Frequently Asked Questions

FAQ

Frequently Asked Questions

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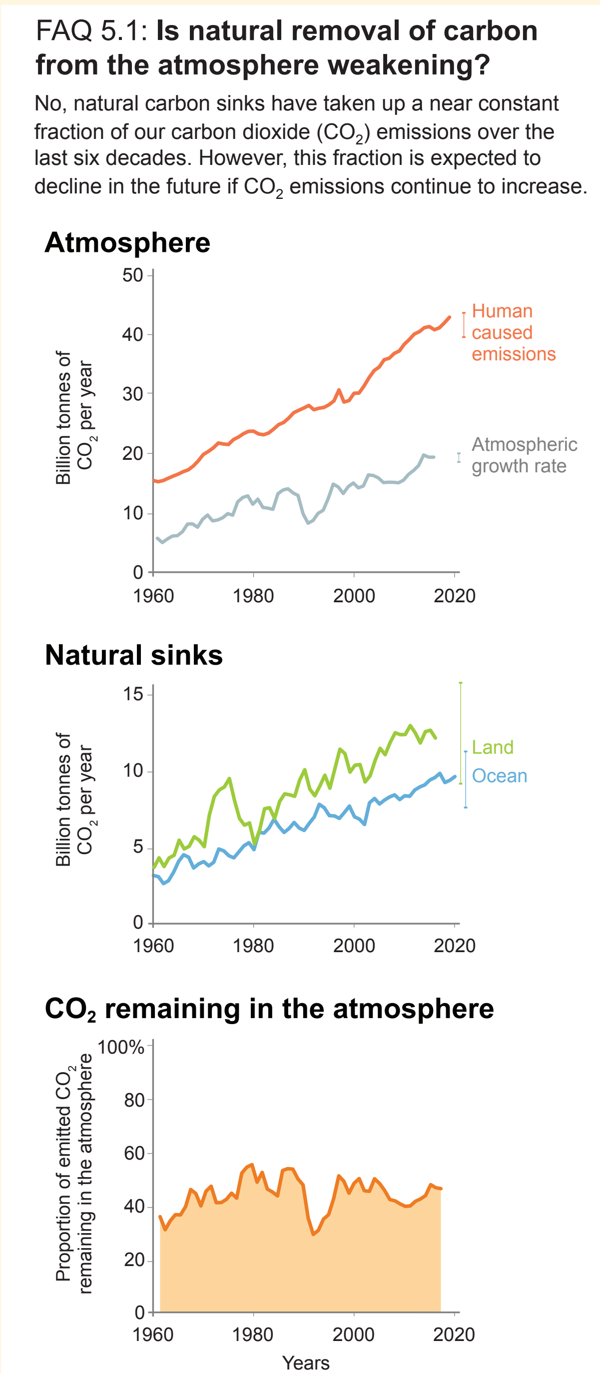
These Frequently Asked Questions have been extracted from the chapters of the underlying report and are compiled here. When referencing specific FAQs, please reference the corresponding chapter in the report from where the FAQ originated (e.g., FAQ 3.1 is part of Chapter 3).

Frequently Asked Questions

FAQ 5.1 | Is the Natural Removal of Carbon From the Atmosphere Weakening?

For decades, about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere has been taken up by natural carbon sinks in vegetation, soils and oceans. These natural sinks of CO_2 have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. However, observations show that the processes underlying this uptake are beginning to respond to increasing CO_2 in the atmosphere and climate change in a way that will weaken nature's capacity to take up CO_2 in the future. Understanding of the magnitude of this change is essential for projecting how the climate system will respond to future emissions and emissions reduction efforts.



