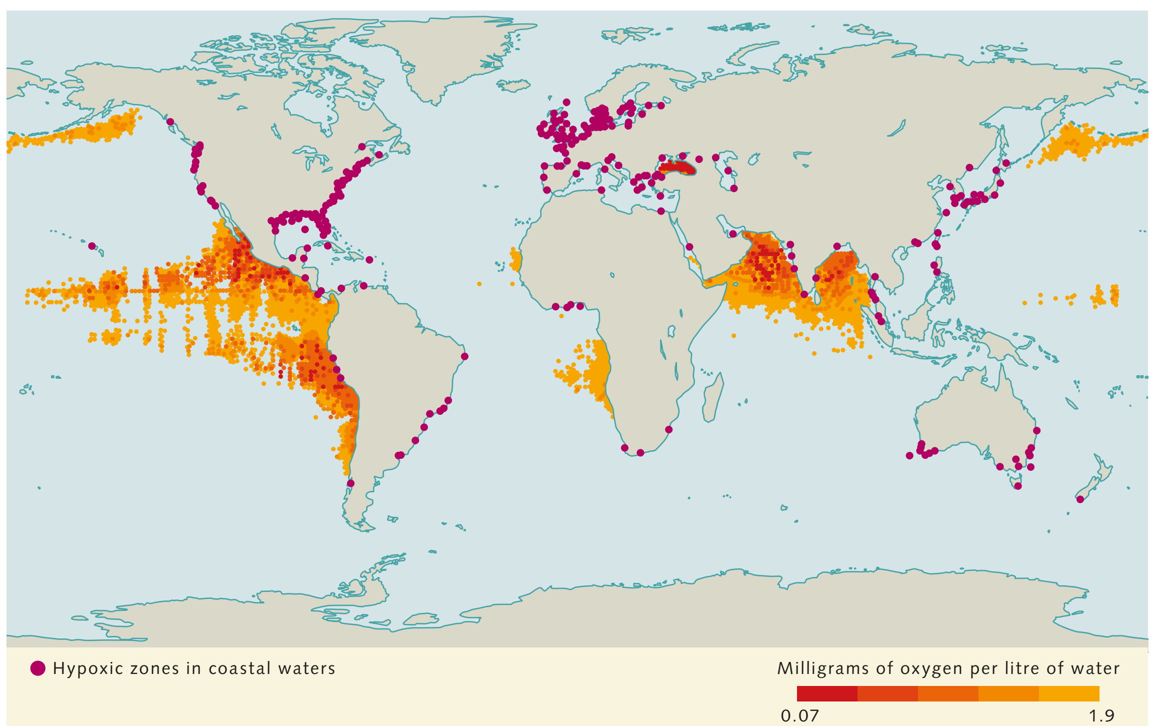
Oxygen in the ocean is not only used by fish and other highly developed marine organisms. It is needed mainly by microbes and multi-celled organisms that break down plant and animal remains (organic material) at great depths, whereby oxygen is consumed. The more biomass that is produced in the zone penetrated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

From this knowledge, scientists can draw two main conclusions.

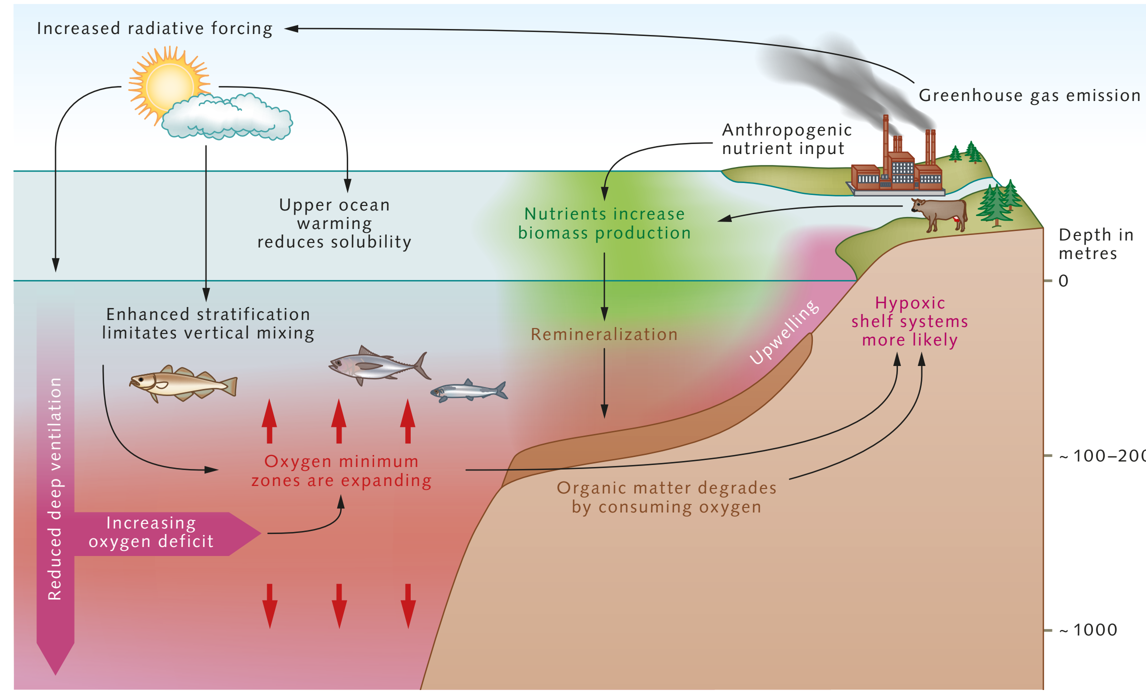
Firstly: Changes in the basic chemical or physical conditions within a water layer – for example, the amount of nutrient input, the temperature, or the amount of incident light – influence biomass production and thus, in the long term, the amount of oxygen-consuming decomposition of the biomass that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

