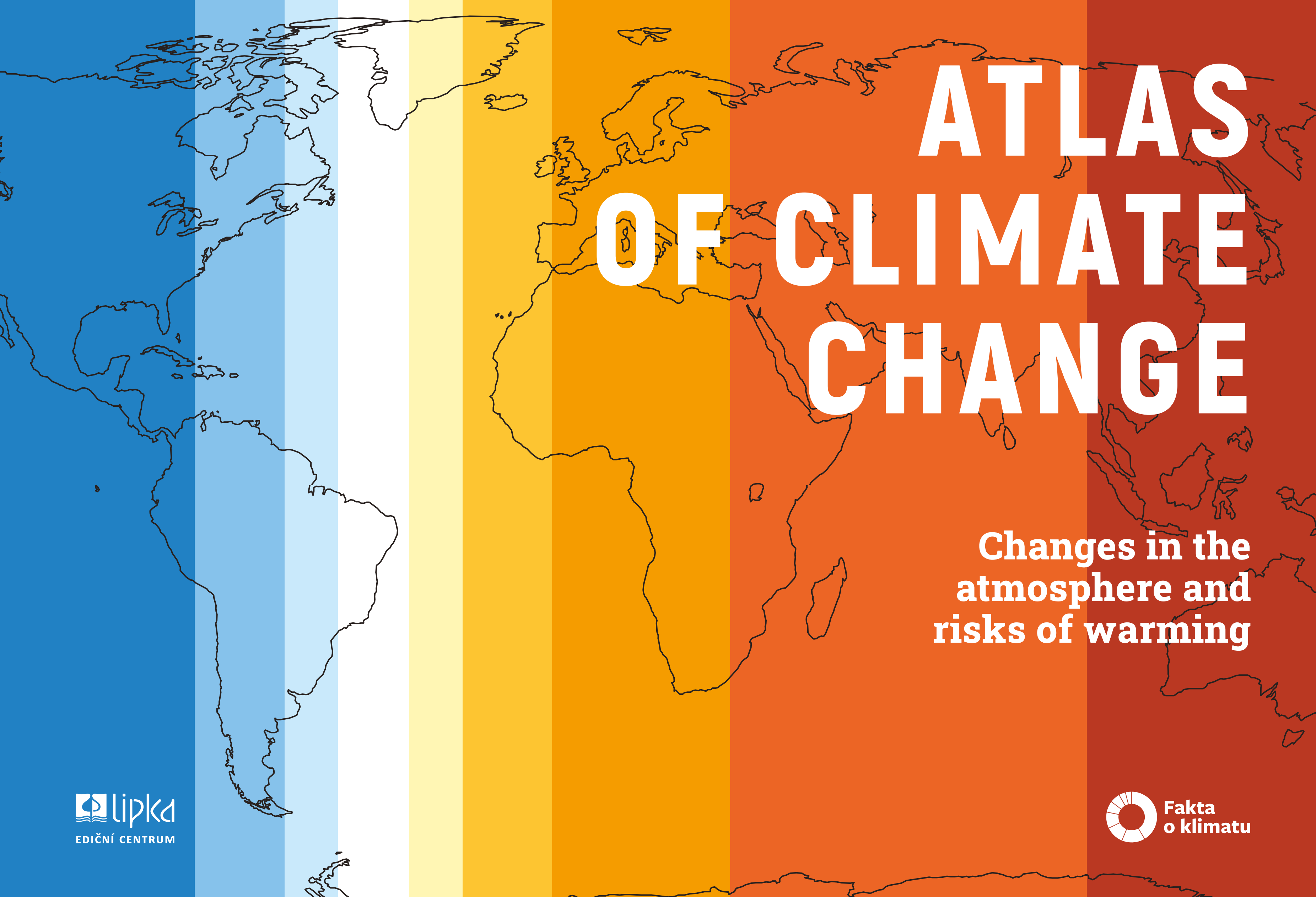

ATLAS OF CLIMATE CHANGE

Changes in the atmosphere and risks of warming

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Fakta o klimatu

ATLAS OF CLIMATE CHANGE

Changes in the atmosphere and risks of warming

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Atlas of Climate Change. Changes in the Atmosphere and Risks of Warming

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WE WANT TO CONTRIBUTE TO A MORE EVIDENCE-BASED DEBATE ON CLIMATE CHANGE

A debate on climate change is complicated: the topic is complex and triggers in people a wide range of different emotions, especially through words and actions of politicians, journalists, activists and others. This booklet called *Atlas of Climate Change* was made by Fakta o klimatu (Facts on Climate) – a Czech team of experts that visualises the latest verified scientific data about climate change and aims to support a more constructive discussion on what needs to be done about it.

We really wish this booklet serves as an inspiration for teachers and students, for politicians and other decision or opinion makers – it can be used as a source of information by anyone. It is easy to pack and read on the train or you can bring a few copies to your company or class and share them as source material for your students or colleagues. Although the texts in the booklet are interconnected, each page can also stand alone. This means that some information may be occasionally repeated but readers can open the *Atlas* anywhere and start reading without missing relevant context.

Every piece of information provided in the booklet comes from reliable public and transparent sources (e.g. NASA, NOAA and Eurostat), and from renowned scientific journals (Nature, Science, etc.). Short links to the original sources are provided directly in the graphs and maps; original articles and datasets used for calculations are available in Czech at www.faktaoklimatu.cz.

To make the booklet accessible for non-experts, we often aimed to strike balance between complexity and simplification. Nevertheless, anything that was simplified is explicitly mentioned and commented on in the text.

Cultivating the public debate about climate change is a long-term effort. That is why this *Atlas* primarily focuses on the description of changes occurring in the atmosphere and the risks of global warming. In addition, it includes some data on greenhouse gas emissions and international pledges. It serves as the first part of a larger series about climate change – later volumes will address possible future scenarios and measures needed to mitigate or adapt to these changes.

The booklet was first published in Czech in 2020 and has been updated several times to include the latest available data. The English version, unlike the original, which mainly focused on the situation in Czechia, provides a bigger picture, including the European Union and a global context. This makes it relevant and useful for readers in other countries as well as in international companies and organizations.

Hope you will find some inspiration here and enjoy exploring the graphs and maps!

Ondráš Přibyla
Director & Founder
Fakta o klimatu

The latest Czech version of the Atlas is available here:

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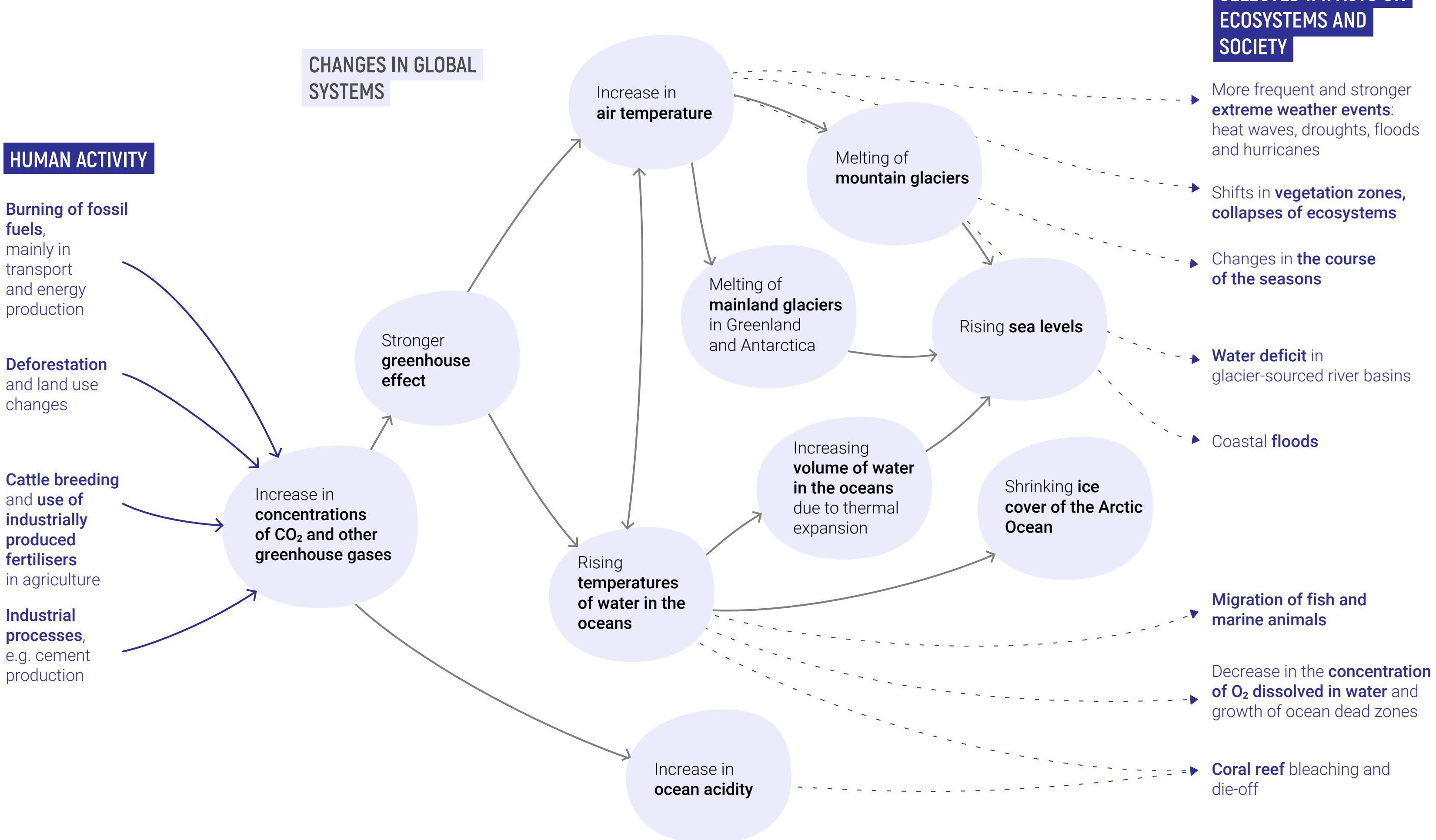
How warming is related to increasing CO_2 concentrations

Greenhouse gas emissions in global context

CLIMATE CHANGE SCHEME

Climate change is much more than rising temperatures.



Climate change is not just a change of temperature – this umbrella term covers several interrelated phenomena. The change of one factor (e.g. higher concentrations of CO_2 in the atmosphere) results in a long chain of interconnected causes and effects.

Human activity, particularly **burning fossil fuels** (coal, oil and natural gas), leads to an increase in the concentration of carbon dioxide (CO_2) in the atmosphere. About 35 billion tons are produced annually in energy production, transportation and industry sectors, while deforestation adds approx. 5 billion tons. On average, every person on Earth therefore accounts for about 5 tons of CO_2 per year. This means that human activity leads to **increased CO_2 concentrations in the atmosphere** (see Cycles of atmospheric CO_2 and O_2 concentrations on pp. 14–15).

There are also other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O). Methane is produced in agriculture (cattle breeding, rice cultivation, etc.) and during oil and shale gases extraction. Nitrous oxide arises due to the use of industrial fertilizers and in some combustion processes.

Higher concentrations of CO_2 and other greenhouse gases in the atmosphere **lead to a more potent greenhouse effect**. Heat radiation, which would otherwise be emitted by Earth into space, is absorbed by greenhouse gases and returned to the surface. The planet is therefore warming.

> A common argument challenging human impact on the climate says that the most potent greenhouse gas is water vapour. This is true. However, the amount of water vapour in the atmosphere is also influenced by human activity, albeit indirectly. The water vapour cycle is controlled by temperature, and this temperature is affected by other greenhouse gases emitted by humans. In the calculations of the strength of the greenhouse effect and climate sensitivity (see History of research of the greenhouse effect on pp. 28–29), the influence of the water vapour is always considered.

Since the industrial revolution, **atmospheric temperature has risen** on average by 1.2 °C. Still, most of the heat has been absorbed by ocean water (its temperature has also been rising for a long time). Temperature changes are not the same around the world – e.g. Arctic regions are warming four times faster than oceans (see Map of temperature changes on pp. 20–21).

Atmospheric CO_2 partially dissolves in the ocean, where it forms carbonic acid. This leads to a drop in pH, or **ocean acidification**, which is dangerous for corals and other marine life (see pp. 8–11).

Warmer sea water temperatures are causing a reduction in the area and thickness of sea ice in the Arctic Ocean. In September 1979, the ice volume in the Arctic Ocean was about 17,000 km^3; in September 2017, it was only 5,000 km^3. Summers during which the entire Arctic Ocean will thaw are expected to first arrive around 2050.

The warming of the planet leads to more frequent and more severe heat waves, stronger hurricanes, longer periods of drought, but also to heavier rains and floods – i.e. to **more frequent extreme events**.

The level of the world's oceans is rising at a rate of 3.3 cm per decade. About half of this rise is caused by the melting of mainland glaciers, the other half is due to the warming of seawater (like most other materials, seawater also increases its volume with temperature).

Rising temperatures cause **melting of mountain glaciers** in the Alps, Himalayas, Andes and other mountain ranges. This will significantly impact agriculture and water supplies, as rivers in many areas are fed by mountain glaciers.

WHY IS GLOBAL WARMING ABOVE 1.5 °C A PROBLEM?

If the global warming crosses a certain threshold, it might trigger "tipping points" of some systems on Earth, leading to their permanent change or even destruction. The danger of tipping points has been reflected in international negotiations, e.g. in the Paris Agreement.

What exactly are tipping points?

If you have ever climbed up a tree, you will probably know: a branch can only hold so much weight and if more weight is applied, the branch will break. Major systems on Earth (ecosystems as well as oceanic currents, water cycle, etc.) are the same – they can keep up for some time and adapt to the changes but then at some point **a threshold is crossed and the whole system breaks down**. The collapse of one such system affects others and makes them more unstable. In some cases, it can significantly speed up climate change (e.g. huge amounts of methane will be released to the atmosphere as a result of thawing permafrost).

A good example of a small-scale tipping point is the recent collapse of coniferous forests in Czechia: although unsuitable for the local conditions, spruce remained the dominant species in Czech forests for over two centuries. When a period of drought occurred and several mild winters helped spruce bugs multiply, large areas of Czech forests quickly collapsed.

> **The Paris Agreement** is a result of a long-term effort by which the United Nations had supported international collaboration around climate change mitigation. Many countries pledged in the agreement to **keep the rise in mean global temperature to well below 2 °C and preferably limit the increase to 1.5 °C** above pre-industrial levels (1850–1900).

Tipping points in ecosystems

Climate change presents a threat both for small local biotopes (e.g. pools and wetlands can run dry more easily), and for large global ecosystems (such as the Brazilian rainforest, boreal forests and coral reefs). Increasing temperatures along with deforestation can disrupt the water cycle in **tropical rainforests**, which **may change into a savannah** as a result.

Warmer ocean water has higher acidity, which leads to dying coral reefs. It is more than likely now that the **ecosystem of coral reefs will not survive the warming of 2 °C** – this fact will have a significant impact on approx. 25% of all marine animal species which depend on this ecosystem.

Tipping points in the cryosphere

The cryosphere is a term for all areas on Earth where water is in solid form. While melting of the huge mass of ice in Greenland or the Antarctic is a slow process which will take hundreds of years, it will lead to a **sea level rise** of several meters, which will have severe consequences for hundreds of millions of people living in coastal lowlands. The melting of mountain glaciers will result in **low water levels in major rivers** and declining water supply, e.g. in Asia.

Tipping points in systems of oceanic and atmospheric currents

If the global temperature keeps rising, these systems may go into a qualitatively different state, changing weather all over the world. **For example, if the Gulf Stream stopped,** countries in large parts of Europe and North America would experience **very cold temperatures (as in ice age climate)**.