Direct observations of CO_2 concentrations in the atmosphere, which began in 1958, show that the atmosphere has only retained roughly half of the CO_2 emitted by human activities, due to the combustion of fossil fuels and land-use change such as deforestation (FAQ 5.1, Figure 1). Natural carbon cycle processes on land and in the oceans have taken up the remainder of these emissions. These land and ocean removals or 'sinks' have grown largely in proportion to the increase in CO_2 emissions, taking up 31% (land) and 23% (ocean) of the emissions in 2010–2019, respectively (FAQ 5.1, Figure 1). Therefore, the average proportion of yearly CO_2 emissions staying in the atmosphere has remained roughly stable at 44% over the last six decades, despite continuously increasing CO_2 emissions from human activities.

On land, it is mainly the vegetation that captures CO_2 from the atmosphere through *plant photosynthesis*, which ultimately accumulates both in vegetation and soils. As more CO_2 accumulates in the atmosphere, plant carbon capture increases through the *CO_2 fertilization effect* in regions where plant growth is not limited by, for instance, nutrient availability. Climate change affects the processes responsible for the uptake and release of CO_2 on land in multiple ways. Land CO_2 uptake is generally increased by longer growing seasons due to global warming in cold regions and by nitrogen deposition in nitrogen-limited regions. Respiration by plants and soil organisms, natural disturbances such as fires, and human activities such as deforestation all release CO_2 back into the atmosphere. The combined effect of climate change on these processes is to weaken the future land sink. In particular, extreme temperatures and droughts as well as permafrost thaw (see FAQ 5.2) tend to reduce the land sink regionally. In the ocean,

FAQ 5.1, Figure 1 | Atmospheric carbon dioxide (CO_2) and natural carbon sinks. (Top) Global emissions of CO_2 from human activities and the growth rate of CO_2 in the atmosphere; **(middle)** the net land and ocean CO_2 removal (natural sinks); and **(bottom)** the fraction of CO_2 emitted by human activities remaining in atmosphere from 1960 to 2019. Lines are the five years running mean, error bars denote the uncertainty of the mean estimate. See Table 5.SM.6 for more information on the data underlying this figure.

FAQ 5.1 (continued)

several factors control how much CO_2 is captured: the difference in CO_2 partial pressure between the atmosphere and the surface ocean; wind speeds at the ocean surface; the chemical composition of seawater (that is, its *buffering capacity*), which affects how much CO_2 can be taken up; and the use of CO_2 in photosynthesis by seawater microalgae. The CO_2-enriched surface ocean water is transported to the deep ocean in specific zones around the globe (such as the Northern Atlantic and the Southern Ocean), effectively storing the CO_2 away from the atmosphere for many decades to centuries. The combined effect of warmer surface ocean temperatures on these processes is to weaken the future ocean CO_2 sink.

The ocean carbon sink is better quantified than the land sink, thanks to direct ocean and atmospheric carbon observations. The land carbon sink is more challenging to monitor globally, because it varies widely, even regionally. There is currently no direct evidence that the natural sinks are slowing down, because observable changes in the fraction of human emissions stored on land or in oceans are small compared to year-to-year and decadal variations of these sinks. Nevertheless, it is becoming more obvious that atmospheric and climate changes are affecting the processes controlling the land and ocean sinks.

Since the land and ocean sinks respond to the rise in atmospheric CO_2 and to human-induced global warming, the absolute amount of CO_2 taken up by land and ocean will be affected by future CO_2 emissions. This also implies that, if countries manage to strongly reduce global CO_2 emissions, or even remove CO_2 from the atmosphere, these sinks will take up less CO_2 because of the reduced human perturbation of the carbon cycle. Under future high-warming scenarios, it is expected that the global ocean and land sinks will stop growing in the second half of the century as climate change increasingly affects them. Thus, the total amount of CO_2 emitted to the atmosphere and the responses of the natural CO_2 sinks will both determine what efforts are required to limit global warming to a certain level (see FAQ 5.4), underscoring how important it is to understand the evolution of these natural CO_2 sinks.

Frequently Asked Questions

FAQ 5.2 | Can Thawing Permafrost Substantially Increase Global Warming?

