1 Urgently sought – ways out of the climate crisis

> We have known for decades that the Earth's atmosphere is warming and the climate is changing, and that this is caused by our emissions of greenhouse gases. Our mindsets, however, have remained unchanged and precious time has been wasted. Only now, with dramatic impacts becoming increasingly obvious, are leaders starting to make serious efforts to find solutions. They are forced to recognize that merely reducing greenhouse gases is not enough to keep climate change within tolerable limits.

Code red for people and nature

> Climate change is now a daily reality. At least half the world's population is already suffering the direct effects of global warming. Wells are drying up, heat levels are becoming unbearable, storms and flood waters are sweeping away goods and property, and already ravaged ecosystems are increasingly failing to deliver their services. The climate and nature make no compromises. For humanity, therefore, everything is at stake, for the change that we ourselves have set in motion is proving to be a potentially lethal risk multiplier.

Our future is at stake

We have known for decades that the Earth's climate is warming, and that this is caused by our greenhouse gas emissions. However, the magnitude of the global climatic changes that have already occurred and the critical situation now facing life on Earth have rarely been described with such urgency as in the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC).

On behalf of the IPCC, more than 750 climate scientists from around the world regularly review the current state of knowledge of global climate change. They analyse the findings of research on the causes and effects of climate change, collate information on the extent to which people and nature have the capacity to adapt to the new climatic conditions, and describe measures that may be effective in mitigating climate risks and limiting global warming.

The core message from the three volumes of the IPCC's *Sixth Assessment Report* is very clear: with its persistently high levels of greenhouse gas emissions, humankind is gambling away the prospects of a liveable future for present and future generations.

1.1 > Smoke rises from the chimneys of a Chinese steelworks in Inner Mongolia. Meanwhile, ore is smelted illegally by workers at a nearby camp. China is the world's largest emitter of carbon dioxide (accounting for around 30 per cent of global emissions in 2022), partly because coal is still the country's main energy source.

Rapid warming and its effects on the Earth's climate

According to data from the IPCC, the global surface temperature during the period from 2010 to 2022 was approximately 1.15 degrees Celsius higher than the reference figure for 1850 to 1900. There were much larger increases over land than over the ocean: mean temperatures over the continents rose by 1.65 degrees Celsius, while air masses over the ocean warmed by 0.93 degrees Celsius. Well-informed readers may wonder at these statistics, as the figure for global warming mentioned by other organizations and well-known news outlets since 2020 is 1.2 degrees Celsius. In light of this, it seems reasonable to ask: is the IPCC working with obsolete data? By no means.

Global climate reports such as those produced by the IPCC or the analyses published regularly by the World Meteorological Organization (WMO) focus on long-term changes in climate parameters. In order to determine global surface temperature, therefore, they do not simply analyse the temperature data for a specific year, as these figures may be influenced by short-term natural temperature fluctuations. Instead, the IPCC authors use monitoring data from the previous 20 years as baseline figures. They are thus able to detect the real long-term trend.

And the fact is that global warming is accelerating: in the past 50 years (1970 to 2020), global surface temperature has increased faster than in any other 50-year period over the last 2000 years. A detailed look at the last four decades (1980 to 2020) reveals that each one of these four decades has been successively warmer than the decade that preceded it.

This development means that many of the Earth's climate system components are changing at a speed not experienced by our planet for many hundreds or even thousands of years. However, the magnitude of these changes is not uniform everywhere. Some regions are more severely affected than others. What's more, with every additional tenth of a degree of warming, the changes under way are amplified. This means that the magnitude and extreme speed of the changes, but also the associated risks, will increase with each additional increment of warming, no matter how small. This applies particularly to ocean warming, acidification and deoxygenation; the continued rise in hot extremes over land and in the oceans; the melting of the ice sheets; sea-level rise; and shifts in the Earth's water cycle.

The oceans and seas – more warming, acidification and oxygen depletion

CURRENT STATUS: The oceans and seas are our planet's largest storehouse for heat. This storehouse is being recharged continuously by climate change and the associated warming of the atmosphere. Over the last 60 years, around 90 per cent of the excess heat retained in the Earth's atmosphere due to the greenhouse effect has been absorbed by the oceans and seas and stored in their depths. As a result, ocean heat content has increased significantly and water temperatures are rising more rapidly than at any time since the last glacial period. Sea surface temperature alone has risen by an average of 0.93 degrees Celsius in the period from 1850 to 1900 to 2022. Researchers describe the increase in ocean temperatures as the clearest indicator of human-induced climate change – firstly, because the ocean absorbs the largest proportion of the excess heat, and secondly, because its surface temperatures are subject to less year-to-year fluctuation than the atmosphere, for example. The warming trend is therefore easier to detect.

As the ocean has warmed, stratification of the water masses in the upper 200 metres of the water column has increased. Concurrently, due to increased evapotranspiration from the sea surface, the surface water at evapotranspiration sites, which already has a higher salt content, has become even more saline.

By contrast, in areas of the sea with heavy precipitation or high meltwater inflow, freshwater influx has increased, further reducing the already low levels of near-surface salinity here.

Both these trends – increased stratification of the water masses, and changes in salinity – have, since the 1950s, reduced the density-dependent mixing of surface water with the underlying water masses, thereby amplifying ocean deoxygenation. Oxygen depletion is particularly noticeable in the oxygen minimum zones which are forming in the Western Pacific, the Indian Ocean and off the west coast of Southern Africa below the surface layer, i.e. in water depths between 100 and 200 metres. In these zones, the seawater contains less than 70 micromoles of oxygen per kilogram (µmol/kg), which means that marine fauna such as sharks and tuna, which rely on a plentiful supply of oxygen, have no chance of survival here.

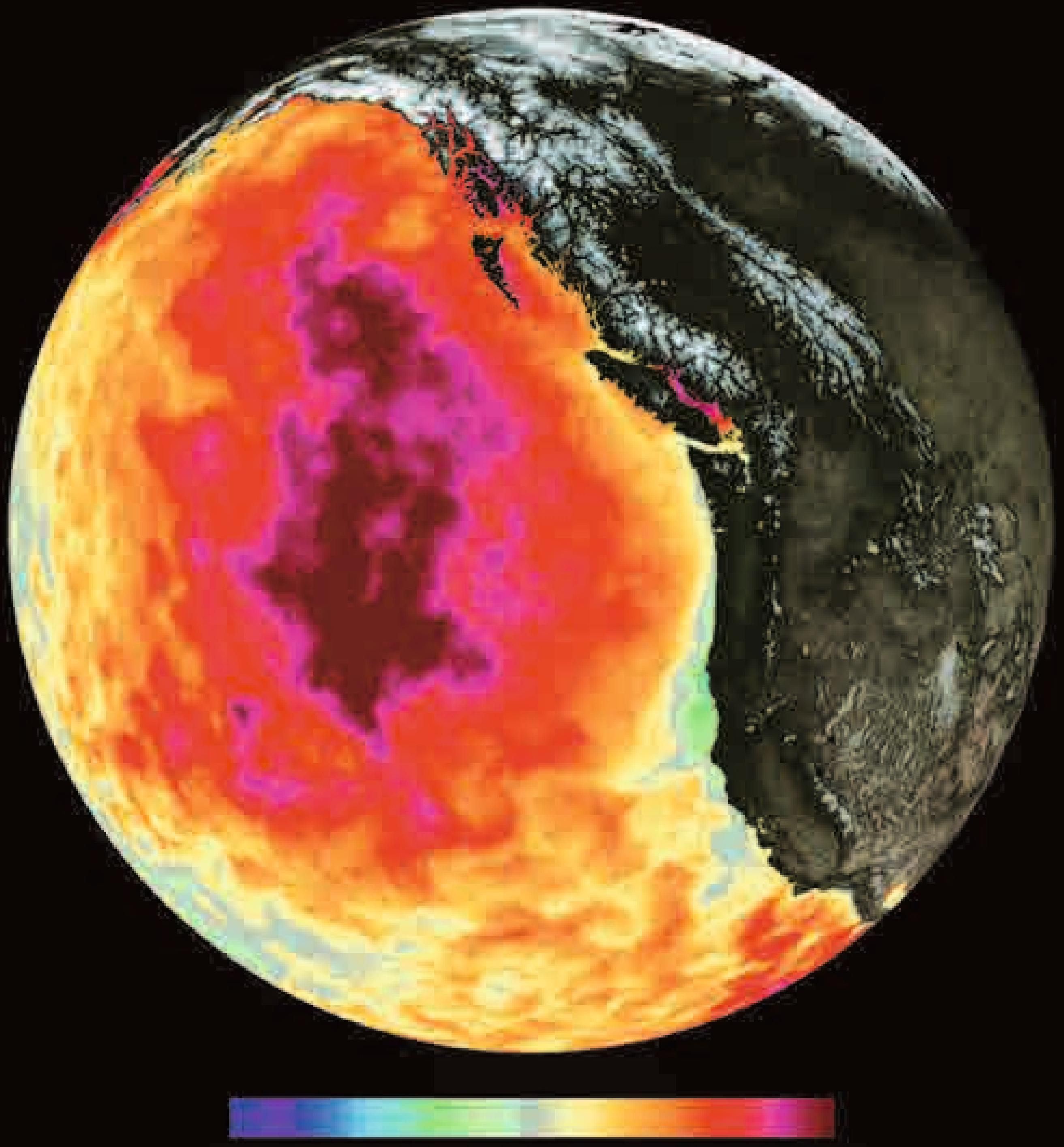
The oceans and seas do not just absorb heat, however; they also take up around a quarter of the carbon dioxide generated by human activity. But unlike oxygen, carbon dioxide does not simply dissolve in seawater: it undergoes a chemical chain reaction which increases the water's acidity. This process of ocean acidification has highly detrimental effects on the habitat conditions of many marine organisms. Experts refer to a reduction in pH as the measure of the ocean's acidity. According to the IPCC, in the last 40 years, ocean surface pH has decreased in almost all areas of the sea – to such an extent that oceanic acidity is now at its highest level for at least 26,000 years. What's more, ocean acidification appears to be taking place with record-breaking speed at present. Making matters worse, acidification is no longer affecting surface water alone; in the last 30 years, it has been detected with increasing frequency in the deeper ocean as well.

OUTLOOK: The temperature of the oceans and seas will continue to increase even if humankind succeeds in limiting global warming to 1.5 degrees Celsius. This can be explained by the inertia of the ocean system: key processes take place so slowly that the effects of any initiated changes are felt over hundreds, if not thousands of years and take just as long to reverse. Even so, we have the solution in our hands: the rate of ocean warming from 2050 will depend entirely on whether we can curb climate change. And it is the future water temperature which will determine how much oxygen the oceans will still contain. The warmer the sea, the less oxygen can be dissolved.

An increase in hot extremes in all regions of the world

CURRENT STATUS: Meteorologists have observed an increase in the frequency and intensity of hot extremes since the 1950s, as well as an increase in heatwave intensity and duration over land. What is new is that these weather extremes are now reaching record temperatures which would have been impossible without human-induced climate change. The extreme heatwave which struck north-west areas of the USA and Canada in late June 2021 is an example: in some localities, temperatures rose to 49.6 degrees Celsius, with highs at some weather stations breaking historically observed heat records by as much as 4.6 degrees Celsius. The research now confirms that temperatures during this heatwave would have been around two degrees Celsius lower without human-induced climate change. In a world with global warming of two degrees Celsius, however, maximum temperatures during this heatwave would have exceeded 50 degrees Celsius. Global warming further increases not only the scale but also the likelihood of another similar heatwave in the North American west. The probability of such a heatwave in June 2021 was estimated at around one in 1000 years, but in a world with two degrees Celsius of global warming, this type of extreme event would occur every five to ten years.

The frequency, intensity and duration of marine heatwaves are also increasing. Marine heatwaves have approximately doubled in frequency since the 1980s and cause major damage to marine biological communities. Here too, researchers can now clearly identify human influence as a factor. Without climate change, the marine heatwave which devastated life in the Northeast Pacific in the years from 2013 to 2015 and has gone down in history as "the Blob" would, in all probability, not have occurred. Among other things, the heatwave caused mass die-offs of the common murre *(Uria aalge)*, with as many as one million of these seabirds dying of starvation because the unusually warm water temperatures greatly reduced populations of their prey species compared with normal levels. As a result, there was a thousand-fold increase in the common murre's mortality rate.



1.2 > In some marine regions of the North Pacific (shown here in dark red), the water temperature in May 2015 was up to 3 degrees Celsius higher than average. The marine heatwave – now known as "the Blob" – which caused this rise in temperature lasted for more than 250 days and killed thousands of fish, seabirds and marine mammals.

1.3 > Weakened by the heat: members of the public seek refuge in the air-conditioned rooms of a convention centre in Portland in the US state of Oregon. The rooms were opened to the public during an extreme heatwave in early summer 2021, providing an opportunity to rest and cool down.

OUTLOOK: The intensity and duration of heatwaves over land will continue to increase even if humankind succeeds in limiting global warming to 1.5 degrees Celsius. Marine heatwaves will also occur more frequently. If the world warms by an average of 1.8 degrees Celsius by the year 2100, there will be a two- to ninefold increase in the number of marine heatwaves over the next 60 to 80 years. If the global mean temperature rises by around 4.4 degrees Celsius relative to preindustrial levels, there will be a three- to 15-fold increase in the frequency of marine heatwaves in the final two decades of this century relative to 1995 to 2014, with the greatest changes predicted for tropical waters and the Arctic Ocean.

Global mountain glacier retreat

CURRENT STATUS: The world's glaciers currently contain less ice than at any time in the last 2000 years. Global retreat of mountain glaciers has been accelerating since the 1990s because air temperatures are increasing at higher altitudes as well. Due to the temperature increase, less snow survives on the glacier's surface until the end of summer, which means that there is less snow available for conversion into ice in subsequent years. Surface melting of mountain glaciers is also increasing. Their meltwater has contributed around 6.72 centimetres of mean sea-level rise in the last 120 years.

OUTLOOK: A further decrease is projected in snow cover and glacial ice mass in the world's mountain ranges in the coming decades, along with permafrost thawing in many high mountain regions. As there will be more heavy rainfall instead of continuous snowfall at the same time, researchers are predicting a growing risk of floods and landslides for many mountain regions. The loss of glacier ice will also adversely affect the vital water resources of millions of people who live along rivers that are fed from glacial meltwater.

A clear decline in Arctic sea ice

CURRENT STATUS: On average, the Arctic has been warming at least twice as fast as anywhere else on Earth in recent years. As a result, the Arctic minimum sea ice extent – when the ice shrinks to its minimum size at the end of summer – has decreased by around 40 per cent since the satellite record began in 1979. The remaining ice is also noticeably thinner than before, which means that it drifts across the Arctic Ocean more rapidly and rarely survives for more than two years before melting.

OUTLOOK: Arctic sea ice will melt at an accelerated rate in summer, while less ice will form in winter. Both these developments mean that the Arctic Ocean will be ice-free at the end of summer at least once by 2050, apart from small residual areas of ice, totalling less than a million square kilometres, in sheltered bays and fjords.

Continued ice-mass loss for the Greenland and Antarctic Ice Sheets

CURRENT STATUS: From 1992 to 2020, an estimated 4890 gigatonnes of ice were lost from the Greenland Ice Sheet; the resulting meltwater added 1.35 centimetres to global sea-level rise. The Antarctic Ice Sheet lost 2670 gigatonnes of ice during the same period, with West Antarctica suffering the most significant ice loss. Both here and on the Antarctic Peninsula, glacier flow velocity has clearly increased in the last two decades. This means that relative to 2000, the glaciers are transporting far more ice from land into the sea today.

OUTLOOK: With further warming, the world's two major ice sheets will lose more ice and their contributions to global sea-level rise will increase. If the world warms by more than two degrees Celsius, the West Antarctic Ice Sheet will very likely collapse and its ice masses will slide into the sea. However, the timing, speed and magnitude of this potential collapse are very difficult to predict with any degree of certainty.

Accelerated sea-level rise

CURRENT STATUS: Between 1901 and 2018, global mean sea level rose by 20 centimetres; moreover, the rate of global mean sea-level rise has increased continuously since the 1960s. In other words, sea-level rise is accelerating. Between 2006 and 2018, sea levels were already rising by 3.7 millimetres per year, and according to the WMO, the figure for 2013 to 2022 reached 4.62 millimetres. This means that global mean sea level has risen faster than at any time in at least the last 3000 years. However, levels may have risen even more sharply in some localities and regions. This can be due to the simultaneous occurrence of coastal subsidence or because the action of wind and ocean currents has caused a localized build-up of water along the coast.