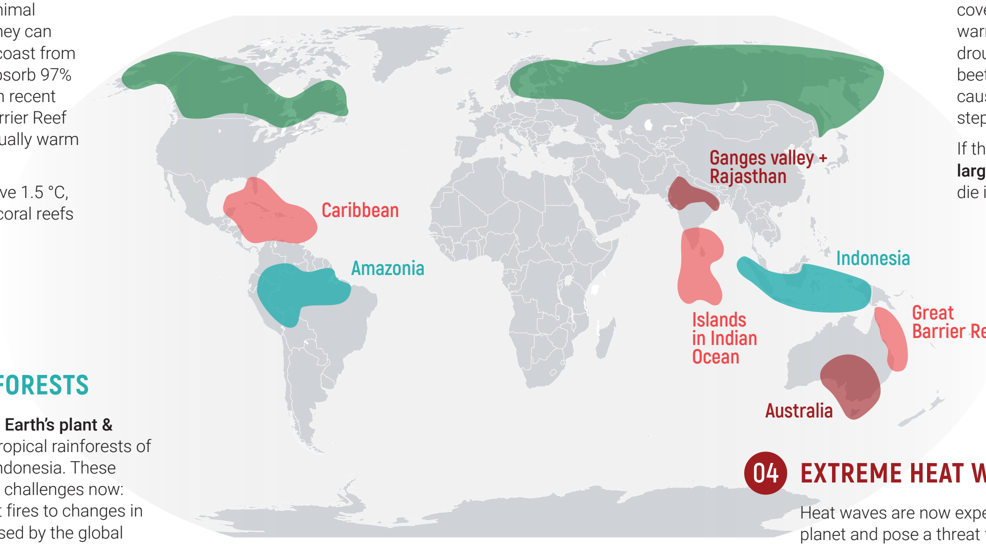
TIPPING POINTS IN ECOSYSTEMS

If global warming stays below 1.5 °C, coral reefs are likely to be the only major ecosystem on Earth at significant risk. However, warming beyond 2 °C is likely to trigger tipping points for a number of other planetary ecosystems.

01 CORAL REEFS

These reefs are characterized by extremely high biodiversity – approx. 25% of all marine animal species depend on them. They can also effectively protect the coast from sea storms, being able to absorb 97% of energy from the waves. In recent years, a half of the Great Barrier Reef has died as a result of unusually warm water in the oceans.

If the temperature rises above 1.5 °C, almost none of the current coral reefs will survive.



02 TROPICAL RAINFORESTS

About **two thirds of the Earth's plant & animal species** live in tropical rainforests of Amazonia, Africa and Indonesia. These ecosystems face many challenges now: from logging and forest fires to changes in precipitation levels caused by the global warming.

If temperatures rise by 3 to 4 °C, **large numbers of trees will probably die** in most rainforest areas. But even if the warming is less dramatic, the ecosystem may still collapse if approx. 40% of the rainforest area is lost to logging.

03 BOREAL FORESTS

Boreal forests (taiga) are **the world's largest ecosystem**, which covers approx. 11% of all land. The warming will lead to longer droughts, more frequent fires, bark beetle spreading, etc. – all of these causing taiga to change into a steppe.

If the temperature rises by 3 to 4 °C, **large numbers of trees** are likely to die in most taiga areas.

04 EXTREME HEAT WAVES

Heat waves are now experienced in different locations around the planet and pose a threat for both communities and animal populations. For example, temperatures in Australia reached 45 °C in January 2019, and hundreds of thousands of fruit bats died as a result – about one third of their population. Extinction of some species of plants or animals may cause **regional ecosystems to collapse**.

Global warming will lead to more frequent and intense heat waves. If the temperature rises by 2 °C, some regions will experience deadly heat waves every year, and if it gets beyond 2 °C, large areas of land may become unlivable.

The temperatures in this infographic refer to global warming above pre-industrial levels. The current warming is approx. 1.2 °C.

Primary data source: IPCC Report

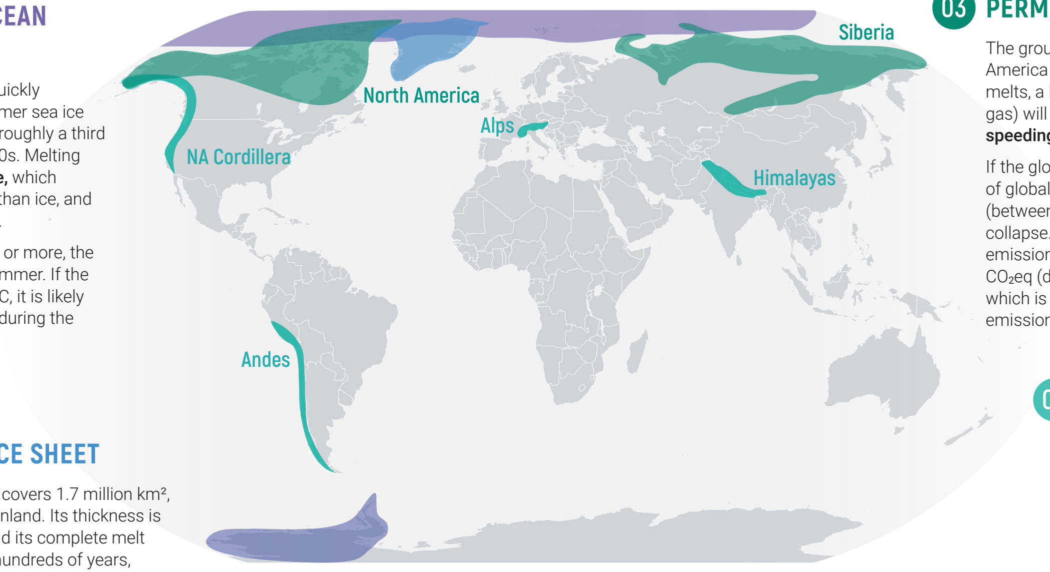
TIPPING POINTS IN THE CRYOSPHERE

The word “cryosphere” refers to all areas on the planet where water remains frozen for a long time. Some mountain glaciers, e.g. in the Alps, have already reached their tipping point and will disappear no matter what, regardless of any further warming. Other large cryospheric systems could reach their tipping points with just a slight increase in Earth’s temperature beyond 1.5 °C. It will take decades, hundreds, in some cases even thousands of years but changes in the cryosphere will have a global impact – rising sea levels, albedo changes or huge amounts of methane released into the atmosphere. All of this would further exacerbate the warming.

01 SEASONAL ARCTIC OCEAN ICE COVER

The Arctic Ocean ice cover is quickly declining – the amount of summer sea ice has dropped in recent years to roughly a third of what it used to be in the 1980s. Melting sea ice **uncovers water surface,** which absorbs more solar irradiation than ice, and thus **exacerbates the warming**.

If the temperature rises by 2 °C or more, the North Pole will be ice-free in summer. If the warming does not exceed 1.5 °C, it is likely that some ice will remain even during the warm season.



02 GREENLAND ICE SHEET

Greenland ice sheet covers 1.7 million km², roughly 80% of Greenland. Its thickness is generally 2000 m and its complete melt would take several hundreds of years, causing a global sea level rise of 7 m.

If the temperature rises by 1.5 to 2 °C, **irreversible melting** of the Greenland ice sheet will probably start, which could result in **a global sea level rise up to 2 m** within the next two hundred years.

03 PERMAFROST

The ground in vast areas of Siberia and North America stays below 0 °C for a long time. If it melts, a huge amount of methane (greenhouse gas) will be released to the atmosphere, **speeding up global warming**.

If the global temperature rises by 2 °C, 28–53% of global permafrost will melt. Further warming (between 2 and 3 °C) may cause permafrost to collapse. The estimated annual methane emissions from melted permafrost are 4–16 Gt CO_2eq (depending on the speed of melting), which is 10–30 % of the annual global emissions caused by human activities.

04 MOUNTAIN GLACIERS

A number of major rivers get their water from glaciers, which are quickly melting in most mountain areas today.

If temperatures keep rising and glaciers grow smaller, large areas of America and Asia **will not have enough water for irrigation**.

05 WEST ANTARCTIC ICE SHEET

This ice sheet contains 2.2 milion km³ of ice. It is not fixed by land very well and it may **“slide” to sea** (marine ice sheet instability). If the West Antarctic ice sheet collapsed, the global sea levels would quickly rise by up to 5 m.

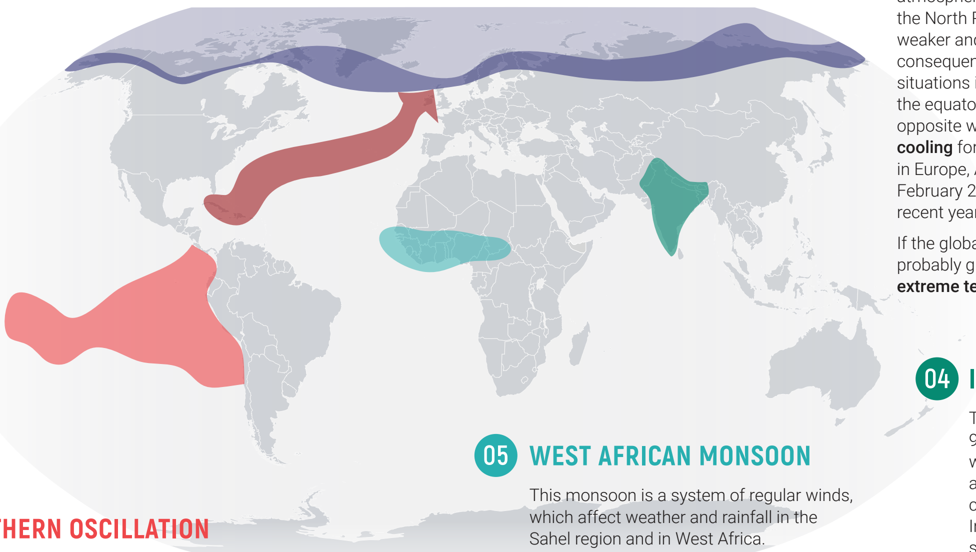
If the temperature increases by 1.5 to 2 °C, **irreversible melting** of the West Antarctic ice sheet will probably start.

The temperatures in this infographic refer to global warming above pre-industrial levels. The current warming is approx. 1.2 °C.

Primary data source: IPCC Report

TIPPING POINTS IN ATMOSPHERIC & OCEANIC CURRENTS

Global warming may cause a significant disruption in the oceanic and atmospheric currents, and trigger major and unexpected weather changes on most continents. Atmospheric and ocean currents cannot be localized easily and precisely, masses of air and water have their dynamics of movements, which is why their location on the map below is rather symbolic.



01 GULF STREAM

The Gulf Stream is a strong warm ocean current which affects the climate in Western Europe and the east coast of North America, making the winters there less severe. It is a part of a global system of surface and deep-water currents (thermohaline circulation), which distributes heat around the planet. Measurements show that the **Gulf Stream** has been **getting weaker** since 1950. It might stop completely in the future, e.g. if a large amount of water is released to the north Atlantic from melting glaciers in Greenland.

The rate of global warming will determine how strong the current will be. Simulations for different emission scenarios predict that it will be **11–54% weaker** by 2100.

02 EL NIÑO – SOUTHERN OSCILLATION

In the South Pacific region, cold and warm periods (El Niño & La Niña) come irregularly every three to ten years. This South Pacific oscillation affects air currents and rainfall on the American and Australian coasts, bringing **extreme weather (floods as well as droughts) and having an impact on crops**.

The global warming leads to more frequent and stronger El Niño (if the global temperature rises by 1.5 °C, El Niño will occur twice as often).

03 JET STREAM & POLAR VORTEX

Jet stream and polar vortex are two interconnected atmospheric currents, which keep cold arctic air over the North Pole. The jet stream has been getting weaker and becoming more meandering as a consequence – and so we experience more frequent situations in which cold arctic air goes down towards the equator and very hot tropical air moves the opposite way: towards the pole. This leads to **rapid cooling** for several days or weeks in various regions in Europe, Asia or America (e.g. −30 °C in Chicago in February 2019) **or rapid warming** (heat waves in recent years in Europe).

If the global warming continues, the jet stream will probably grow even weaker and we can expect **extreme temperatures more frequently**.

04 INDIAN MONSOON

The regular Indian monsoon brings up to 90% of precipitation to the region. Global warming, land use changes and the amount of aerosols released to the air may cause the monsoons to be unstable on the Indian subcontinent, sometimes weak and sometimes very strong, which will lead to **extreme floods in some years and severe droughts in other years**.

05 WEST AFRICAN MONSOON

This monsoon is a system of regular winds, which affect weather and rainfall in the Sahel region and in West Africa.

If the global temperature rises by 2 to 3 °C, the West African Monsoon may **become stronger**, which may result in **renewed vegetation cover** in the Sahel and in the western Sahara. However, this would also increase the temperature stress, which is why a green Sahara would not be more livable for people.

The temperatures in this infographic refer to global warming above pre-industrial levels. The current warming is approx. 1.2 °C.

Primary data source: IPCC Report

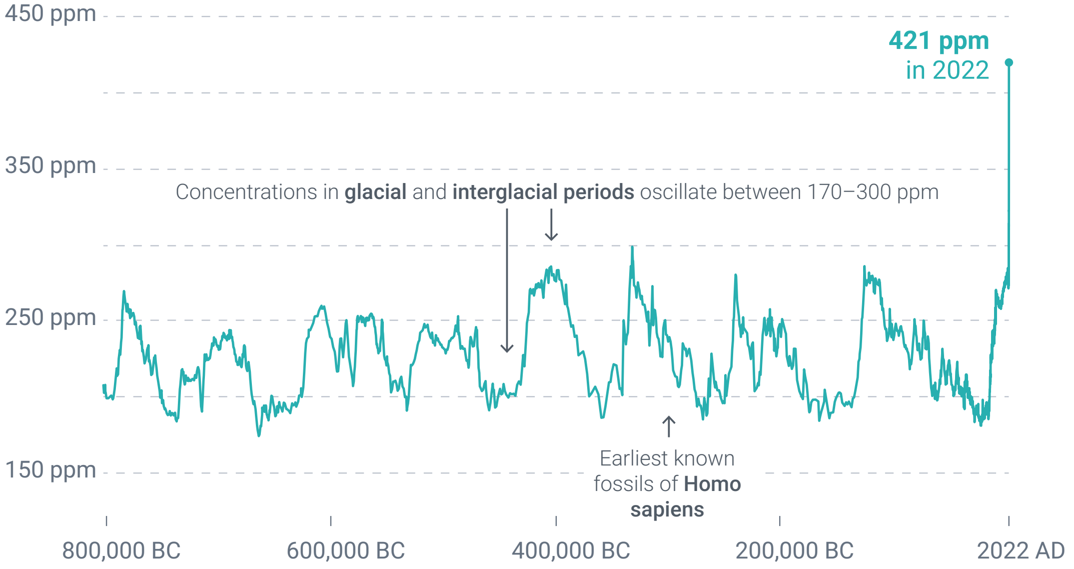
HISTORICAL CONCENTRATIONS OF ATMOSPHERIC CO_2

The concentration of atmospheric CO_2 today is the highest since the dawn of humanity.

The unit of measurement used for concentration is **ppm (parts per million)**.

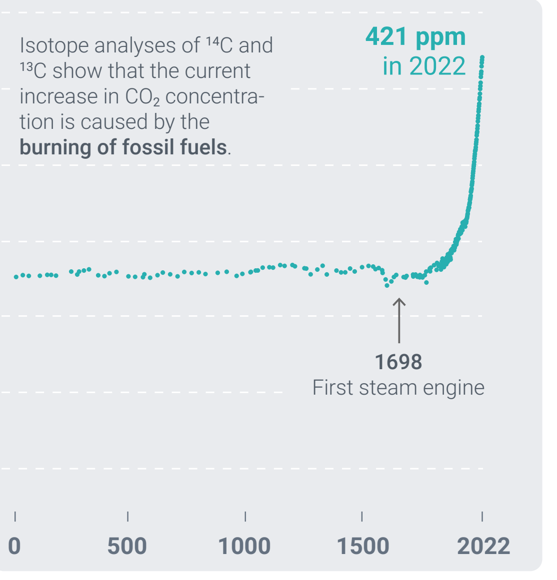
A concentration of 400 ppm CO_2 in the atmosphere means that there are 400 molecules of CO_2 in one million molecules of air.