In the Arctic, large amounts of organic carbon are stored in permafrost – ground that remains frozen throughout the year. If significant areas of permafrost thaw as the climate warms, some of that carbon may be released into the atmosphere in the form of carbon dioxide or methane, resulting in additional warming. Projections from models of permafrost ecosystems suggest that future permafrost thaw will lead to some additional warming – enough to be important, but not enough to lead to a 'runaway warming' situation, where permafrost thaw leads to a dramatic, self-reinforcing acceleration of global warming.

The Arctic is the biggest climate-sensitive carbon pool on Earth, storing twice as much carbon in its frozen soils, or *permafrost*, than is currently stored in the atmosphere. As the Arctic region warms faster than anywhere else on Earth, there are concerns that this warming could release greenhouse gases to the atmosphere and therefore significantly amplify climate change.

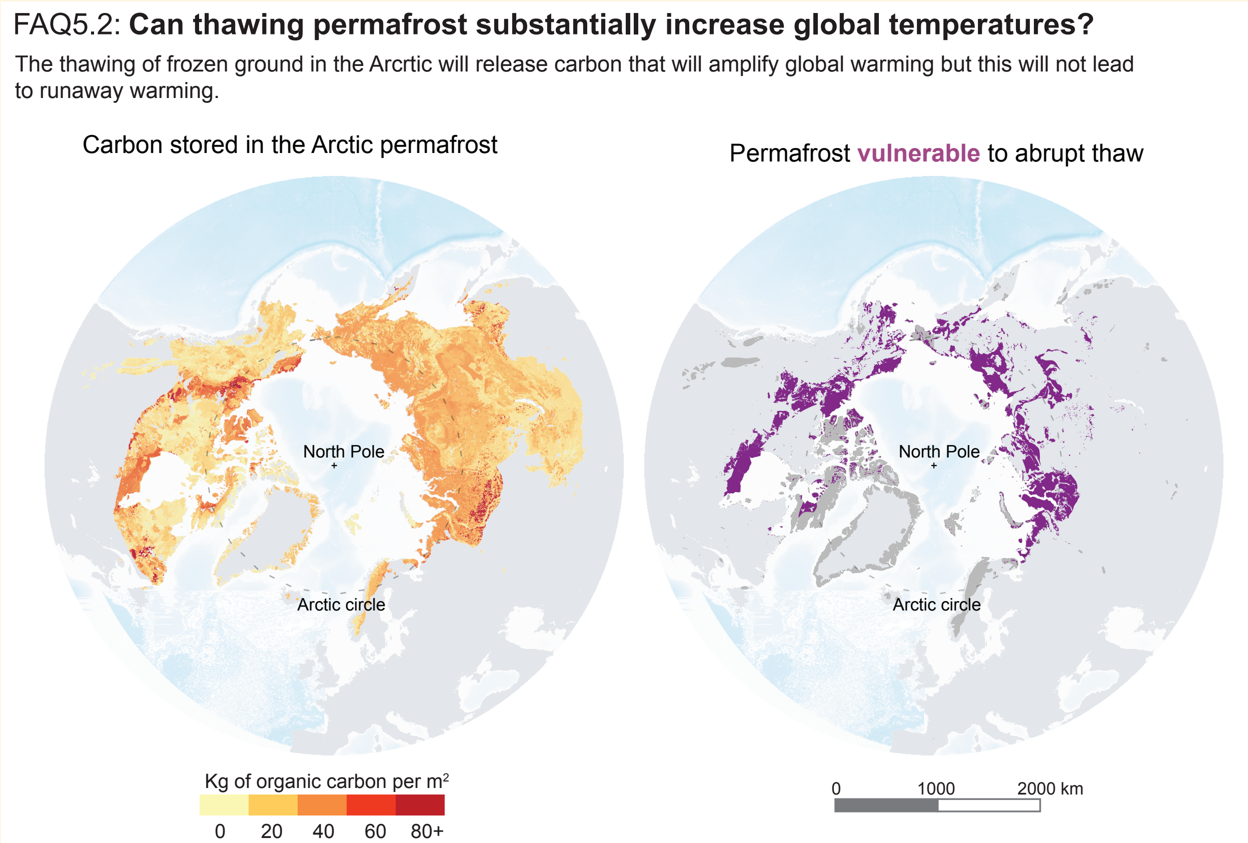
The carbon in the permafrost has built up over thousands of years, as dead plants have been buried and accumulated within layers of frozen soil, where the cold prevents the organic material from decomposing. As the Arctic warms and soils thaw, the organic matter in these soils begins to decompose rapidly and return to the atmosphere as either carbon dioxide or methane, which are both important greenhouse gases. Permafrost can also thaw abruptly in a given place, due to melting ice in the ground reshaping Arctic landscapes, lakes growing and draining, and fires burning away insulating surface soil layers. Thawing of permafrost carbon has already been observed in the Arctic, and climate models project that much of the shallow permafrost (<3 m depth) throughout the Arctic would thaw under moderate to high amounts of global warming (2°C–4°C).