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

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



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



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

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

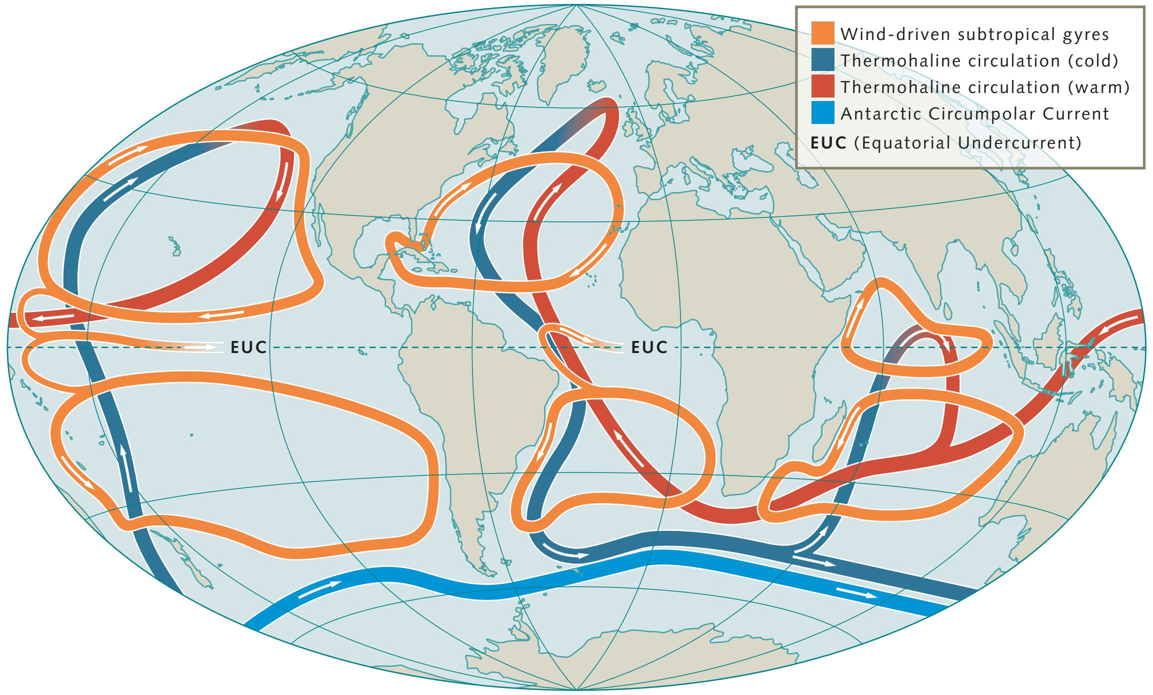
Scientists have studied how great the respective influences of temperature and salinity changes have been on the oxygen content of the oceans through recent decades. They have concluded that the decrease of oxygen in the upper 1000 metres of the water column is primarily due to the increasing levels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

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

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

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

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



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

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

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

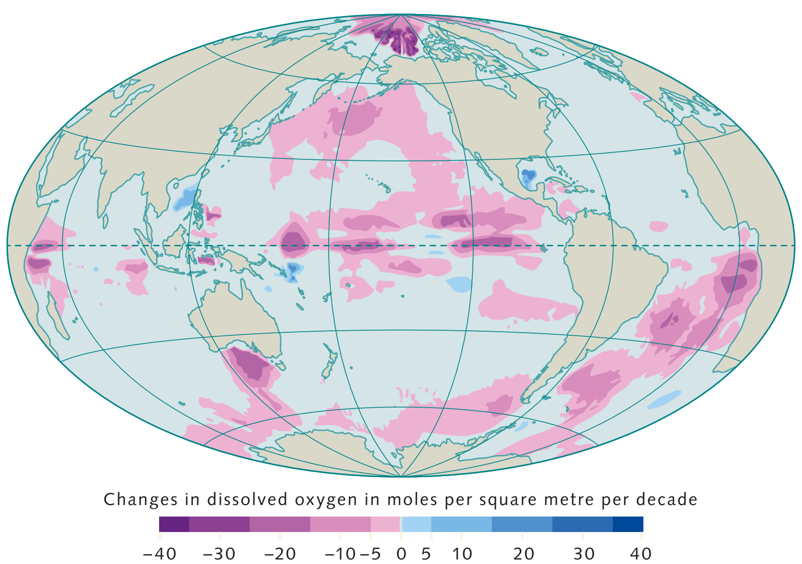
However, its operation is impeded by climate change, because when the water masses at the sea surface become warmer and lighter, the overturning by thermohaline circulation proceeds more slowly. This process entails the cooling and sinking of enormous masses of water, both in the middle latitudes where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

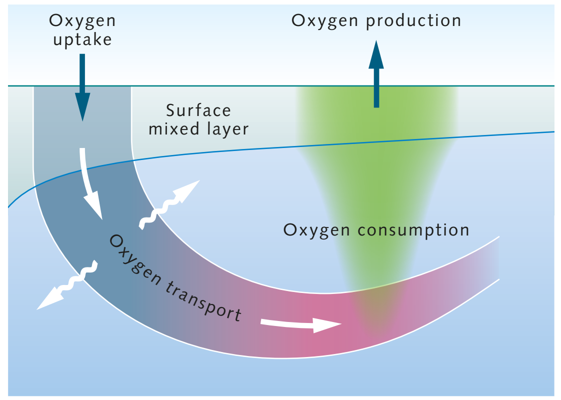
There is now evidence from many parts of the world that the conveyor belt of thermohaline circulation is slowing down as a result of climate change. It indicates not only that less oxygen-rich surface water is reaching greater depths, but that the individual water masses, on their journey through the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

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

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

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





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

Fuel for hurricanes and heavy rains

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

The amount of water that evaporates above the ocean to take up this journey depends greatly on the air and water temperatures. The more the atmosphere warms, the more water vapour it can hold (seven per cent more moisture per one degree Celsius of warming). And the warmer the seawater is, the more readily it evaporates at the surface. As a result, significant patterns of water distribution within the hydrological cycle are changing in the wake of climate change. Higher evaporation rates, for example, amplify the intensity of heavy rainfall events that mostly build up over the ocean. This means that during this kind of extreme weather event much more rain will fall today than it would have in the past.