OUTLOOK: The development of the global sea level is determined by two factors: seawater temperature (the warmer the water, the more it expands and takes up more space); and changes in water storage by terrestrial water systems (ice masses, groundwater, rivers, lakes). If more terrestrial water enters the ocean, sea levels will rise. A further aspect of relevance to every local stretch of coastline is whether the coastal area itself has undergone any changes in elevation; this can occur, for example, if large quantities of groundwater are extracted, resulting in underground subsidence, or if geological processes cause the land surface to rise or sink. Localized sea-level changes may therefore be significantly higher or, indeed, lower than the global trend.

According to the IPCC's projections, global mean sea level will continue to rise even if humankind succeeds in reducing its greenhouse gas emissions to zero within a short time frame. Possible scenarios range between an additional 18 centimetres and 23 centimetres by 2050. A 38 to 77 centimetre rise is expected by the end of the century.

Changes in the water cycle

CURRENT STATUS: Global warming is increasing evapotranspiration from both land and sea worldwide. This in turn increases the amount of water vapour in the atmosphere, making it more likely that rain droplets will form. A further effect of evapotranspiration is loss of soil moisture, which is vital for plant growth. These two physical processes cause permanent changes in the weather and climate: an increase in the frequency and intensity of

1.4 > This iceberg has broken off the Greenland Ice Sheet. Since 1996, the Greenland Ice Sheet has lost more ice due to surface melting and iceberg calving than can be formed through the compression of fresh snow.

heavy precipitation events has been observed since the 1950s, at least in those regions of the world with continuous weather records. Concurrently, climate change heightens the risk of drought in some regions due to a lack of precipitation, especially during the driest months, although there may be heavy rainfall at other times of the year in such torrential amounts that it causes surface runoff, with very little water penetrating the soil. Reduced snow cover is also a significant problem. Winter snowfall has become a less common occurrence since the 1950s, with the result that snow cover is no longer forming in many localities. In the past, meltwater from snow provided a water supply for people and nature in spring, but is now largely unavailable in many areas, particularly in mountain regions and the tundra.
OUTLOOK: Heavy precipitation is projected to intensify and be more frequent in many localities. As a result, the high-water and flood risk will also increase. There will also be a higher risk of drought, with more regions affected by drought more frequently and for longer periods in future. Snow cover will continue to decrease, mainly in the northern hemisphere, with earlier temperature-related onset of spring snowmelt and potentially smaller volumes of water in rivers and streams.

More typhoons and hurricanes

CURRENT STATUS: The global proportion of tropical cyclone occurrence in Category 3 to 5 on the Saffir-Simpson Hurricane Wind Scale (wind speeds from 178 kilometres per hour) has increased in the last four decades, as has the frequency with which a fairly weak storm rapidly develops to hurricane strength. In the West Atlantic, tropical cyclones are now moving more slowly landward from the open sea; when they make landfall, they linger for longer, often resulting in increased damage. In the North Pacific, extratropical cyclones have shifted their tracks northward and now make landfall at different locations relative to 40 years ago.
OUTLOOK: Researchers are predicting very little change in the number of cyclones overall. In the tropical regions, however, the proportion of very strong – and therefore destructive – storms will continue to increase.

When extremes collide

As well as warming up the world, climate change is exposing people and nature much more frequently to weather and climate extremes. They include heatwaves, heavy rainfall, severe storms, droughts and floods, as well as storm surge due to sea-level rise, which can cause extensive flooding in coastal areas. The frequency with which two or three weather extremes occur concurrently is also increasing. In the last 100 years, for example, more heatwaves have been observed in regions already affected by drought.

When such extremes collide, the climate impacts on people and nature are amplified. For example, a heatwave

Climate change in figures – the WMO's seven Global Climate Indicators

The increase in global mean surface temperature is the parameter generally used by the media and policy-makers to convey the magnitude of the changes occurring across the climate system. On its own, however, this single parameter is insufficient to provide a detailed picture of the overall state of the Earth's climate and any changes that may have occurred. In 2018, the World Meteorological Organization (WMO) therefore identified seven key indicators which it has used since then to describe the global changes in the climate system to the general public and decision-makers. These indicators are:
(1) global mean surface temperature,
(2) ocean heat content,
(3) global mean sea-level change,
(4) Arctic and Antarctic sea-ice extent,
(5) changes in the mass balance of the Greenland and Antarctic Ice Sheets,
(6) global mean ocean pH (ocean acidification) and
(7) mean atmospheric carbon dioxide concentrations.

Each of these indicators is scientifically assessed at least once a year, with monitoring data collected using a standardized global methodology. Together, they capture changes in the Earth's atmosphere and energy balance and provide an initial insight into the current state of the global climate. All seven indicators can be described in simple numerical terms. The latest figures for the seven indicators are published by the WMO in its *State of the Climate* report, which is produced annually. In 2021/2022, four of the seven indicators set new records. This means that in 2021 and 2022, atmospheric carbon dioxide concentrations, sea-level rise, ocean acidification and ocean heat content were higher than at any time since weather and climate records began.

combined with drought causes far more extensive damage than would result from just one of these extreme events. This applies not only to heatwave-drought compounds but also to cases in which coastal regions are affected by severe storms involving both storm surge (marine flooding) and heavy rainfall (flooding on land, river floods). In combination, a storm, storm surge and heavy rainfall cause flooding on a much wider scale than would be induced by just one of these weather extremes.

The risk that extreme events will occur concurrently and that their respective impacts will be amplified is increasing as a result of climate change. Low-lying coastal regions which are regularly affected by cyclones are especially at risk.

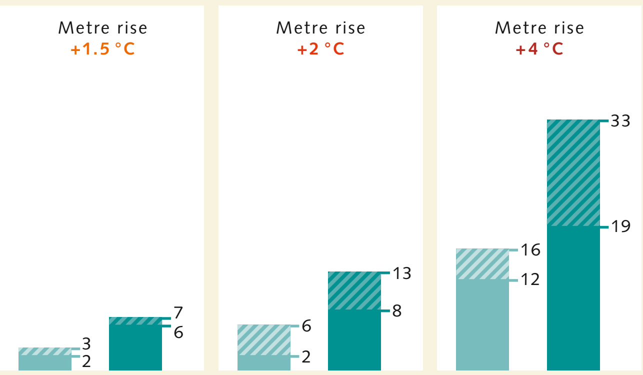
Response of the climate system relative to 1850 to 1900
(Figures in brackets indicate the minimum to maximum range)

	Today: Response to +1.1 °C	Response to +1.5 °C	Response to +2 °C	Response to +4 °C
Temperature Hottest day in a decade (+ °C)	+1.2 °C (+0.7 to +1.5 °C)	+1.9 °C (+1.3 to +2.3 °C)	+2.6 °C (+1.8 to +3.1 °C)	+5.1 °C (+4.3 to +5.8 °C)
Drought A drought that used to occur once in a decade now happens x times more	x1.7 (x0.7 to x4.1)	x2.0 (x1.0 to x5.1)	x2.4 (x1.3 to x5.8)	x4.1 (x1.7 to x7.2)
Precipitation What used to be a wettest day in a decade now happens x times more	x1.3 (x1.2 to x1.4)	x1.5 (x1.4 to x1.7)	x1.7 (x1.6 to x2.0)	x2.7 (x2.3 to x3.6)
Snow Snow cover extent change (%)	–1 % (–3 to 1)	–5 % (–7 to 2)	–9 % (–13 to 2)	–26 % (–35 to –15)
Tropical cyclones Proportion of intense tropical cyclones (%)		+10 %	+13 %	+30 %

Long-term consequences: Sea level rise
Today, sea level has already increased by 20 cm and will increase an additional 30 cm to 1 m or more by 2100, depending on future emissions. Sea level reacts very slowly to global warming so, once started, the rise continues for thousands of years.

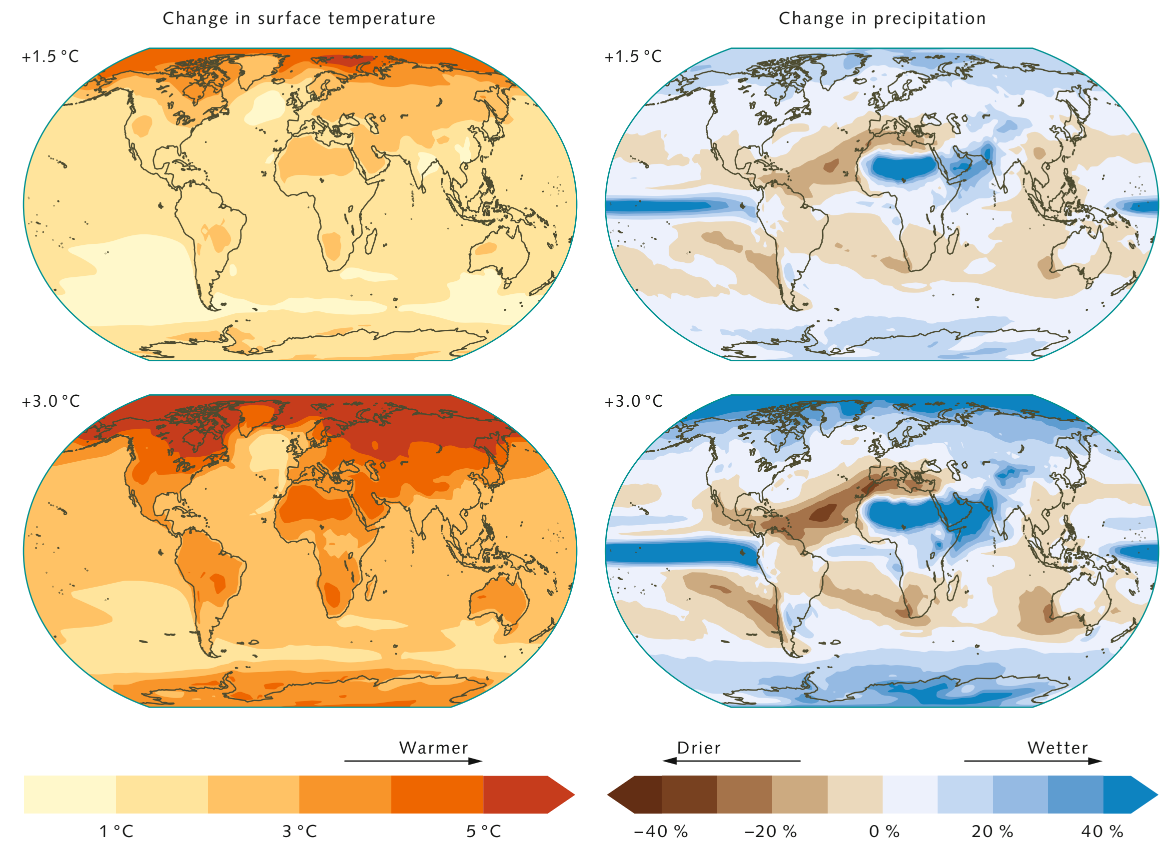
Projected maximum increase
Projected minimum increase
Within 2000 years

Projected maximum increase
Projected minimum increase
Within 10,000 years



1.5 > Many climate system components react swiftly to global warming – and the higher the temperature increase, the greater the changes. Other climate impacts have a slower onset but become locked in and cannot be reversed in the short term once they have begun. Sea-level rise is the most striking example.

Climate change and regional impacts



1.6 > Climate change is not uniform in all parts of the world. Instead, there are regional differences which will become more apparent as global warming continues. For example, precipitation will increase in high latitudes, the tropics and monsoon regions and decrease in the subtropics.

The impacts – extensive damage to people and nature

The physical climate parameters determine the broad framework within which life on Earth can exist. Any change in these parameters affects the survival conditions not only for people and nature, but also for our built environment. Buildings, roads, power grids, bridges and other key infrastructures are, after all, designed to withstand specific environmental conditions. Global warming of 1.15 degrees Celsius has already led to wide-scale loss and damage for people and nature, and every additional tenth of a degree of warming will further increase the risk of harm.

The IPCC's conclusions on the observed and future impacts of climate change on the various forms of life on Earth can be summarized as follows:

Reorganization of natural biological communities

Global warming is causing drastic and ever-increasing changes in the natural world. These changes affect species composition in natural biological communities on land and in lakes, rivers and seas, weakening their functionality and resilience. Slow onset changes (sea-level rise, ocean acidification) are as problematical as the increased frequency and intensity of extreme events.

In all regions of the world, rising temperatures and weather extremes such as droughts, heatwaves, storms, heavy rainfall and floods are creating climatic conditions that animal and plant species have not experienced for thousands of years. In many cases, the record-breaking temperatures measured already exceed living organisms' tolerance limits. Furthermore, weather extremes are now occurring so frequently that ecosystems have little or no time to recover from one heat shock before the next one follows.

For example, the time needed for tropical coral reefs to recover from temperature-induced coral bleaching is at least ten years. However, in Australia, the Great Barrier Reef has experienced a total of six mass bleaching events since 2000, four of which occurred between 2016 and 2022. It is important to note that the coral bleaching event during the Australian summer of 2021/2022 was the first to occur under La Niña conditions, when cooler water temperatures would normally be expected off the east coast of Australia. And yet 91 per cent of corals on the Great Barrier Reef showed signs of significant heat stress.

Approximately 14 per cent of the world's corals – equal to 11,700 square kilometres of reef – has been lost since 2009, mainly as a result of marine heatwaves. However, scientists are also documenting mass mortality of trees, e.g. in boreal forests and mixed forests in western regions of North America. Stressed by drought and heat, they succumb to diseases or pests, fall victim to forest fires or dry out.

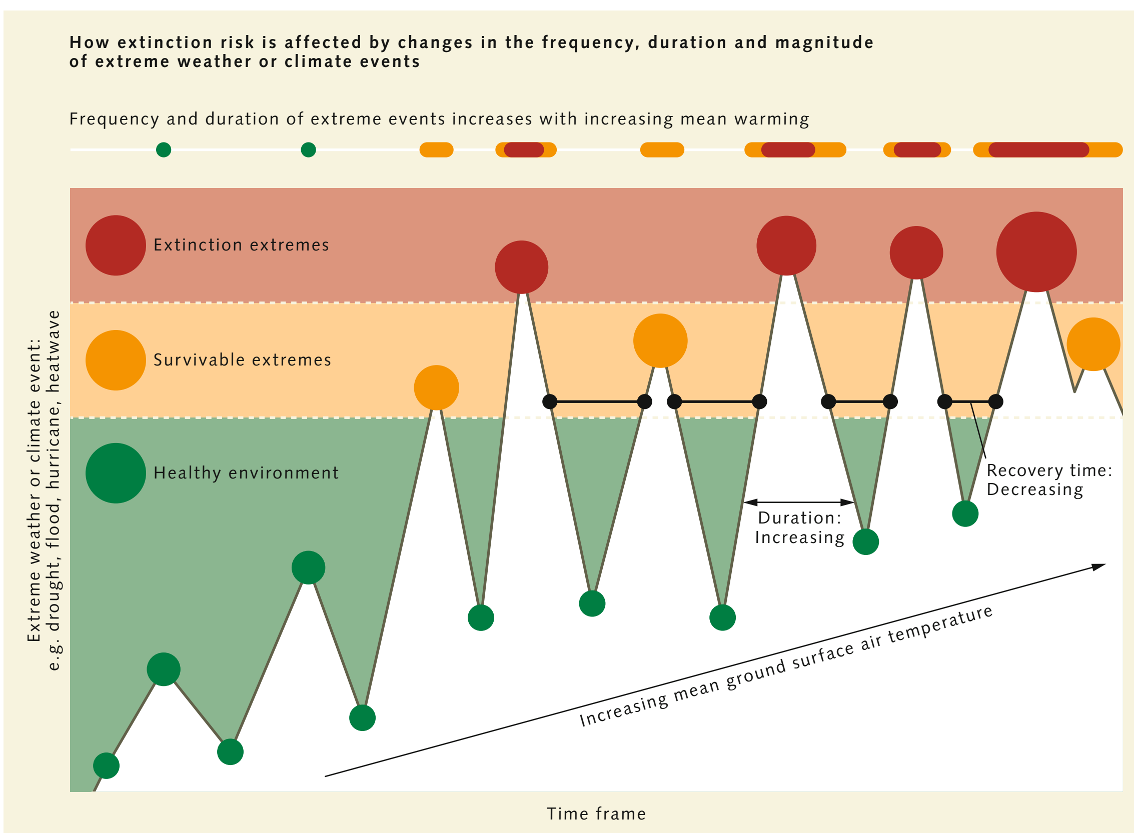
In light of recent studies on the impacts of climate change, combined with a better understanding of natural processes, the IPCC also concludes that the extent and magnitude of climate change impacts on nature are far greater than previously assumed. Most of the climate-induced changes that we are already seeing today are occurring more rapidly than was predicted 20 years ago. They also cause far more damage and affect much larger areas.

