

Path-dependent reductions in CO₂ emission budgets caused by permafrost carbon release

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Emission budgets are defined as the cumulative amount of anthropogenic CO₂ emission compatible with a global temperature change target. The simplicity of the concept has made it attractive to policy-makers, yet it relies on a linear approximation of the global carbon-climate system's response to anthropogenic CO₂ emissions. Here, we investigate how emission budgets are impacted by inclusion of CO₂ and CH₄ emissions caused by permafrost thaw, a non-linear and tipping process of the Earth system. We use the compact Earth system model OSCAR v2.2.1 in which parameterization of permafrost thaw, soil organic matter decomposition, and CO₂ and CH₄ emission was introduced, based on four complex land surface models that specifically represent high-latitude processes. We find that permafrost carbon release makes emission budgets path-dependent (i.e. budgets also depend on the pathway followed to reach the target). The median remaining budget for the 2°C target is reduced by 8% [1–25%] if the target is avoided and net negative emissions prove feasible, by 13% [2–34%] if they do not prove feasible, by 16% [3–44%] if the target is overshoot by 0.5°C, and by 25% [5–63%] if it is by 1°C. (Uncertainties are the minimum-to-maximum range across permafrost models and scenarios.) For the 1.5°C target, reductions in the median remaining budget range from ~10% to more than 100%. We conclude that the world is closer to exceeding the budget for the long-term target of the Paris climate agreement than previously thought.

Sometimes called “carbon budgets”, cumulative anthropogenic CO₂ emission budgets compatible with a given global mean warming target have been evaluated in many ways¹⁻¹⁰. Yet, only a handful of studies¹¹⁻¹³ made (incomplete) preliminary attempts to account for permafrost thaw. Additional emission of CO₂ and CH₄ caused by this natural process triggered by warming in the high

latitudes^{13,14} will indeed diminish the budget of CO₂ humankind can emit while staying below a certain level of global warming. Permafrost carbon release is also an irreversible process over the course of a few centuries^{13,14}, and may thus be considered a “tipping” element of the Earth’s carbon-climate system centuries¹⁵, which puts the linear approximation of the emission budget framework^{1,4,5,16,17} to the test.

To quantify the impact of permafrost carbon release on emission budgets, we use an Earth system model of reduced complexity whose processes are parameterized to faithfully emulate more complex models. OSCAR v2.2.1 – a minor update of v2.2 (ref.¹⁸) – is run in its default configuration which is comparable to the median of its probabilistic setup. Therefore, all our results are for ~50% chance of meeting the temperature targets. OSCAR is extended here with a new permafrost carbon module that emulates four state-of-the-art land surface models: JSBACH (Methods), ORCHIDEE-MICT (ref.¹⁹), and two versions of JULES (ref.^{20,21}). These complex models have been specifically developed to represent high latitude processes, in particular soil thermic and biogeochemistry mechanisms that control carbon sequestration and emission. In this new emulator, permafrost carbon in two high-latitude regions is represented as an initially frozen pool that thaws as global temperature increases. Thawed carbon is not immediately emitted: it is split between several pools, each with its specific timescale of emission. We assume 2.3% of the emission occurs as methane¹⁴ ([see discussion and Methods regarding the uncertainty of this value](#)), and this emitted CH₄ is fully coupled to the dynamical atmospheric chemistry of OSCAR. More details on the protocol, the emulator and the models are provided in Methods.

We do not assume a priori that reductions in emission budgets can simply be calculated as the cumulative permafrost carbon release in a given scenario. Quite the opposite, we apply three specifically designed approaches to estimating emission budgets. The first one is the “exceedance” approach, in which the budget is a threshold in terms of cumulative anthropogenic CO₂ emissions above which the temperature target is exceeded (with a given probability). The second one is the “avoidance” approach, in which the budget is another – typically lower – cumulative emissions threshold below which the target is avoided (also with a given probability). These two approaches were used in the fifth IPCC assessment report^{6,22}. However, none of them considers the possibility of overshooting the target first, and returning below it in a second time. To investigate such a case, we adapt the approach by MacDougall et al.¹² to create “overshoot” budgets.

Reductions in exceedance and avoidance budgets

With the exceedance approach, budgets are calculated in any given scenario as the maximum cumulative CO₂ emissions before the point in time when global temperature reaches the target level for the first time. This is illustrated in Figure 1 (see also Methods and example in Supplementary Figure 1). Here, our exceedance budgets are based upon the four extended RCP emission scenarios²³ and two idealised scenarios (Methods and Supplementary Figure 2).

When permafrost carbon is ignored, we estimate total exceedance budgets of 2320 [2260–2450] Gt CO₂ for the 1.5°C target and 3230 [3080–3530] Gt CO₂ for 2°C, with 1870 as the preindustrial reference year (Supplementary Table 1; budgets for 2.5°C and 3°C also provided therein). (Uncertainties are the minimum-to-maximum range across permafrost models and scenarios.) Our results are ~2% different from the IPCC estimates based on complex models⁶. This confirms that OSCAR’s default configuration gives results consistent with the Earth system models used in previous climate change assessments.