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

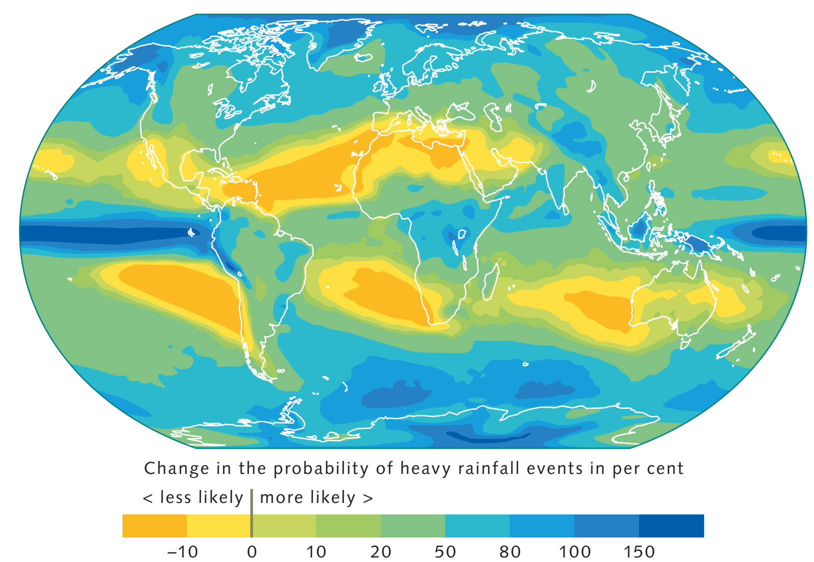
After this extreme event, climate researchers collected all of the available meteorological data from the region – current weather data as well as historical records going back at least 80 years. Using climate models, they then calculated the degree to which climate change had increased the probability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

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

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

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

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



Oxygen distress in eutrophic coastal waters

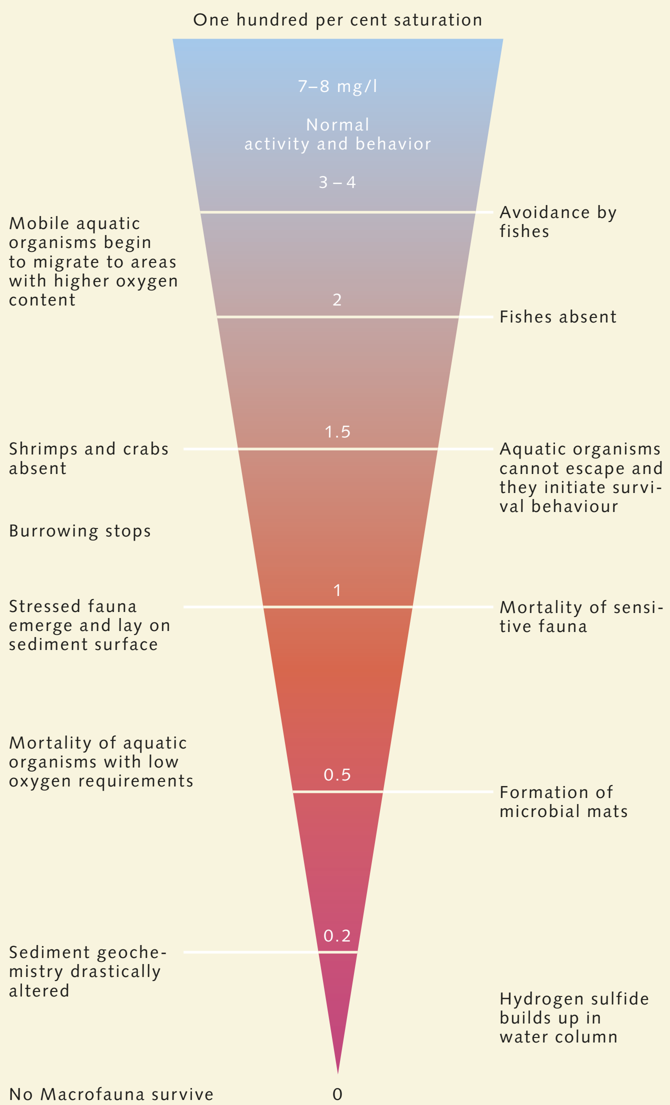
Every year in June, scientists from the US National Oceanic and Atmospheric Administration (NOAA) publish a prediction of the size of the dead zone that will form in the northern part of the Gulf of Mexico during the summer. Dead zones refer informally to near-coastal marine areas where the water is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

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

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

A problem caused on land

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



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

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

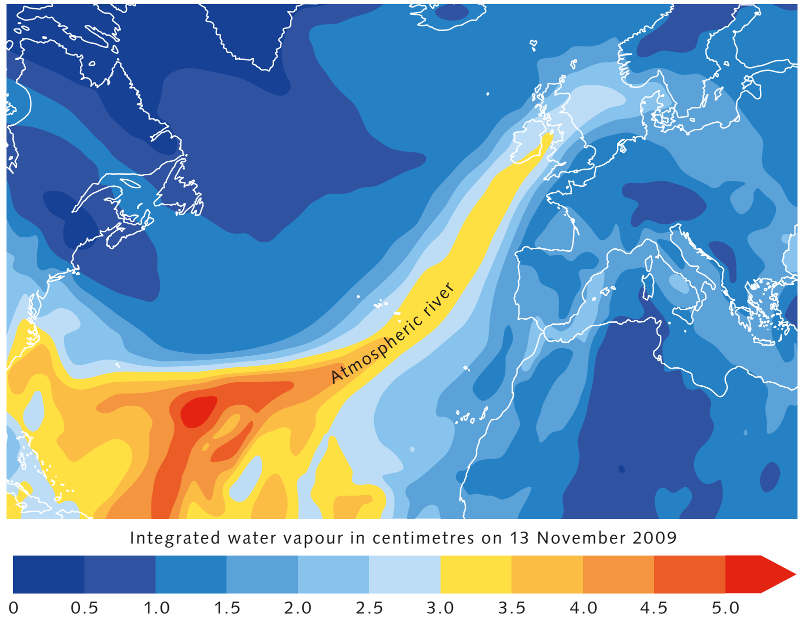
Proportionally small with a large effect