For example, as a result of climate change, many biotic communities' biological clocks are changing, disrupting the synchronization of once finely coordinated events or processes. In the ocean, algal blooms are now occurring earlier, before the fish larvae which feed on them start to hatch. By the time the juvenile fish have developed to the stage where they are able to forage for food, the algal blooms have long gone. On land, hibernating animals are waking too early from their winter sleep, only to search in vain for food. Trees and flowers are coming into bloom before any pollinators appear, and when hungry chicks open their beaks for food, parent birds struggle to find enough insects with which to feed them.

In order to escape the rising temperatures, flora and fauna around the world are abandoning their established habitats or dying out locally. Around half of the many thousands of species assessed appear to be reacting in this way. Marine species are shifting polewards or into greater depths in search of the ambient temperatures to which they are habituated. The current rate of their habitat shift averages around 59 kilometres per decade. However, ocean warming is not the only stress factor affecting flora and fauna. Habitat conditions are also worsening due to increasing ocean acidification and oxygen depletion. Collectively, all three factors have resulted in a reorganization of life in the ocean, particularly near the surface, in the last 50 years.

Terrestrial organisms are also shifting polewards or migrating to higher elevations. Organisms which are only able to move slowly, if at all, run the risk of extinction, at least at local scale. This applies to terrestrial and marine biological communities alike. The prospects of survival are particularly bleak for organisms which live in geographically restricted habitats such as ponds and lakes, meaning that they have no chance of migrating, and for species which are adapted to cold habitat conditions in polar and mountain regions. Very few suitable refuge areas will be available globally for these cold-climate specialists in future.

Making matters worse, the impacts of climate change on nature and species diversity are compounded by other human-induced stress factors – first and foremost the wide-scale destruction of natural habitats through de-



1.7 > The increasing frequency and intensity of extreme events pose a genuine threat to plants and animals. The more frequently an individual species or entire ecosystem is affected by an extreme event and the less time organisms have to recover from the shock, the greater the risk that they will die out locally.

1.8 > A coral colony before bleaching (right) and afterwards (left). If the water is too warm, the corals expel the symbiotic algae that supply them with food, consequently losing their colour. If these conditions persist, coral starvation occurs.

Mass extinction
A mass extinction is defined by scientists as an event in which more than 75 per cent of species of flora and fauna die out, usually within a time span of less than two million years, and their roles in the ecosystem are not filled soon afterwards by new or different species. There is evidence that this has already occurred five times in the last 540 million years; however, these individual events took place over timespans up to several million years.

forestation, drainage of wetlands, coastal construction and development, overfishing of the seas, and resource extraction. Environmental pollution also plays a major role, as do uncontrolled soil sealing and the spread of invasive species. Wherever these stress factors overlap, their effects are mutually reinforcing, weakening the resilience of natural ecosystems. For many biological communities, climate change is thus a risk multiplier – and as warming continues, it will become a lethal threat for many. One fact stands out: with each tenth of a degree of warming, the impacts and climate risks for terrestrial and marine ecosystems will increase.

The world's oceans, for example, face the prospect of a mass extinction due to the combined effects of climate change and human overexploitation of the marine environment. This would be the sixth mass extinction in Earth's recent history. New research shows that if atmospheric and ocean temperatures continue to rise, the loss of marine species due to heat stress and oxygen depletion over the next 75 years will equal the losses from overfishing, pollution and habitat destruction. In sum, global warming of up to 4.9 degrees Celsius by the end of this century would cause so many marine species to die out that this would qualify for definition as mass extinction.

The extinction rate would be particularly high in the polar regions, where cold-climate specialists are struggling to adapt due to the speed of the changes. However, the greatest decline in diversity would be observed in the currently still species-rich tropics, where biological communities have already reached their maximum temperature tolerance limit. But the research also shows that if global warming can be held below two degrees Celsius, the risk of a mass extinction decreases significantly.

Climate change – a risk multiplier

The upheavals in the natural world have far-reaching implications for humankind. One by one, ecosystems are denying us their vital services. Cereals, fruit trees and other crops are no longer being adequately pollinated; grazing for livestock – cattle, sheep and goats – is proving increasingly difficult to find; more and more often, coastal fisherfolk are pulling in empty nets, particularly in the warm, tropical regions, because fish populations are migrating to cooler waters. There is less air and water purification, less effective protection of coasts from erosion, and popular holiday destinations are losing their main attractions – forests, snow-capped mountains and coral reefs. In parallel, many people who enjoy woodland walks or relaxing by the sea are finding that their mental health is suffering. In short, the more the ecosystems change, the more we lose our vital natural resources.

Water – too much or too little

Climate change also directly affects human communities and our built environment. For example, more frequent heavy rainfall increases the risk of river floods in some regions of the world. The potential damage induced by this type of natural disaster is estimated to be four to five times greater in a world with four degrees Celsius of warming than if global warming were limited to 1.5 degrees Celsius. However, even with warming of 1.5 degrees Celsius, more people will lose their lives and property to floods than at present. In Colombia, Brazil and Argentina, for example, the number of people affected by river floods would increase by 100 to 200 per cent, with an increase of 300 per cent in Ecuador and even 400 per cent in Peru.

Rising spring and winter temperatures, in turn, cause earlier snowmelt at high altitudes, resulting in changes in average water levels in mountain streams and rivers. For human communities, this development means that the rivers may carry a large volume of water during periods when it is scarcely needed, while later in the year, water levels are too low to allow extraction of the required quantities.

Already, more than half the global population lives under conditions of severe water scarcity, at least partly induced by climate change, for at least one month of the year; this may be due to extreme aridity, but also to floods, storms and heavy rainfall events whose impacts also put the drinking water supply at risk in many localities. The effects are felt particularly by cities, municipalities and villages whose residents rely on meltwater from the shrinking mountain glaciers, as well as by people living in areas without a central water supply. If rivers burst their banks here or if a natural spring dries up due to drought, many thousands of people are often left without access to clean water.

Alongside agriculture, which is the world's largest consumer of freshwater, the energy sector is also affected by water scarcity: since the 1980s, the amount of power generated in hydroelectric plants has decreased by four to five per cent worldwide due to falling water levels and reduced flow rates. Indeed, in some localities, hydropower plants are threatened with closure due to water scarcity. Conditions at Lake Powell, the second largest artificial reservoir in the USA, illustrate the gravity of the situation until the winter of 2022/2023. The Lake is located on the border between Utah and Arizona. It is fed by the Colorado River and together with the Lake Mead reservoir further downstream, supplies around 40 million people with drinking water. Farms along the length of the river also extract water to irrigate their fields and crops. After 22 years of drought in the western USA and persistently excessive water extraction from the Colorado River, the reservoir was filled to just 24 per cent of its capacity at the end of March 2022. Between 2019 and 2022 alone, the water level dropped by more than 30 metres, coming close to the critical threshold below which the lake's hydroelectric dam is unable to generate power. The federal agency responsible for the reservoir therefore decided to release less water than usual from the lake during the rest of the year and to open the dam gates of another reservoir further upstream in order to provide an additional water inflow into Lake Powell. The drought in the American West has stretched over 22 years (2000 to 2022/2023) and is now classed as the driest period in 800 years.

Food – hard times for arable farming, livestock husbandry and aquaculture

Wherever there is too much rainfall, or it rains at the wrong time of the year, arable and livestock farming becomes more challenging. According to the IPCC, farmers and foresters, fishers and aquaculturists around the world are already adversely affected by climate change to such an extent that they are no longer able to produce sufficient staple crops and timber to meet the global population's needs.

With higher temperatures and increased aridity, cereals and fodder crops wilt in the fields and diseases spread. Due to ocean acidification, rising water temperatures and multiple algal blooms (eutrophication), fish farmers are finding it increasingly difficult to bring mussels and other shellfish to maturity. Global warming also increases the complexities – and therefore the costs – of transporting, storing and selling perishable foods such as fruit and vegetables safely so that once purchased, they stay fresh for a few days at home. Climate change thus affects not only the producers but the entire supply chain up to and including the consumer, posing a threat to food security throughout the world.

The losses are particularly severe when regions are affected by extreme events such as droughts, floods and heatwaves. The frequency of these sudden harvest or production losses on land and in the sea has steadily increased since the 1950s and often has a domino effect. For farming families, crop failure means the loss of their food supply and livelihoods. Concurrently, the availability of basic foodstuffs is reduced, pushing up prices and making staple foods unaffordable, especially for low-income families. The resulting hunger and malnutrition have particularly negative effects on child health. These developments can be observed in Asia, Central America, the sub-Saharan regions, the Arctic, the small island states and elsewhere – and once again, it is the smallholder farmers and artisanal fisherfolk who are impacted most severely by climate change.

The situation will worsen as warming continues – in part because higher temperatures mean that more water is lost through evapotranspiration from foliage and soil. Water demand from agriculture will therefore increase. This situation will be compounded by the substantially reduced availability of water during the growing season in many regions, multiplying the risks. To take just three examples:

- With global warming of two degrees Celsius by 2100, the probability of extreme droughts occurring across wide areas in Northern South America, the Mediterranean region, Western China and at high latitudes in Europe and North America will increase by 150 to 200 per cent.

- Whereas around 40 per cent of total croplands (approximately 3.8 million square kilometres) experienced water scarcity in the period from 1981 to 2005, a new study shows that agricultural water scarcity will intensify in more than 80 per cent of global croplands by 2050 – even if the world warms by just 1.6 degrees Celsius by 2050 relative to preindustrial levels.
- During the same period, the impacts of climate change alone will mean that an estimated eight to 80 million people in South Asia, Central America and sub-Saharan Africa will no longer have access to adequate food and will therefore suffer from hunger. The precise figure will depend on the degree of warming and hence the magnitude of future climate change.

Health – the limit of human tolerance

Climate change adversely affects both the physical and the mental health of people in all regions of the world. Severe mental health challenges are reported mainly by people who have been exposed to extreme weather events or by rescue workers deployed during such events, and by people who have suffered loss of livelihoods or even their homes, communities or culture as a result of climate change. Physical health is adversely affected primarily by extreme heat. Rising air temperatures and longer and more intense heatwaves have increased the occurrence of diseases and led to higher mortality worldwide, including in the middle latitudes. The elderly, people with medical conditions and outdoor workers are particularly impacted. Additionally, for this latter group, warming is often associated with loss of earnings if extreme heat makes outdoor labour in fields or on construction sites impossible.

Extreme heat is particularly hazardous when it is compounded by very high humidity. If the air is so humid that water and therefore also sweat cannot evaporate, the human body's cooling mechanism begins to fail. As a result, the body steadily overheats, ultimately causing circulatory collapse and – in extreme cases – fatal heat stroke.

The human heat tolerance limit can be determined using the cooling limit temperature. This captures both ambient temperature and humidity. Until recently, it was assumed that a healthy individual cannot survive a cooling limit temperature of 35 degrees Celsius for more than around six hours. This limit is derived from the combination of temperature and humidity and corresponds to 35 degrees Celsius at 100 per cent humidity or 46 degrees Celsius when humidity is 50 per cent.

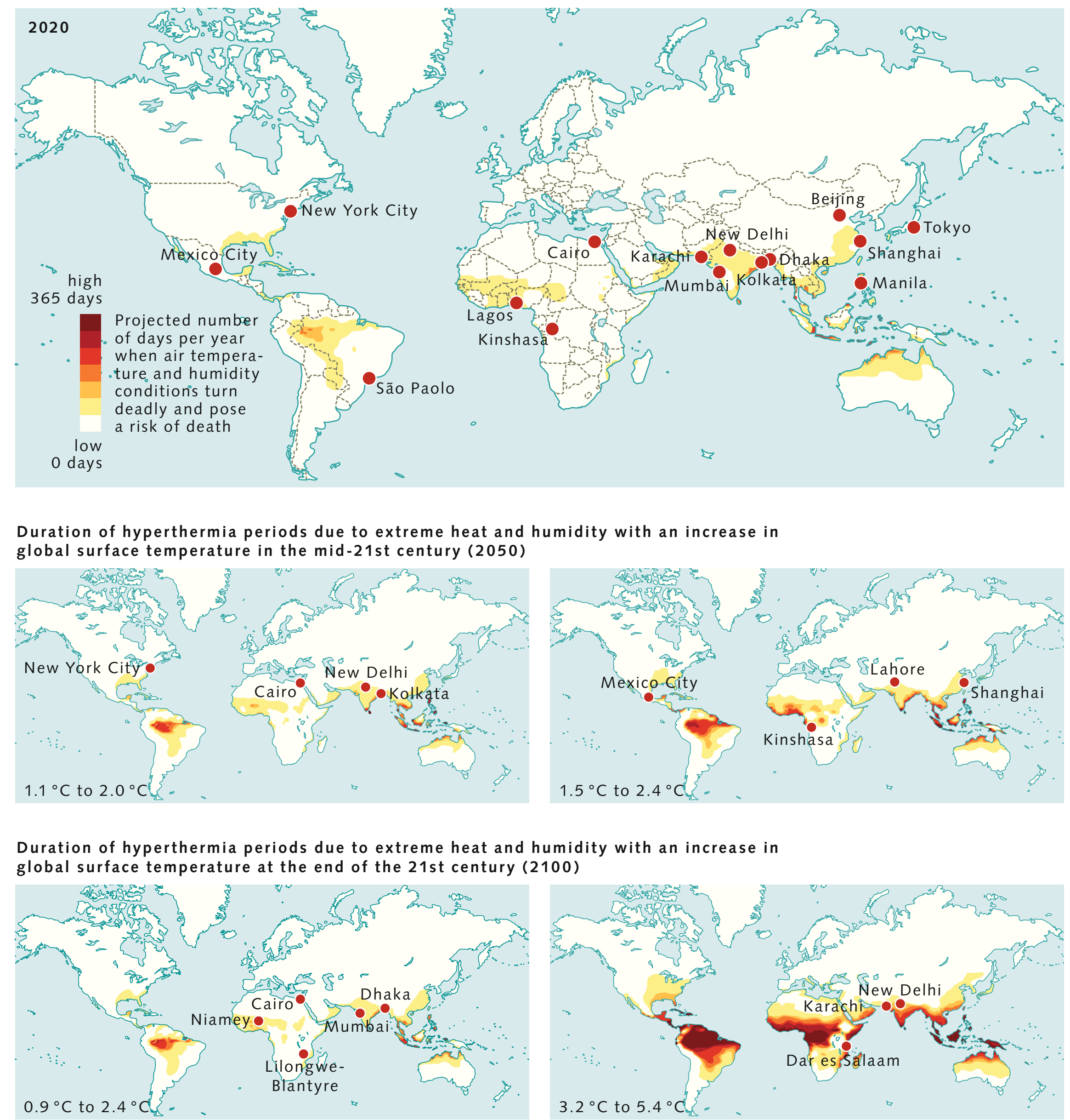
When researchers at Pennsylvania State University in the USA tested this assumption for the first time in heat stress experiments, they found that the theoretical threshold was far too high. In climate chambers with a high level of humidity, an ambient temperature of 30 to 31 degrees Celsius was enough to induce dangerously elevated core temperature in healthy young human test subjects. Contrary to all expectations, a slight decrease in humidity did not increase the test subjects' heat tolerance. Instead, the critical cooling limit temperature under these conditions was just 25 to 28 degrees Celsius – almost ten degrees Celsius lower than scientists had previously assumed. The explanation offered by the research team is that despite the reduction in humidity, the test subjects' sweat production did not increase above a certain temperature.

In the face of continued climate change, these research findings give cause for concern. They show that the heat risk to human health has been underestimated and that with accelerated global warming, more regions will be periodically affected by a level of heat stress that will make it impossible to survive without additional cooling.

In the long term, the situation is likely to be particularly challenging for the many millions of people living in mega-cities in the tropics and subtropics. Firstly, air temperature and humidity here are consistently high for most of the year, and secondly, the heat island effect also comes into play. This is a term used to describe the observation that conurbations reach higher daytime temperatures than less built-up outlying areas. Urban areas also cool down more slowly at night. It may be concluded from this that in mega-cities in the tropics and subtropics, it would only take a comparatively small amount of warming to push inner-city air temperature to such a high level that many people's heat tolerance limit is exceeded.