While permafrost processes are complex, they are beginning to be included in models that represent the interactions between the climate and the carbon cycle. The projections from these permafrost carbon models show a wide range in the estimated strength of a carbon–climate vicious circle, from both carbon dioxide and methane, equivalent to 14–175 billion tonnes of carbon dioxide released per 1°C of global warming. By comparison, in 2019, human activities have released about 40 billion tonnes of carbon dioxide into the atmosphere. This has two implications. First, the extra warming caused by permafrost thawing is strong enough that it must be considered when estimating the total amount of remaining emissions permitted to stabilize the climate at a given level of global warming (i.e., the remaining carbon budget, see FAQ 5.4). Second, the models do not identify any one amount of warming at which permafrost thaw becomes a 'tipping point' or threshold in the climate system that would lead to a runaway global warming. However, models do project that emissions would continuously increase with warming, and that this trend could last for hundreds of years.

Permafrost can also be found in other cold places (e.g., mountain ranges), but those places contain much less carbon than in the Arctic. For instance, the Tibetan plateau contains about 3% as much carbon as is stored in the Arctic. There is also concern about carbon frozen in shallow ocean sediments. These deposits are known as *methane hydrates* or *clathrates*, which are methane molecules locked within a cage of ice molecules. They formed as frozen soils that were flooded when sea levels rose after the last ice age. If these hydrates thaw, they may release methane that can bubble up to the surface. The total amount of carbon in permafrost-associated methane hydrates is much less than the carbon in permafrost soils. Global warming takes millennia to penetrate into the sediments beneath the ocean, which is why these hydrates are still responding to the last deglaciation. As a result, only a small fraction of the existing hydrates could be destabilised during the coming century. Even when methane is released from hydrates, most of it is expected to be consumed and oxidised into carbon dioxide in the ocean before reaching the atmosphere. The most complete modelling of these processes to date suggests a release to the atmosphere at a rate of less than 2% of current human-induced methane emissions.

Overall, thawing permafrost in the Arctic appears to be an important additional source of heat-trapping gases to the atmosphere, more so than undersea hydrates. Climate and carbon cycle models are beginning to consider permafrost processes. While these models disagree on the exact amount of the heat-trapping gases that will be released into the atmosphere, they agree that: (i) the amount of such gases released from permafrost will increase with the amount of global warming; and (ii) the warming effect of thawing permafrost is significant enough to be considered in estimates of the remaining carbon budgets for limiting future warming.

FAQ 5.2 (continued)



FAQ 5.2, Figure 1 | The Arctic permafrost is a big pool of carbon that is sensitive to climate change. (Left) Quantity of carbon stored in the permafrost, to 3 m depth (NCSCDv2 dataset) and **(right)** area of permafrost vulnerable to abrupt thaw (Circumpolar Thermokarst Landscapes dataset).