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

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

Oxygen content

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



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

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

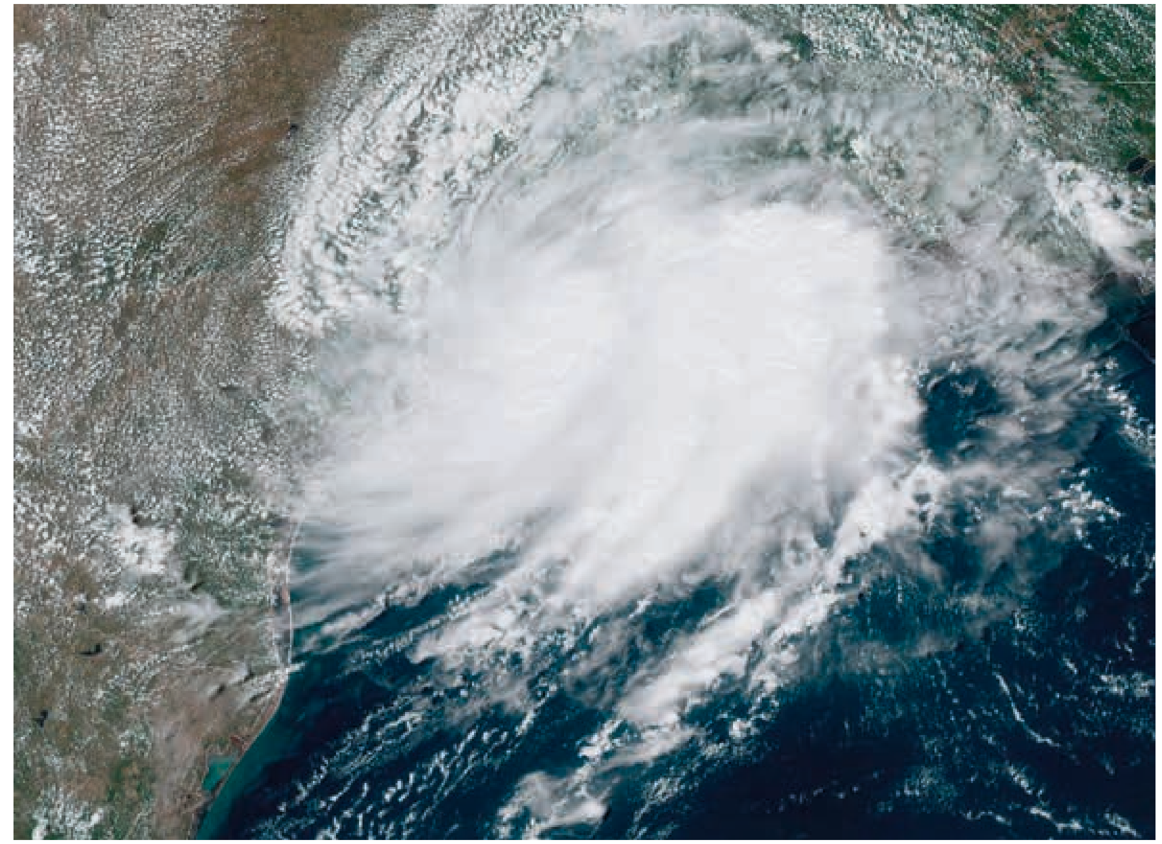
More intensive rainfall is one consequence of ocean warming, but there is also a second consequence. Researchers are now able to confirm that rising water temperatures at the ocean surface are increasing the destructive power of large tropical storms. The physical principle is quite simple: Hurricanes,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

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

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

Marine heatwaves

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

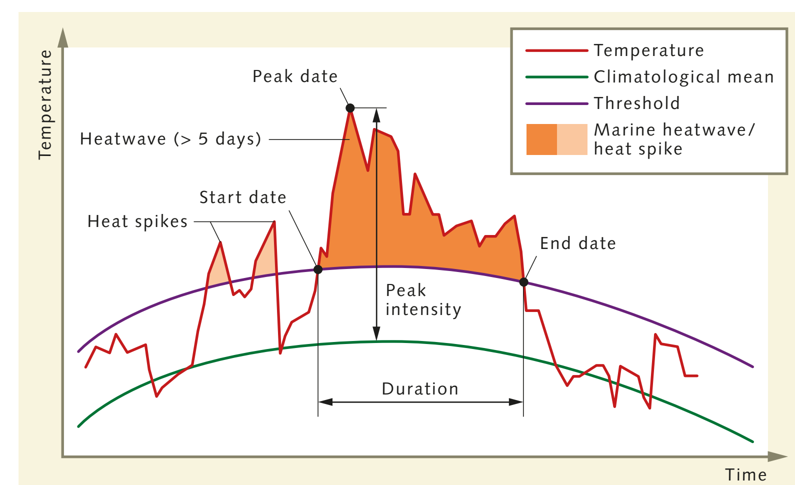


2.20 > The tropical cyclone Imelda made landfall on the Gulf Coast of the US state of Texas on 17 September 2019. Soon afterward, it rained so heavily in parts of Texas that Imelda was ranked at number seven on the list of tropical cyclones with the most abundant precipitation in the USA.