There is much evidence to suggest that city dwellers are generally exposed to much higher temperatures than those reported for a wider region. For example, during the severe heatwave in India and Pakistan in May 2022, when daytime temperatures climbed as high as 51 degrees Celsius, temperatures remained high overnight, at 35 to 39 degrees Celsius, in the Indian capital New Delhi and neighbouring towns, whereas the air cooled to a tolerable 15 degrees Celsius in nearby fields and forests. Subsequent analyses by an international research team found that human-induced climate change had made this record-breaking heatwave 30 times more likely.

Duration of hyperthermia periods due to extreme heat and humidity



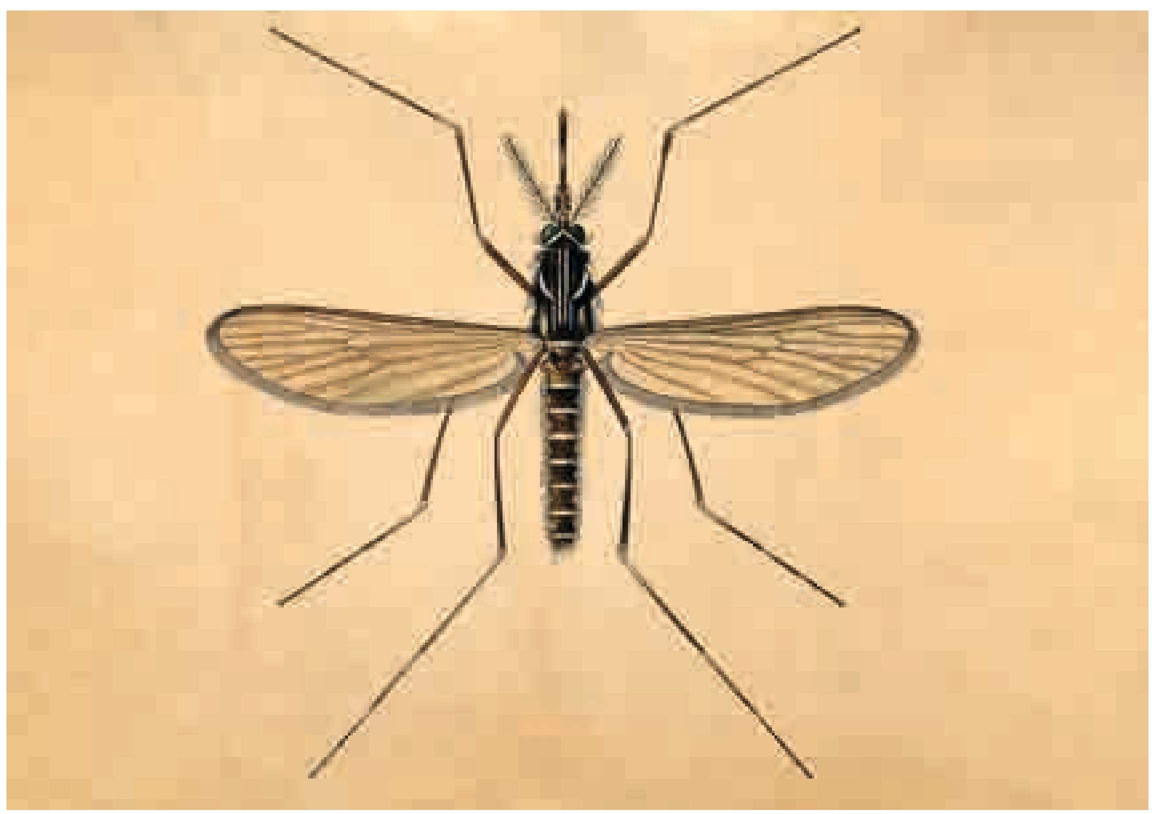
1.9 > When extreme heat is compounded by high humidity, the human body can quickly overheat – a potentially life-threatening situation. This figure from the IPCC shows the various regions of the world where people will be exposed to the risk of overheating (hyperthermia) in future and for how many days a year. The core message: the sooner climate change is curbed, the fewer people will be exposed to this threat to life.

Climate change also increases the occurrence of many infectious diseases. Droughts, for example, heighten the risk that wells will dry up, while heavy precipitation can cause contamination or flooding of wells. In both cases, if communities then extract their drinking water from contaminated sources, their risk of contracting bacterial infections such as cholera increases. Higher temperatures enable *Aedes* mosquitoes to expand their habitat range north- and southwards from the tropics. These insects carry the dengue fever and yellow fever viruses, among others. The risk of contracting dengue fever is already increasing worldwide. Due to the more frequent occurrence of forest fires across larger areas, the risk of respiratory diseases is also increasing in affected regions.

Sea-level rise – land under water!

As a consequence of sea-level rise, the climate risks to people, nature and built assets in the world's coastal areas will increase at least tenfold by 2100, mainly due to the greater frequency of extreme floods. Sea-level rise poses a particular threat to the many millions of people living in low-lying coastal areas and on small islands. Higher tidal floods destroy the species-rich ecosystems in the tidal range, cause salinization of groundwater reservoirs and inundate large areas of land, affecting coastal forests and croplands, as well as coastal districts of large metropolitan areas. Due in part to these areas' uncontrolled growth, ongoing sea-level rise will put increasing numbers of people at risk over time. In Africa, for example, some 108 to 116 million people will be living in high flood-risk areas by 2030, compared with just 54 million in 2000.

Globally, the numbers affected are very much higher: according to figures from the IPCC, more than a billion people in coastal cities and conurbations worldwide will be living with a high flood risk in 2050. The threats they face include recurrent storm surge, as well as the prospect of permanent flooding of their villages and districts.



1.10 > *Aedes* mosquitoes are also known as yellow fever or dengue mosquitoes as they are vectors of both these diseases. As a result of climate change, their range is expanding. Originally found only in the tropics and subtropics, they are now spreading further north and south.

1.11 > The eye-catching collage on the title page of the IPCC's report *Impacts, Adaptation and Vulnerability*, published in February 2022. Its key message: humanity knows what needs to be done to mitigate the impacts of climate change. What is lacking is resolute global action.

Climate change adaptation – the world is unprepared

In order to mitigate the impacts and risks of climate change, people and nature must adapt to the new environmental conditions. For us humans, this primarily entails taking measures to protect our lives, goods and property against high temperatures, weather extremes and sea-level rise. This can be achieved if we relocate from at-risk regions or make local lifestyle changes – for example, by greening our settlements and cities in order to minimize the heat island effect, or by conserving water so that we have sufficient reserves available during droughts.

The list of potential solutions is long. Nevertheless, the IPCC concludes that globally, there is a substantial gap between current adaptation planning and implementation and the levels needed to provide effective and sustainable protection for everyone. What is certain, however, is that there is now a greater awareness of the growing risks. More than 170 countries and many cities are now including adaptation in their climate policies and planning processes. Private sector and civil society actors are also engaging for more adaptation. Pilot projects are being implemented in various sectors, although in many cases, they simply aim to minimize the local storm, flood, heat or drought risk and therefore result in only minor changes with regional and time-limited impact.

In order to mitigate the impending climate risks on a long-term basis, holistic policies and fundamental

Climate justice – the heaviest burden falls on the poor

Climate change confronts humankind with a growing justice problem, namely that the impacts of global warming and more frequent extreme events are felt mainly by low-income and marginalized population groups. For these groups, climate change often poses an existential threat, for it multiplies – by several orders of magnitude – their already substantial economic, social and health challenges and concerns. The greater vulnerability of low-income and marginalized population groups to climate risks stems from three sources:

- The poorest communities generally live in regions where they are particularly exposed to weather extremes and other natural hazards. Examples are slums by rivers (flood risk), illegally constructed housing on mountain slopes (risk of landslides after heavy rainfall) and settlements without mature trees to provide shade and cooling during periods of extreme heat.
- Low-income families often lack access to the financial resources and infrastructures needed for resilience to climate and weather extremes. These resources include energy and water security, access to sanitation and emergency shelters, a well-performing health system, and a reliable supply of all the staple foods. Furthermore, low-income groups very often work in occupations in which both their earnings and their food supply are heavily dependent on the climate, such as agriculture and fishing.
- Low-income and marginalized population groups are often excluded from decision-making at the political level and their needs are rarely, if ever, considered. The IPCC concludes, inter alia, that the adaptation gap between the measures currently being implemented and the levels needed to respond to impacts is significantly greater in low-income regions than in areas inhabited by higher-income groups.

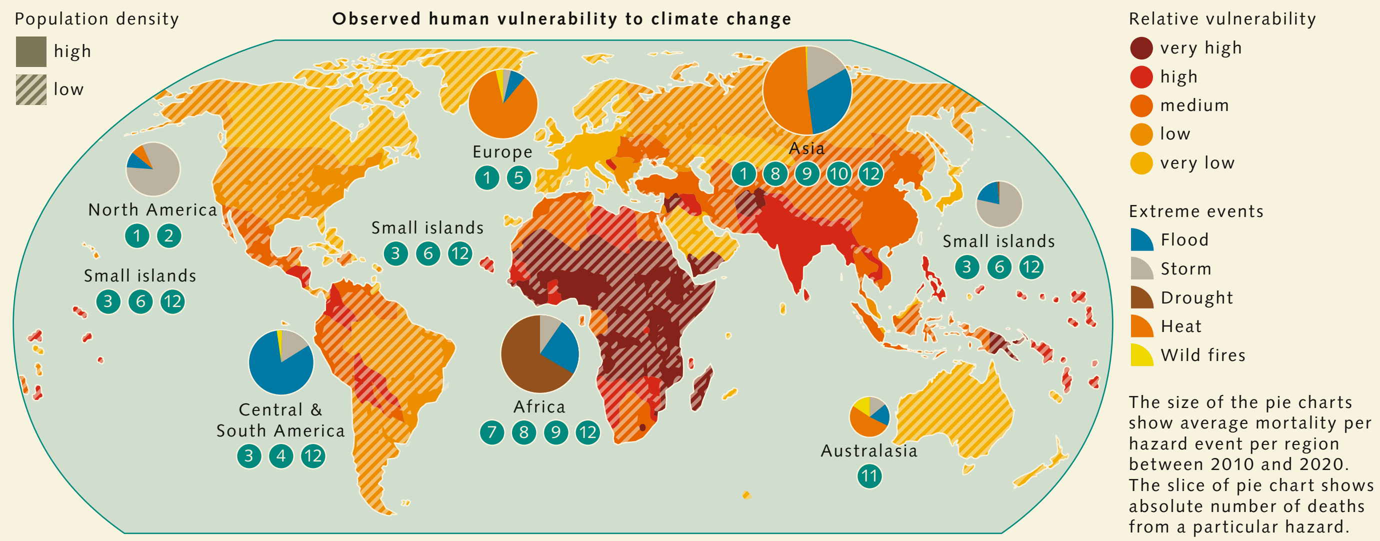
Worldwide, 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change impacts. The implications of this are illustrated by the mortality rates, among other things: over the last decade, human mortality from storms, floods and droughts was 15 times higher in highly vulnerable regions, compared to countries with very low vulnerability. Members of low-income groups are also exposed comparatively often to extreme heat as they tend to be employed in outdoor occupations such as farming, landscaping, construction and artisanal trades.

Adaptation and inclusion – building the resilience of vulnerable groups
Based on these findings, the IPCC has developed an approach for climate resilient development, which focuses primarily on the needs of the most vulnerable population groups. In essence, this approach adroitly combines climate change adaptation and mitigation strategies in such a way that many other social challenges – such as poverty, hunger and discrimination against women – can be addressed at the same time.

Its successful implementation, however, is contingent on various conditions which, in essence, necessitate a transformation of human society and a shift away from current values, economic systems and life goals. If efforts to preserve Earth as a liveable planet for people and nature are to be successful, humankind must take the following action without delay:

- *conserve and sustainably use at least 30 to 50 per cent of Earth's land and ocean areas:* this means only removing the amount of a natural resource (fish, timber, etc.) that can regenerate itself;
- *in decision-making, include all affected population groups in the debate from the outset:* this requires transparent, democratically organized processes in which there is cooperation across all social divides, as well as efforts to achieve a fair balance between diverse interests, values and worldviews;
- *base all decision-making on expert knowledge:* alongside representatives of science and engineering, it is essential to give a hearing to representatives of local expertise and to local interest groups and indigenous communities;
- *prioritize issues of justice and fairness:* the precarious situation of low-income or marginalized population groups will change only if they are given a voice and this voice is heard and considered. In many regions, these still marginalized groups mainly include women, young people and members of indigenous communities;
- *provide adequate funding for climate change adaptation measures and for the transformation of the economy and society;*
- *cooperate on a transboundary and transnational basis.*

Even in a world without climate change, effecting this transformation would be an immense challenge for society. If climate-related loss and damage are factored in, the situation becomes very much worse, for every additional tenth of a degree of warming further limits our scope for action. The IPCC (Intergovernmental Panel on Climate Change) sums up what is at stake: in a world that has warmed by more than two degrees Celsius, humankind will likely have no chance of creating a liveable future for all the Earth's citizens.



Vulnerability at the national level varies. Examples of particularly vulnerable groups in local contexts are:

1. Indigenous Peoples of the Arctic: health inequality, limited access to original hunting grounds and culture
2. Urban ethnic minorities: structural inequality, marginalization, exclusion from planning and decision-making processes
3. Smallholder coffee producers: limited market access and stability, single crop dependency, limited institutional support
4. Indigenous Peoples in the Amazon: land degradation, deforestation, poverty, lack of support
5. Older people, especially those poor and socially isolated: health issues, disability, limited access to support
6. Island communities: limited land, population growth and coastal ecosystem degradation
7. Children in rural low-income communities: food insecurity, sensitivity to undernutrition and disease
8. People uprooted by conflict in the Near East and Sahel: prolonged temporary status, limited mobility
9. Women and non-binary: limited access to and control over resources, e.g. water, land, credit
10. Migrants: informal status, limited access to health services and shelter, exclusion from decision-making processes
11. Aboriginal and Torres Strait Islander Peoples: poverty, food and housing insecurity, dislocation from community
12. People living in informal settlements or slums: poverty, limited basic services and often located in areas with high exposure to climate hazards

1.12 > People throughout the world are exposed to the impacts of climate change. There are, however, some particularly vulnerable groups with less resilience to extreme events such as heat, drought, storms, floods and forest fires.

1.13 > A vivid comparison: In the US city of Los Angeles, an adequate number of roadside trees to provide shade exists only in districts where residents have sufficient resources to pay for the trees' upkeep (above). Trees are absent in poorer districts, partly because the city government does not invest in roadside trees. As a result, there is no cooling shade for local residents when temperatures soar.

adjustments to our lifestyles are required, which must include how we work, how we produce our food and treat the natural environment, and how we plan and construct our cities and settlements. The IPCC concludes that at present, humanity is completely unprepared for all the challenges that lie ahead as a result of climate change – particularly if the world warms by more than 1.5 degrees Celsius. Scientists refer in this context to an adaptation gap.

This gap is particularly large in regions where people are poor and highly exposed to climate risks. Furthermore, if the adaptation measures currently being planned are compared with the climate impacts predicted by scientists, it is already clear that this adaptation gap will widen steadily.

The limits to adaptation

Also new is the clarity with which the IPCC now describes the limits to human adaptation to climate change. In doing so, it differentiates between hard and soft limits. Hard limits are those where adaptive actions are no longer possible. For example, if an atoll is inundated by waves due to sea-level rise, resulting in the complete salinization of all the drinking water reserves, the island dwellers' only long-term option is to leave. The same applies to flora and fauna that have already reached their upper temperature limit. If their habitats continue to warm, they are forced to migrate.

Soft limits, by contrast, are ones where options for adaptive action may exist. However, this requires political commitment, sufficient financial resources, scientific knowledge and local know-how. If all four factors are in place, it may be possible, for example, for farmers in drought-affected regions to cultivate new species that are resistant to aridity and to install modern irrigation systems in order to reduce their demands upon lakes, rivers and groundwater resources.

It is already clear, however, that many species of flora and fauna have already reached or are about to reach their hard adaptation limits. If they were to die out locally, this would destroy the livelihoods of the many millions of farming, fishing and pastoralist families who depend on these species. With global warming of 1.5 degrees Celsius or more, the ongoing decrease in snowfall and glacier retreat will mean that communities whose water supply depends on meltwater no longer have access to adequate water resources. And with warming of two degrees Celsius or more, it will become far more difficult to make a success of arable farming in many of the world's cereal-growing areas.

