

What Quantity of CO2 Emission-equivalents from Natural Feedbacks are Included in the IPCC's Carbon Budget Calculations?

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Background

The IPCC's carbon budget¹ is arguably the world's most important climate change metric as climate scientists have recently concluded that a global temperature increase over 1.5°C could be devastating for our civilization and the IPCC carbon budget was designed to calculate the maximum post-2019 cumulative CO2 emissions that humans could emit and still have the global temperature increase remain below 1.5°C. "The exact quantity of emissions from these feedbacks included in the IPCC carbon budget is complex to pinpoint due to the inherent uncertainties and model variations. The IPCC often uses a range to express these budgets, reflecting the current scientific understanding and the potential for unforeseen feedbacks"^{2,3,4}. Table 1 indicates how the feedbacks are incorporated into the IPCC budget calculations.

Size of Natural Feedbacks the IPCC Budget

	Feedback	Incorporation in the IPCC carbon budget
1	CO2	The models used to determine the carbon budget include current estimates of the carbon cycle, including the role of natural sinks and sources. These processes influence the budget by affecting the fraction of anthropogenic CO2 that remains in the atmosphere ⁵
2	CH4	These are less well-represented in models due to uncertainties in how these feedbacks might evolve under different warming scenarios ²
3	Albedo	Can partially be determined by the value used for climate sensitivity (which includes "fast feedback" such as water vapor, clouds, and sea ice ⁶) and the projected amount of summertime Arctic sea ice and snow cover in 2100. The AR6 summary report does indicate that, for a "low emissions scenario", "the Arctic may retain some summer ice throughout the century" ⁷ .

Table 1. Incorporation of Feedbacks in the IPCC carbon budget

The quantity of CO2 emission-equivalents from natural feedbacks that are included in the IPCC's carbon budget calculations can either be expressed in terms of "GTCO2 per degree C of warming" or "natural emissions for a temperature increase target". For the former, there are several estimates – which one (if either) is the best to use?

- "The AR6 estimates to appropriately include the effect of all these feedbacks, remaining carbon budgets have to be reduced by 26 ± 97 GtCO2 per degree Celsius of additional warming"⁸
- Based on Table 5.29 of the AR6's *Climate Change 2021: The Physical Science Basis*, a good "planning" number for the expected emissions from natural feedbacks appears to be about 225 GTCO2 per degree C of temperature increase⁹
- Based on the data from "AR6 Scenario Explorer and Database hosted by IIASA", the expected emissions from natural feedbacks appears to be between 217 and 234 GTCO2 per degree C of temperature increase¹¹

For the latter, most estimates appear to be "general" (e.g., "with CO2 emissions from permafrost and soils adding tens to hundreds of gigatonnes, and methane from wetlands and permafrost contributing several gigatonnes by 2100"⁴).

	Feedback	Likely CO2e through 2100 (GTCO2e)	CO2e Through 2100 Included in Climate Models For A Temperature Increase Target of 1.5° in 2100 (GTCO2e)
A	Permafrost (CO2 and CH4)	200	225
B	Subsea Permafrost (CH4)	150	0
C	Amazon Rainforest Dieback (CO2)	100	0
D	Arctic sea ice (Albedo)	320	150
E	Northern hemisphere snow cover extent (Albedo)	200	95
F	Peatlands (CH4)	100	61
G	Wildfires (CO2)	200	73
H	Surface Waters and Waste (CH4)	150	
I	Soils (extra due to higher temperatures) (CO2)	200	
J	Oceanic changes that reduce CO2 uptake (CO2)	???	
K	Antarctic sea ice (Albedo)	???	
L	Land use changes (CO2)	???	
M	Other forest dieback (CO2)	???	
N	Insect outbreaks (CO2)	???	
O	Desertification (CO2)	???	
P	Deforestation (Albedo)	???	
Q	Deforestation (CO2 and CH4)	???	
R	Other natural feedbacks (CO2 and CH4)	???	
	Sub Total For CO2 and CH4	1100	337
	Total	1650	582

Footnotes

1 IPCC AR6 Summary For Policy Makers - Carbon Budget

Table SPM.2: Estimates of historical CO₂ emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO₂ emissions are reached. They refer to CO₂ emissions, while accounting for the global warming effect of non-CO₂ emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years. {Table TS.3, Table 3.1, Table 5.1, Table 5.7, Table 5.8, 5.5.1, 5.5.2, Box 5.2}

Global warming between 1850–1900 and 2010–2019 (°C)	Historical cumulative CO ₂ emissions from 1850 to 2019 (GtCO ₂)
1.07 (0.8–1.3; <i>likely</i> range)	2390 (± 240; <i>likely</i> range)

Approximate global warming relative to 1850–1900 until temperature limit (°C)* ⁽¹⁾	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 (GtCO ₂)					Variations in reductions in non-CO ₂ emissions* ⁽³⁾
		<i>Likelihood of limiting global warming to temperature limit*⁽²⁾</i>					
		17%	33%	50%	67%	83%	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO ₂ emissions can increase or decrease the values on the left by 220 GtCO ₂ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

*⁽¹⁾ Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

*⁽²⁾ This likelihood is based on the uncertainty in transient climate response to cumulative CO₂ emissions (TCRE) and additional Earth system feedbacks, and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 GtCO₂) and non-CO₂ forcing and response (±220 GtCO₂) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 GtCO₂) and the climate response after net zero CO₂ emissions are reached (±420 GtCO₂) are separate.