CO_2 concentrations over the last **800,000 years**



CLOSER LOOK

Last 2022 years



The CO_2 concentration values come from the EPICA **analysis of samples from deep ice core drilling** in Antarctica and from **direct measurements** at Mauna Loa, Hawaii.

Data source: NOAA

The last time the composition of the atmosphere was similar to that of today was four million years ago. Earth was about 3 °C warmer back then, sea levels were 20 m higher, elephants and saber-toothed cats were roaming around Europe and the first Hominidae were coming down from trees.

How to read this graph?

The left graph shows ● a trend in CO_2 concentrations over the last 800,000 years. One can see how these **concentrations oscillated in glacial and interglacial periods** – while typical concentrations in glacial periods were 170 ppm, in interglacial periods they were around 280 ppm.

The right graph has a different time scale and shows in detail a trend in CO_2 concentrations over the last 2,000 years. **The concentrations were around 280 ppm the whole time until the industrial revolution**; then they started to rise.

How do scientists know what composition the atmosphere had in the past?

The composition of the atmosphere half a million years ago would be easy to know if we had some kind of container in which such ancient air is preserved. Scientist would just open it in a laboratory and measure the composition with the latest available methods. Well, scientists did find such **"canned" ancient air: bubbles of air in glaciers**. If you take a chunk of ice cut off from a glacier and melt it in a lab, you can analyze what composition the atmosphere had when the ice froze. How ancient the sample is depends on how deep down in the glacier you are able to drill. Glaciers in Greenland and the Antarctic are so thick that it is possible to analyze air bubbles which are now about 800,000 years old – but scientists need to drill about three kilometers deep.

Could the current climate change be a part of a natural cycle?

The oscillation of CO_2 and temperature levels in glacial and interglacial periods validates the latest calculations of climate sensitivity: **if the concentration of atmospheric CO_2 doubles, Earth will be about 3 °C warmer**. We live in an interglacial period and if the cycle continued naturally, Earth would be slowly cooling now – CO_2 concentrations would be slowly declining and another glacial period would start within a few dozens of thousands of years.

Natural advancing and retreating of glacial periods is caused by variations of Earth's axial tilt (Milankovitch cycles). This process triggers a complex system of interrelated changes in which CO_2 as a greenhouse gas plays a major role and which causes transitions between glacial and interglacial periods.

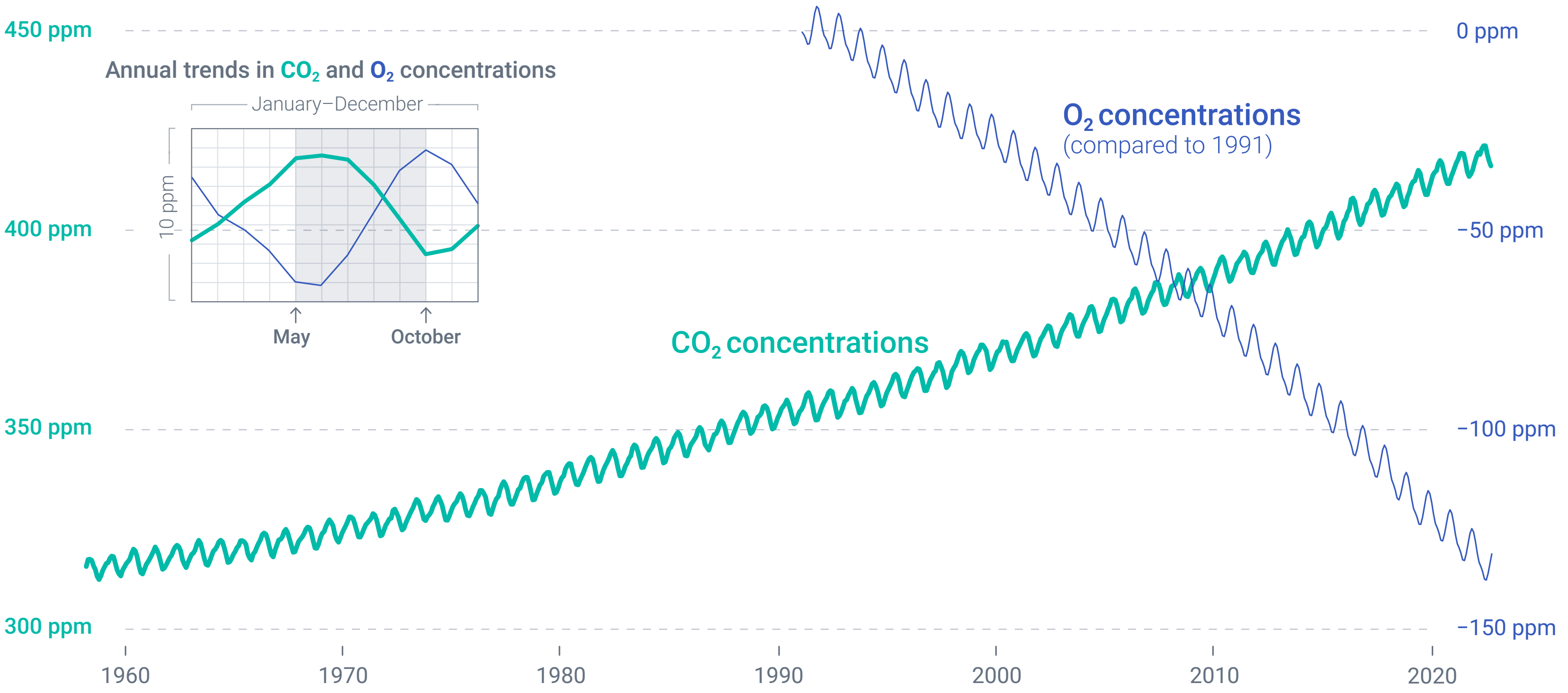
There is enough evidence that the climate change happening in our times is unrelated to the natural variation of glacial and interglacial periods – current CO_2 concentrations are high above the range typical for this variation, and the amount of solar radiation determined by Milankovitch cycles shows no unusual trends for our times. In addition, fossil fuel combustion further increases CO_2 concentrations (see Cycles of concentrations of atmospheric CO_2 and O_2 on pp.14–15), and with the current rate of their combustion, the concentrations would double compared to pre-industrial times (reach 540 ppm) around 2060–2080. This would mean that Earth would be more than 3 °C warmer by the end of this century, which would have very serious consequences (see Why is global warming above 1.5 °C a problem? on pp. 8–11).

To prevent this from happening, most countries in the world recently pledged to reach climate (carbon) neutrality between 2050 and 2070 – i.e. add no more greenhouse gases to the atmosphere. The most important step towards this target is the phase-out of fossil fuels.

CYCLES OF CONCENTRATIONS OF ATMOSPHERIC CO_2 & O_2

Changes of carbon dioxide and oxygen concentrations in time show **annual cycles of breathing and photosynthesis on Earth as well as long-term effects of fossil fuel combustion**.

Air contains 78.1% nitrogen, **20.9% oxygen**, 0.9% argon and approximately **0.04% CO_2**. **Concentrations of CO_2 are measured in units of ppm (parts per million)**. A concentration of 400 ppm CO_2 in the atmosphere means that there are 400 molecules of CO_2 in one million molecules of air, which corresponds to a concentration of 0.04% CO_2 in the atmosphere. The graph shows a continuous decrease in oxygen concentrations: about 140 ppm (about 0.014%) since 1991.



Data source: **NOAA**

A long-term trend in increasing concentrations of carbon dioxide and declining concentrations of oxygen shows that humans have been causing changes in the atmosphere composition by their activity – primarily by burning fossil fuels.

How to read this graph?

● **Concentrations of carbon dioxide (CO_2)** oscillate during the year, but **keep increasing in the long term: approx. 20 ppm per decade**. While they were still around 315 ppm in 1960, they were already around 415 ppm in 2020 – which means they have risen by roughly 30% in only sixty years.

The graph also shows a trend in the ● **concentrations of oxygen (O_2)**: how much it changed in a given year as compared to the reference year (1991). **O_2 concentrations** also oscillate during the year but **keep declining in the long term: about 40 ppm per decade**.

In absolute numbers, the increase in CO_2 concentrations by dozens of molecules may not feel like a major change. However, even such small changes may have a major impact – if the CO_2 concentrations double, Earth's temperature will rise by about 3 °C and stay this warm for a long period of time.

How are CO_2 and O_2 concentrations measured?

The method for exact determination of CO_2 concentrations (to 0.1 ppm, i.e. 0.00001%) was developed by **Charles Keeling** in 1952. He was surprised by the results of his measurements at first as the concentrations appeared to be changing chaotically, depeding on the direction of the wind. Then he realized that his results in San Francisco were influenced by nearby forests (photosynthesis) and local factories (combustion) and that concentrations must be measured at a place which is far enough from such factors. Therefore he moved to the central Pacific: to Mauna Loa in Hawaii. It was not until he got there that his measurements started to make sense – concentrations remained stable in Hawaii. After some time Keeling noticed that **concentrations oscillate during the year – falling from May to October and rising in the remaining part of the year**. He understood that what was unfolding before his eyes was Earth's breathing.

> During **photosynthesis**, plants capture CO_2 from the air and produce O_2. Conversely, they use O_2 and release CO_2 during **breathing**.
>
> $CO_2 + H_2O \leftrightarrow O_2$ + carbohydrates

Most of the global forests can be found in the Northern Hemisphere. In summer, deciduous trees have foliage and photosynthesis prevails – plants capture CO_2 from the air and store carbon in their trunks and leaves. In autumn, they typically shed their leaves, which rot on the ground and CO_2 is released back to the air.

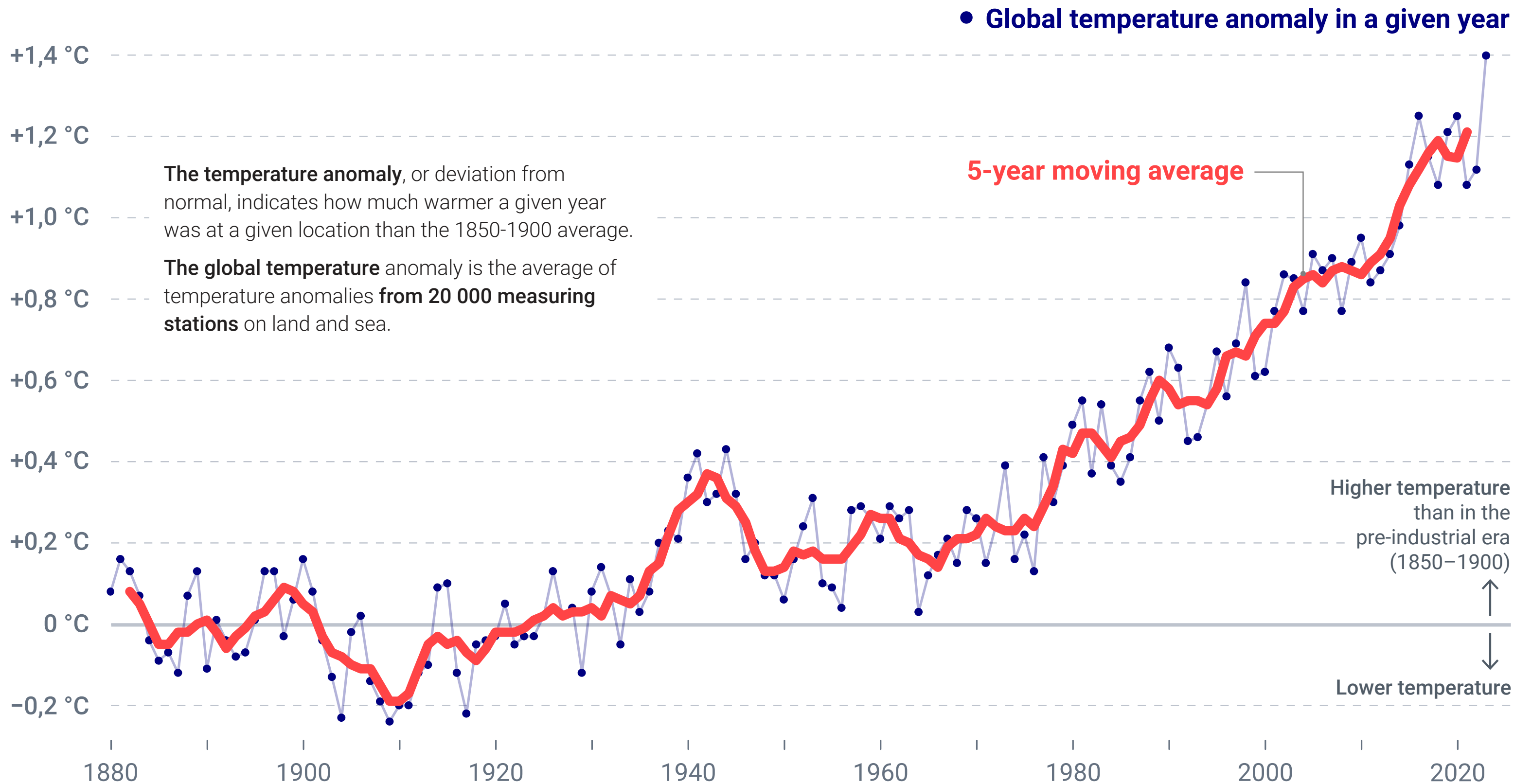
Keeling observed this oscillation between summer and winter but also noticed a long-term increase in CO_2 concentrations which he believed was caused by the combustion of coal, oil and natural gas.

> **During combustion**, O_2 is consumed and CO_2 released. When coal is burned, the chemical reaction is simple: $C + O_2 \rightarrow CO_2$.
>
> When natural gas is burned, even more O_2 is consumed as water vapour is produced as well: $CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$

The fact that rising CO_2 concentrations are really caused by combustion was proven by Keeling's son Ralph, who found a very precise method to measure concentrations of oxygen in 1988. His results show an unnatural long-term decline in O_2 concentrations. A number of other papers have been published since then, including research of isotope traces, which confirmed that the increase in atmospheric CO_2 is due to fossil fuel combustion. **It is therefore certain now that the increasing CO_2 concentrations are really caused by humans.**

TREND IN GLOBAL TEMPERATURE ANOMALY

The world is now **approximately 1.2 °C warmer** than in 1850–1900. Over the last forty years, **the warming rate has been 0.2 °C per decade**.



Data source: **NASA** Goddard Institute for Space Studies

The data from scientific measurements show that temperatures keep rising with increasing CO_2 concentrations, exactly as predicted by computer simulations.

Between 1900 and 2020, the concentration of CO_2 in the atmosphere increased from 295 ppm to 415 ppm, i.e. by 40%. If doubling the concentrations is estimated to make Earth about 3 °C warmer, the 40% increase should make it 1.2 °C warmer. And indeed, temperature anomalies measured by scientists show that the world is now 1.2 °C warmer than in the pre-industrial era. This comparison is somewhat simplified as it does not include other greenhouse gases (such as methane CH_4 and nitrous oxide N_2O) or climate inertia. Nevertheless, it clearly shows that temperatures keep increasing (more or less) as predicted by simulations.

How to read this graph?

The graph shows the trend in **temperature anomaly over the past 140 years**. Until 2023, the hottest year on record was 2016. The year of 2020 was almost as hot, followed by 2019. In the top twenty hottest years, there is only one before 2000 (1998), all the others are from this century. **The five hottest years on record until 2022** are: 2016, 2020, 2019, 2017 and 2015.

What is a reference period?

Whenever we say how much the global temperature has increased, we also need to be clear since when (what the reference period for that warming is). For example, 2016 was 1.2 °C warmer than the average temperature in 1850–1900, but only 0.6 °C warmer than the average temperature in 1981–2010.

Climate scientists often use 1850–1900 as a reference period (also called "the pre-industrial era"). It is not really accurate because the industrial revolution had already been underway at that time, but the concentrations of CO_2 in the atmosphere were around 280 to 300 ppm back then – and Earth's temperature was not yet affected by the stregthening greenhouse effect very much.