As these few examples of adaptation limits show, the more quickly humankind acts to curb climate change, the more opportunities there will be to adapt to the new conditions and the more effective these options will be. Actions which will work with warming of 1.5 degrees Celsius may prove to be completely ineffective once warming reaches two degrees Celsius. For that reason, the effectiveness of all adaptation actions must be continuously monitored and the effects of the various measures regularly reviewed.

Climate, people and nature can only be winners together

The IPCC's *Sixth Assessment Report* also highlights the scientific community's new understanding of the close interconnections and interactions between nature, people and the climate. For example, if humans impair species diversity by destroying natural habitats and exploiting their resources, they deprive themselves of their most important partner in the fight against climate change. Yet at the same time, humanity is forcing the climate-related decline of natural ecosystems with its persistently high greenhouse gas emissions.

Breaking out of this conflict spiral and reversing past mistakes must henceforth be the goal of all human action. Among other things, this means thinking holistically about people, nature and the climate – in our daily lives and in all our decision-making, whether at local, national or international level. Only then will it be possible to identify solutions that benefit all three systems in the long term and guarantee a liveable future on Earth for present and future generations.

Solutions to the greenhouse gas problem?

> Climate change is man-made and undeniably a consequence of the unchecked emission of greenhouse gases. Stopping emissions is thus the only way out of the climate crisis. There is presently an abundance of suggestions for how human societies can avoid a large portion of their emissions. However, it will certainly not be possible to eliminate all emissions by the year 2050, even if a great effort is made towards that end. Residual amounts will thus have to be compensated for by the deliberate removal of carbon dioxide from the atmosphere.

Humankind alone is responsible for climate change and its consequences

Halting climate change and preventing its drastic consequences is the duty of humans because they alone are responsible for the global warming that has occurred up to now. There is no longer any doubt that climate change is man-made. According to the Intergovernmental Panel on Climate Change, global warming over the past 120 to 170 years can be clearly attributed to human-induced greenhouse gas emissions. The primary contributors include carbon dioxide, methane, nitrous oxide (laughing gas) and chlorofluorocarbons (CFCs), as well as 16 additional chemicals.

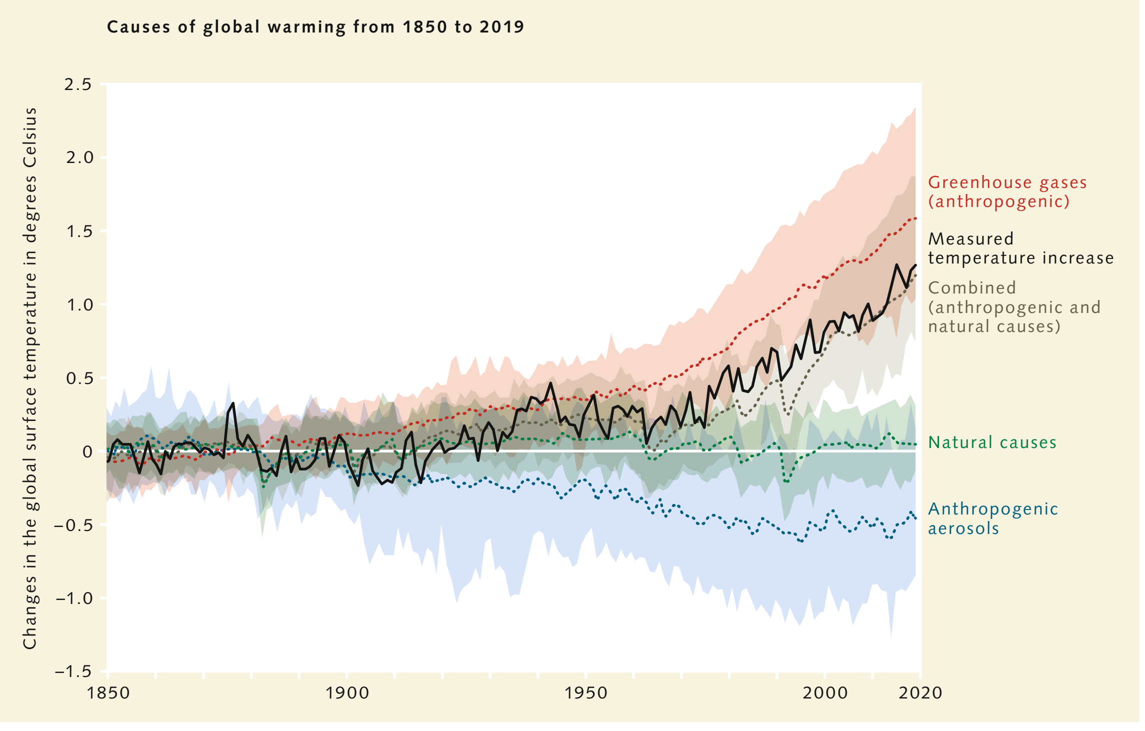
The enrichment of these greenhouse gases in the atmosphere is steadily reducing our planet's ability to radiate heat energy into space. The surplus heat in the Earth's atmosphere first warms its air masses, then subsequently also the ocean. This process is based on the same physical principle that warms a garden greenhouse. The consequences of increasing atmospheric greenhouse gas concentrations are therefore known as the greenhouse effect. It is important to understand that a significant portion of the total warming triggered by greenhouse gases is not yet being observed by humans or in nature because it is masked by the cooling effects of aerosols like soot particles and sulphur dioxides, as well as by changes in the reflectivity of the Earth's surface. Without these cooling components the level of global warming would already be at 1.5 degrees Celsius today.

The concentrations of greenhouse gases in the Earth's atmosphere are being monitored around the world by research institutions such as the US American National Oceanic and Atmospheric Administration (NOAA). Each year NOAA publishes its *Annual Greenhouse Gas Index* (AGGI). This is a numerical expression of how much additional heat energy has remained in the atmosphere as a result of man-made greenhouse gas emissions compared to the reference year 1990, and is continuing to drive global warming. In 2022 the NOAA Greenhouse Gas Index rose to a value of 1.49. This means that the greenhouse gases released by human activities trapped an astonishing 49 per cent more heat energy in the Earth's atmosphere in 2022 than they did in the reference year.

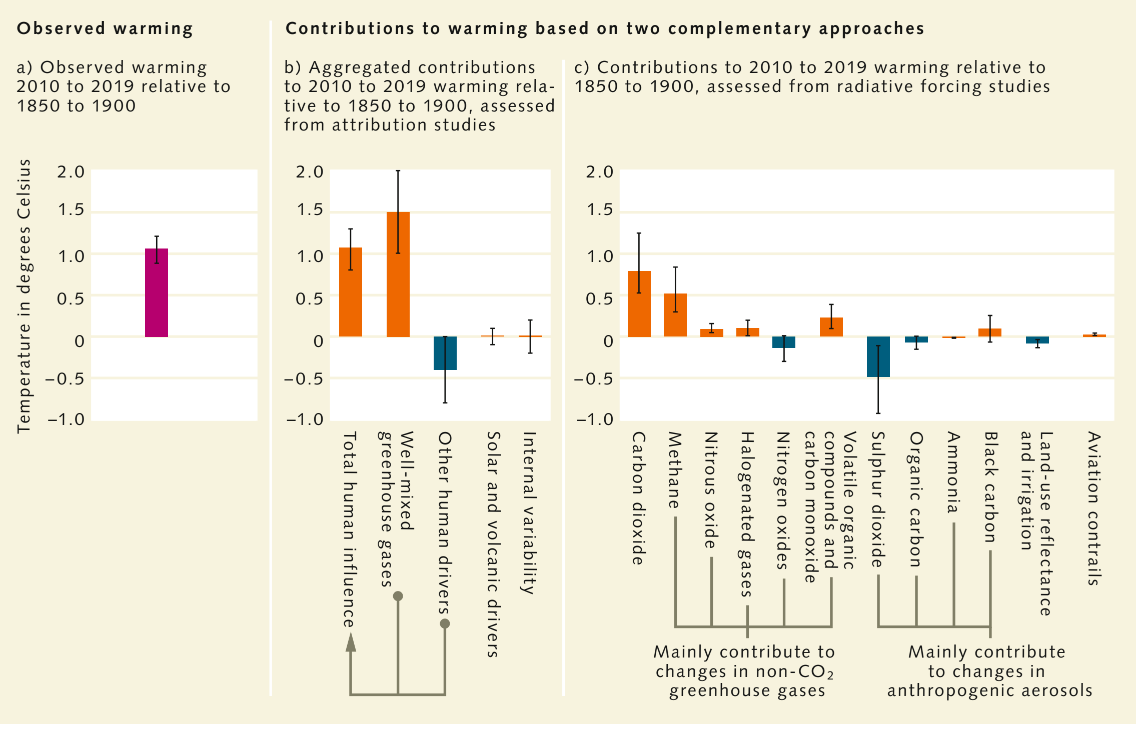
The greatest proportion by far of this increasing heat accumulation, around 80 per cent, has been contributed by carbon dioxide (chemical formula: CO_2). This greenhouse gas is especially long-lived. It does not break down chemically in the atmosphere, and thus can only be removed through a variety of processes (such as CO_2 uptake by plants). For this reason, carbon dioxide can remain in the Earth's atmosphere for as long as 1000 years and thus has a long-term effect on the climate.

Carbon dioxide is emitted as a product of almost all human activities. It is primarily produced by:

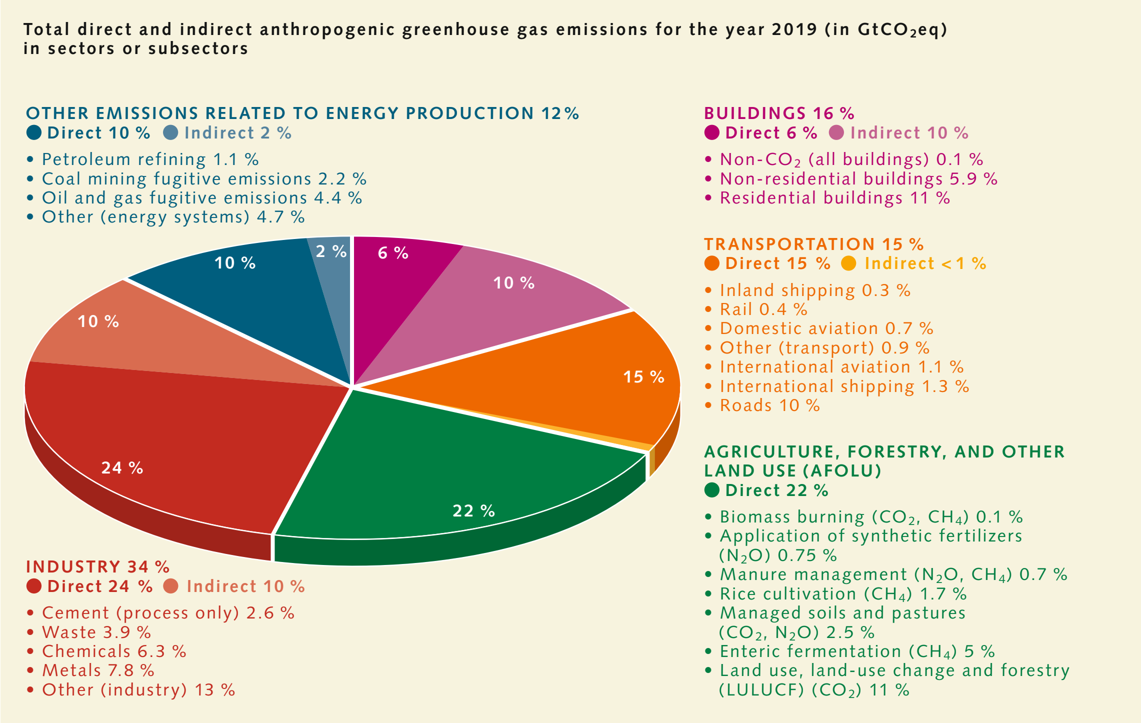
- *the burning of fossil fuels such as coal, oil and natural gas:* According to the Intergovernmental Panel on Climate Change, around 34 per cent of the global carbon dioxide emissions in the year 2019 came from the energy sector, while the traffic and transport sector accounted for 15 per cent and the industrial sector for 24 per cent;
- *the decomposition of organic materials (animal and plant remains) due to land-use changes:* Agricultural, forestry and other land-use changes accounted for around 22 per cent of the global carbon dioxide emissions in 2019;



1.14 > Humans are causing climate change. This is clearly evidenced because the measured warming of the Earth (black line) can only be realistically represented in climate models when they combine the natural with all human-influence factors (grey dotted line and shading).



1.15 > Global warming is a result of anthropogenic greenhouse gas emissions. Aerosols released by human activities, mainly sulphur and nitrous oxides, have so far had a cooling effect by reflecting incoming sunlight back into space.

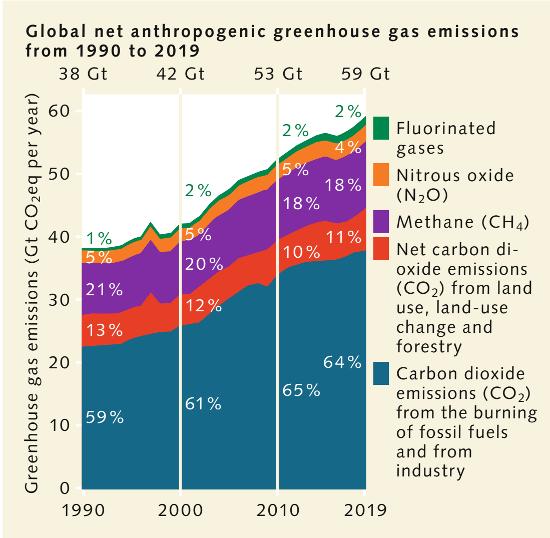


1.16 > Overview of the direct and indirect greenhouse gas emissions for the individual sectors in the year 2019. The total emissions are recalculated to carbon dioxide equivalents. The percentage values shown in the sums do not always add up to 100 per cent due to rounding.

Direct and indirect emissions

Direct emissions are closely related to activities within a clearly defined area, region, sector or company (for example, CO_2 emissions by the burning of oil in the heater of a building). Indirect emissions, on the other hand, are produced outside the defined area (heating a building by district heat: Indirect emissions result from combustion in the geographically removed gas or coal power plant).

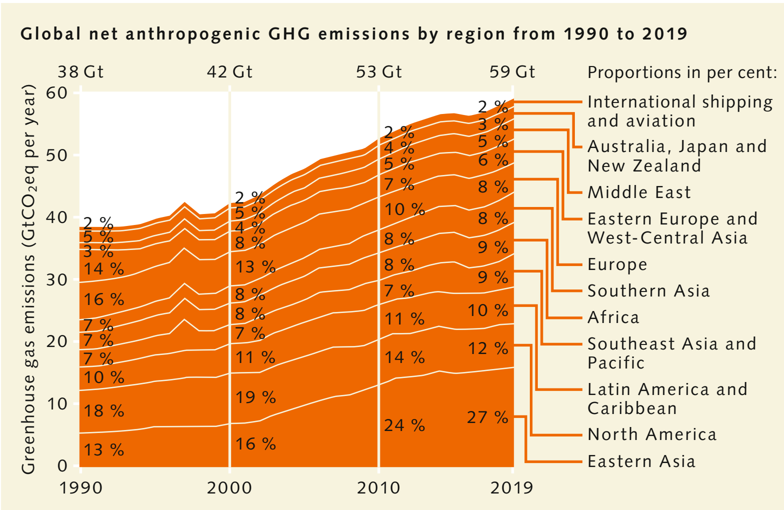
- *industrial processes such as the production of cement:* Cement is made of limestone, which is burned at temperatures of 1450 degrees Celsius to achieve the required material properties. During the burning process, carbon dioxide escapes from the primary material in large quantities. The process-related emissions from cement production alone accounted for around 2.6 per cent of the total global carbon dioxide emissions in the year 2019. This amount does not include indirect emissions, which include the energy used in the process and for transport. In Germany, the production of one tonne of cement is responsible for around 600 kilograms of carbon dioxide emissions. Approximately two-thirds of this amount are due to raw-material processing emissions, and one-third to fuel emissions.