*⁽³⁾ Remaining carbon budget estimates consider the warming from non-CO₂ drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO₂ emissions.

Every tonne of CO₂ emissions adds to global warming

Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO₂ emissions (GtCO₂)

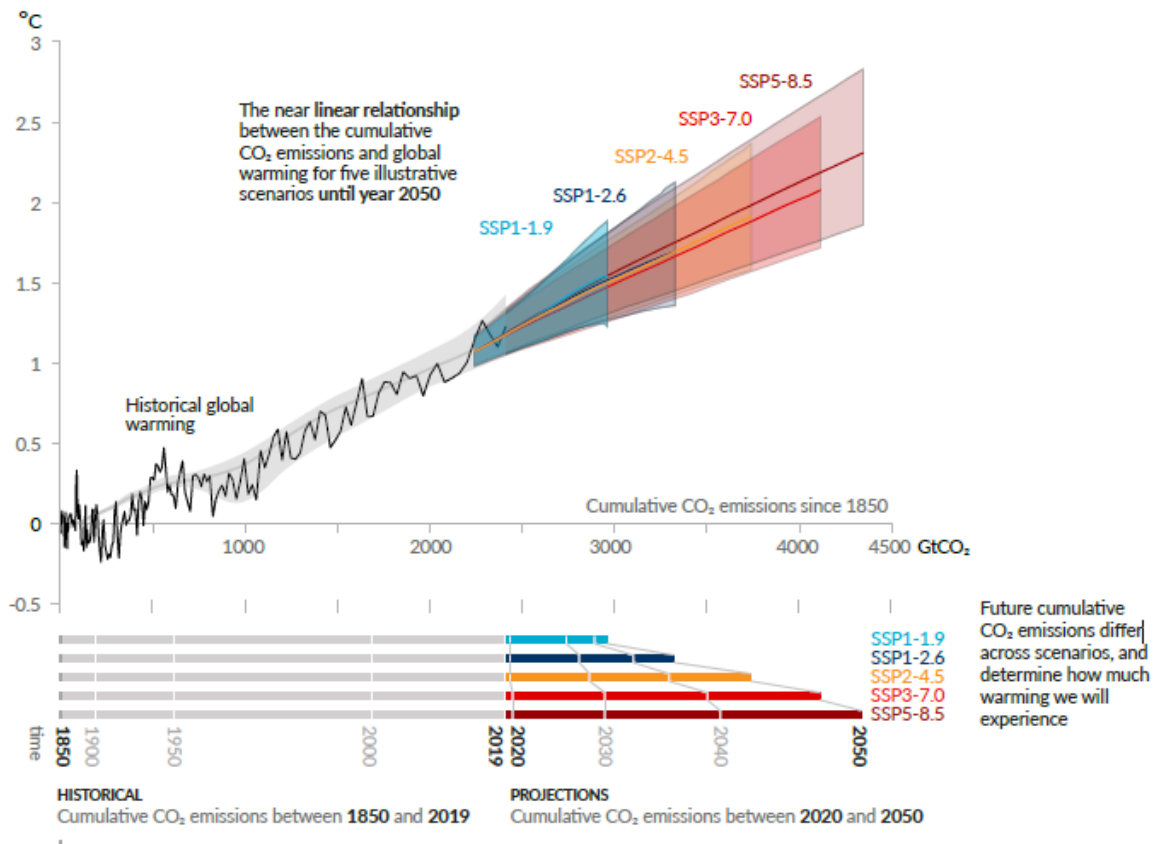


Figure SPM.10: Near-linear relationship between cumulative CO₂ emissions and the increase in global surface temperature.

Top panel: Historical data (thin black line) shows observed global surface temperature increase in °C since 1850–1900 as a function of historical cumulative carbon dioxide (CO₂) emissions in GtCO₂ from 1850 to 2019. The grey range with its central line shows a corresponding estimate of the historical human-caused surface warming (see Figure SPM.2). Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO₂ emissions from 2020 until year 2050 for the set of illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, see Figure SPM.4). Projections use the cumulative CO₂ emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcings. The relationship is illustrated over the domain of cumulative CO₂ emissions for which there is *high confidence* that the transient climate response to cumulative CO₂ emissions (TCRE) remains constant, and for the time period from 1850 to 2050 over which global CO₂ emissions remain net positive under all illustrative scenarios as there is *limited evidence* supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO₂ emissions.

Bottom panel: Historical and projected cumulative CO₂ emissions in GtCO₂ for the respective scenarios.

{Figure TS.18, Figure 5.31, Section 5.5}

IPCC_AR6_WGI_SPM.pdf

2 What quantity of emissions from natural feedbacks is included the IPCC carbon budget?

ChatGPT:

The IPCC carbon budget primarily focuses on human-caused (anthropogenic) emissions, including fossil fuel burning, deforestation, and other land-use changes. However, it also considers some natural feedbacks,

particularly those that are well-understood and can be reasonably projected within the current climate models.