Any warming mentioned in this booklet is also compared to this pre-industrial era. If you find different temperatures in other sources, always check which reference period is used.

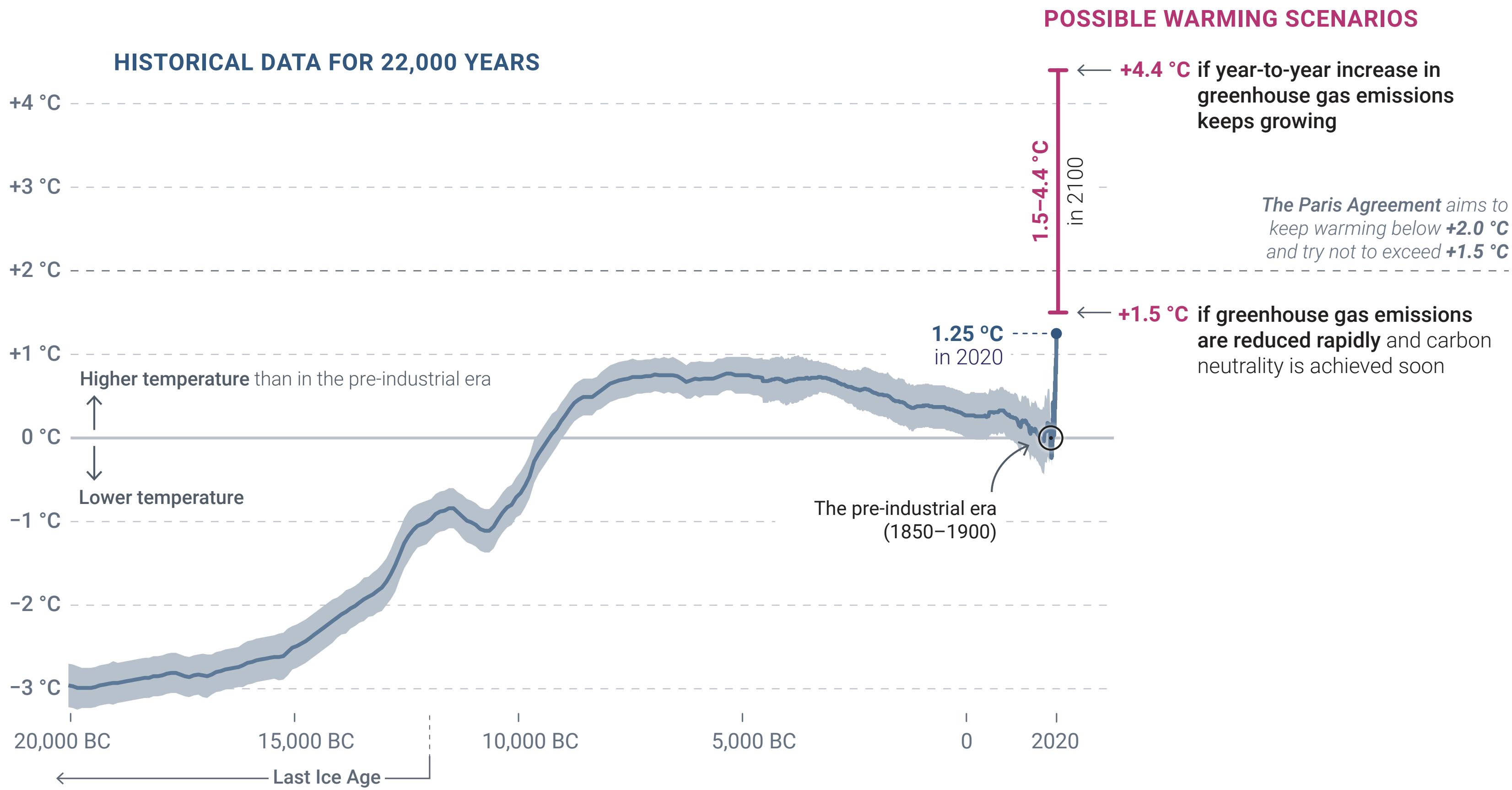
What is a temperature anomaly?

Whenever global warming is mentioned in the text, it is **never about rising mean global temperature**. This is because calculating the mean temperature for a non-homogenous entity such as Earth leads to a number of methodological as well as practical problems. On a global scale it is more useful to talk about a temperature anomaly. Neverthless, mean temperatures can also be useful – e.g. for smaller entities such as cities or small countries.

A temperature anomaly for any given year says how much warmer the world is/was when compared to the average temperature in the reference period. The temperature anomaly in 2016 was 1.2 °C – meaning that year was globally (on average) 1.2 °C warmer than the world in 1850–1900. However, people in different parts of the world were experiencing different temperatures. For example, November 2016 in Canada was more than 5 °C warmer while most of Russia was 4 °C colder and temperatures in Europe was just slightly above average. On the global scale, when the average temperature is calculated, warmer and colder locations even out – this temperature for 2016 was 1.2 °C.

GLOBAL TEMPERATURE CHANGES IN THE LAST 22,000 YEARS

Scenarios estimate **global warming of 1.5–4.4 °C by 2100** (compared to the pre-industrial era).



Data source: Shakun (2012): 22,050–4,550 BC, Marcott (2013): 4,540 BC–1860, NASA GISS: 1880–2020

Some say that climate has always been changing. However, this argument is not relevant in today's debate on climate change – the rate of global warming observed in the past one hundred years is completely outside of the range for natural climate processes.

How to read this graph?

In Earth's history, one can find periods in which the climate was much colder than today (ice ages) as well as much warmer (e.g. the age of dinosaurs). However, climate changes were always slow. From this historical perspective, — **the temperature change in the last hundred years** shown in the graph **is huge and abrupt – such a trend is by no means natural for the world's climate**.

— **Computer simulations** also show that by the end of this century the planet will be 4.4 °C warmer than in 1900 unless the production of greenhouse gas emissions is radically reduced.

What does the temperature change mean for humans and for the living world?

During the last ice age (about 22,000 years ago), Canada and northern Europe were covered with a massive glacier, and cold tundra stretched all the way down to the Mediterranean coast. Continental glaciers were holding a great deal of water at that time so global ocean levels were about 120 meters lower than today.

In the following ten thousand years, temperatures were slowly rising and the world became 3 °C warmer: glaciers melted away and the natural world adapted to this change – including humans who could now settle in previously uninhabitable northern areas. This was followed by a long era in which the annual global temperature did not change very much, which was favourable for the civilization growth.

The current warming, however, is much faster than that and **does not give enough time to the living world to adapt**. This may have far-reaching consequences for life on the planet as well as for the human civilization (see Why is global warming above 1.5 °C a problem? on pp. 8–11).

How do scientists measure past temperatures?

Air temperatures have been reliably measured since the 18th century. Temperatures in earlier or even pre-historic times can be calculated based on some natural processes affected by temperature changes. An example: dating of tree rings. When a piece of wood is found by archaelogists as a part of their excavations, the growth rings give scientists an idea of temperatures in the period when the tree was growing.

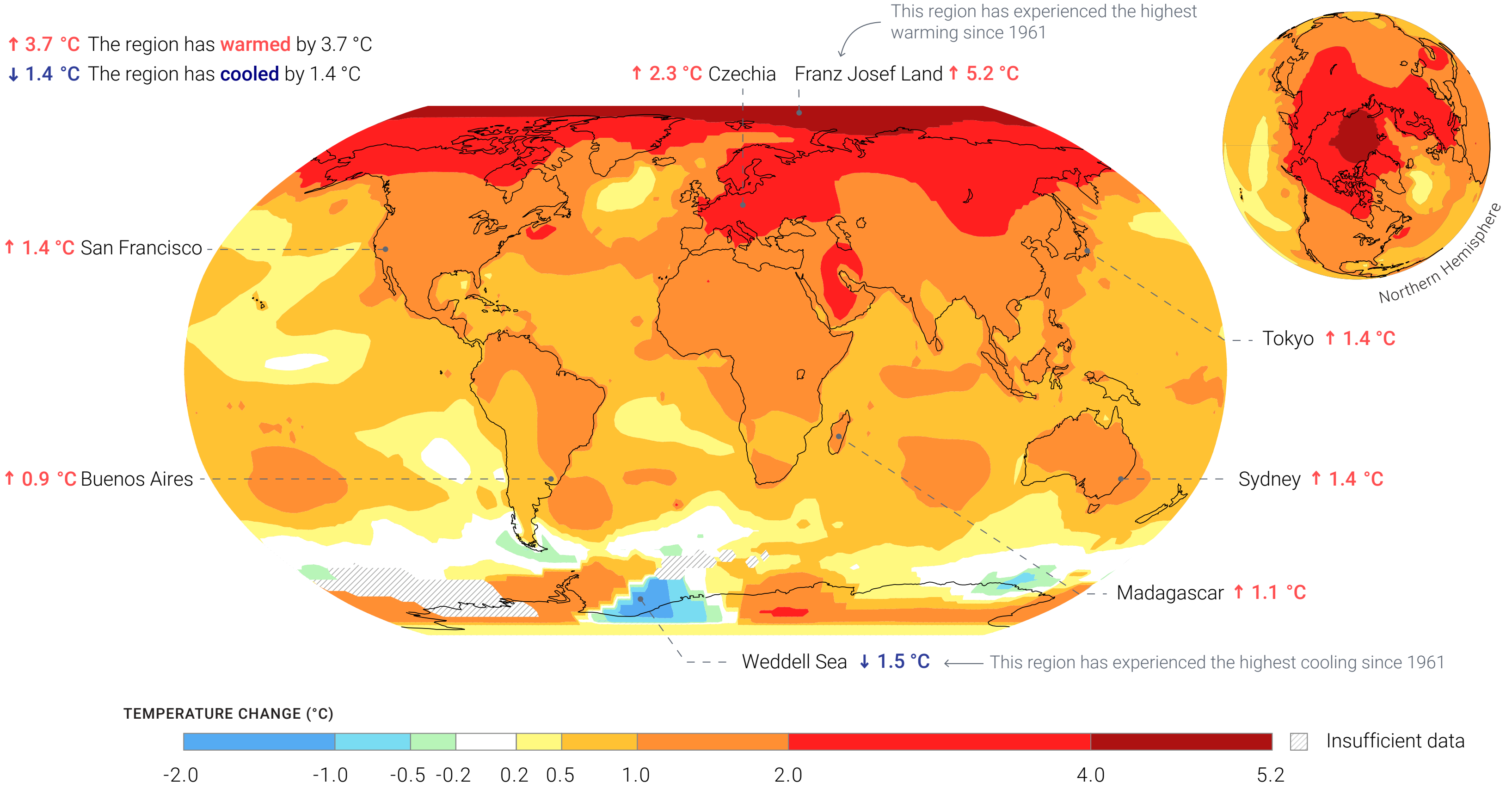
Another method studies pollen grains found at bottoms of lakes – this pollen provides useful information about plants growing by the lake in the past and researchers can thus estimate the temperatures in those days.

The most accurate data about temperatures in the past can be obtained from **analyses of isotopes in marine sediments**. In normal water (H_2O), not all the atoms of oxygen are the same – most of them are isotope ^{16}O and about one in five hundred atoms is isotope ^{18}O, which has two more neutrons in its nucleus.

The number of ^{18}O isotopes in water depends on the temperature of the planet. The analysis of marine sediments thus provides scientists with reliable information about temperatures in ancient times.

MAP OF TEMPERATURE CHANGES (1961–2021)

The warming rate is not the same around the globe. For example, **when compared to oceans, continents warm approximately twice as fast**.



Data source: **NASA** Goddard Institute for Space Studies

Computer simulations in the past predicted that the warming rate might vary across different regions, with some warming faster than others. Changes over the last six decades have shown that this prediction was correct. Today we are able to say which areas on the planet will be warming the fastest and predict the impact of climate change on them.

How to read this map?

The map shows in detail how much temperatures changed between 1961 and 2021 in different parts of the world. Landmasses are warming faster than oceans, **the warming is the fastest over the Arctic** – the climate above some islands in this area is now more than 5 °C warmer than it was six decades ago.

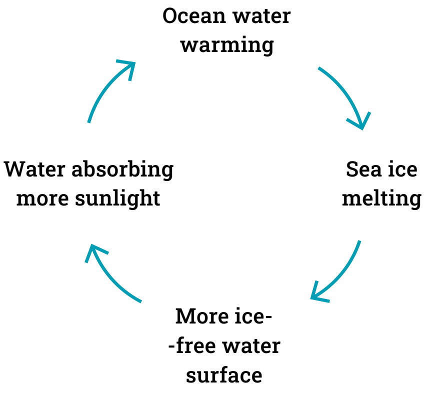
Nonetheless, there are also regions which are not warming at all, and some regions are even getting slightly cooler.

Why is the North warming so fast?

The amplification of warming over the Arctic Ocean is related to different physical properties of ice and water. While water is dark and absorbs almost all of the incoming solar radiation, ice is white and reflects most of the incoming solar radiation back into space – this reflectance of the surface is called **albedo**.

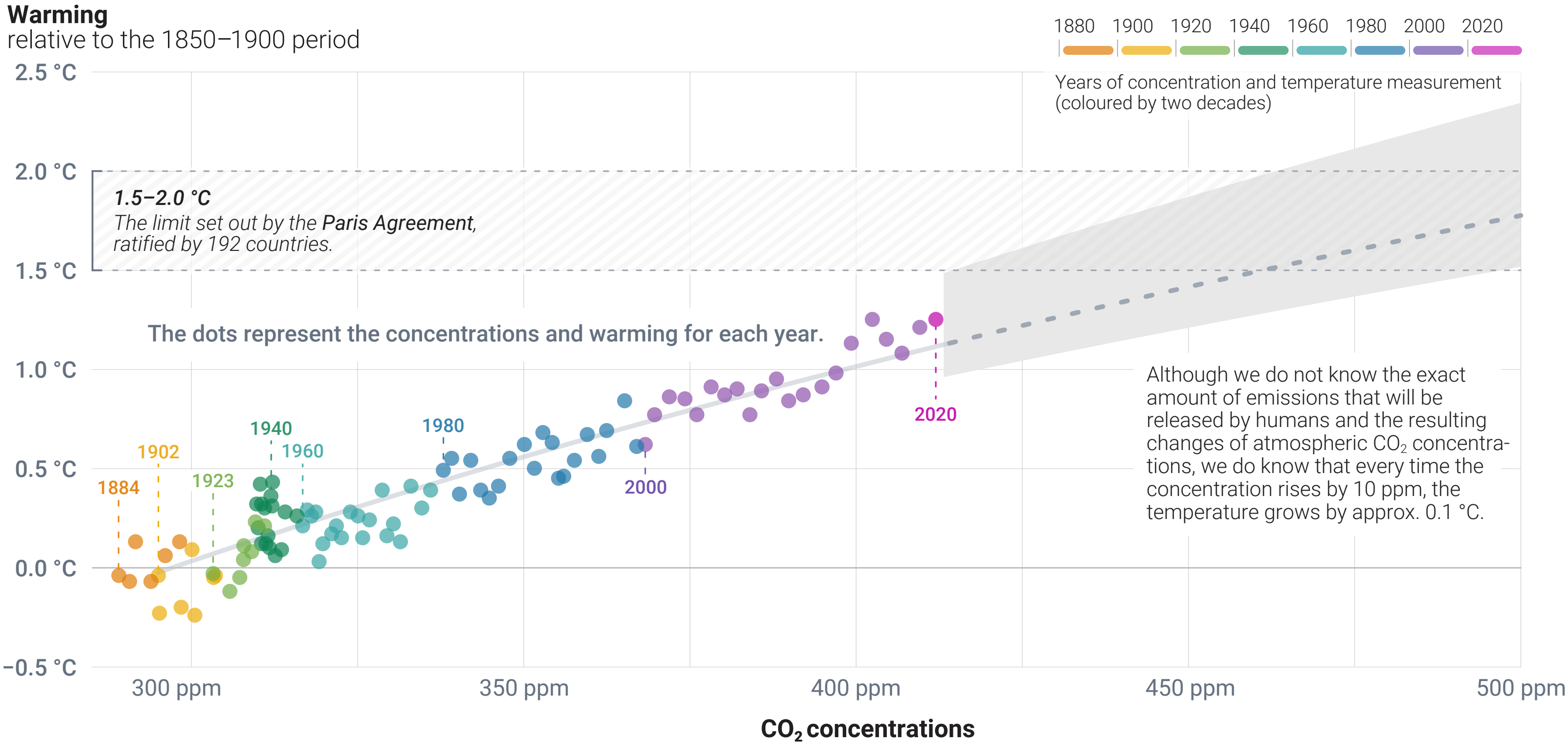
Due to increasing temperatures over the Arctic Ocean, sea ice is melting. As a result, more water surface is ice-free and more solar radiation is being absorbed, which leads to further warming of the ocean, further temperature increase, more ice melting, and so on.