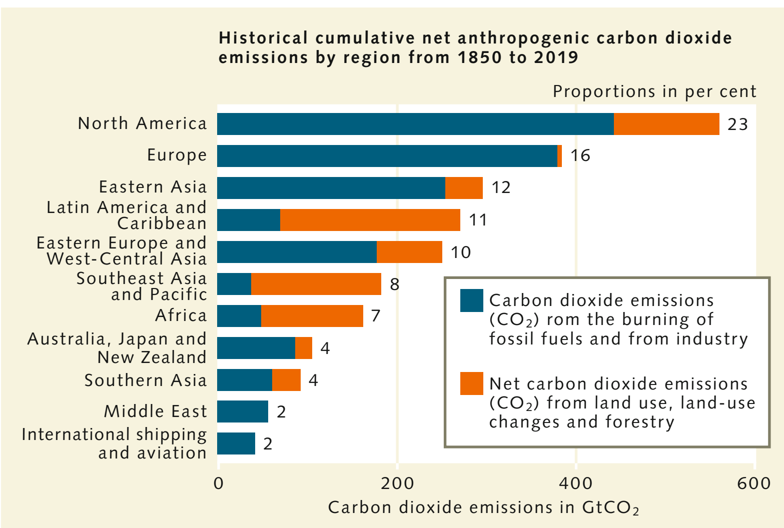


1.17 > The amount of all relevant anthropogenic greenhouse gases has steadily increased during the period from 1990 to 2019.

The annual worldwide carbon dioxide emissions resulting from cement production and the burning of fossil raw materials now add up to around 36 billion tonnes of CO_2. Added to this are the emissions from agriculture and forestry as well as changes in land use, at levels of around four billion tonnes of carbon dioxide. On a global scale, these emissions have been increasing for the past 270 years, although their growth has slowed down for the present.

1.18 > Gravel is produced at a Chinese quarry. Industrial companies like this one are responsible for more than one-third of the world's greenhouse gas emissions.





1.19 and 1.20 > Various regions of the world contribute to greenhouse gas emissions to greatly different degrees – both at present and in retrospect, whereby all emissions are added cumulatively.

Record values – every year

Consistently high emission levels are resulting in a steady rise in carbon dioxide concentrations in the Earth's atmosphere. For the month of May 2023, the carbon dioxide monitoring station at the Mauna Loa Observatory on the Island of Hawaii observed a record-high monthly value of 424 parts per million (ppm), an increase of 3.0 ppm compared to the value of may 2022, and the highest atmospheric CO_2 concentration in the past two million years. Carbon dioxide is definitely the strongest driver of climate change, but it is not the only one. In addition to the long-lasting gas, human societies are also increasingly releasing more short-term climate-impacting pollutants such as methane (CH_4), laughing gas (N_2O) and fluorinated greenhouse gases. Unlike carbon dioxide, these compounds break down chemically in the atmosphere. As a rule, their effect on climate becomes negligible in less than 20 years. But for as long as they exist in the atmosphere, the short-lived greenhouse gases do contribute significantly to climate change. Methane, for example, over a period of 20 years, retains 80 times more heat in the Earth's atmosphere than the same amount of carbon dioxide.

In its current report, the Intergovernmental Panel on Climate Change concludes that the increased emissions of methane from 1850 to 2019 were responsible for around 0.5 degrees Celsius of the global warming observed during that time. Converting methane concentrations and their climate impacts to carbon dioxide equivalents reveals that anthropogenic methane emissions accounted for around 18 per cent of total emissions in 2019.

Methane concentrations in the Earth's atmosphere have been directly measured since 1983. According to NOAA, the average methane concentration in the year 2022 was exactly 1911.8 parts per billion (ppb). In the year 1750, based on climate archives, it was only 729 ppb. This means that the Earth's atmosphere now contains 162 per cent more methane than it did at that time. Methane concentrations have not been this high in the past 800,000 years.

Methane is released, on the one hand, through natural sources such as swamps, mangrove forests, salt marshes and seagrass meadows. But it is also released by human activities, particularly:

- *in agriculture:* digestive processes of ruminants, rice cultivation, and manure, slurry and digestate management;
- *in the energy sector:* coal production, oil and natural gas production and transport, burning of biomass and biofuels; as well as
- *in solid waste and wastewater management:* releases from landfills, wastewaters and sewage sludges.

These anthropogenic methane emissions can be reduced with relatively little effort. Furthermore, because atmospheric methane breaks down chemically within a time frame of about nine to twelve years, thus losing its impact on climate, strategies to reduce the release of methane are seen as especially promising measures in the struggle against climate change. Recent research indicates, for example, that by the year 2050 around 0.25 degrees Celsius of additional warming could be prevented through the immediate implementation of all the presently known options for curbing man-made methane emissions.

When will global warming exceed the 1.5-degree mark?

Every additional tonne of released greenhouse gases continues to advance the progress of global warming. This near-linear relationship has been well documented by science, at least for carbon dioxide. It is now known that 1000 billion tonnes (one thousand gigatonnes) of carbon dioxide emissions cause the global surface temperature to rise an additional 0.27 to 0.63 degrees Celsius – and this occurs every time that the atmosphere is newly enriched by this amount of carbon dioxide.

But a much more common question in the climate change debate is when a particular warming level will be reached. The 2015 Paris Climate Agreement, for example, sets a target of limiting global warming to well below two degrees Celsius, and if possible to 1.5 degrees Celsius compared to preindustrial levels. A difficulty with this, however, is that the Agreement explains neither how the specific warming levels are defined, nor exactly what time period is meant by the term "preindustrial".

Climate researchers, therefore, have agreed on a common baseline. The warming level is defined with respect to the time period from 1850 to 1900 – although with full

Carbon dioxide equivalent
In order to compare the impacts of the different greenhouse gases, researchers calculate how much carbon dioxide would be required, within a certain time frame, to produce the same effect on a particular climate parameter with a given amount of methane, laughing gas, or a mix of other greenhouse gases. This calculated amount of CO_2 is referred to as the carbon dioxide equivalent.

1.21 > Farmers in the province of Sindh, Pakistan, herd their goats over flooded terrain. Heavy rains and flash floods in July and August 2022 inundated large areas of Pakistan, causing severe damage in half of its provinces.

Sector	Selected measures to reduce anthropogenic methane emissions
Farming: livestock	• Use of a pre-treated, more easily digestible animal feed • Feeding seaweed and other emission-reducing additives • Improved herd management • Improved handling of manure (e.g. covering) • Introduction of anaerobic fermentation systems for cattle and pig manure • Use of the slurry in biogas plants • Breeding livestock that produce less methane • Behavioural change: largely abstaining from meat and changing to a plant-based diet
Agriculture, especially rice cultivation	• Improved irrigation and cultivation techniques, including regular flooding of rice fields and allowing them to dry out again • Use of new rice varieties • Measures to improve soils • Behavioural change: reduction of food waste
Oil, natural-gas and coal production	• Recovery and utilization of escaping gas • Sealing methane leaks at active boreholes and pipelines • Avoiding methane leaks during transport of oil and gas • Closing boreholes no longer in use • Employing modern pumping and production technology • Flooding of disused coal mines • Ending the use and production of fossil fuels
Waste and wastewater management	• No landfilling of organic waste, instead utilize it in biogas plants • Recovery of landfill gases and their direct use for production of energy • Recycling of industrial and municipal waste • Conversion from open sewers to aerobic wastewater treatment • Conversion of the treatment of household wastewater to anaerobic treatment with biogas recovery and utilization • Conversion of industrial-wastewater and sewage-sludge treatment to a two-stage process – anaerobic treatment with biogas recovery followed by aerobic treatment

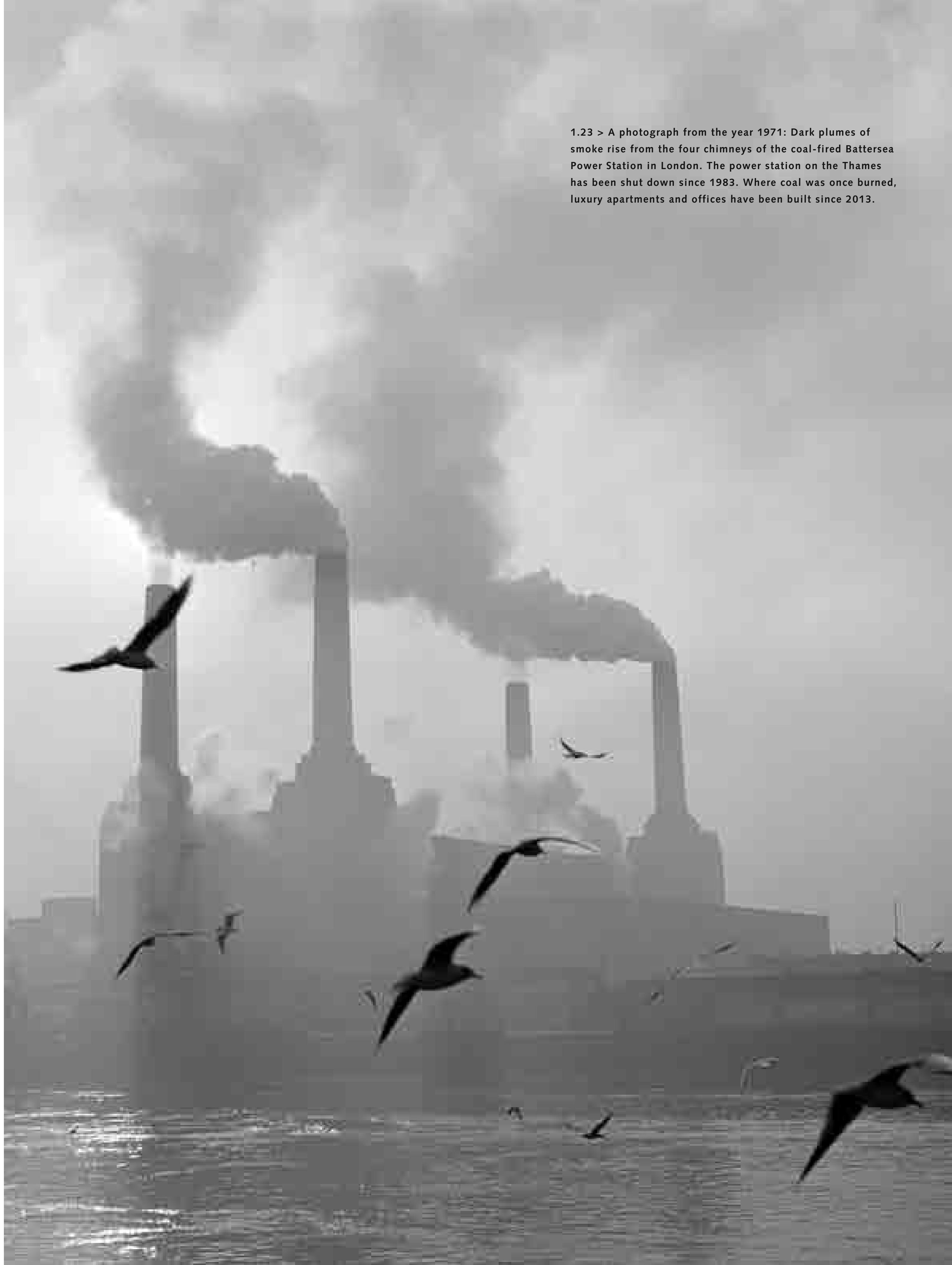
1.22 > Climate change could be mitigated effectively if human societies were able to reduce their methane emissions. The steps needed to do this are well known. But the solutions would have to be implemented comprehensively.

awareness that industrialization had actually begun 100 years earlier and that carbon dioxide emissions had already risen rapidly, especially in Great Britain. Data of acceptable quality on the global surface temperatures of the Earth, however, only extend back to the year 1850. Researchers have therefore selected the period of 1850 to 1900 for comparison purposes.

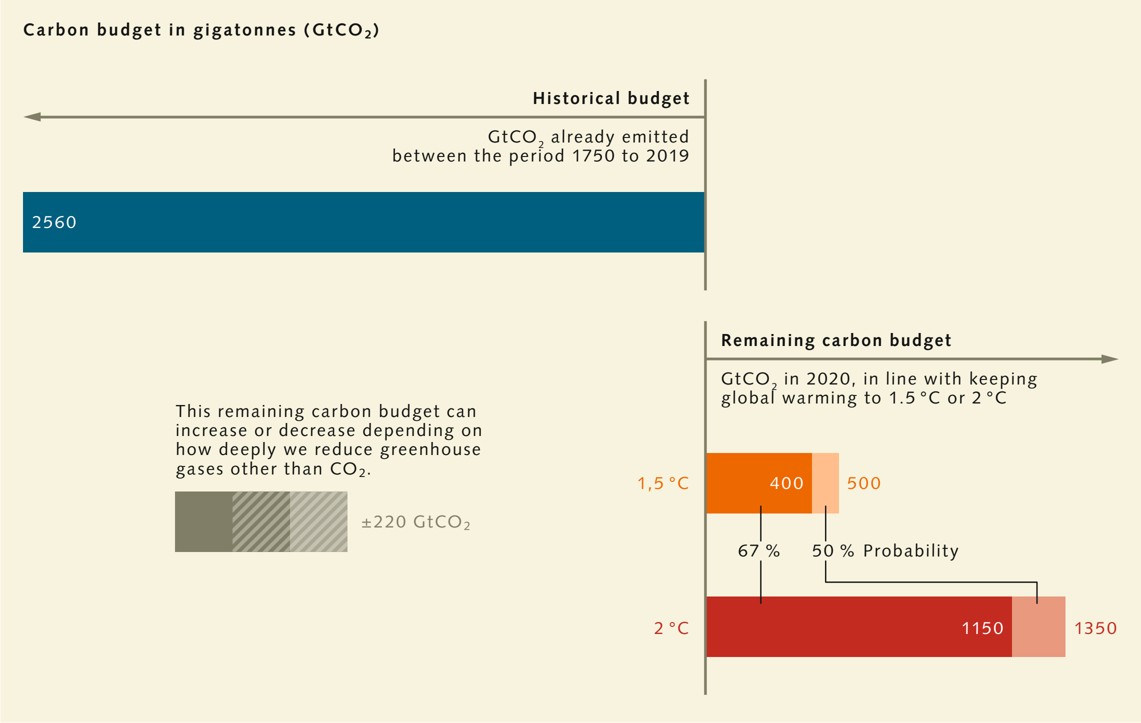
The answer to the question of when global warming exceeds a certain temperature limit is constrained by calculating warming as an average value over a 20-year period. For climate researchers, this means that the 1.5-degree limit is reached when the average surface temperature over a 20-year period lies 1.5 degrees Celsius above the average value between 1850 and 1900. But what exactly would that value be?

Precisely predicting the trend of temperature change is still difficult because the amount of future warming depends on four factors: the amount of future greenhouse gas emissions, the internal variability of the climate system (i.e., the natural fluctuations), climate sensitivity, and the uncertainties in determining the temperature levels for the reference time period of 1850 to 1900.

Researchers use the term “climate sensitivity” to refer to the amount of long-term climate warming that would be triggered by an abrupt doubling of the carbon dioxide concentration in the Earth’s atmosphere. According to current figures from the Intergovernmental Panel on Climate Change, there is a 90 per cent probability that this value would be between two and five degrees Celsius, whereby it would take several decades to centuries for the warming



1.23 > A photograph from the year 1971: Dark plumes of smoke rise from the four chimneys of the coal-fired Battersea Power Station in London. The power station on the Thames has been shut down since 1983. Where coal was once burned, luxury apartments and offices have been built since 2013.



1.24 > Because carbon dioxide accumulates in the atmosphere, scientists can calculate the amounts that can still be released before a certain level of warming is reached. In the year 2020 this amount was an additional 400 gigatonnes of carbon dioxide for the world to reach the 1.5-degree target with a probability of 67 per cent.

to occur and for the climate system to return to a state of equilibrium after the disturbance (i.e., after the doubling of the carbon dioxide concentration).

Because the range of this value has a span of three degrees Celsius, climate models can produce significantly different results. If scientists use an intermediate sensitivity value in their climate models, calculations based on the five Shared Socioeconomic Pathways indicate that the 20-year average temperature in the time frame from 2020 to 2039 will reach the 1.5-degree limit, totally regardless of what amounts of greenhouse gases humans release in the coming years. If emissions remain at the present high levels or continue to increase, global warming will exceed the limit of two degrees by the year 2050.

The amount of time remaining to curb climate change can be assessed by what scientists call the carbon budget, which is an expression of how much carbon dioxide can still be emitted by human activities before a given level of warming is reached. The calculations for this are based on the assumption that the global surface temperature rises by around 0.45 degrees Celsius (0.23 to 0.65 degrees) when humankind releases an additional 1000 billion tonnes of carbon dioxide into the atmosphere. Other factors that are considered include past warming, the contribution of greenhouse gases other than carbon dioxide to future warming, and the question of how long the warming will continue to progress even if humans manage someday to reduce their carbon dioxide emissions to zero.