Natural feedbacks included in the IPCC carbon budget models typically encompass:

1. **Permafrost Thaw:** The gradual release of greenhouse gases from thawing permafrost is included to some extent, but the uncertainty is high due to the complexity and variability in permafrost regions.
2. **Land and Ocean Carbon Sink Saturation:** The reduced capacity of oceans and terrestrial ecosystems to absorb CO₂ as concentrations increase is factored in, acknowledging that these sinks may become less efficient over time.
3. **Changes in Vegetation and Soil Carbon Storage:** The response of terrestrial ecosystems to changing climate conditions, including alterations in vegetation types and soil carbon dynamics, is considered to some degree.

However, **not all feedbacks are fully accounted for** due to the significant uncertainties and potential for rapid, nonlinear changes. For example:

- **Methane Emissions from Wetlands and Clathrates:** These are less well-represented in models due to uncertainties in how these feedbacks might evolve under different warming scenarios.
- **Abrupt Carbon Release Events:** Such as rapid permafrost thaw or large-scale forest dieback, are difficult to predict and therefore not fully included in the budget.

The exact quantity of emissions from these feedbacks included in the IPCC carbon budget is complex to pinpoint due to the inherent uncertainties and model variations. The IPCC often uses a range to express these budgets, reflecting the current scientific understanding and the potential for unforeseen feedbacks.

3 **What quantity of emissions from natural feedbacks is included the IPCC carbon budget?**

Google:

The IPCC carbon budget does not directly include emissions from natural feedbacks; it focuses solely on calculating the cumulative amount of anthropogenic (human-caused) carbon dioxide emissions allowed to limit global warming to a certain level, meaning natural feedbacks are considered as part of the Earth's response to those emissions, not as a separate emission source to be directly accounted for in the budget itself.

Key points about this:

- **Focus on human emissions:**
The carbon budget primarily looks at the total amount of CO₂ humans can emit before exceeding a specific temperature threshold, taking into account how the Earth's natural systems will absorb some of that CO₂ through feedbacks like ocean uptake and plant growth.
- **Feedbacks are factored in indirectly:**
While not explicitly included as emissions, the IPCC's climate models used to calculate the carbon budget do incorporate natural feedbacks, meaning the estimated remaining carbon budget reflects the expected response of the Earth's climate system to human emissions, including both positive and negative feedbacks.
- **Uncertainty in feedbacks:**
Due to the complexity of natural systems, there is inherent uncertainty in how much natural feedbacks will mitigate or exacerbate human-induced warming, which is reflected in the range of estimates within the carbon budget.

4 What quantity of natural emissions do the Earth System Models expect

ChatGPT

The quantity of natural greenhouse gas (GHG) emissions expected by **Earth System Models (ESMs)** varies based on different feedbacks, regions, and gases. Natural emissions from ecosystems and the ocean are dynamic and depend on several factors, including temperature changes, soil moisture, ocean chemistry, and permafrost thawing. While the exact values vary among models and scenarios, we can provide general insights into the expected magnitude of natural emissions based on current ESM projections.

1. Carbon Dioxide (CO₂) Natural Emissions

Natural CO₂ emissions come primarily from soil respiration, forest decay, and ocean-atmosphere exchange.

- **Pre-industrial baseline:** Before industrialization, natural CO₂ emissions were roughly balanced by natural sinks (forests and oceans), with net zero impact on atmospheric CO₂ levels.
- **Post-industrial emissions:** As warming progresses, ESMs project that natural CO₂ emissions will increase due to enhanced soil respiration, forest decay, and oceanic outgassing. However, the increase is scenario-dependent.

In lower-emission scenarios like SSP1-1.9, the warming is limited, and natural CO₂ emissions are expected to remain relatively modest compared to high-emission scenarios like SSP5-8.5. Even so, there will still be increased emissions from:

- **Permafrost thaw:** Projections suggest this could release between **30 to 150 GtCO₂** by 2100, depending on the rate of warming.
- **Soil and plant respiration:** Warming will increase microbial activity in soils, releasing more CO₂. Models suggest that soil carbon loss could contribute **tens of gigatonnes (Gt)** of CO₂ to the atmosphere by 2100.

2. Methane (CH₄) Natural Emissions

Methane is released naturally from wetlands, thawing permafrost, and methane hydrates in the ocean.

- **Wetlands:** Wetland areas are the largest natural source of methane. Warming increases methane emissions from wetlands by enhancing microbial activity. Projections suggest an increase of around **5 to 20 million tonnes (Mt) CH₄ per year** under scenarios with limited warming (like SSP1-1.9).
- **Permafrost:** As permafrost thaws, previously frozen organic matter decomposes, releasing methane. By 2100, permafrost-related methane emissions could range from **5 to 30 Gt of CH₄**, depending on the severity of thawing.
- **Methane hydrates:** Although more uncertain, methane hydrates (frozen methane deposits on the ocean floor) could be destabilized with significant warming. These are not expected to contribute significantly in the SSP1-1.9 scenario due to limited temperature increases.