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

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

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



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

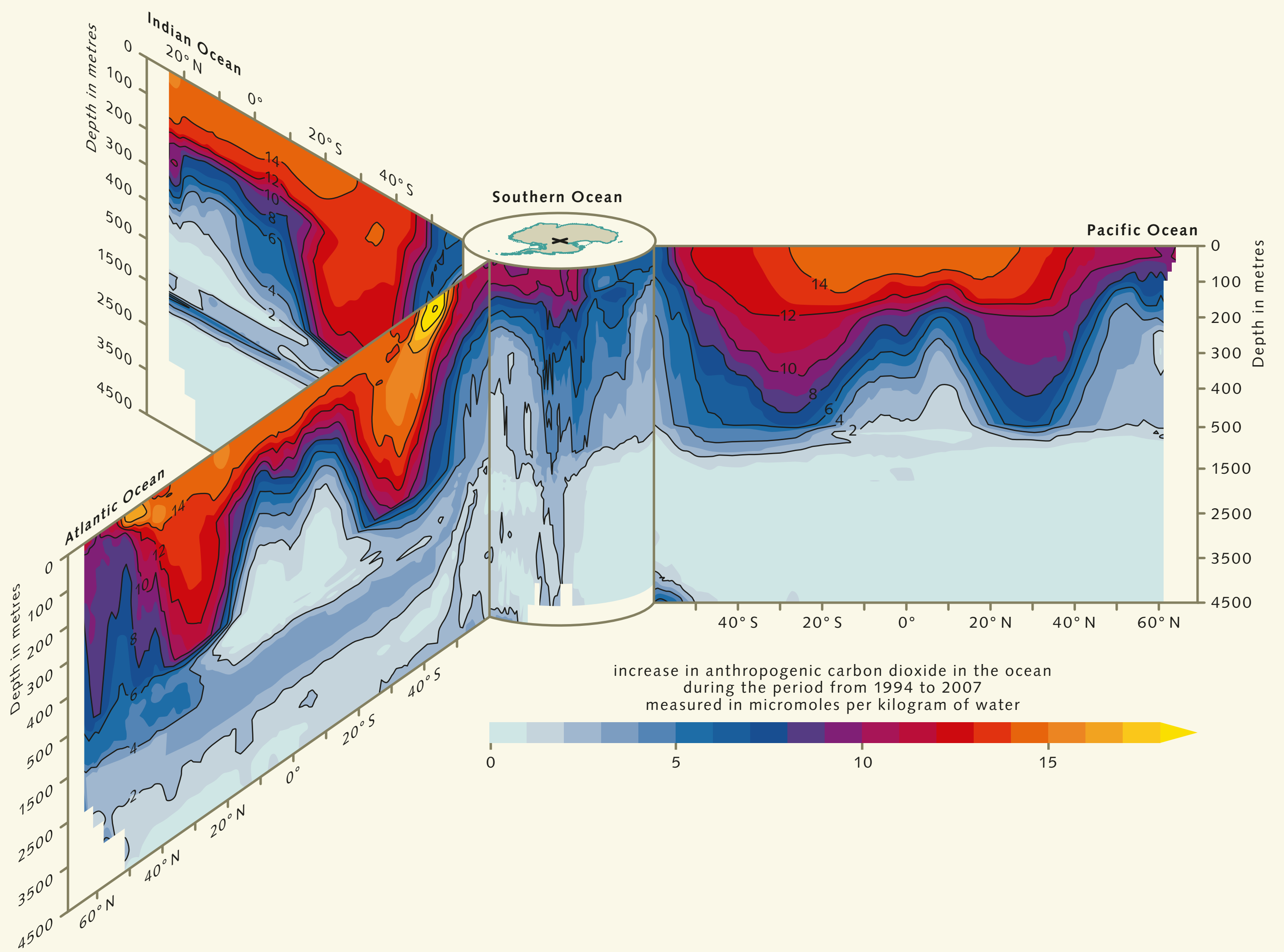
The ocean is acidifying

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

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

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

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



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

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

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

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

No longer a reliable constant

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

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

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

Biodiversity under assault

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

The limits of endurance

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

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

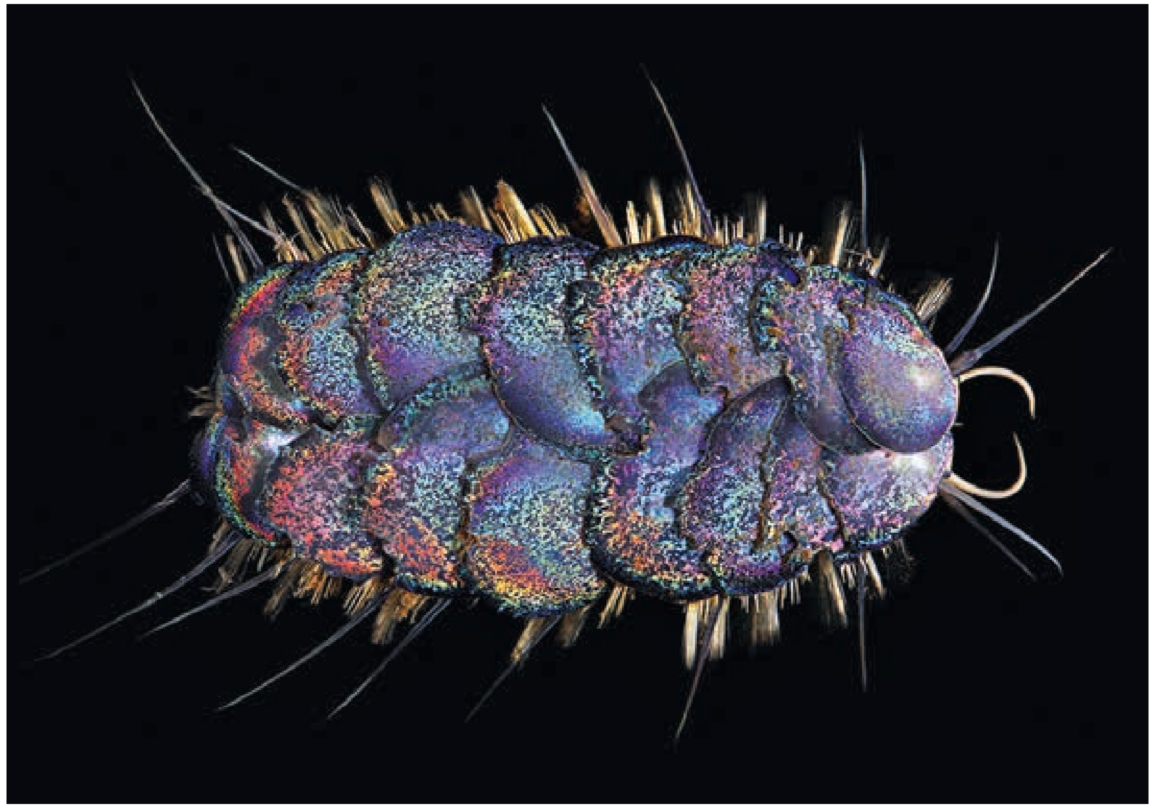
In order to understand how and why marine organisms react to climate change, it is necessary to realize that most marine inhabitants, with the exception of birds and mammals, are cold-blooded animals. These are creatures whose body temperatures are determined by the temperature of their surroundings.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

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

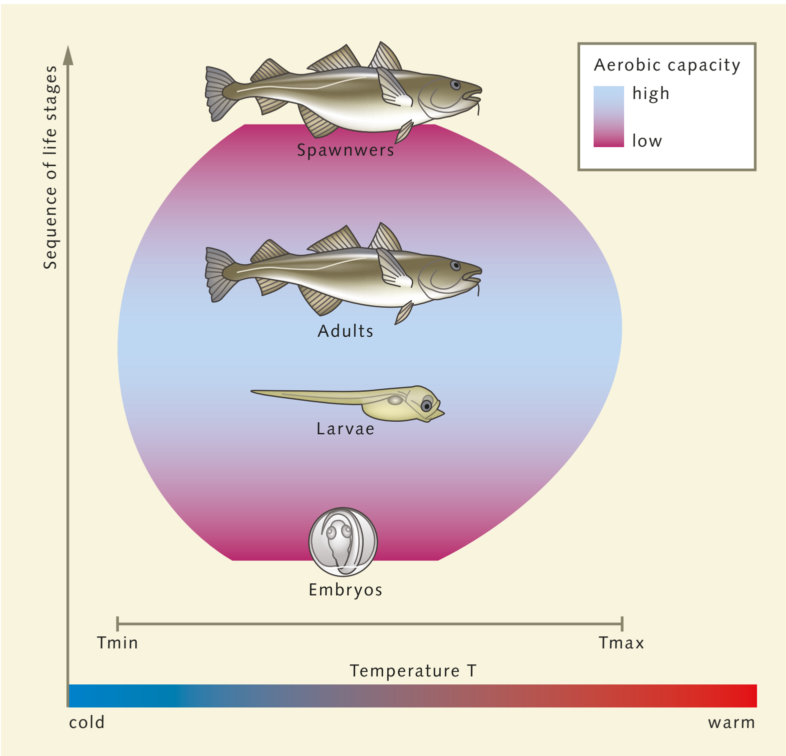
But icefish live at the extreme boundary. If the temperature rises by just a few degrees Celsius, the animals quickly find themselves at their physical limit. At this point they are no longer able to generate sufficient energy to maintain all of their bodily functions. The reason for this is that the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