In the Southern Hemisphere, this chain reaction does not occur as the ice in the Antarctic is on land and several kilometres thick. When it melts, deeper layers of ice become uncovered and the albedo thus remains unchanged.



HOW ARE CO_2 CONCENTRATIONS RELATED TO WARMING?

The higher the CO_2 concentration in the atmosphere, the higher the Earth's temperature.
The levels of atmospheric CO_2 depend on the amount of emissions produced by humankind.



CO_2 concentration is measured in ppm (parts per million). The CO_2 concentration of 400 ppm means that one million of air molecules contains 400 molecules of CO_2.
Carbon dioxide (CO_2) contributes to global warming more than any other greenhouse gas: the greenhouse effect is intensifying and 70% of this change is caused by CO_2.

VERSION 2024-03-22

Data source: **NOAA**, **NASA** Goddard Institute for Space Studies

Global warming is (approximately) directly proportional to the increase of CO_2 concentrations in the atmosphere. Every time the concentrations rise by 10 ppm, the temperature increases by 0.1 °C.

How to read this graph?

The points in the left part of the graph show the period of 1884–2020 year by year. The location of each point corresponds to the CO_2 concentration in that year (on the horizontal axis) and the temperature anomaly values for that year (on the vertical axis). The graph indicates that the relationship is approximately proportional: **each 10 ppm increase in CO_2 concentration leads to a temperature increase of about 0.1 °C**.

The dots in the graph are colour-coded and grouped (each period of 20 years has its own colour). It is clear that the increase in CO_2 concentrations has been accelerating in recent years. This corresponds to increasing annual CO_2 emissions.

The right part of the graph shows the **expected global warming** for higher CO_2 concentrations in the future if emissions continue to be produced at the current rate.

In what ways is the relationship between CO_2 concentrations and global warming inaccurate?

The climate system has its inertia – some processes reach equilibrium within several years, others need dozens or hundreds of years. The data shown in the graph are continuous and correspond to a short-term climate response (processes which last only several years). The inertia of the climate system means that **even if we stopped adding greenhouse gases to the atmosphere now** (i.e. their concentrations would no longer increase), **global temperature would still continue to rise for one, maybe two decades**. Then, several hundred years later, the warming would become stable and the values would correspond to balanced climate sensitivity.

Carbon dioxide is responsible for about 70% of global warming. The remaining 30% is due to other greenhouse gases, mainly methane and nitrous oxide: their concentrations in the atmosphere are also increasing. Along with greenhouse gases, however, mankind also emits aerosols, which have a cooling effect on the planet – they reflect solar radiation and participate in the formation of clouds.

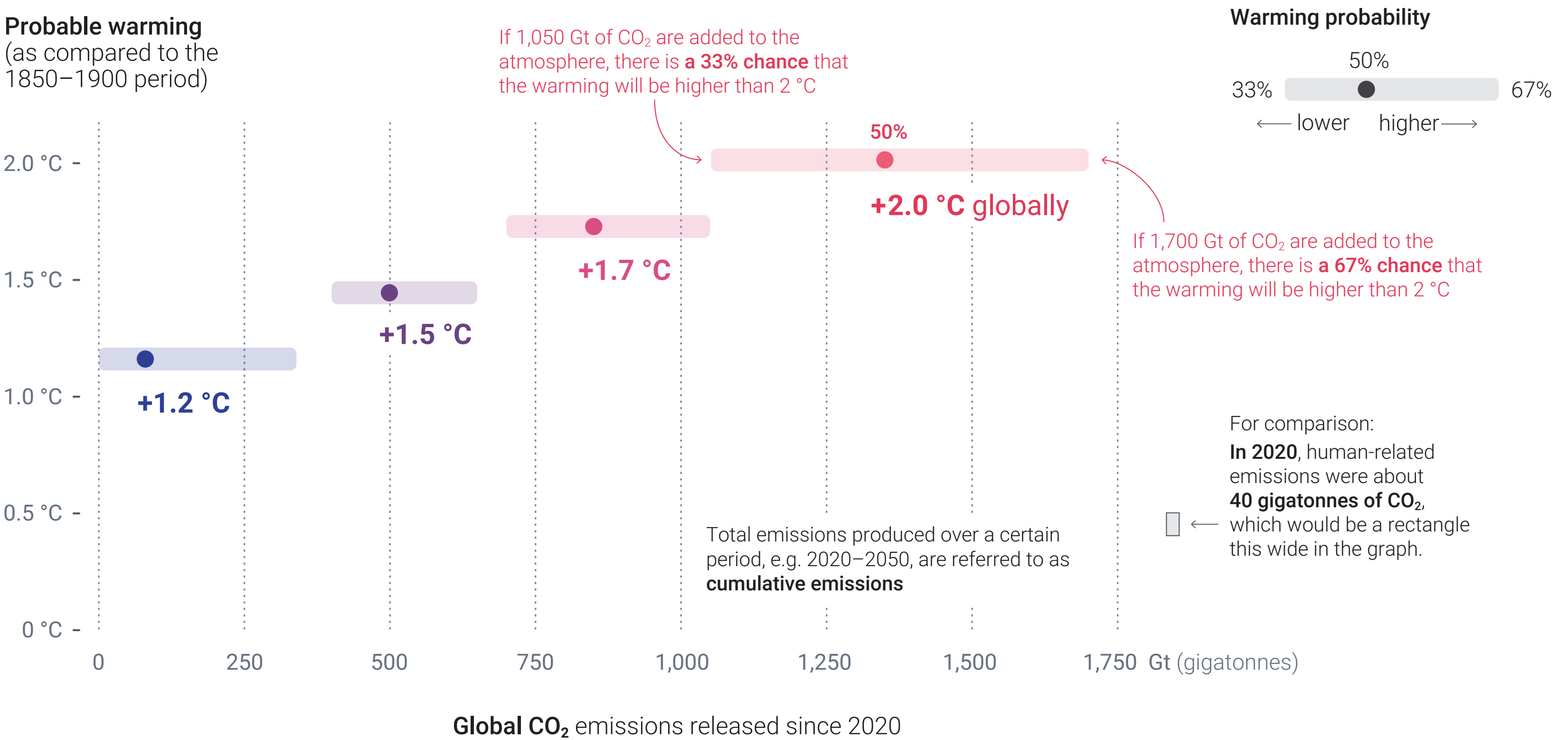
The global warming shown in the graph includes all of these phenomena, but only CO_2 concentrations are plotted on the horizontal axis. Thus, the claim of direct proportionality between increasing concentration and warming is somewhat misleading as it only shows a dependence on the dominant factor. However, because the cooling effect of aerosols and the warming effect of other greenhouse gases partially cancel out, it can be argued that **CO_2 is the driving factor behind well over 70% of global warming**.

The link between global warming and atmospheric concentrations of carbon dioxide is one of the most crucial and longest-studied phenomena in climate science (see History of research of the greenhouse effect on pp. 28–29).

HOW WARMING DEPENDS ON FUTURE CO_2 EMISSIONS

The extent of global warming mainly depends on how much more CO_2 humans will add to the atmosphere in the future.

Due to emissions released until 2020, Earth is now about 1.2 °C warmer.



Data source: IPCC (SR15 for 1.2 °C and AR6 for 1.5–2.0 °C)

The extent of global warming mainly depends on how much more CO_2 humans will add to the atmosphere before climate neutrality is reached. For any scenario, however, scientists can only predict the probability of temperature increase.

How to read this graph?

The graph shows the expected global warming for different amounts of CO_2 added to the atmosphere.

For example, if approx. 1,750 Gt CO_2 are emitted after 2020, the probability of **global warming over 2 °C** is 67%. If the emissions are lower, the probability of the same warming is lower too: 33% for 1,100 Gt CO_2, and 50% for approx. 1,400 Gt CO_2. In other words – **the more we want to be sure that the warming will not exceed a certain threshold, the less carbon dioxide we can add to the atmosphere**.

The differences in probability can be easily explained as follows: if you roll the dice and want to get one of two different numbers (e.g. 1 or 6), there is a 33% probability that you will get one. To get one of four different numbers (e.g. 2, 3, 4, 5), the probability that you will get it is higher: 67%.

The warming indicated in the graph shows how much the global temperature has changed since 1850–1900 (or more precisely, it shows the anomaly from the average annual temperature for that reference period). The cummulative emissions on the horizontal axis refer to 2020.

What is carbon budget?

We can calculate how much more CO_2 humans can add to the atmosphere to keep global warming below a certain level. This amount of emissions is called the remaining **carbon budget** for that level of warming.

The word “budget” is meant as a metaphor here: just like your vacation budget says how much you can afford to spend on your vacation, carbon budget says how much CO_2 humans can “afford” to emit to keep global warming below a certain level.

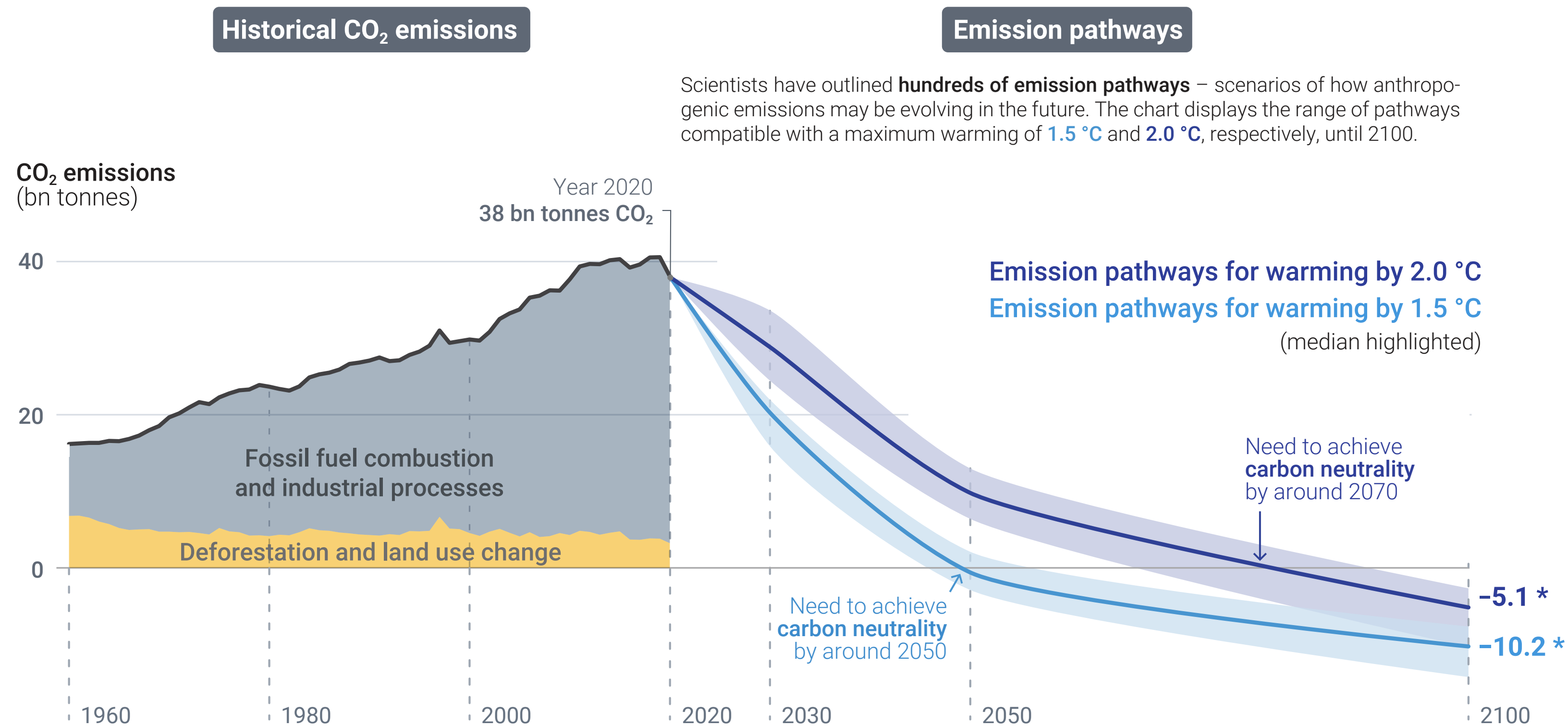
How is carbon budget different from carbon neutrality (net zero)?

The difference between carbon budget and carbon (climate) neutrality can be explained through another metaphor: think of someone who wants to quit smoking. The day on which this person smokes their last cigarette (carbon neutrality) and the total number of cigarettes smoked before that day (carbon budget) are two very different things. And yet it is clear that the impact on the person‘s health will be determined by the total number of cigarettes smoked, not by the day on which the person quits smoking.

The concept of carbon budget is therefore very important and has been used by scientists in order to communicate the urgency of climate change but also to encourage more ambitious pledges to reduce CO_2 emissions. Some countries and cities are already using this concept in their strategic planning.

EMISSION PATHWAYS TOWARDS PARIS AGREEMENT

The signatories of the Paris Agreement have **committed to keep the global temperature increase well below 2.0 °C** and to pursue efforts to limit the increase to 1.5 °C as compared to 1850–1900.



* **Negative emissions values** indicate that carbon capture technologies capture more atmospheric carbon than produced by human activity.

Data source: Global Carbon Project, IPCC SR15

If we are to keep global warming below a level that will not lead to large-scale destruction of the environment, we must substantially reduce our greenhouse gas emissions. The pathways for keeping global warming below 1.5 °C assume that global carbon neutrality (no more CO_2 added to the atmosphere) is reached by 2050.

How to read this graph?

The graph shows the **trend in CO_2 emissions over the last 60 years** and presents various future scenarios, which would make it possible to keep global warming below 1.5 or 2 °C and thus meet the aims of the Paris Agreement.

The pathways for keeping global warming below 1.5 °C (above pre-industrial levels) require half of the CO_2 emissions to be reduced by 2030 and carbon neutrality to be achieved by 2050.

To keep the **warming below 2 °C**, about 25% of CO_2 emissions would need to be cut by 2030 and **global net-zero would need to be achieved around 2070**.

What are emission pathways?

Emission pathways show variations of possible future development – different amounts of emissions that humans may (not) add to the atmosphere. These scenarios often depend on a number factors: from global population growth and higher demand for electricity to the number of wind farms and other technologies built or deployed. The pathways are used as primary input data for simulations of the future climate.

Of course, the emission pathways presented in the graph are not the only options. For example, in the "business as usual" scenario, **CO_2 emissions are not significantly curbed** and keep rising at their current rate. As a result, **CO_2 concentrations will be around 1000 ppm by the end of the century and Earth will be almost 5 °C warmer** (compared to the pre-industrial era, i.e. 1850–1900).

At the moment, the most likely scenario, which reflects measures already planned but not yet implemented, leads to the global warming of 2.6 °C by 2100. However, this warming is far above the 1.5–2 °C goal set out in the Paris Agreement.

How can emissions be reduced?

Emissions can be significantly cut if humans stop using fossil fuels (coal, oil and natural gas) in transport, industry and energy sectors. Moving away from fossil fuels requires shifting to low-emission solutions, such as using renewable sources (solar, wind) or nuclear power, and lower consumption by using better insulation, more efficient technologies, etc.