3. Nitrous Oxide (N₂O) Natural Emissions

Natural N₂O emissions come from soils, especially in forests, wetlands, and agricultural areas where nitrogen cycling occurs.

- **Soil emissions:** N₂O emissions increase with warming and changes in soil moisture. ESMs predict that **soil N₂O emissions could increase by 5-10%** by the end of the century under moderate warming scenarios like SSP1-1.9.
- **Ocean emissions:** Warming and changes in ocean circulation can enhance natural N₂O emissions from

marine systems, particularly in oxygen-deficient areas. This could add **several teragrams (Tg)** of N₂O annually, but these numbers remain relatively small compared to anthropogenic sources.

4. Overall Natural Emission Expectations in SSP1-1.9

In the **SSP1-1.9 scenario**, which aims to limit global warming to about **1.5°C** by 2100, the increase in natural GHG emissions is constrained compared to higher-warming scenarios. While the exact quantities of natural emissions vary across models, the general expectations are:

- **CO₂**: Natural CO₂ emissions from permafrost thaw, soil respiration, and ocean release could contribute **tens to hundreds of gigatonnes (Gt)** of additional CO₂ by 2100. However, the contribution is relatively small compared to anthropogenic emissions and much lower than in high-warming scenarios.
- **CH₄**: Natural methane emissions, particularly from wetlands and permafrost, could add **5-30 Gt** of methane by 2100, but warming is constrained in SSP1-1.9, limiting large-scale permafrost thaw.
- **N₂O**: Natural emissions of N₂O are expected to rise moderately, with a **5-10% increase** in natural sources, adding a small fraction to the global N₂O budget compared to anthropogenic emissions.

5. Comparison with Anthropogenic Emissions

- **Anthropogenic CO₂ emissions**: Human-caused emissions are projected to be around **40 GtCO₂ per year** in 2020. Under SSP1-1.9, aggressive mitigation could reduce this to near-zero by the second half of the century.
- **Natural CO₂ emissions**: These are much smaller, with expected additional releases in the range of **tens to hundreds of gigatonnes** over the century, compared to cumulative anthropogenic emissions of several hundred gigatonnes.
- **Methane and N₂O**: Anthropogenic sources of methane and N₂O are dominant. Natural emissions are expected to increase modestly, but they are small compared to the human-caused component.

Conclusion

Earth System Models project that natural GHG emissions will increase in response to warming, even under low-emission scenarios like SSP1-1.9. **The quantities are moderate, with CO₂ emissions from permafrost and soils adding tens to hundreds of gigatonnes, and methane from wetlands and permafrost contributing several gigatonnes by 2100.** These natural emissions are small compared to historical and projected anthropogenic emissions, but they are significant in the context of long-term carbon cycle feedbacks and the challenge of limiting warming to 1.5°C.

5 Is the IPCC's remaining carbon budget for both anthropogenic and natural emissions?

ChatGPT

The IPCC's remaining carbon budget primarily focuses on limiting anthropogenic (human-caused) CO₂ emissions to meet specific global temperature targets, such as 1.5°C or 2°C above pre-industrial levels. This budget outlines the maximum amount of CO₂ that can be emitted while still having a likely chance of staying within these temperature limits. The calculation of this budget considers natural processes and feedbacks indirectly but does not explicitly allocate space for natural emissions.

Key Points about the Carbon Budget and Natural Emissions

1. Anthropogenic Emissions Focus:

- The carbon budget is mostly concerned with human-caused CO₂ emissions from fossil fuel

combustion, industrial processes, and land-use changes. This is because anthropogenic emissions are the primary driver of the recent rapid increase in atmospheric CO₂ levels and global warming.

2. Incorporation of Natural Processes:

- Natural processes, such as the carbon uptake by oceans and terrestrial ecosystems, play a role in determining the carbon budget. These natural sinks absorb about half of the CO₂ emitted by human activities, which is factored into the calculation of the remaining carbon budget.
- The models used to determine the carbon budget include current estimates of the carbon cycle, including the role of natural sinks and sources. These processes influence the budget by affecting the fraction of anthropogenic CO₂ that remains in the atmosphere.

3. Natural Feedbacks and Their Uncertainties:

- The carbon budget does not directly account for future emissions from natural feedbacks like permafrost thawing, increased soil respiration, or methane release from wetlands. These feedbacks are recognized as potential contributors to future warming but are difficult to predict with high confidence.
- Some IPCC scenarios and models include estimates of these feedbacks to explore their potential impact on the carbon budget and temperature projections. However, the exact contribution of these natural emissions to future warming is uncertain and varies across models.

4. Implications for the Carbon Budget:

- If natural feedbacks significantly increase future emissions, the remaining carbon budget for anthropogenic emissions would effectively shrink. This means that if such feedbacks are stronger than expected, the world would have less room for human-caused emissions to stay within temperature targets.
- The potential for these natural emissions adds to the urgency of reducing anthropogenic emissions, as reliance on natural sinks and the stability of these sinks cannot be guaranteed.