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

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



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



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

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

More rapid species turnover than on land

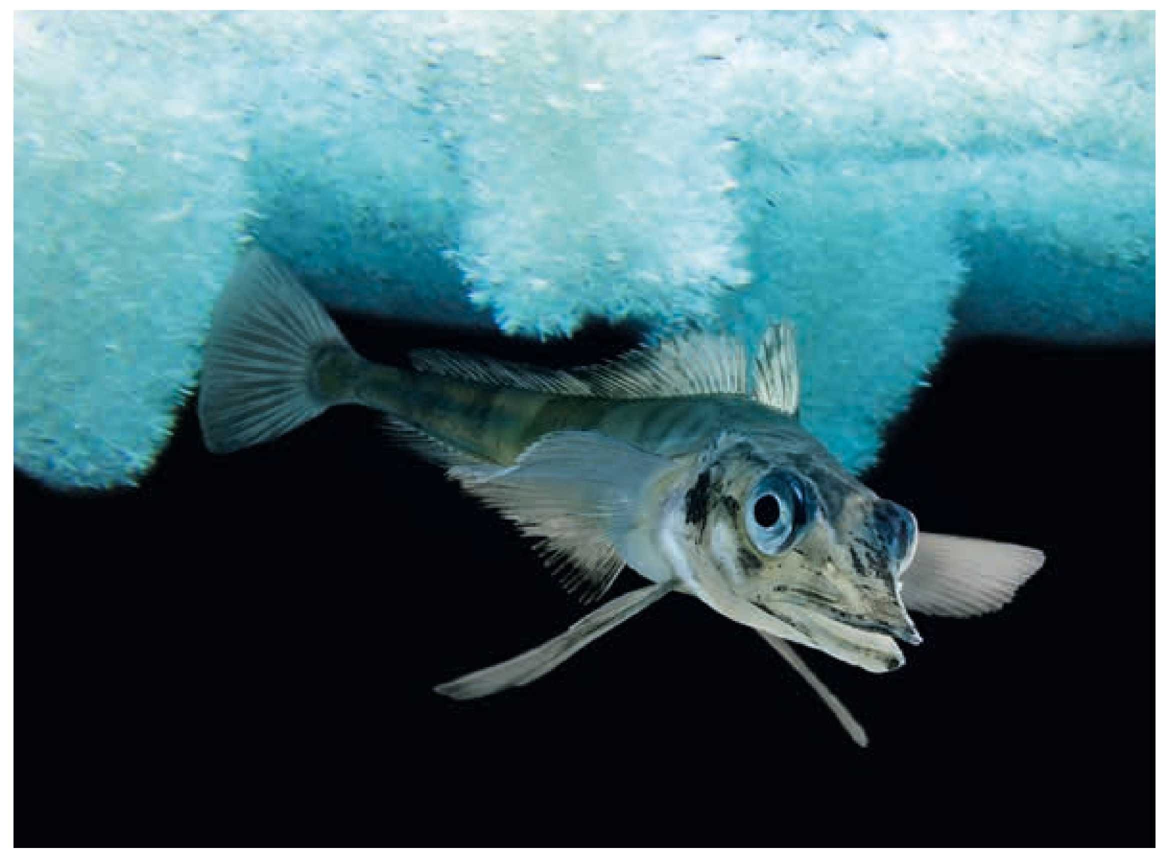
All organisms, like fish, will react to changes in their environment by first attempting to adapt their individual behaviour to the new conditions. Scientists refer to this kind of adaptation as acclimatization. The organisms ramp up respiration and metabolic processes, pump more blood or water and nutrients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

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

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

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

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



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

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

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

Fleeing from the heat

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

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

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

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

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

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

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

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

Heat-driven upheaval of ecosystems

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

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

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

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

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

A further aspect of carbon dioxide

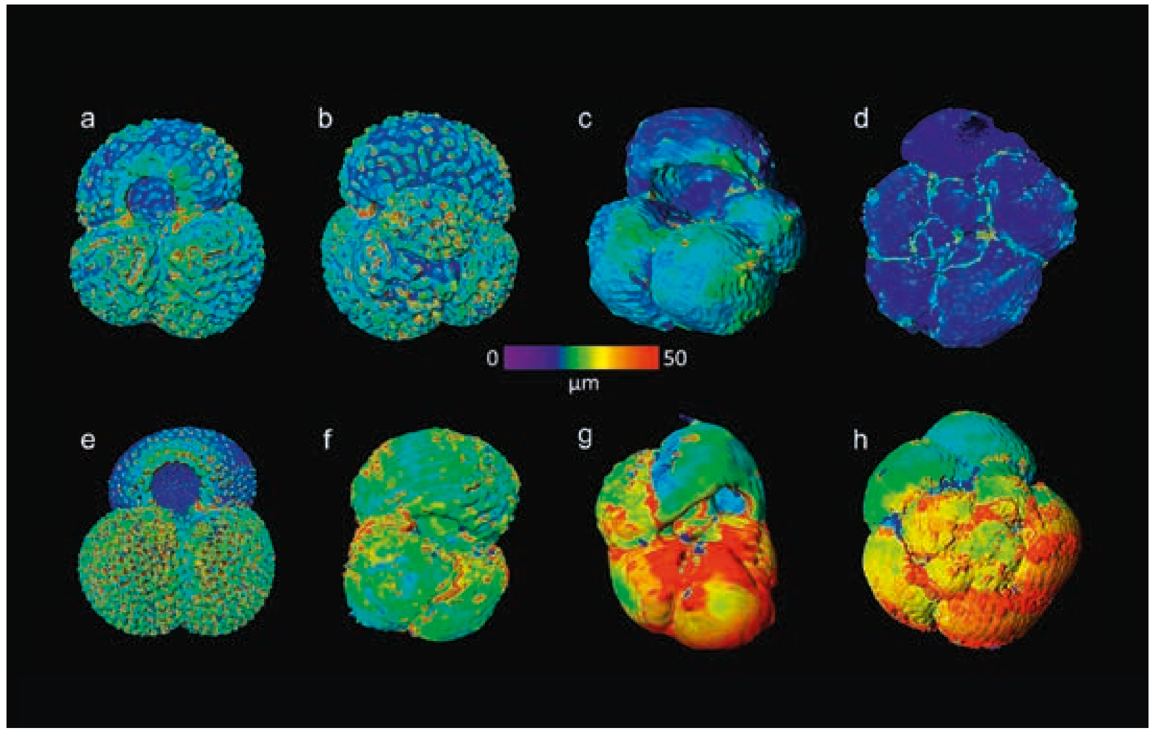
Ocean warming is the most widespread climatic stress factor for biological communities in the oceans today, and it is thus also the major force driving changes in the species distributions in the sea. But there are other responses acting parallel to this that are altering the living conditions in all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