During the period from 1750 to 2019, human societies emitted around 2560 billion tonnes of carbon dioxide. Taking all methodological uncertainties into account, the Intergovernmental Panel on Climate Change finds that this amount of greenhouse gas is probably already enough to reach the 1.5-degree mark. According to the experts, this means that the remaining carbon budget would be zero, although the probability of this would be low. However, if the "best estimates" are used for the most important parameters, the calculated carbon budget is greater than zero.

Nonetheless, the results indicate that it is still small: If humans want to limit global warming to 1.5 degrees Celsius with a probability of 67 per cent, they can only release

Paris Climate Agreement
The Paris Climate Agreement was adopted on 12 December 2015 at the 21st Climate Conference in Paris and entered into effect on 4 November 2016. By September 2022, 194 countries and the European Union had signed and ratified the agreement.

a total of 400 billion tonnes of carbon dioxide, calculated for the period beginning on 1 January 2020. This corresponds roughly to the amount of carbon dioxide emitted by the international community over the past decade (2010 to 2019). The budget for the two-degree target is 1150 billion tonnes. Based on constant continued emissions at the current level of around 40 billion tonnes per year, the two budgets would be exhausted by the years 2030 or 2050, respectively.

The following statistic also shows how little margin we have remaining: If humankind were to allow all fossil infrastructures already in operation in 2018 – i.e., coal and natural-gas power plants, oil refineries, blast furnaces, combustion engines, etc. – to continue running at the same capacity as they have in the past until the end of their respective lifetimes, an additional 660 billion tonnes of carbon dioxide would be released in the coming decades. If this calculation is expanded to include all of the installations that were planned or under construction in the year 2018, another 187 billion tonnes of carbon dioxide would have to be added to that sum. Limiting global warming to less than two degrees Celsius under these conditions would be in serious jeopardy. A ban on new coal or natural-gas power plants would thus be an important step towards preventing future emissions.

The ultimate goal: greenhouse gas neutrality

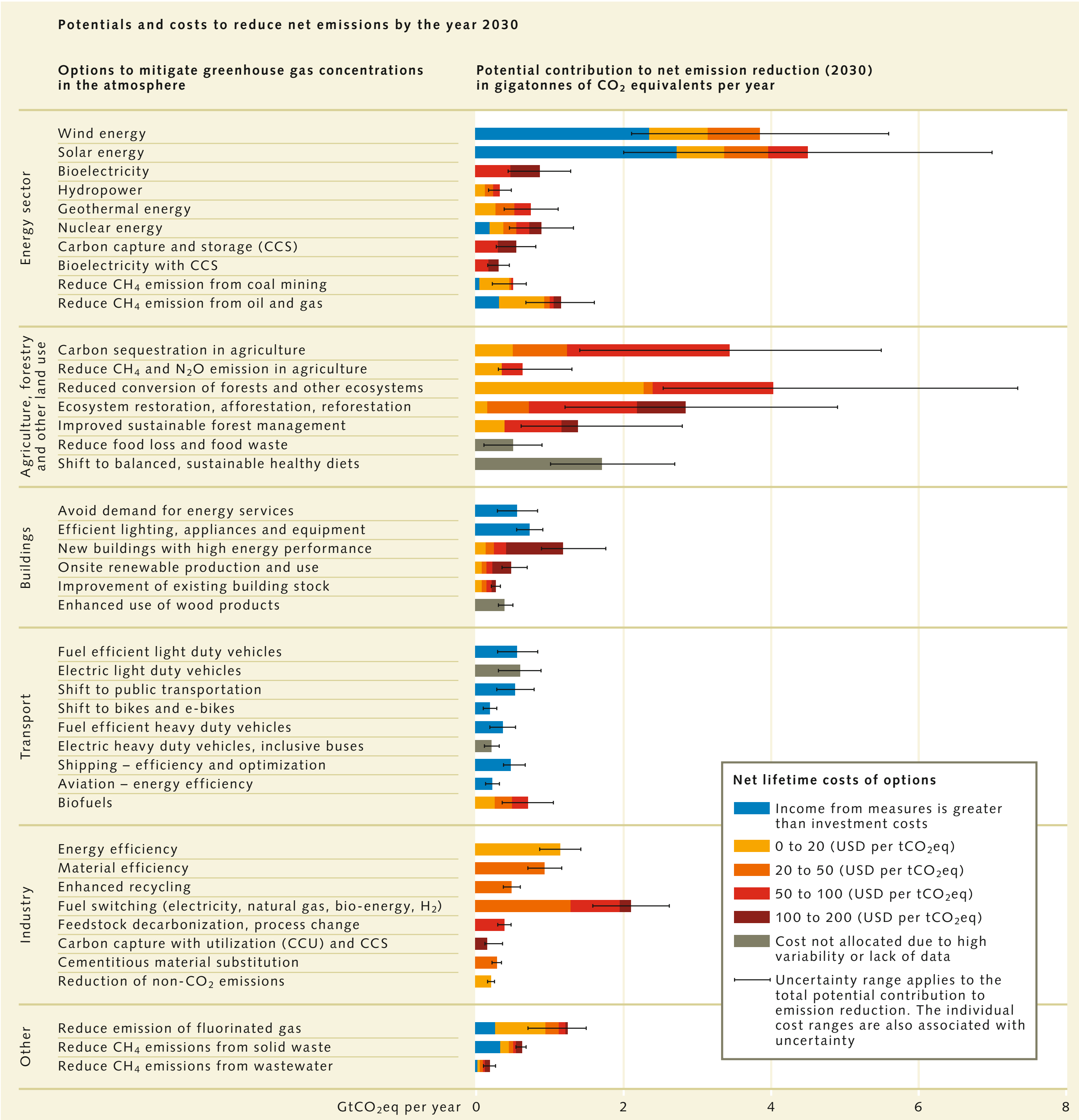
Limiting global warming to 1.5 degrees in the coming decades will now hardly be possible – at least not without overshooting the temperature target for a few decades (surplus scenario). Through a huge effort, however, it may be possible to limit global warming to less than two degrees Celsius. To realize this goal would require immediate and wide-ranging reductions of global greenhouse gas emissions, as well as achieving net zero carbon dioxide emissions by the year 2050.

There are ideas for far-reaching emission reductions in every sector. According to the Intergovernmental Panel on Climate Change, it is possible to cut global greenhouse gas emissions in half by 2030 based on known options. More than half of the potential reduction can be realized through measures that would cost less than 20 US dollars per tonne of carbon dioxide that is eliminated, a fact that is especially important for poorer countries. Examples of these include the worldwide expansion of wind-power and photovoltaic systems for generating electricity from renewable sources, an end to deforestation and the draining of wetlands, improved carbon storage capacities in many fields through sustainable and soil-conserving agriculture, a substantial reduction in meat consumption, construction of energy-efficient buildings, the use of alternative fuels in industry, and measures to curb methane emissions.

This may appear to be a perfectly feasible programme. It requires, however, the successful implementation of comprehensive structural and societal changes, as well as restructuring and rethinking at all levels, including new ideas about what people need (and must consume) and do not need to live. Furthermore, cutting the emissions by half would only be the first step.

This would have to be followed by a reduction of greenhouse gas emissions to such an extent that greenhouse gas neutrality is achieved as soon as possible. The term "greenhouse gas neutrality" and the synonymously used term "net-zero greenhouse gas emissions" both describe a world in which humans or individual entities such as states and companies only release as much greenhouse gas as they can remove again from the Earth's atmosphere. Experts distinguish the terms "carbon neutrality" (net zero carbon dioxide emission) and "greenhouse gas neutrality" (net zero of all greenhouse gas emissions, including carbon dioxide). The reason, in terms of climate physics, is that the global surface temperature could be stabilized if humans would release only as much carbon dioxide as they can remove, while at the same time reducing the release of short-lived air pollutants such as methane and laughing gas by a certain amount. If all greenhouse gas emissions could be reduced to net zero, on the other hand, the global temperature would even begin to fall over the long term. A net zero of carbon dioxide emissions is thus a major, indeed fundamental prerequisite to halting global warming. But with the added help of a net zero of all greenhouse gas emissions it would even be possible to roll back global warming by a small amount.

Surplus scenario
A development in which the global surface temperature rises above a defined climate target (for example, 1.5-degree target) for an initial time period of one or more decades, but subsequently falls again below the temperature threshold, is called a surplus scenario. However, the temperature decline can only occur if the greenhouse gas concentration in the atmosphere is really decreased through a process of carbon dioxide removal.



1.25 > Approaches are now available that would effectively reduce greenhouse gas emissions in all areas of life by the year 2030. This figure from the Intergovernmental Panel on Climate Change lists the most effective measures and shows the costs at which the reductions would be possible. It is important to note that investing in such reductions would cost much less than remedying the consequences of continued climate change.

Methods for carbon dioxide removal

The term "carbon dioxide removal" (CDR) is used to discuss and research the methods that can be applied for removing carbon dioxide from the atmosphere. Although ideas for the removal of methane are also beginning to be suggested, scientific assessment of their feasibility is not yet possible due to insufficient research at present.

CDR covers a wide range of processes that can be used to remove carbon dioxide from the atmosphere and then store it permanently. Possible storage sites include the deep geological subsurface, the oceans and sites on land, especially soils and vegetation. A fourth option would be to use the extracted carbon dioxide to make various products from carbon.

Carbon dioxide removal – offsetting residual emissions that are difficult to avoid

Climate researchers assume that the international community, despite its highly ambitious climate policies, will still be emitting several billion tonnes of residual greenhouse gases (carbon dioxide, methane, laughing gas) by the middle of the 21st century. These hard-to-avoid residual emissions will be generated, for example, in the production of cement and steel, in aviation and heavy-duty transport, and in agriculture and waste incineration.

To achieve greenhouse gas neutrality, these residual emissions will have to be compensated for using carbon dioxide removal methods. There are various proposals for solutions that involve either the expansion of natural carbon sinks or technological approaches. Experts assign the numerous CDR methods to four categories:

- enhancement of the biological carbon dioxide sinks on land, e.g. through reforestation,
- enhancement of the biological carbon dioxide sinks in the ocean, e.g. through the restoration of damaged or dead mangrove forests and seagrass meadows,
- geochemical approaches, and
- chemical methods.

It is important to note that only those methods can be counted that result from human efforts to enhance the removal of carbon dioxide from the atmosphere. Trees that naturally establish themselves somewhere, photosynthesize, absorb and sequester carbon dioxide should not be included in the CDR balance. The official CDR definition of the Intergovernmental Panel on Climate Change is so narrow that even approaches in which carbon dioxide from fossil sources is captured at the emission site and subsequently stored underground (Carbon Capture and Storage, CCS) or processed into products (Carbon Capture and Utilization, CCU) may not be considered as CDR. In this case carbon dioxide is not actually removed from the atmosphere, rather its escape into the atmosphere is simply prevented.

The IPCC's definition of CDR
The term "carbon dioxide removal methods" applies exclusively to such practices in which the carbon dioxide removed comes from the atmosphere, its subsequent storage is durable, and its removal is an outcome of human action and is thus additional to the natural carbon dioxide removal processes of the Earth system.

Some CDR methods have been carried out for centuries, although not with the explicit purpose of removing carbon dioxide from the atmosphere. These include the reforestation of deforested areas, the sustainable management of existing forests, and the conservation of peat- and wetlands. They also include regenerative types of agriculture that lead to increased humus or carbon content in the soil by removing carbon dioxide and other carbon compounds from the atmosphere and storing them in the soil, mostly in the form of organic material (plant remains, manure, etc.). The best-known practices for enriching soils with carbon include the cultivation of perennial grasses and legumes, improved crop rotation including catch cropping, the application of compost and manure, and reduced soil tillage.

There are other comparatively new CDR methods, however, whose specific purpose is to decrease greenhouse gas concentrations in the atmosphere. These include methods such as the capture of carbon dioxide from the air and its subsequent storage (Direct Air Carbon Capture and Storage, DACCS) or the generation of bioenergy with subsequent carbon dioxide capture and storage (Bioenergy with Carbon Capture and Storage, BECCS). Experience and knowledge of these approaches are growing, but they are still being applied on a comparatively small scale.

Furthermore, CDR methods differ with respect to the length of time that the carbon dioxide is removed from the atmosphere. The possible time frames range from a few decades to millions of years, and depend specifically on the storage site. Carbon dioxide that is absorbed by the ocean or is stored in deep-lying rock layers usually remains there for a longer time than carbon dioxide that is sequestered by forests on the land. Natural storage sites on land are also more susceptible to disruption. Wetlands, for example, can dry out, and forests can burn down. In both cases the carbon dioxide will escape into the atmosphere again. The risk of escape is somewhat lower when trees are felled and used for durable timber elements (e.g. roof beams) or when long-lived products are made from captured carbon dioxide.

Afforestation and reforestation
The Intergovernmental Panel on Climate Change defines the term "afforestation" as the planting of trees in an area that was not forested in the past. One could therefore also refer to this as "forestation". "Reforestation", on the other hand, means the planting of young trees in an area whose former forest cover has been destroyed by clearing, fire or other human activities.

Last of all, the various CDR methods differ from one another in the extent to which they can be applied, how much carbon dioxide can be removed from the atmosphere with their help, what possible risks and advantages a method poses, the costs associated with their large-scale application, and whether the necessary technology has even been developed and is ready for implementation. Science is presently searching for the answers to these and many other questions in various research projects.

No substitute for comprehensive emission reductions

Considering the enormous speed at which the Earth's climate is changing, there is no longer any question as to whether mankind must remove carbon dioxide from the atmosphere in order to limit global warming to a tolerable minimum level for humans and nature. Without a doubt the answer is yes! But the unresolved questions now are how, to what extent, with what goals, and under what basic conditions such removal should and can happen.

It is certain that if humankind is to achieve the Paris climate goal, removing carbon dioxide can never be accepted as a substitute for comprehensively reducing emissions. The Intergovernmental Panel on Climate

1.26 > Iceland has achieved some small-scale success in removing carbon dioxide from the atmosphere and sequestering it underground. The process involves dissolving the extracted gas in fresh water and injecting it into the warm volcanic basalt rocks. The components of the rocks react chemically with the carbon dioxide, resulting in its mineralization and conversion to rock material itself.

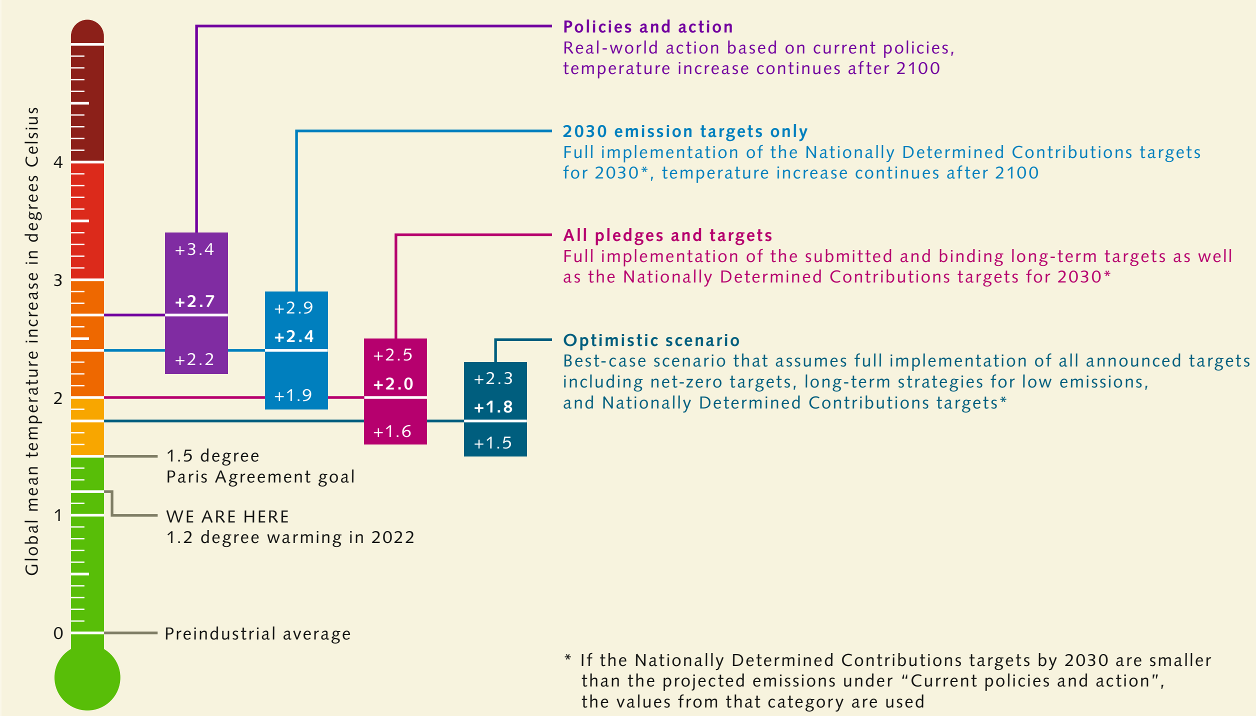
Climate goals – progress at a snail's pace

In the Paris Climate Agreement, all signatory states committed to limiting global warming to well below two degrees Celsius. A prerequisite for this is net-zero greenhouse gas emission by the second half of this century. To achieve this goal, the countries are all required to develop a national long-term climate strategy and to establish and publish Nationally Determined Contributions (NDCs) every five years. More than 140 states have already complied in this task. The Federal Republic of Germany, for example, has committed to becoming greenhouse gas neutral by the year 2045. This commitment will be facilitated by the Climate Change Act, amended in June 2021, which imposes mandatory emission caps on the energy sector, industry, agriculture, transport and buildings. By the year 2030, according to the plan, German greenhouse gas emissions will be reduced by 65 per cent compared to the year 1990.