5. Current Budget and Future Projections:

- The current carbon budget calculations assume that natural sinks continue to function as they do today. However, there is an acknowledgment in IPCC reports that climate change could weaken these sinks (e.g., reduced ocean uptake efficiency, decreased carbon storage in forests) and that natural feedbacks could increase.
- Future iterations of the carbon budget may need to account more explicitly for these feedbacks as our understanding of them improves and as they potentially begin to play a more significant role in the global carbon cycle.

Conclusion

The IPCC's remaining carbon budget is designed primarily to guide reductions in anthropogenic emissions to meet climate targets. It indirectly includes natural processes through their influence on the current carbon cycle but does not explicitly set aside space for future emissions from natural feedbacks. The potential impact of these feedbacks introduces uncertainty into the carbon budget, emphasizing the need for swift and significant reductions in human-caused emissions to minimize the risk of exceeding critical temperature thresholds.

6 Fast climate feedbacks

Google:

Fast climate feedbacks are climate processes that respond quickly to increases in atmospheric greenhouse gases (GHGs). These feedbacks include:

- Water vapor
As temperatures rise, more water evaporates from the Earth's surface, increasing the amount of water vapor in the atmosphere. Water vapor is a greenhouse gas, so higher concentrations in the atmosphere have a warming effect.
- Clouds
Clouds can warm or cool the planet, depending on their height and the size of their water droplets. Most scientists expect clouds to warm the planet overall.

	<ul style="list-style-type: none"> • Sea ice Changes in sea ice extent are a fast climate feedback. • Snow and ice albedo Some albedo cooling effect of snow and ice is included in fast climate feedbacks.
7	<p>Arctic Sea Ice Chat GPT</p> <p>The IPCC climate models, as presented in the 2021 report Climate Change 2021: The Physical Science Basis, project that the Arctic could become ice-free in summer by the middle of the 21st century under various emissions scenarios. Specifically:</p> <p>High-emission scenario (SSP5-8.5): This pathway suggests that an ice-free Arctic is almost certain by 2050. Under this scenario, the Arctic could experience ice-free summers as early as the 2030s. If greenhouse gas emissions continue unabated, sea ice loss will accelerate, with ice-free conditions occurring nearly every summer.</p> <p>Intermediate scenarios (SSP2-4.5): Even with moderate reductions in emissions, the Arctic is still likely to experience ice-free summers by the second half of the century, potentially between 2050 and 2080.</p> <p>Low-emission scenario (SSP1-2.6): In this case, significant reductions in emissions slow the pace of ice loss, and the Arctic may retain some summer ice throughout the century. However, ice-free events remain possible later in the century.</p> <p>These projections are based on CMIP6 models, which simulate various possible future outcomes based on different levels of greenhouse gas concentrations. The loss of Arctic sea ice has significant global consequences, including enhanced Arctic warming (the albedo effect), disruptions to weather patterns, and feedback loops that further accelerate climate change</p>
8	<p>A deep dive into the IPCC's updated carbon budget numbers 12 Aug 2021</p> <p>Other Earth system feedbacks – The last piece is to account for Earth system feedbacks that would otherwise not be covered. SR1.5 assumed an additional blanket reduction of 100 GtCO₂ for this century for these feedbacks. This was a crude estimate and therefore not included as a central part of the remaining carbon budget numbers in SR1.5 AR6 updates this assessment entirely and includes this contribution in its main estimates.</p> <p>Taking into account not only permafrost thaw, but also a host of other biogeochemical and atmospheric feedbacks, the AR6 estimates to appropriately include the effect of all these feedbacks, remaining carbon budgets have to be reduced by 26 ± 97 GtCO₂ per degree Celsius of additional warming.</p> <p>Altogether these updates mean AR6 remaining carbon budget estimates are very similar compared to SR1.5, while they additionally include the effect of Earth system feedbacks that would otherwise not be covered.</p> <p>https://www.realclimate.org/index.php/archives/2021/08/a-deep-dive-into-the-ipccs-updated-carbon-budget-numbers/</p>

9 **Global Carbon and Other Biogeochemical Cycles and Feedbacks** (*Climate Change 2021: The Physical Science Basis*)