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

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

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

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



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

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

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

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

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

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

Less oxygen, less energy

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

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

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

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

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

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

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

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

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

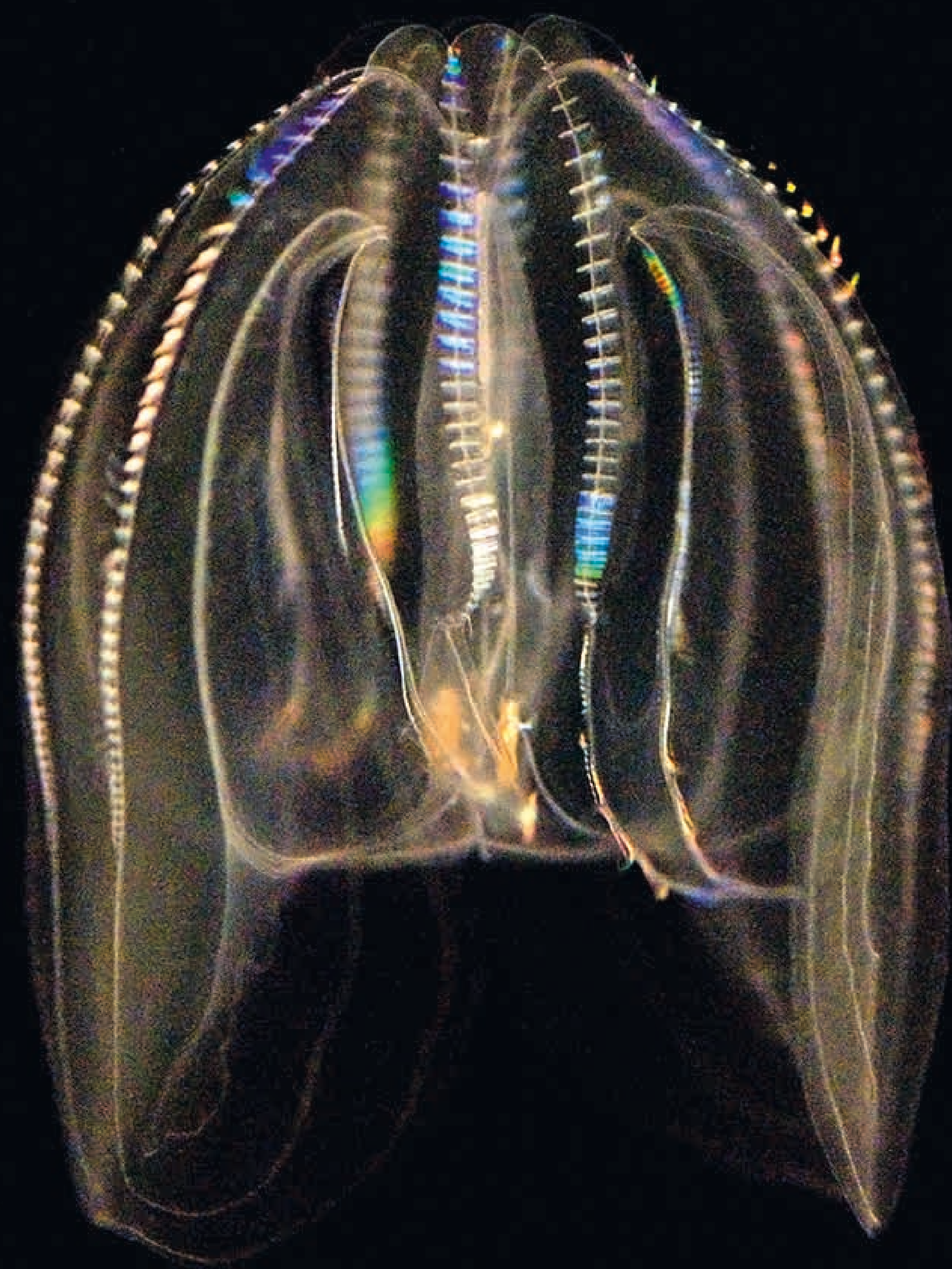
The deadly trio and its ramifications

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

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

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

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



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

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

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

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

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

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

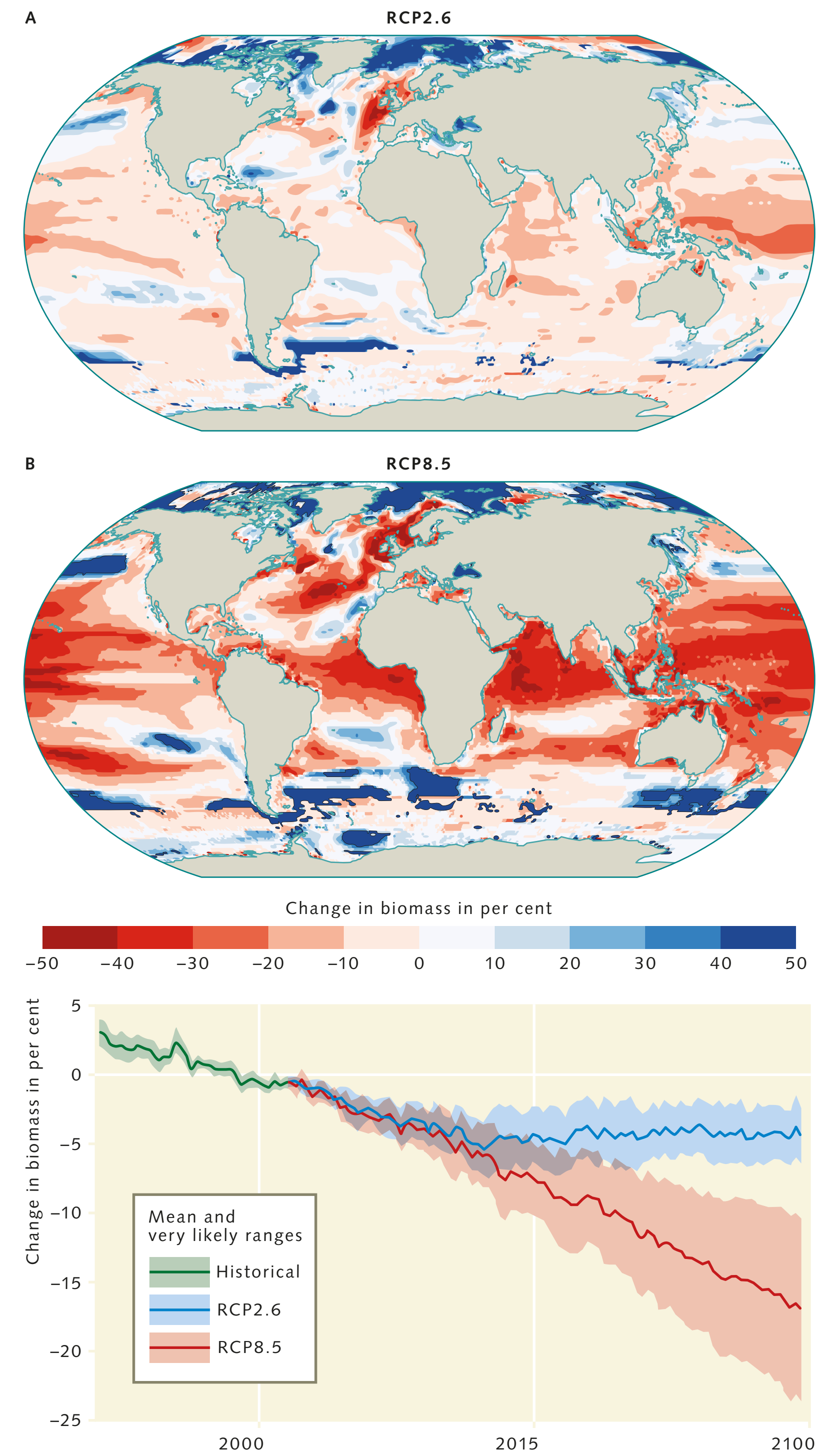
Furthermore, climate stressors amplify the detrimental effects of direct human interference in marine communities. Diminished fish stocks, for example, react much more sensitively to the effects of climate change than healthy abundant stocks. The same is true for coral reefs that have already been damaged by untreated sewage, or for benthic communities that are disrupted by frequent bottom trawling. When extreme climate events such as heatwaves or abrupt decreases in oxygen content strike these already vulnerable communities, they will have little or no chance of fully recovering from them.