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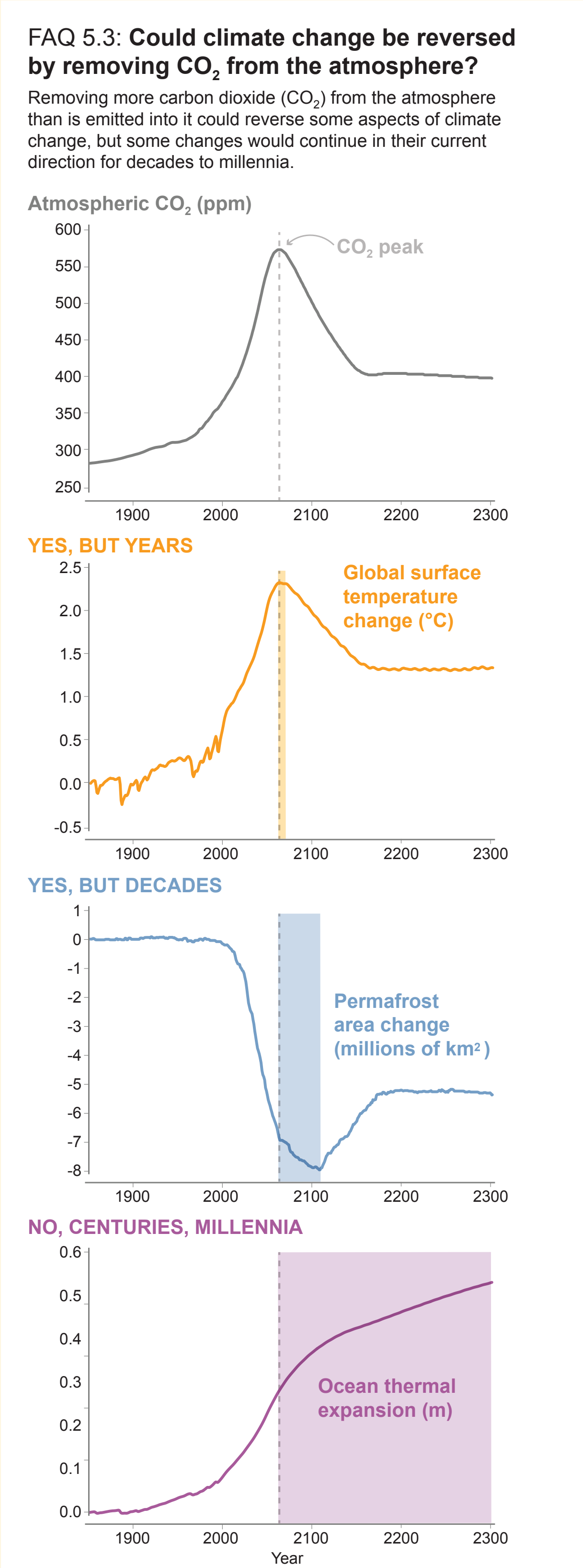
FAQ 5.3 | Could Climate Change Be Reversed By Removing Carbon Dioxide From the Atmosphere?



Deliberate removal of carbon dioxide (CO_2) from the atmosphere could reverse (i.e., change the direction of) some aspects of climate change. However, this will only happen if it results in a net reduction in the total amount of CO_2 in the atmosphere, that is, if deliberate removals are larger than emissions. Some climate change trends, such as the increase in global surface temperature, would start to reverse within a few years. Other aspects of climate change would take decades (e.g., permafrost thawing) or centuries (e.g., acidification of the deep ocean) to reverse, and some, such as sea level rise, would take centuries to millennia to change direction.