An essential **mechanism for transitioning over to a low-carbon economy are CO_2 pricing schemes** that create economically favourable conditions for low-carbon technologies.
For example, the Emissions Trading Scheme (ETS), introduced by the European Union in 2005, which system obliges coal-fired power plants, iron and steel works and other greenhouse gas emitters to cover their production with **allowances**. The companies obtain one part of the allowances free of charge, while the rest is auctioned in the market. The quantity of allowances issued each year is limited and gradually decreasing. As the price of allowances rises, companies are motivated to reduce their emissions. As a result, fossil fuel combustion is no longer profitable. For example, some coal-powered plants are being decommmissioned and replaced by more environmentally friendly energy sources such as solar or wind. Companies that choose to reduce emissions the most can also make a profit by selling some of their emission allowances. Other countries, including China, Australia and some US states, are introducing similar schemes.

HISTORY OF RESEARCH OF THE GREENHOUSE EFFECT

We have known about climate change caused by CO_2 emissions **for more than a hundred years**.

First industrial revolution – due to coal mining, steam engines and first railways CO_2 emissions start to increase

1856
Using a glass cylinder experiment, **Eunice Newton Foote** concludes that **the atmosphere warms up with increasing CO_2 concentration.**

1859
John Tyndall investigates the absorption of thermal radiation by carbon dioxide and **formulates the principles of the greenhouse effect.**

1896
Svante Arrhenius publishes the **first calculation of the strength of the greenhouse effect**. It was an estimate but his conclusion (climate sensitivity is about 4 °C) was not far from today's scientific estimates.

World War I

Oil production begins in Texas and the Persian Gulf

1938
Guy Stewart Callendar links observed rising temperatures to rising CO_2 emissions. He argues that the **warming is the result of the greenhouse effect.**

World War II

1957
In his research, **Roger Revelle** concludes that the **ocean can only absorb about a half of all CO_2 emissions.**

1960
Charles Keeling measures **CO_2 concentrations** in the atmosphere and **finds a long-term increase.**

1969
Satellites enable **precise measurements of atmospheric temperature** at high altitudes and over oceans.

1972
Ice core drilling shows **historical CO_2 concentrations** and their influence on transitions between glacial and interglacial periods.

Ozone hole discovered

1979
The US Academy of Sciences publishes the so-called **Charney Report**, based on computer models, which concludes that **climate sensitivity ranges from 1.5 to 4.5 °C** (the median being 3 °C).

1985
Scientists at the international conference in Villach **agree that global warming is happening** and global effort to reduce CO_2 emissions is needed.

Montreal Protocol: regulation of freons (ozone-depletion)

1988
Ralph Keeling discovers a method of **precise measurement of oxygen concentrations** in the atmosphere.

Ozone hole begins to shrink (measures succeeded)

2018
IPCC Special Report examines in detail if the 1.5 °C limit of warming can be achieved. It concludes that **with large-scale reduction of emissions it is still possible to keep the warming below 1.5 °C.**

2020
Latest research provides detailed analyses of climate changes in the past. **Climate sensitivity** is now estimated to be **2.6–4.1 °C.**

A key concept for understanding climate change is **climate sensitivity**. This value indicates how much Earth's temperature will change if concentrations of atmospheric CO_2 double. Latest estimates of climate sensitivity range from 2.6–4.1 °C (the median being 3 °C).

The strength of the greenhouse effect was first estimated over a hundred years ago. Latest calculations and simulations have only made this estimate slightly more accurate: if the concentrations of atmospheric carbon dioxide double, the planet will be about 3 °C warmer.

Due to quickly advancing science in the nineteenth century, people learned about the composition of the atmosphere (79% nitrogen, 21% oxygen and small amounts of other gases) but also knew that CO_2 absorbs thermal radiation. With the industrial revolution well underway and more intense coal mining and combustion, some scientists began to wonder: perhaps there is more CO_2 in the atmosphere now, and if so, could this affect the temperature of the planet in some way?

The first calculation of the greenhouse effect was made in 1896 by Svante Arrhenius. Beside the effects of CO_2, his calculation included the effect of water vapour, which also acts as a greenhouse gas and its amount in the atmosphere depends on temperature – there is more vapour in warmer air, and when temperature drops, the vapour becomes condensed and falls down as rain. Arrhenius concluded that if CO_2 concentrations in the atmosphere doubled (which would also lead to a higher concentration of water vapour), the planet would be about 4 °C warmer.

> Climate sensitivity means how much warmer (or cooler) Earth's surface will get. If the concentrations of atmospheric greenhouse gases double, it is now estimated that the planet will get 2.6–4.1 °C warmer (the expected warming is 3 °C).

Early computer simulations of global climate began to appear in the **1970s**. At first, they only simulated temperature and air streams above land and oceans. Later, they also included simulations of oceanic currents, rain, snow, glaciers and vegetation. Physicists who made those simulations already knew the exact concentrations of CO_2 in the atmosphere and how quickly they rise (see Cycles of CO_2 and O_2 concentrations in the atmosphere on pp. 14–15). Their simulations only made Arrhenius' estimate more accurate: if the concentrations of atmospheric CO_2 double, the planet will be about 3 °C warmer. The simulations also showed more precisely that the **warming will be significantly stronger over the Arctic**.

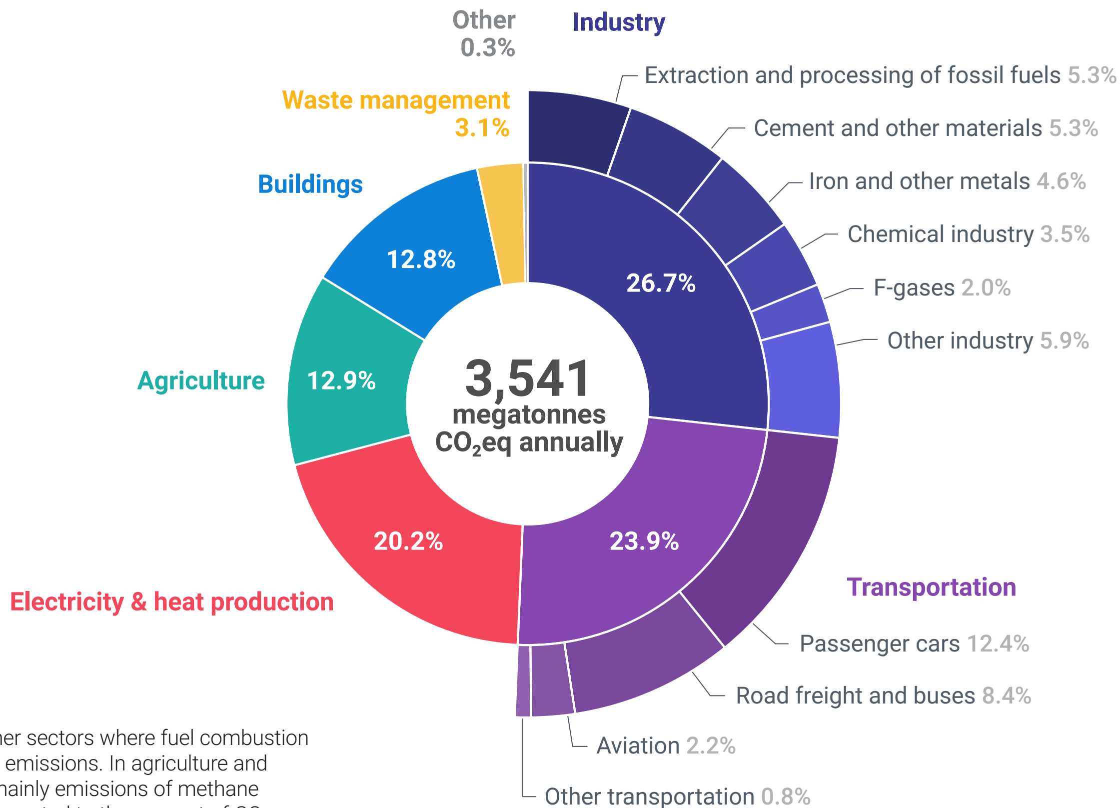
The results of several computer simulations were **presented by scientists in the "Charney Report" (1979)**. Back in the 1970s, the authors already **warned about the expected negative impact** of such climate changes and urged to reduce CO_2 emissions. Interestingly enough, major oil companies came to the same conclusion around that time. The internal report of ExxonMobil from 1982 describes in detail how Earth's temperature depends on the concentrations of atmospheric CO_2 – with the same estimated climate sensitivity.

Latest computer simulations show in detail the temperature, humidity and airflow in many atmospheric layers, deep and surface currents in oceans, and include factors such as geography or vegetation, clouds in various heights, sea ice, glacier trends and many other variables. The simulations of the past climate are now so accurate that even meteorologists find it hard to distinguish them from the actual climate trends in the past – cyclones and anticyclones move as if they were real. **Even these most advanced simulations conclude** that if the concentrations of greenhouse gases double, **the world will be approximately 3 °C warmer.**

> When we speak of global warming, it is the average of temperatures from different areas (see Map of temperature changes on pp. 20–21).

GREENHOUSE GAS EMISSIONS IN EU BY SECTORS

Total greenhouse gas emissions in the European Union in 2021.



What does CO_2eq mean?

In energy, transportation and other sectors where fuel combustion is essential, these are direct CO_2 emissions. In agriculture and waste management, these are mainly emissions of methane (CH_4) and nitrous oxide (N_2O) converted to the amount of CO_2 emissions, which would have the same warming effect.

Emissions from forestry and land use are not included.

Data source: Eurostat

VERSION 2024-03-22

Most EU emissions come from industry and transportation but a signicant part is also related to electricity and heat production.

How to read this graph?

The graph includes emissions of methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases expressed in carbon dioxide equivalent (CO_2eq). This equivalent shows for any greenhouse gas how much CO_2 released to the atmosphere would have the same greenhouse effect.
In 2021, the total annual emissions of greenhouse gases in the European Union (EU-27) reached 3,541 million tons of CO_2eq, which is **7.93 tons per capita every year**. That is almost twice the global average and five times more than average emissions of people living in Africa or India.

Where are greenhouse gases produced?

● **Industry** (2,120 kg CO_2eq per capita). Greenhouse gases in industry come from **combustion** and from **chemical reactions** which are part of the production process. Emissions from chemical reactions can be lowered e.g. by using the **CCS technology** (Carbon Capture and Storage), **hydrogen** or **using alternative materials**. As for combustion, these are primarily emissions from the burning of fossil fuels, which are used for reaching temperatures required by the production process (the melting of iron ore, glass or lime, drying paper, etc.). Low-carbon solutions in this sector include **electrification** (if renewable electricity is used), **CCS**, hydrogen and **more efficient manufacturing technologies**.

● **Transportation** (1,897 kg CO_2eq per capita). Aviation (flights from the EU airports) accounts for 178 kg, almost all the other emissions come from road transportation. Solutions for emission reduction include **using alternative fuels, better public transport, less travel** (e.g. working from home more often), car sharing, etc. **Electromobility** can be helpful too but only if vehicles use clean, renewable energy.

● **Electricity and heat production** (1,606 kg CO_2eq per capita). These emissions are related to electricity production and heating. Many EU countries have been lately investing in **new wind farms, solar plants and other sources of low-carbon energy** but more collaboration on the EU level is necessary – both for renewable energy production and its distribution from country to country (a **robust continental grid** is still missing). **Energy saving** will play another important role.

● **Agriculture** (1,022 kg CO_2eq per capita). Most emissions in this sector are CH_4 and N_2O related to intensive farming, and combustion of fossil fuels in agriculture. Measures that would lead to lower emissions in agriculture include **a smart reduction in the number of livestock kept** (to make sure there is still enough natural fertiliser and the soil quality is not harmed), **a change in the management of manure** and **less intensive chemical fertiliser application**. Livestock reduction is also possible if there is less demand for dairy and meat products.

● **Buildings** (about 1,018 kg CO_2eq per capita). As the largest part of these emissions comes from heating, cooking and water heating in households, offices and institutions, a great deal can be reduced by lower consumption: if **good insulation and more energy-efficient technologies are used in buildings**.

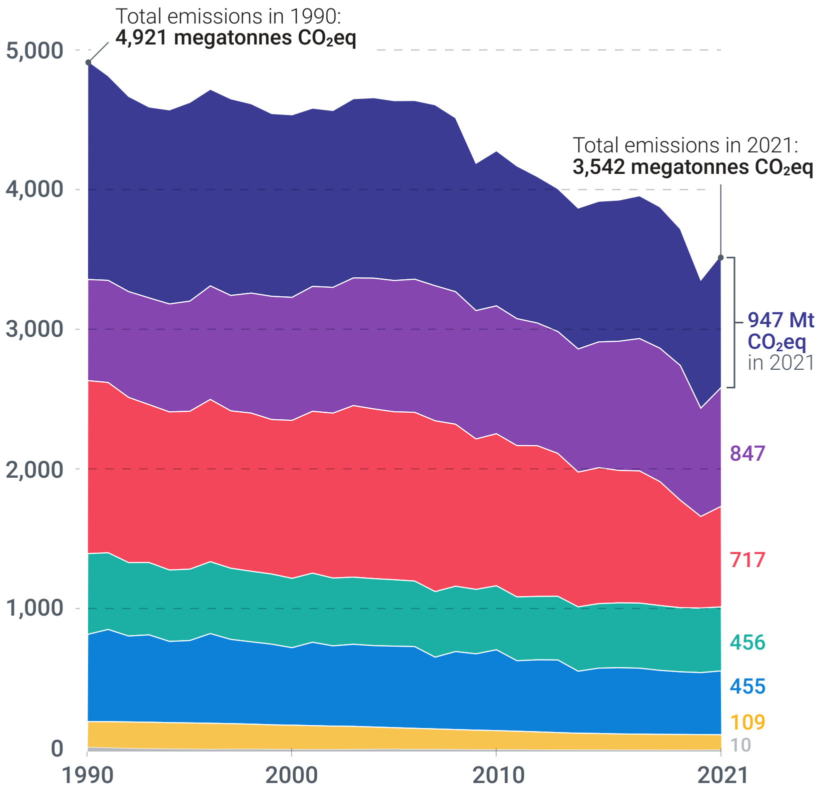
● **Waste management** (about 245 kg CO_2eq per capita). These emissions can be cut down if less waste is produced, **recyclable waste** is **banned from landfills** (already banned in many EU countries) and **biodegradable waste** is **turned into biomethane**, which can be used as fuel in transporation, etc.

EU EMISSIONS IN 1990–2021

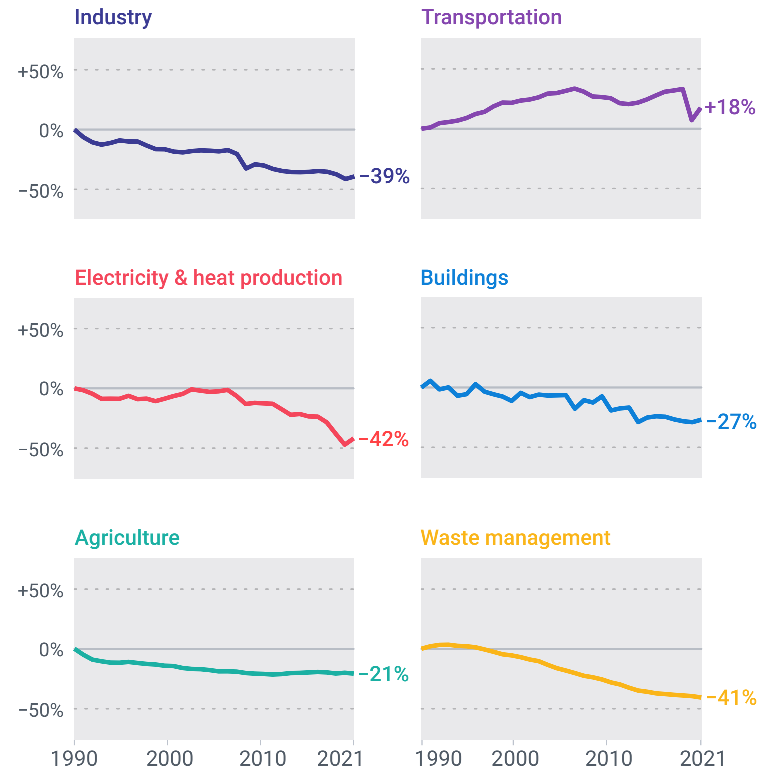
The EU emissions **have dropped by 28% since 1990.** Only emissions from transportation keep rising.