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

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

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

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



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

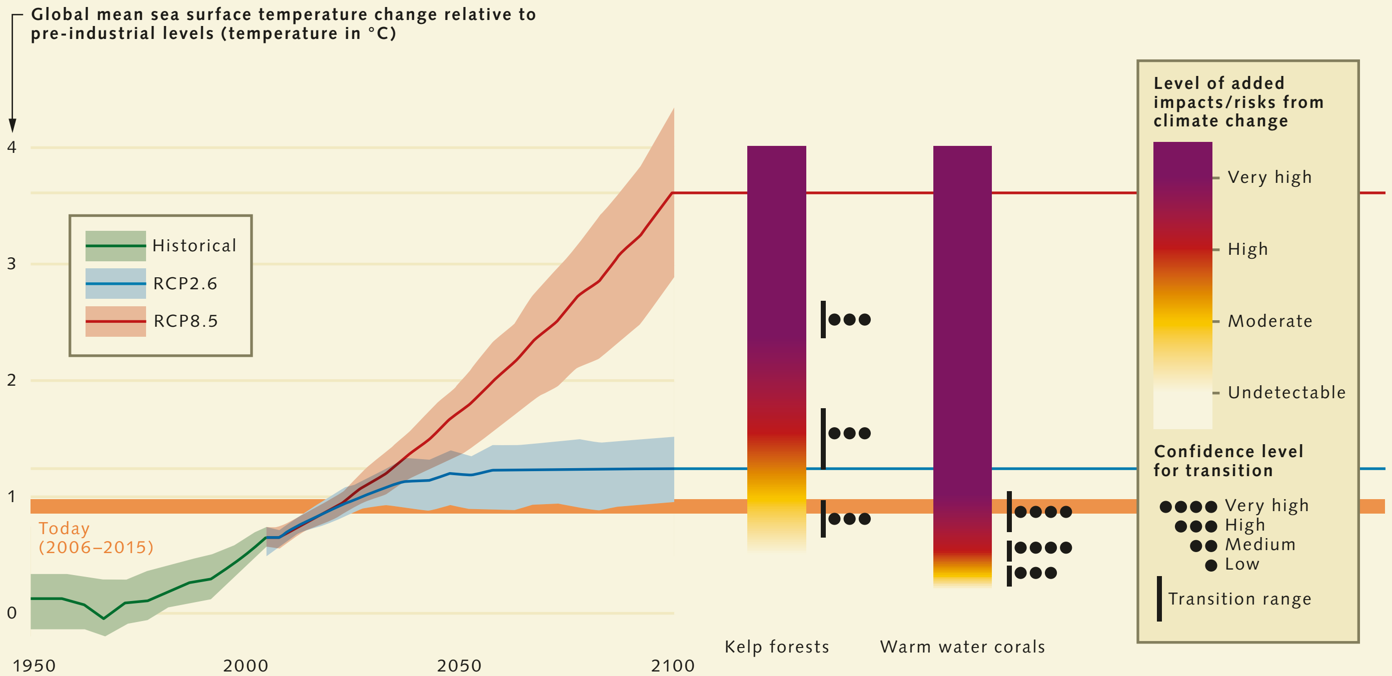
Coral reefs and kelp forests – no chance under extreme temperatures

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

Corals – destructive bleaching

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

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



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

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

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

Kelp forests – retreating toward the poles

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

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

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

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

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

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

Less bounty from the sea

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

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

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

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

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

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

Conclusion

Ocean barometer

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

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

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

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

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

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

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