The term *negative carbon dioxide (CO_2) emissions* refers to the removal of CO_2 from the atmosphere by deliberate human activities, in addition to removals that occur naturally, and is often used as synonymous with *carbon dioxide removal*. Negative CO_2 emissions can compensate for the release of CO_2 into the atmosphere by human activities. They could be achieved by strengthening natural CO_2 sequestration processes on land (e.g., by planting trees or through agricultural practices that increase the carbon content of soils) and/or in the ocean (e.g., by restoration of coastal ecosystems) or by removing CO_2 directly from the atmosphere. If CO_2 removals are greater than human-caused CO_2 emissions globally, emissions are said to be *net negative*. It should be noted that CO_2 removal technologies are unable, or not yet ready, to achieve the scale of removal that would be required to compensate for current levels of emissions, and most have undesired side effects.

In the absence of deliberate CO_2 removal, the CO_2 concentration in the atmosphere (a measure of the amount of CO_2 in the atmosphere) results from a balance between human-caused CO_2 release and the removal of CO_2 by natural processes on land and in the ocean (natural 'carbon sinks'; see FAQ 5.1). If CO_2 release exceeds removal by carbon sinks, the CO_2 concentration in the atmosphere would increase;

FAQ 5.3, Figure 1 | Changes in aspects of climate change in response to a peak and decline in the atmospheric CO_2 concentration (top panel). The vertical grey dashed line indicates the time of peak CO_2 concentration in all panels. It shows that the reversal of global surface warming lags the decrease in the atmospheric CO_2 concentration by a few years, the reversal of permafrost area decline lags the decrease in atmospheric CO_2 by decades, and ocean thermal expansion continues for several centuries. The quantitative information in the figure (i.e., numbers on vertical axes) is not to be emphasized as it results from simulations with just one model and will be different for other models. The qualitative behaviour, however, can be expected to be largely model independent.

FAQ

FAQ 5.3 (continued)

if CO_2 release equals removal, the atmospheric CO_2 concentration would stabilize; and if CO_2 removal exceeds release, the CO_2 concentration would decline. This applies in the same way to *net* CO_2 emissions – that is, the sum of human-caused releases and deliberate removals.

If the CO_2 concentration in the atmosphere starts to go down, the Earth's climate would respond to this change (FAQ 5.3, Figure 1). Some parts of the climate system take time to react to a change in CO_2 concentration, so a decline in atmospheric CO_2 as a result of net negative emissions would not lead to immediate reversal of all climate change trends. Recent studies have shown that global surface temperature starts to decline within a few years following a decline in atmospheric CO_2, although the decline would not be detectable for decades due to natural climate variability (see FAQ 4.2). Other consequences of human-induced climate change, such as reduction in permafrost area, would take decades; yet others, such as warming, acidification and oxygen loss of the deep ocean, would take centuries to reverse following a decline in the atmospheric CO_2 concentration. Sea level would continue to rise for many centuries to millennia, even if large deliberate CO_2 removals were successfully implemented.

'Overshoot' scenarios are a class of future scenarios that are receiving increasing attention, particularly in the context of ambitious climate goals, such as the global warming limits of 1.5°C or 2°C included in the Paris Agreement. In these scenarios, a slow rate of reduction in emissions in the near term is compensated by net negative CO_2 emissions in the later part of this century, which results in a temporary breach or 'overshoot' of a given warming level. Due to the delayed reaction of several climate system components, it follows that the temporary overshoot would result in additional climate changes compared to a scenario that reaches the goal without overshoot. These changes would take decades to many centuries to reverse, with the reversal taking longer for scenarios with larger overshoot.

Removing more CO_2 from the atmosphere than is emitted into it would indeed begin to reverse some aspects of climate change, but some changes would still continue in their current direction for decades to millennia. Approaches capable of large-scale removal of CO_2 are still in the state of research and development or unproven at the scales of deployment necessary to achieve a net reduction in atmospheric CO_2 levels. CO_2 removal approaches, particularly those deployed on land, can have undesired side effects on water, food production and biodiversity.

Frequently Asked Questions

FAQ 5.4 | What Are Carbon Budgets?