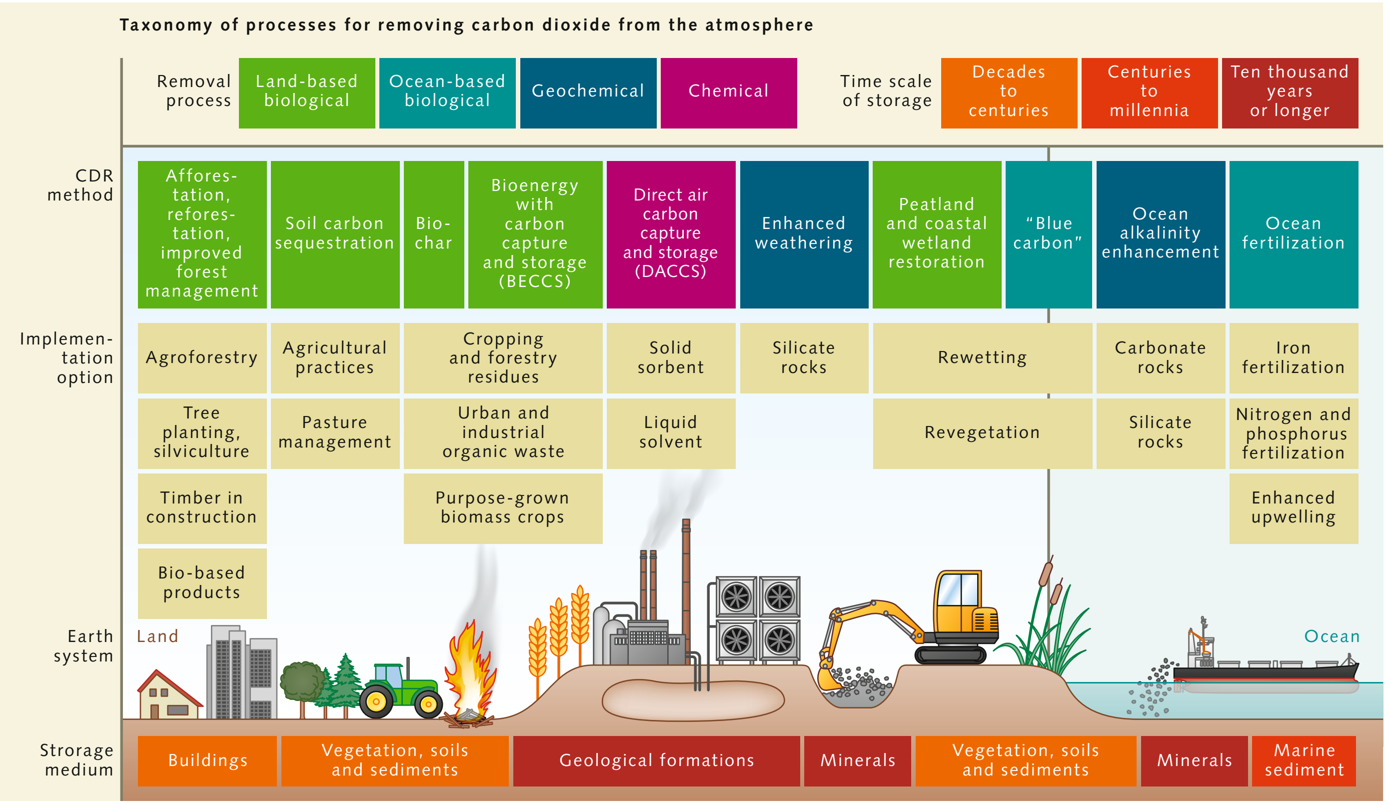
However, Germany and many other countries are lagging behind in the implementation of their self-imposed climate targets. Progress in the fight against climate change is still moving at a snail's pace worldwide.

Based on the current climate protection laws and catalogues of measures, experts are projecting global warming of two to 3.6 degrees Celsius by the year 2100. More commitment, political will and investment in climate action are therefore vital. According to the International Energy Agency (IEA), in the year 2022 almost 89 per cent of the record-high global carbon dioxide emissions in the energy sector were still attributable to the burning of fossil raw materials and the accompanying industrial processes (production, processing). This confirms that humanity is still firmly entrenched in the fossil age.

Global temperature increase by 2100, calculated by Climate Action Tracker experts (date: November 2022)



1.27 > Experts at the Climate Action Tracker regularly analyse international climate policies and, based on climate action taken and pledged by all countries, calculate how much warming the planet is approaching by the year 2100. In November 2022, the measures implemented up to that point indicated a warming of 2.2 to 3.4 degrees Celsius.



1.28 > Processes of carbon dioxide removal from the atmosphere could be employed both on land and in the ocean. This chart shows the different approaches, sorted by type of removal and by subsequent storage medium.

Change says that the level of greenhouse gas emissions is far too high for that. The use of CDR methods is conceivably a way to compensate for residual emissions that are difficult to eliminate. They can help to reduce the net anthropogenic emissions more quickly in the near future. In the long term, CDR would help humanity to compensate for unavoidable carbon dioxide residual emissions as well as the emissions of other greenhouse gases. In the best case, it would one day be possible to achieve net-negative emissions. This would mean that the amount of carbon dioxide being removed from the atmosphere would exceed the amount of CO_2 equivalents being released. As a consequence, the greenhouse gas concentrations in the atmosphere would decrease, which would be followed by a decline in the global surface temperature.

But the first milestone along this path would be to achieve net-zero carbon dioxide emissions. The goal of comprehensive greenhouse gas neutrality would then follow after about ten to 40 years, or maybe even much later depending on the amount of residual greenhouse gas emissions (methane, laughing gas, etc.) that would have to be compensated for by carbon dioxide removal.

For a global net zero of carbon dioxide emissions, not all countries would have to offset their residual emissions. If some countries are able to remove more carbon dioxide than they release into the atmosphere by emissions, there would be a condition of net-negative emissions, or an emission credit. Other countries could then redeem this credit. They would then have more time to reduce their own greenhouse gas emissions without an increase in the overall carbon dioxide concentrations in the Earth's atmosphere and the accompanying rise in average global temperatures.

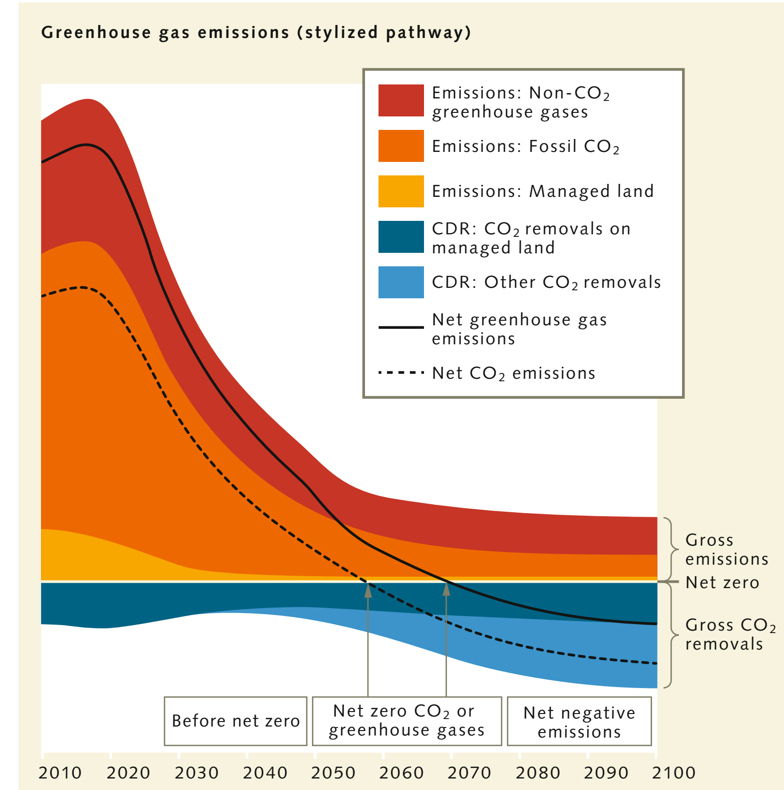
Major concerns and many unanswered questions

So far, only a few countries have adopted CDR methods beyond afforestation and reforestation in their long-term climate strategies. Nevertheless, according to the Intergovernmental Panel on Climate Change, there is concern in many circles that simply the theoretical possibility and feasibility of increased carbon dioxide removal could lull governments and other societal stakeholders into half-hearted attitudes in implementing ambitious greenhouse gas reduction plans, or lure them into placing their trust in technologies that have not yet been sufficiently developed and researched in the fight against climate change.

A further misgiving is that the hope for effective CDR measures could induce decision-makers to fail to rigorously address the challenges associated with drastic greenhouse gas reductions, and instead defer action to the future. This would mean that the next generation would have to deal with the steadily growing problem. It is also unclear how the costs, risks and burdens of large-scale CDR efforts can be evenly distributed, and how negative effects can be avoided, particularly in the areas of food production, biodiversity and the availability of land.

Furthermore, reliable and globally standardized methods would be needed to measure, verify and assess the carbon dioxide removal and storage achieved through CDR measures. A transparent and functioning market, in which emission credits could be traded and financial resources generated for the implementation of CDR measures, can only be realized when these conditions are met.

In the view of the Intergovernmental Panel on Climate Change, there are still many challenges that need to be overcome before CDR methods more sophisticated than reforestation can be implemented on a large scale. These include the many unanswered research questions, the immature state of technological development, high costs, and the fact that the possible implementation of new kinds of CDR methods in the future needs to conform with the overarching development and sustainability goals of the international community. This calls for matching laws and regulations, along with the corresponding decision-making processes, before novel CDR methods can be implemented.



How much CDR is needed in the future?

Science is investigating approaches and ideas for the struggle against climate change with the help of Integrated Assessment Models (IAMs). These are being developed in order to understand how particular societal or economic developments affect nature and the climate. To this end, the models are fed with information about the Earth system as well as about society. The models thus consider natural laws as well as the behavioural changes of humans, and they also assess the undesirable side effects or desired advantages of particular measures and decisions. Although the model predictions are always subject to some degree of uncertainty, IAMs do provide valuable insights. They can demonstrate, for example, how our economy, society and energy supply would have to change in order to achieve a given climate goal, or show us what impacts certain emission reductions would have for humans and nature.

1.29 > The active removal of carbon dioxide from the atmosphere will be necessary to reduce net anthropogenic emissions in the short term, to achieve the goals of carbon-dioxide and greenhouse gas neutrality in the intermediate term, and in the long term to reduce the carbon dioxide concentration in the atmosphere by negative emissions.

Researchers in IPCC Working Group III evaluated thousands of such integrated assessment models for the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change. This work has clearly illustrated that all models that project a limit on global warming of two degrees Celsius or less include a robust implementation of methods for carbon dioxide removal at significantly higher levels than any that are being carried out at present.

The amount of carbon dioxide that will have to be removed from the atmosphere in the future in order to stabilize the climate has not yet been clearly determined. The model results only allow rough estimates. But for land-based biological methods such as afforestation and reforestation, the estimates fall within the order of 900 million tonnes of net carbon dioxide in the year 2030. In this case, net means that the carbon dioxide removal through afforestation and reforestation must be 900 million tonnes greater than the sum of global land-use emissions produced at the same time (such as deforestation in certain regions). Two decades later the net removed amount would have to be almost three billion tonnes of carbon dioxide if global warming is to be held to less than two degrees Celsius over the long term. In addition, similarly large amounts of carbon dioxide would have to be removed through energy generation from biomass and through direct air capture. For both of these methods the captured carbon dioxide would subsequently have to be safely and permanently stored somewhere.

In light of these high estimates, the IPCC has concluded that existing programmes of land-based carbon dioxide removal need to be expanded massively and very rapidly. It is questionable, however, whether this can be achieved at the necessary scale.

The assessment models being studied by the IPCC have not yet been able to integrate ocean-based methods of carbon dioxide removal. The *Sixth Assessment Report* therefore does not provide any information on how much they could contribute to achieving the Paris Climate Agreement goals. The first research teams, however, including scientists from Germany, have begun to take on the task of developing IAMs with components of marine-based carbon dioxide removal. Their motivation for this work is fuelled by the knowledge that the ocean has already absorbed and stored one quarter of the carbon dioxide emissions caused by human activities in the past, with wide-ranging consequences for humanity and nature.

1.30 > Here, near the Brazilian city of Porto Velho, slash-and-burn clearing of the Amazon rainforest has provided arable land for the cultivation of soya beans. Along with the forests, enormous areas of carbon storage are lost because the trees store carbon in their wood and leaf mass as well as in the forest soils.

Conclusion

There is only one solution to the climate crisis – greenhouse gas neutrality

With their emissions of greenhouse gases over the past 120 to 170 years, humans have caused global surface temperatures to increase by around 1.15 degrees Celsius. Because of this warming, many components of the Earth's climate have been changing at rates that our planet has not experienced in thousands of years. The consequences of climate change are harming humanity and nature to an increasing degree and are slowly depriving people of their basic needs. Foremost among these are health and physical integrity, along with sufficient water and food.

All regions of the Earth are being affected by climate change. The magnitude of the changes and the consequences and risks for people and nature, however, vary from one region to another. The increasing occurrence of extreme events presents a particular danger. If heat waves, heavy rains, severe storms, droughts or floods occur simultaneously, the overall risk is multiplied and it becomes more difficult for people and nature to respond effectively. Climate change also magnifies the risks of other man-made stressors such as environmental degradation, resource over-exploitation and urbanization, further curtailing the adaptive capacities of all inhabitants of the Earth.

Every additional tenth of a degree of warming provides climate change with more momentum. This means that the magnitude and the extreme rate of the changes, as well as the consequences and risks, increase with every added temperature rise. Escalation of the climate and biodiversity crises can only be addressed through effective adaptive measures, along with avoidance of any further greenhouse gas emissions (greenhouse gas neutrality).

Even with very ambitious climate policies, climate scientists assume that the international community will still be emitting residual greenhouse gases in the middle of the 21st century including carbon dioxide residues, but especially methane (CH_4) and nitrous oxide (N_2O). These hard-to-eliminate residual emissions are generated by cement and steel production, aviation and heavy-duty transport, but also by agriculture and the burning of waste.

To stop global warming, the residual emissions will have to be offset. This will require equal amounts of carbon dioxide to be removed from the atmosphere, and feasible ideas exist for achieving this. They focus either on the expansion of natural carbon sinks or are based on technological approaches. Furthermore, the capture methods are classified according to the time frame in which the carbon dioxide is removed from the atmosphere and by the scale at which they can be applied.

In many cases, however, the possible risks associated with a given method are not clear, particularly the costs and whether the necessary technology is sufficiently developed and ready to be employed. Thus, elementary knowledge is lacking for measures that will soon need to be carried out at industrial scale to achieve the goal of greenhouse gas neutrality in the future. One thing is certain: Measures to remove carbon dioxide can never be used as an excuse to continue the avoidable emission of greenhouse gases because, ultimately, every single tonne of carbon dioxide avoided counts in the fight against the climate and biodiversity crises.