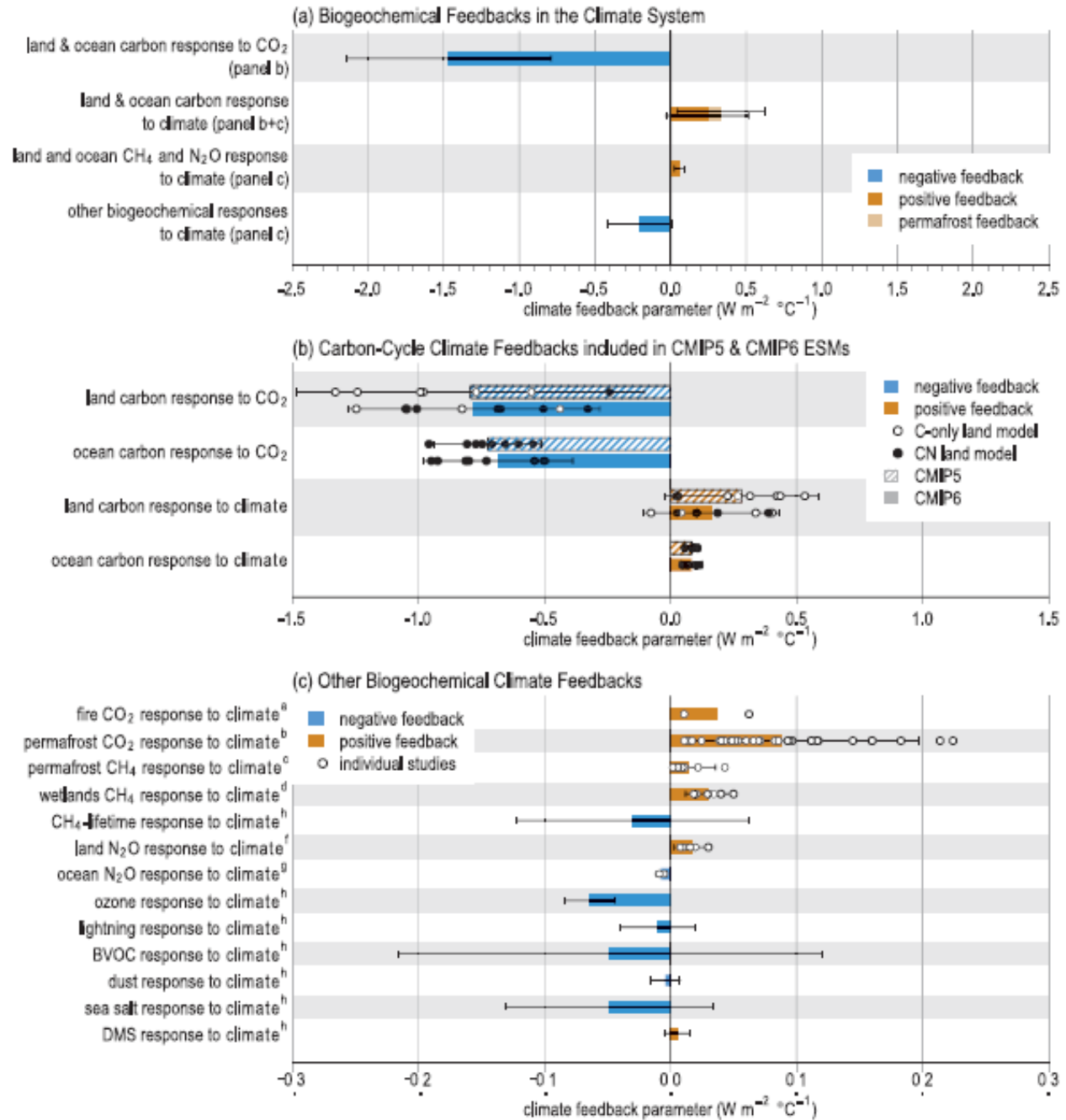


Figure 5.29 | Estimates of the biogeochemical climate feedback parameter (α). The parameter α ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$) for a feedback variable x is defined as $\alpha_x = \frac{\Delta F_{\text{toa}}}{\Delta T_s}$ where $\frac{\Delta F_{\text{toa}}}{\Delta T_s}$ is the change in top-of-atmosphere energy balance in response to a change in x induced by a change in surface temperature (T_s), as in Section 7.4.1.1. **(a)** Synthesis of biogeochemical feedbacks from panels (b) and (c). Orange (blue) bars correspond to positive (negative) feedbacks increasing (decreasing) radiative forcing at the top of the atmosphere. Bars denote the mean and the error bar represents the 5–95% range of the estimates; **(b)** carbon-cycle feedbacks as estimated by coupled carbon-cycle climate models in the CMIP5 (Arora et al., 2013) and CMIP6 (Arora et al., 2020) ensembles, where dots represent single model estimates, and filled (open) circles are those estimates which do (not) include the representation of a terrestrial nitrogen cycle; **(c)** Estimates of other biogeochemical feedback mechanisms based on various modelling studies. Dots represent single estimates, and coloured bars denote the mean of these estimates with no weighting being made regarding the likelihood of any single estimate, and error bars the 5–95% range derived from these estimates. Results in panel (c) have been compiled from (a) Section 5.4.3.2 (Eliseev et al., 2014; Harrison et al., 2018); (b) Section 5.4.3.3 (Schneider von Deimling et al., 2012; Burke et al., 2013, 2017b; Koven et al., 2015a, c; MacDougall and Knutti, 2016b; Gasser et al., 2018; Kleinen and Brovkin, 2018), where the estimates from Burke et al., 2013 have been constrained as assessed in their study (c) Section 5.4.7 (Schneider von Deimling et al., 2012, 2015; Koven et al., 2015; Turetsky et al., 2020); (d) Section 5.4.7 (Armeth et al., 2010; Denisov et al., 2013; Shindell et al., 2013; B.D. Stocker et al., 2013; Zhang et al., 2017); (f) Section 5.4.7 (Xu-Ri et al., 2012; B.D. Stocker et al., 2013; Zaehle, 2013; Tian et al., 2019); (g) Section 5.4.7 (Martinez-Rey et al., 2015; Landolfi et al., 2017; Battaglia and Joos, 2018b). (h) Section 6.3, Table 6.9 mean and the 5–95% range the assessed feedback parameter. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