There are several types of carbon budgets. Most often, the term refers to the total net amount of carbon dioxide (CO_2) that can still be emitted by human activities while limiting global warming to a specified level (e.g., 1.5°C or 2°C above pre-industrial levels). This is referred to as the 'remaining carbon budget'. Several choices and value judgements have to be made before it can be unambiguously estimated. When the remaining carbon budget is combined with all past CO_2 emissions to date, a 'total carbon budget' compatible with a specific global warming limit can also be defined. A third type of carbon budget is the 'historical carbon budget', which is a scientific way to describe all past and present sources and sinks of CO_2.

The term *remaining carbon budget* is used to describe the total net amount of CO_2 that human activities can still release into the atmosphere while keeping global warming to a specified level, like 1.5°C or 2°C relative to pre-industrial temperatures. Emissions of CO_2 from human activities are the main cause of global warming. A remaining carbon budget can be defined because of the specific way CO_2 behaves in the Earth system. That is, global warming is roughly linearly proportional to the total net amount of CO_2 emissions that are released into the atmosphere by human activities – also referred to as cumulative anthropogenic CO_2 emissions. Other greenhouse gases behave differently and have to be accounted for separately.

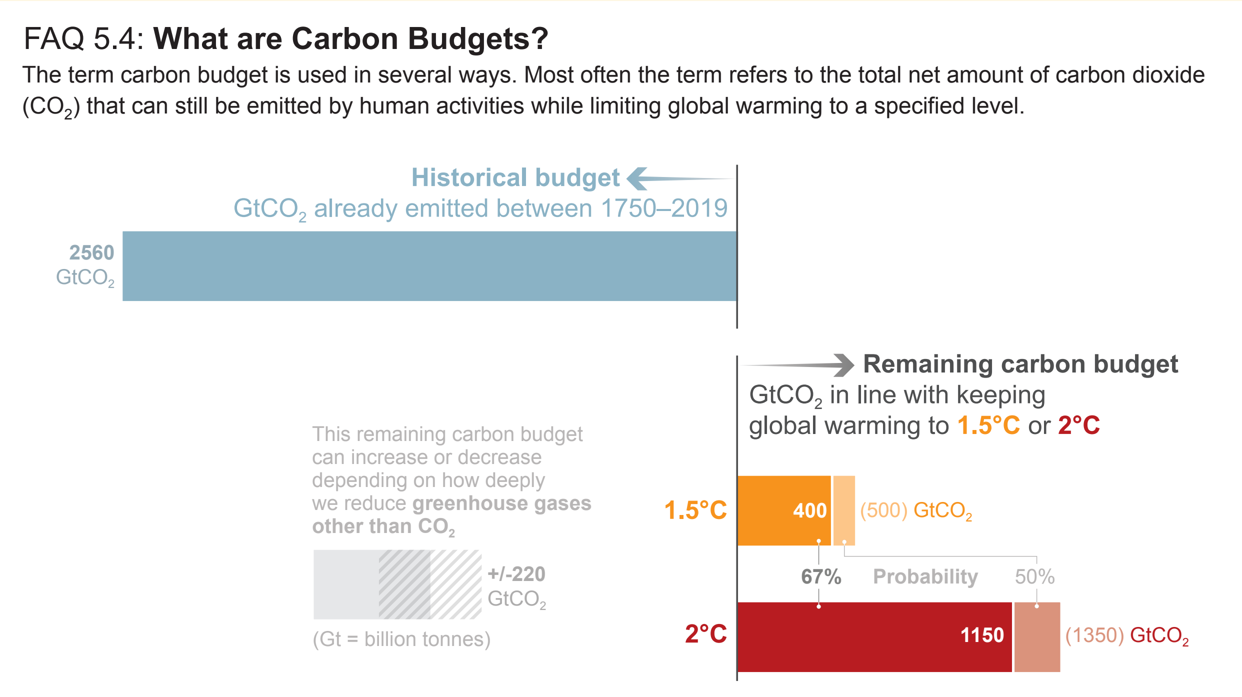
The concept of a remaining carbon budget implies that, to stabilize global warming at any particular level, global emissions of CO_2 need to be reduced to net zero levels at some point. 'Net zero CO_2 emissions' describes a situation where all the anthropogenic emissions of CO_2 are counterbalanced by deliberate anthropogenic removals so that, on average, no CO_2 is added or removed from the atmosphere by human activities. Atmospheric CO_2 concentrations in such a situation would gradually decline to a long-term stable level as excess CO_2 in the atmosphere is taken up by ocean and land sinks (see FAQ 5.1). The concept of a remaining carbon budget also means that, if CO_2 emissions reductions are delayed, deeper and faster reductions are needed later to stay within the same budget. If the remaining carbon budget is exceeded, this will result in either higher global warming or a need to actively remove CO_2 from the atmosphere to reduce global temperatures back down to the desired level (see FAQ 5.3).