Industry · Transportation · Electricity & heat production · Buildings · Agriculture · Waste management · Other

TOTAL EMISSIONS in 1990—2021



EMISSIONS TRENDS PER SECTOR as compared to 1990



Emissions from forestry and land use are not included.

Data source: Eurostat

VERSION 2024-03-22

The European Union has reduced its emissions by 28% since 1990. The only sector in which emissions keep rising is transportation.

How to read this graph?

The graph shows carbon dioxide emissions produced by humans as well as emissions of nitrous oxide (N_2O), methane (CH_4) and other greenhouse gases, which are expressed in CO_2 (CO_2eq) – carbon dioxide equivalent. For any greenhouse gas, this equivalent shows the amount of CO_2 which would warm the planet as much as the amount of the gas. The equivalent is used because it is necessary to have some kind of common measurement scale: some greenhouse gases are much more potent than others or last in the atmosphere much longer.

The left part of the graph shows the total amount of emissions produced annually in the EU-27 (EU members in 2021) in CO_2eq over the past three decades – and how these emissions have been reduced from 5 billion tons in 1990 to 3.5 billion tons in 2021. Each sector has a different colour. The right part of the graph highlights the changes in each sector.

The graph also indicates that total EU emissions have been decreasing more quickly after the Global Financial Crisis of 2007–2008.

How did emissions change in each sector?

● **Industry.** These emissions have been reduced by 39% since 1990. Some of them come from chemical reactions in the production of cement, steel, aluminium, glass, chemicals, etc. and they are quite difficult to cut down – sometimes there is no substitute available for those materials or no alternative method of production. Other emissions arise from combustion of fossil fuels for industrial use, typically when a material needs to be heated in the production process (during melting, drying, destilation, etc.).

● **Transportation.** Emission from transportation have increased by 18% since 1990. There was a temporary drop after 2007 due to the Global Financial Crisis but the emissions started to rise again after 2013. Most of them are produced by road vehicles (87% in 2021; aviation accounted for 9% of emissions).

● **Electricity and heat production.** Emissions in this sector have been reduced by 42% since 1990. The trend has been accelerating in the past few years and because the EU has committed to reach net zero (climate neutrality) by 2050, it is likely to accelerate in the future as well.

● **Agriculture.** Emissions in this sector have fallen by 21% since 1990. They mainly come from livestock farming and soil management practices (N_2O emissions) used in intensive farming, and from combustion of fossil fuels in agriculture.

● **Buildings.** Emissions fell by 27% compared to 1990. These emissions arise from heating and hot water used in institutions, offices and households (unless the energy is provided by a heating facility), cooking, etc.

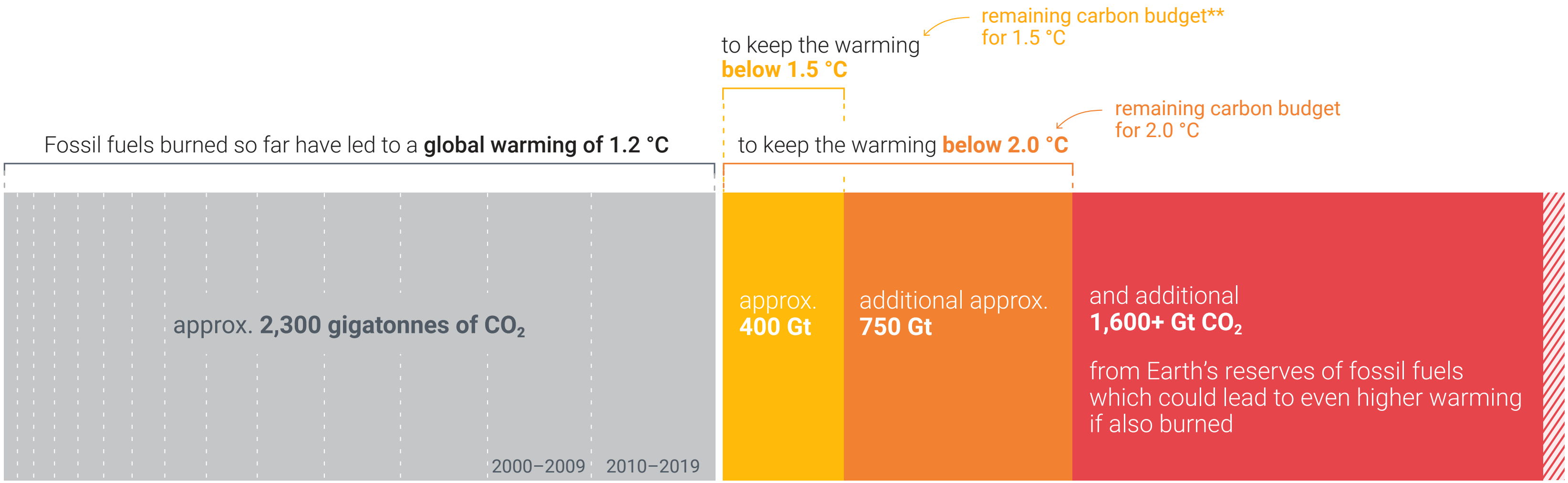
● **Waste management.** Emissions in this sector have been reduced by 41% since the mid-1990s. These emissions are primarily produced by landfills, which leak methane into the atmosphere. This methane is produced by decomposing biodegradable material (paper, cardboard, textiles and bio-waste).

CONCEPT OF CARBON BUDGET

Global warming depends on the total amount of CO_2 added by humans to the atmosphere. **The maximum additional CO_2 that can be released** to keep the rise in temperature below some level **is called a carbon budget**.

HOW MUCH CO_2 **HAS BEEN EMITTED** BY HUMANS

HOW MUCH MORE CO_2 **CAN BE EMITTED***



Historical CO_2 emissions since 1880 by decade

Global CO_2 emissions from further combustion of fossil fuels

* Values calculated as of 2020

** The remaining carbon budget is often simply referred to as the carbon budget

VERSION 2024-03-22

Data source: IPCC

Just like your vacation budget says how much you can afford to spend on your vacation, the carbon budget says how much carbon dioxide humans can add to the atmosphere if they want to keep global warming below a certain level.

How to read this graph?

The grey part of the graph shows how much carbon dioxide (CO_2) has been released by humans to the atmosphere since 1880 (pre-industrial times): around 2,300 billion tons (Gt).
It is evident that the amount of CO_2 released per decade has been growing steadily.

The right part of the graph shows the amount of CO_2 that can be emitted by humans in the future if the warming is to stay below a certain level: only about 400 Gt for 1.5 °C and another 750 Gt (=1,150 Gt) for 2 °C. It is estimated that the world's fossil fuel reserves could add another 1,600 Gt on top of the previous 1,150 Gt if we decided to burn them. In that scenario, however, the warming would go far beyond 2 °C (see Why is global warming above 1.5 °C a problem? on pp. 8–11).

How is carbon budget different from carbon neutrality?

Carbon neutrality (net-zero) and carbon budget are two different concepts. **Carbon neutrality** is primarily about a date: by which year the world (or a country, company or organization) pledges to stop adding greenhouse gases to the atmosphere – without specifying the amount of greenhouse gas emissions which can be released before that date. **Carbon budget**, on the other hand, is based on a different goal: the total amount of fossil fuels that can be burned to keep global warming below a certain level – without specifying when the last ton of fossil fuels can be burned.

The two concepts can be also explained through a metaphor of a smoker. The day on which the smoker will quit smoking (net-zero) and how many cigarettes they will have smoked by that day (carbon budget) are two very different things. And yet it is clear that the amount of cigarettes smoked will have a much stronger impact on the smoker's health than when exactly they will smoke the last one.

The concept of carbon budget has been used to show the urgency of climate change and to encourage adoption of adequate policies and measures. Some cities and countries already have their own carbon budgets and use them in their own strategies and planning.

How is carbon budget calculated?

Due to a number of feedback loops in Earth's climate (the effects of water vapour, soot, melting glaciers, etc.) it is not possible to calculate precisely how much warmer the planet will get if a certain amount of greenhouse gases is added to the atmosphere. For example, it is known that water vapour absorbs a great deal of thermal radiation and thus makes the greenhouse effect of these gases stronger but scientists can only estimate how much warming will be caused by this factor. That is why they usually talk about probability and temperature ranges: e.g. if CO_2 concentrations double, the global temperature is likely to rise by 2.6–4.1 °C, depending on climate sensitivity. In other words, this means that if we want to be sure that the warming will stay below a certain level, we need to burn less than the estimated amount because the climate might be actually more sensitive than we believed (see also How warming depends on future CO_2 emissions on pp. 24–25).

INTERNATIONAL CLIMATE TREATIES

Key milestones in global effort to protect the world's climate – important summits, panels, negotiations and treaties.

IPCC Intergovernmental Panel on Climate Change
UNEP United Nations Environment Programme
WMO World Meteorological Organization
UNFCCC United Nations Framework Convention on Climate Change
COP Conference of Parties

MEETINGS

CONFERENCES, SUMMITS, MEETINGS AND PANELS of climate policy makers (especially politicians or representatives of NGOs and business)

1979 – First world climate scientific conference in Geneva
Convened by the World Meteorological Organization (WMO); the key decision is to create the Intergovernmental Panel on Climate Change (IPCC).

1988 – Intergovernmental Panel on Climate Change (IPCC) established
An apolitical body of scientists, which publishes a detailed report on climate every 5 years. Founded by the WMO and the UN Environment Programme (UNEP).

1992 – United Nations Conference on Environment and Development in Rio de Janeiro, also known as the Earth Summit
Convened by the UN, attended by 172 countries and representatives of non-governmental organisations. The key outcome: the Framework Convention on Climate Change (UNFCCC) is established.

1995 – First UNFCCC Conference of Parties (COP) in Berlin

1997 – COP 3 Kyoto

2010 – COP 16 Cancún

2015/16 – COP 21 Paris

2021 – COP 26 Glasgow

1979 – 1988 – 1992 – 1995 – 1997 – 2005 – 2010 – 2015/16 – 2018 – 2020 – 2021

OUTCOMES

INTERNATIONAL AGREEMENTS

(multilateral agreements, conventions, protocols) providing a general framework for pledges of parties

United Nations Framework Convention on Climate Change (UNFCCC) established (1992)
International consensus: climate change needs to be addressed, and countries are obliged to report their emissions and participate in annual conferences of parties (COPs).

Kyoto Protocol (1997)
International treaty to the UNFCCC. Industrialised countries must reduce their greenhouse gas emissions by 5.2%. No longer in force – replaced by the Paris Agreement.

Paris Agreement (2015/16)
International treaty to the UNFCCC signed by 195 countries and replacing the Kyoto Protocol. Key target: keep global warming below 2 °C and aim to stay below 1.5 °C.

IPCC Special Report 1.5 °C (2018)
A report for governments, in which scientists summarize the pathways needed to keep global warming below 1.5 °C and describe various scenarios: the impacts of warming if this threshold is crossed.

POLICIES

(steps to be taken, legislative measures and instruments) to implement obligations under international treaties – with respect to the context each country

EU Emission Trading System (ETS) (2005)
Greenhouse gas emitters in selected sectors of economy will be charged for their emissions.

Green Climate Fund (2010)
Economically developed countries pledge to provide financial support for climate action in developing countries.

European Green Deal (2020)
EU climate policy outlining the path towards an environmentally sustainable and emission-free economy and society.

European Climate Law (2021)
The EU is legally committed to achieving climate neutrality by 2050.

Fit for 55 (2021)
A package of legislative proposals aimed at reducing EU emissions by 55% (compared to 1990 levels) by 2030.

Data source: **UN, IPCC, European Commission**

Climate change is a global challenge, which requires long-term collaboration on both national and international levels. While this has not always been the case, most countries and regions are now ready to talk and work together and some have already presented their ambitious climate plans.

How to read this infographic?

This timeline includes the most important international events related to climate change. It begins with the First World Climate Conference in 1979 and goes all the way to the European Green Deal and recent Conferences of Parties (COPs) where many country leaders meet on an annual basis and discuss what steps need to be taken to mitigate global warming and boost the transition to a low-carbon economy.

What is IPCC and how does it work?

Although the name might suggest it is a political body, the Intergovernmental Panel on Climate Change (IPCC) is in fact a panel of climate experts from 195 countries who work together to review the latest research on climate change and publish an extensive Assessment Report once every few years. By doing so, they summarise the latest **reliable scientific findings and predictions about future climate**, and make them **understandable for politicians and other decision makers**. The report goes beyond a mere description of trends and focuses on mitigation and adaptation efforts as well. Many recent strategic documents (also in the EU) are based on or inspired by IPCC's conclusions.

What is Paris Agreement and why is it important?

The treaty was adopted in 2015 and has been signed by 195 countries so far (the USA withdrew from it in 2020, but rejoined in 2021).

Its long-term goal is to **keep the rise in mean global temperature to well below 2 °C above pre-industrial levels** (see Trend in global temperature anomaly on pp. 16–17) and **preferably limit the increase to 1.5 °C**. To achieve this goal, global climate neutrality (net-zero) needs to be reached by the middle of this century. That is why 2050 is often used as a reference year in climate debates.

The agreement is a legally binding document and the key framework for future climate negotiations and policy making. It has also been used in climate litigation to force fossil companies as well as governments to strengthen their climate action.

What is the purpose of climate funds?

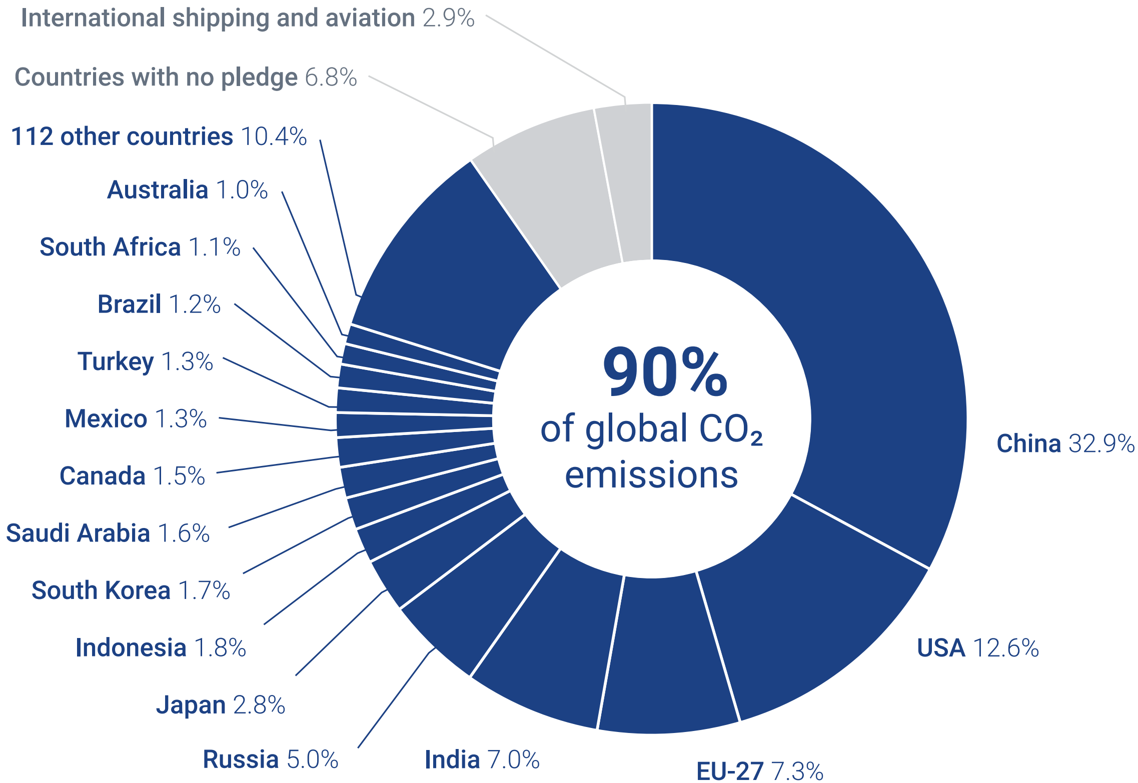
The idea that **wealthy countries should assist developing countries in tackling climate change** first appeared at the COP15 in Copenhagen in 2009. Twenty seven developed states pledged to send 100 billion USD annually to climate funds (as of 2020), each state contributing according to its GDP.