Table 5.29 can be used to determine that the expected climate feedback factor is 0.166 W/m-2 (0.036 + 0.0870 + 0.013 + 0.03) for the three natural feedbacks (fire, permafrost, and wetlands) included in the budget analysis. The CO2 emissions that would result in that radiative forcing for two values of airborne fraction and two values for the starting atmospheric CO2 concentration are shown in the following table:

Airborne Fraction	Starting PPM	
	420	450
45	230	246
50	207	222
CO2 Emissions for 0.166 W/m-2		

Since the airborne fraction is apt to rise this century, a good “planning” number for the expected emissions from natural feedbacks appears to be about 225 GTCO2 per degree C of temperature increase (or 130 GTCO2/0.1 W/m-2)

<https://doi.org/10.1017/9781009157896.007>

10 Airborne fraction and natural emissions

ChatGPT

The **airborne fraction** and **natural emissions** are two interrelated concepts within the carbon cycle and play key roles in determining the concentration of CO₂ in the atmosphere, thereby affecting climate change.

1. Airborne Fraction

The **airborne fraction** refers to the proportion of total CO₂ emissions (both anthropogenic and natural) that stays in the atmosphere, while the remainder is absorbed by natural carbon sinks, such as oceans, forests, and soils. On average, the airborne fraction has remained around **40-45%** in recent decades, meaning that about 55-60% of CO₂ is taken up by natural sinks. However, this fraction can vary year by year due to fluctuations in natural processes.

2. Natural Emissions

Natural emissions are the CO₂ and other greenhouse gases (e.g., methane and nitrous oxide) released from natural processes such as:

- **Plant and soil respiration:** Plants take in CO₂ during photosynthesis and release it during respiration. Soil microbes break down organic matter and release CO₂.
- **Oceans:** CO₂ is exchanged between the atmosphere and the oceans through diffusion. Warming oceans may release more CO₂ back into the atmosphere.
- **Volcanic activity:** Releases CO₂ and other gases from the Earth's interior.
- **Wetlands:** Produce methane through anaerobic decomposition of organic matter.
- **Permafrost thaw:** Releases both methane and CO₂ as frozen organic material decomposes.

These natural emissions are part of the **natural carbon cycle**, which has historically been balanced, with natural sinks absorbing an equivalent amount of CO₂ as natural emissions. However, this balance has been disrupted by human activities that emit large amounts of CO₂ from fossil fuels, deforestation, and land-use changes.

3. Interaction Between Airborne Fraction and Natural Emissions

The **airborne fraction** is influenced by the ability of natural sinks to absorb both anthropogenic and natural CO₂

emissions. Several factors determine how the airborne fraction evolves over time, especially under future climate change scenarios:

a. Warming-Induced Changes to Natural Emissions

As the planet warms, natural emissions from processes like soil respiration, permafrost thaw, and ocean outgassing are expected to increase. This means that:

- **Increased soil respiration:** Higher temperatures stimulate microbial activity in soils, leading to greater CO₂ emissions. This adds to the overall pool of CO₂ in the atmosphere.
- **Permafrost thaw:** Releases significant amounts of methane and CO₂ as frozen organic matter begins to decompose in warming conditions.
- **Ocean outgassing:** Warmer waters hold less CO₂, leading to higher emissions from the ocean back into the atmosphere.

These changes in natural emissions could **increase the airborne fraction**, as natural sinks might not be able to keep up with the rising influx of CO₂ and other GHGs.

b. Sink Saturation and Decreased Carbon Sequestration

As natural emissions increase, the capacity of carbon sinks to absorb CO₂ can weaken. Some of the key processes affecting this include:

- **Ocean saturation:** The ocean's ability to absorb CO₂ may decrease as it becomes saturated with carbon and as surface waters warm, reducing solubility.
- **Forest dieback:** Forests may lose their capacity to sequester carbon as they face stress from droughts, wildfires, and other climate impacts. In some cases, forests could even become net sources of CO₂.

As sinks weaken, a greater proportion of the emitted CO₂ (both from human activities and natural processes) will remain in the atmosphere, raising the airborne fraction.

c. Positive Feedback Loops

The relationship between natural emissions and the airborne fraction can create positive feedback loops. For example:

- **Permafrost-carbon feedback:** Warming causes permafrost to thaw, releasing methane and CO₂, which leads to more warming, further thawing more permafrost, and so on.
- **Soil-carbon feedback:** Warming increases microbial activity, releasing more CO₂ from soils, which enhances warming, leading to more soil carbon release.

These feedbacks accelerate the amount of CO₂ staying in the atmosphere, increasing the airborne fraction.

4. Projected Changes in Airborne Fraction Due to Natural Emissions

Over the 21st century, **Earth System Models (ESMs)** predict that the airborne fraction will likely increase due to weakening carbon sinks and increasing natural emissions. The degree of change depends on the emission scenario:

- **In high-emission scenarios (e.g., SSP5-8.5), large-scale warming is expected to significantly increase natural CO₂ emissions (from sources like permafrost thaw and soil respiration), and carbon sinks will weaken more**

rapidly. In this scenario, the airborne fraction could exceed **50-60%** by 2100, as sinks become saturated or reverse their role as carbon absorbers.