Estimating the size of remaining carbon budgets depends on a set of choices. These choices include: (1) the global warming level that is chosen as a limit (for example, 1.5°C or 2°C relative to pre-industrial levels); (2) the probability with which we want to ensure that warming is held below that limit (for example, a one-in-two, two-in-three, or higher chance), and (3) how successful we are in limiting emissions of other greenhouse gases that affect the climate, such as methane or nitrous oxide. These choices can be informed by science, but ultimately represent subjective choices. Once these choices have been made, to estimate the remaining carbon budget for a given temperature goal, we can combine knowledge about: how much our planet has warmed already; the amount of warming per cumulative tonne of CO_2; and the amount of warming that is still expected once global net CO_2 emissions are brought down to zero. For example, to limit global warming to 1.5°C above pre-industrial levels with either a one-in-two (50%) or two-in-three (67%) chance, the remaining carbon budgets amount to 500 and 400 billion tonnes of $CO_{2,}$ respectively, from 1 January 2020 onward (FAQ 5.4, Figure 1). Currently, human activities are emitting around 40 billion tonnes of CO_2 into the atmosphere in a single year.

The remaining carbon budget depends on how much the world has already warmed to date. This past warming is caused by historical emissions, which are estimated by looking at the *historical carbon budget* – a scientific way to describe all past and present sources and sinks of CO_2. It describes how the CO_2 emissions from human activities have redistributed across the various CO_2 reservoirs of the Earth system. These reservoirs are the ocean, the land vegetation, and the atmosphere (into which CO_2 was emitted). The share of CO_2 that is not taken up by the ocean or the land, and that thus increases the concentration of CO_2 in the atmosphere, causes global warming. The historical carbon budget tells us that, of the about 2560 billion tonnes of CO_2 that were released into the atmosphere by human activities between the years 1750 and 2019, about a quarter were absorbed by the ocean (causing ocean acidification) and about a third by the land vegetation. About 45% of these emissions remain in the atmosphere (see FAQ 5.1). Adding these historical CO_2 emissions to estimates of remaining carbon budgets allows an estimate of the *total carbon budget* consistent with a specific global warming level.

FAQ 5.4 (continued)

In summary, determining a remaining carbon budget – that is, how much CO_2 can be released into the atmosphere while stabilizing global temperature below a chosen level – is well understood but relies on a set of choices. However, it is clear that, for limiting warming below 1.5°C or 2°C, the remaining carbon budget from 2020 onwards is much smaller than the total CO_2 emissions released to date.



FAQ 5.4, Figure 1 | Various types of carbon budgets. Historical cumulative carbon dioxide (CO_2) emissions determine to a large degree how much the world has warmed to date, while the remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below specific temperature thresholds. Several factors limit the precision with which the remaining carbon budget can be estimated. Therefore, estimates need to specify the probability with which they aim at limiting warming to the intended target level (e.g., limiting warming to 1.5°C with a 67% probability).