This could help less developed countries in their transition to modern low-carbon solutions and somewhat balance out the fact that industrialized countries of Global North typically produce a lot more emissions than developing countries of Global South. Most developing countries are also more vulnerable and suffer more from the impact of global warming but have a very limited capacity to do something about it. And even if their economies do take off, without international help and modern technologies, the growth is likely to take the same trajectory as it once had in the countries of Global North: massive combustion of fossil fuels leading to a lot more greenhouse gases in the atmosphere.

So far, the amount allocated to climate funds has not reached **100 billion US dollars annually** as pledged in Copenhagen, and the developing countries are pleading for help and urging the international community to keep their promises.

GLOBAL EMISSIONS AND CARBON NEUTRALITY PLEDGES

The **153 countries** which have pledged to become or consider becoming carbon neutral account for **90% of global CO_2 emissions**.



Data source: EDGAR (emissions for 2022), Net Zero Tracker

Some countries (incl. the EU member states) have pledged to reach climate neutrality by 2050, others a decade or two later. In 2023, the pledges covered over 90% of global emissions – only 7% is produced in states that have not presented their emission targets yet. Aviation and maritime transport account for about 3% of global emissions.

How to read this graph?

The world's **five largest emission producers** are: **China** (pledged for net-zero by 2060), **USA** (2050), **EU-27** (2050), **India** (2070) and **Russia** (2060). Together, these five countries produce 64.8% of global greenhouse gas emissions.

The numbers in the graph are based on global CO_2 emissions in 2022 and include **emissions from all sectors except LULUCF** (Land use, land use change and forestry).

Some countries already have their own climate laws and ambitious strategies, others are having a serious debate about their pledges.

The infographic is somewhat simplified as it includes both pledges to climate neutrality and to carbon neutrality, despite the fact that these two are actually different commitments: while climate neutrality (net-zero) covers all greenhouse gases, carbon neutrality is only about CO_2 emissions. This distiction is important to point out here as the two terms are often mixed up.

Why are these pledges so important?

Countries that signed the Paris Agreement in 2015 agreed to do their best to limit global warming to 1.5 °C (compared to the pre-industrial levels). But to achieve this goal, global carbon neutrality must be reached by 2050 – pledges to later dates are insufficient, which means the temperature will rise more (see more at Why is global warming above 1.5 °C a problem? on pp. 8–11). Some developed countries, such as Sweden or Finland, have pledged to reach net-zero well before 2050 but for many others even mid-century remains to be a major challenge.

What about countries like China or India?

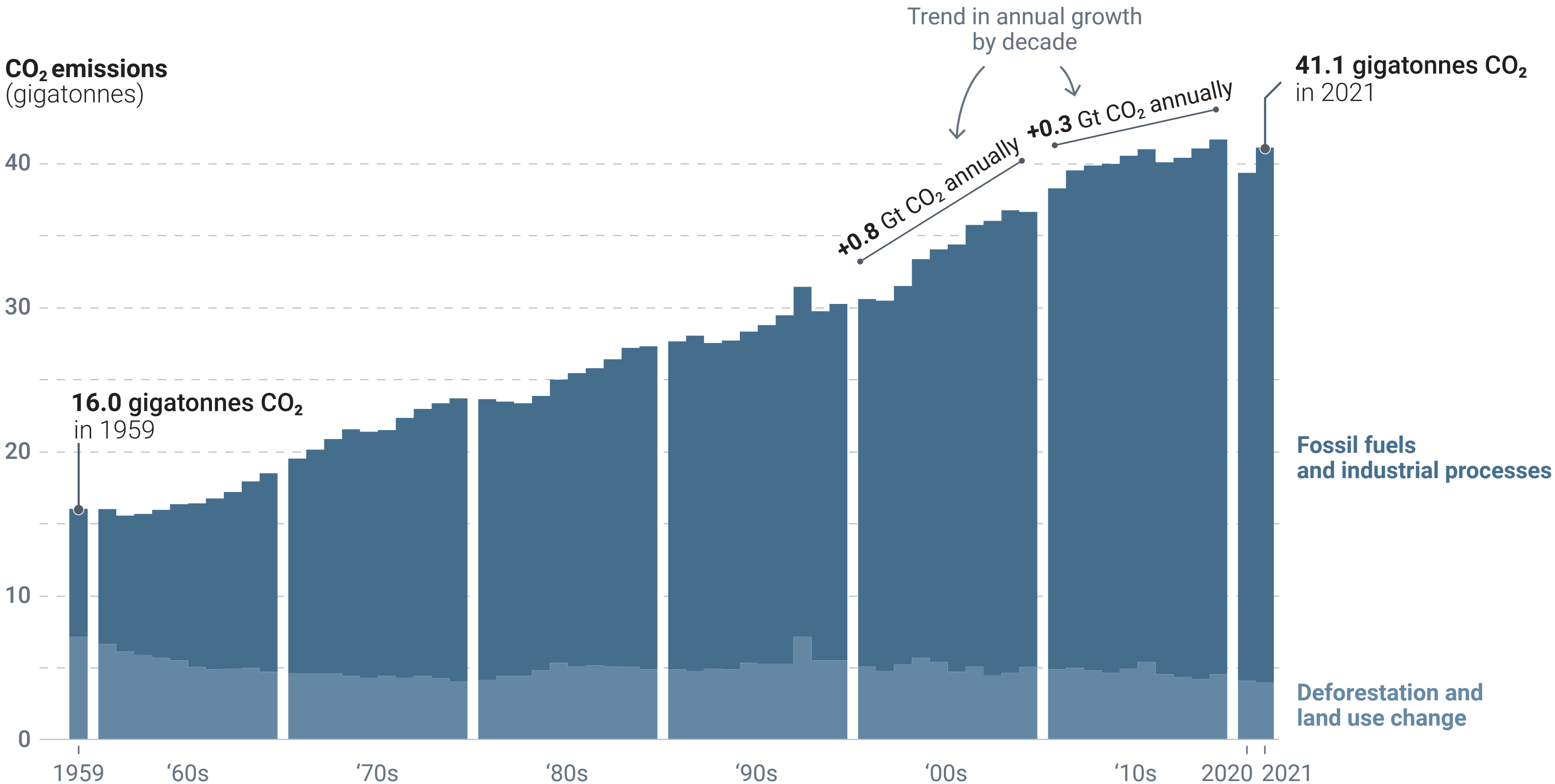
Neither China nor India have reached their peak emissions yet. Nevertheless, both countries have also been **investing massively in renewable energy and low-emission technologies** lately – they have recognized the business opportunities, and having had a good share of extreme events related to climate change (such as heat waves) in recent years, they are also well aware of the risks coming with insufficient mitigation efforts.

What about the European Union?

The EU published **the European Green Deal** in 2019, a key strategic document which sets out how to reach net-zero by 2050 and thus meet the aims of the Paris Agreement. This was followed by the European Climate Law approved in 2021. In the same year, a package of legislation proposals called **Fit for 55** was also introduced, which outlined the goals for the nearest decade: how emissions need to decline by 2030 if the EU wants to achieve net-zero by 2050. This ambition was further reinforced by REPowerEU after the invasion of Ukraine in 2022 – a policy proposal that should end European reliance on Russian fossil fuels.

TREND IN GLOBAL CO_2 EMISSIONS

Over the past **60 years**, global CO_2 emissions have **increased 2.5 times**. They keep increasing but the trend was considerably slower in the past decade.



Data source: Global Carbon Project (Friedlingstein et al. 2022)

Most of these CO_2 emissions come from fossil fuel combustion and industrial processes. Some are related to deforestation and land use change.

How to read this graph?

The graph shows the trend in total emissions of carbon dioxide produced by humans since 1959. While emissions from fossil fuel combustion and industrial processes keep rising, emissions from agriculture and forestry (LULUCF) have not changed much or have somewhat declined. The largest increase of CO_2 emissions happened in 2000–2009, then the trend has slowed down.

How strong is CO_2 when compared to other greenhouse gases?

About two thirds of global warming can be attributed to increasing concentrations of carbon dioxide in the atmosphere, which means that this greenhouse gas is the most important factor. Methane (CH_4), nitrous oxide (N_2O) and aerosols also play a role. Although potent (e.g. methane is more than 28 times as potent as carbon dioxide at trapping heat in the atmosphere), they usually do not stay in the atmosphere for a long time. So **from a long-term perspective it is the cumulative emissions of CO_2 that matter the most** – i.e. how much carbon dioxide humans have added to the atmosphere so far. The cumulative emissions are very important for future as well: to keep global warming below a certain level (e.g. 1.5 °C or 2 °C), humans can only add a certain amount of CO_2 to the atmosphere (see How warming depends on future CO_2 emissions on pp. 24–25). If more emissions are released, the global temperature will rise more.

How are global emissions measured?

The **Global Carbon Project** is an international organization of climate scientists from universities around the world who collect and analyze data on emissions of greenhouse gases and create a knowledge base, which includes information about bio-geo-chemical cycles on Earth. The organization regularly publishes a report about CO_2 emissions called the Global Carbon Budget.

Data on emissions produced by fossil fuel combustion and industrial processes is rather easy to obtain: it is provided by countries and international organizations and based on standardized methodology. It is more challenging to collect data on emissions from land use (mainly intensive farming) and deforestation – deforested areas can be measured by satellites but the total amount of carbon released to the atmosphere from these areas can only be calculated: the number is an average of values provided by various computer simulations.

What about emissions from natural phenomena such as wildfires?

Wildfires are definitely a source of greenhouse gas emissions – the carbon from the burning wood cannot just disappear but ends up in the atmosphere as carbon dioxide. However, it is questionable how much wildfires can be deemed “natural phenomena”: some are sparked by a lightning (and always have been), but according to the Food and Agriculture Organization of the UN, 90% of forest fires in the world today are human-caused (arson, negligence, uncontrolled grass burning, etc.).

However, what could be a real problem in the future: if humans keep burning fossil fuels and global warming continues, large amounts of greenhouse gases might be released to the atmosphere from melting permafrost or collapsing ecosystems (see Why is global warming above 1.5 °C a problem? on pp. 8–11).

SOME THINGS IN THIS BOOKLET ARE SIMPLIFIED

Making complex data and scientific hypotheses understandable for the general public

It was our priority to make the *Atlas* understandable and easy to use for non-experts – even if it sometimes means that some issues are not described in full complexity. This is mainly true for the following areas:

1. CO_2 is not the only greenhouse gas

The booklet focuses on carbon dioxide (CO_2), a greenhouse gas causing about 70% of global warming. To be really consistent, we would also need to deal with increasing concentrations of methane, nitrous oxide and other greenhouse gases in the atmosphere, which also contribute to the greenhouse effect. In some cases, it made sense to express all greenhouse gases in the same unit of measurement so the CO_2 equivalent (CO_2eq) was used. However, it is often important to look at emissions and concentrations of different greenhouse gases separately – and this would already make the *Atlas* quite complicated for non-expert readers. For anyone who wishes to learn more about the effect of other greenhouse gases, more information is available and easy to find.

2. Atmospheric proceses are really complex

The *Atlas* is not intended to be a textbook of atmospheric physics or climate science. Therefore it does not deal with issues such as atmospheric currents and their dynamics or the thermal radiation passing through the atmosphere. The increasing greenhouse gas effect is simply stated here as a fact. Anyone who wants to understand atmospheric physics more or has any doubts if the calculations are correct can find more in textbooks for university students.

3. Data, statistics & interpretation

The largest part of specialized texts dealing with temperature measurements typically focuses on methodology, statistics, data homogenization, etc. This aspect is deliberately left out in the *Atlas* and the booklet is primarily about research results and providing relevant context. To learn more about the methods used for the data collection and processing, please use links included in the graphs and maps or refer to standards of the World Meteorological Organization.

Description or solution?

The *Atlas* focuses mainly on climate changes that can already be observed, and adds some basic context. This should be sufficient for most people, who want to have basic understanding of climate change, and inspire them to think about possible consequences and potential solutions.

The following volumes of the *Atlas* will aim to present various pathways for tranformation in the sector of energy production as well as other scenarios of future development.

OTHER SOURCES OF RELIABLE INFORMATION ON CLIMATE CHANGE

WEBSITES:

www.skepticalscience.com

Climate change from the perspective of skeptical empirism
Articles in three different levels of difficulty, debunking common myths about climate and climate change

www.giss.nasa.gov

Website of Goddard Institute for Space Studies (NASA Research Center), focusing on atmospheric physics and climate change simulations
A large collection of datasets and a detailed description of methodology used for temperature measurements

www.ipcc.ch

Website of Intergovernmental Panel on Climate Change (IPCC) – an international organization with experts from almost 200 countries
Detailed Assessment Reports published by IPCC (reviewing and evaluating recent research on climate change), brief Summaries for Policy Makers

www.carbonbrief.org

Commentaries on recent news from climate scientists as well as latest trends and events in energy production and climate-related politics
Articles systematically explaining a wide variety of topics related to climate change

BOOKS:

BERNERS-LEE, M. **There is No Planet B. A Handbook for the Make or Break Years**. Cambridge: Cambridge University Press, 2019.
PIERREHUMBERT, R. T. **Principles of Planetary Climate**. Cambridge: Cambridge University Press, 2011.

Fakta o klimatu (Facts on Climate) is a team of independent analysts and experts commited to cultivating the debate on climate change to be factual, constructive and based on science and verified data. By making visualisations of scientific data, Fakta o klimatu bring attention to issues that really matter, and provide information and consulting to anyone who might need it: journalists, politicians, business decision makers, teachers as well as the general public. The materials can be useful in any discussion focusing on climate change or solutions needed for the transition to a low-carbon economy.

Lipka – School Facility for Environmental Education is based in Brno and it is one of the oldest and largest organizations in the Czech Republic focusing on public environmental education. Under its wide range of activities, Lipka offers one-day or longer environmental educational programmes in schools and preschools (for both teachers and children/teenagers), in summer camps and after-school clubs as well as a number of family events for the public. The first Czech edition of the Atlas was created in collaboration with Lipka.

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Atlas of Climate Change. Changes in the Atmosphere and Risks of Warming

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HOW IS EARTH'S CLIMATE CHANGING? AND IS THERE ANYTHING THAT WE CAN DO ABOUT IT?

Climate change is no longer a distant future prediction or a would-be scenario – it **is happening now**. Having a major impact on the world today, it is not something that we can just leave to scientists and experts to discuss; it is essential that each and every one of us understands this change better so that we can all engage in an ongoing, solution-oriented debate about it.

However, such a debate is only possible if we have **solid data, clearly explained and widely understood**. To help facilitate that, this booklet presents simple maps and graphs which are easy to grasp and remember – along with brief accompanying texts explaining the data depicted in each graph and providing relevant context.

As the first part of a series of materials, the Atlas of Climate Change primarily focuses on the rising global temperature and its consequences, explaining why this trend is occuring and how various Earth systems are currently affected (along with potential impacts in the coming decades). The booklet also provides some basic data on greenhouse gas emissions – the driving factor of warming – both in the EU and globally. In addition, it outlines international pledges aimed at transitioning to low-carbon economies.

The Atlas is intended mainly for **non-experts** – for anyone who wants to learn more about one of the greatest challenges our civilisation is facing today.

Created with kind support from PPG