- **In low-emission scenarios** (e.g., SSP1-1.9), the rise in the airborne fraction is more limited. However, even under these scenarios, some increase is expected because of warming-induced changes to natural processes. The airborne fraction may still rise to around **50%** by 2100, as sinks weaken in response to modest climate change.

5. Role of Natural Emissions in Shaping Future Carbon Budgets

The **increase in natural emissions** due to climate feedbacks and the subsequent increase in the airborne fraction have major implications for global climate targets:

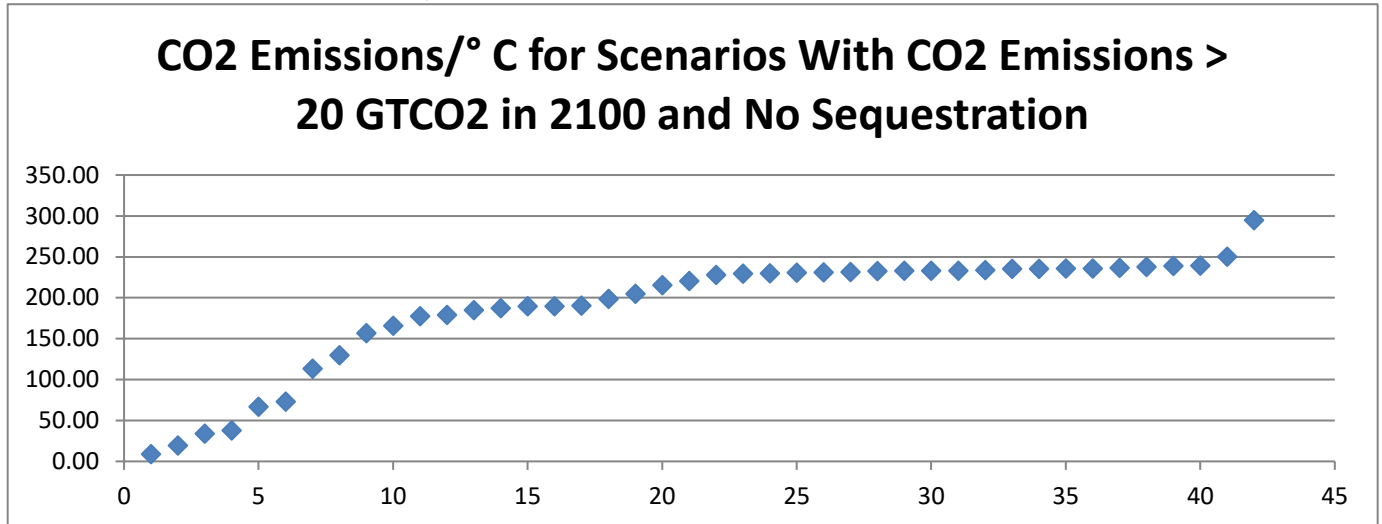
- **Carbon budgets:** As the airborne fraction rises, more CO₂ remains in the atmosphere, meaning that future carbon budgets for limiting warming to 1.5°C or 2°C will shrink. This could necessitate more rapid and aggressive reductions in anthropogenic emissions or increased reliance on **Carbon Dioxide Removal (CDR)** technologies.
- **Climate mitigation:** Limiting future climate change will require not only reducing human emissions but also maintaining and enhancing natural carbon sinks. Reforestation, wetland restoration, and ocean protection could help stabilize or even reduce the airborne fraction over time.

Conclusion

The **airborne fraction** is expected to increase over the century, primarily due to weakening natural carbon sinks and rising natural emissions driven by climate feedbacks. As warming accelerates natural emissions (e.g., from permafrost thaw and soil respiration), and as sinks such as oceans and forests become less effective at absorbing CO₂, a larger portion of total emissions will remain in the atmosphere. This underscores the importance of both reducing anthropogenic emissions and protecting natural carbon sinks to mitigate climate change effectively.

11 **Calculation of CO2 Emissions/° C from AR6 Data**

1. Data source: AR6 Scenario Explorer and Database hosted by IIASA
<https://data.ene.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces>
2. Used 42 scenarios with CO2 Emissions > 20 GTCO2 in 2100 and no sequestration
3. Airborne Fraction in 2015 – 47.9
4. Airborne Fraction in 2100 – 55 (see #10 above)
5. Calculated natural emissions for each year based on anthropogenic emissions, atmospheric growth, and airborne fraction (Natural Emissions = Atmospheric Growth / Airborne Fraction - CO2 emissions/1000)
6. Summed emissions from 2025-2100
7. Calculated CO2 Emissions/° C (= sum/temperature increase) for each scenario
8. Plot of Calculated CO2 Emissions/° C



9. Averages

Average CO2 Emissions/° C	
Average (All)	198
Average between 150 and 250	217
Average between 200 and 250	234

10. Similar value to that obtained in #9 above (220)

11. Calculation in the spreadsheet at <https://www.chesdata.com/documents/AR6 Natural Emission Analysis.xlsx>