When permafrost carbon processes are included, exceedance budgets are reduced by 30 [10–120] Gt CO₂ for 1.5°C and 60 [10–200] Gt CO₂ for 2°C (Figure 2a and Supplementary Table 1). This is only a few percentage points of the total budgets, but it corresponds to a more substantial reduction in the remaining budgets (Figure 2b). It is also smaller in magnitude than previously estimated with a model of intermediate complexity¹², which can be explained by the over-sensitivity of the permafrost carbon model used in this earlier study (Table 1). An important (known) caveat of the exceedance approach is that it ignores the system’s dynamics after the point in time at which the temperature target is reached²². This is especially important for permafrost carbon, since a significant part of the thawed carbon keeps being emitted long after the target is first reached (Supplementary Figure 3), implying the temperature target will actually be surpassed if budgets are based on this approach.

With the avoidance approach, budgets are calculated using a large ensemble of peak-and-decline emission scenarios whose values of peak temperature and maximum cumulative CO₂ emissions are used for interpolation (Figure 1, Methods and Supplementary Figure 1). This approach accounts for the complete system’s dynamic by ensuring that the temperature target is never exceeded. Its drawback, however, is its intense computing requirement that makes it extremely costly to follow by complex models. Here, we create and use an ensemble of 3,120 scenarios, by combining 520 fossil-fuel CO₂ emission scenarios of our own making (Supplementary Figure 4) to the land-use and non-CO₂ climate forcings from the six scenarios previously used for exceedance budgets (Methods).

Permafrost carbon reduces avoidance budgets by 60 [10–180] Gt CO₂ for 1.5°C and 100 [20–270] Gt CO₂ for 2°C (Figure 2a). This reduction in avoidance budgets is systematically larger than for exceedance budgets: by 20% to 140% across all the emulated permafrost carbon models (Figure 3). This confirms that the exceedance approach only partially captures the impact of permafrost carbon release on emission budgets. We conjecture that other slow and strongly non-linear processes such as forests dieback^{15,24,25} would also be incompletely accounted for with exceedance budgets. Since the exceedance approach was the only one used by complex models in the fifth IPCC assessment report^{6,22}, we conclude that future updates of emission budgets based on such models will remain biased without a change in experimental protocol.

Path-dependency and overshooting pathways

Our ensemble of 3,120 scenarios for avoidance budgets covers a large enough spectrum of possible futures that it can be split into two groups (Methods and Supplementary Figure 4). In the subgroup of scenarios which have no net negative emissions (noted “NetNegEm0”), the permafrost-induced reduction in avoidance budgets is 90 [10–230] Gt CO₂ for 1.5°C and 150 [30–340] for 2°C (Figure 2a). This is systematically more than in the subgroup of scenarios in which net negative emissions are extensively implemented (“NetNegEm+”) (Figure 3). The physical reason for this is that extensive net negative emissions artificially make temperature peak a few years after they are introduced, whereas when net negative emissions are not available the peak of temperature is entirely caused only by natural processes, and permafrost carbon emissions can delay it for decades (Supplementary Figure 5). The fact that the effect of permafrost carbon release depends on the emission pathway is proof that inclusion of such a previously unaccounted for tipping process renders emission budgets path-dependent. In other words, the emission budget compatible with a given target depends on both the timing and magnitude of anthropogenic emissions, and not only on their magnitude.

To investigate further this path-dependency, we look into overshoot budgets using the same ensemble of scenarios as for avoidance budgets (Methods). Net overshoot budgets are calculated as the sum of two gross budgets: a “peak” budget that is exactly the same as an avoidance budget for a given peak temperature above the long-term target, and a “capture” budget that corresponds to the amount of net negative emission required to return below the long-term temperature target (Figure 1, Methods and Supplementary Figure 1). Capture budgets have a mathematical definition analogous to exceedance budgets, and so these budgets have the same caveat of overlooking the system’s evolution after the target is met. Longer-term requirements in CO₂ capture to compensate for lasting permafrost emissions^{26,27} are therefore ignored in our capture budgets (provided in Supplementary Table 2). Also, only net negative emission requirements can be estimated this way: gross negative emissions could be much larger if decrease in fossil-fuel consumption were not rapid enough²⁸.

In the case of an overshoot amplitude of 0.5°C, emissions from permafrost thaw reduce net emission budgets by 130 [30–300] Gt CO₂ for the 1.5°C long-term target (i.e. for a peak temperature of 2°C, a case corresponding to the Paris climate agreement), and by 190 [50–400] Gt CO₂ for 2°C (Figure 2a). For an overshoot amplitude of 1°C, permafrost-induced reductions reach 210 [50–430] Gt CO₂ for the 1.5°C target, and 270 [70–530] Gt CO₂ for 2°C. (Budgets for other targets and other levels of overshoot are provided in Figure 2 and Supplementary Table 1.) The permafrost-induced reduction is systematically more pronounced in these cases than in non-overshooting scenarios (Figure 3) because of the additional capture required to counteract the extra emission from thawed permafrost that occur during the overshoot period. It is already known that the rest of the carbon-climate system (i.e. excluding permafrost) exhibits a path-dependent behaviour under overshooting scenarios²⁹ (see also Supplementary Figure 6), but our results show that permafrost carbon release strongly reinforces this rupture of the linear approximation of the emission budget framework.

Discussion and policy implications

A permafrost-induced path-dependency of emission budgets was already implied by MacDougall et al.¹², although their quantification of the effect was biased by the high sensitivity of their permafrost carbon release in response to high-latitude warming (Table 1; note that an update of their model showed a lower bias²⁶). Their study also focused on exceedance budgets and a handful of overshooting scenarios that did not correspond to political commitments. The Paris climate agreement indeed aims at avoiding 2°C, which implies avoidance budgets are needed. It also recognizes an overshooting trajectory by setting the long-term target to 1.5°C, which means overshoot budgets are also needed.

A few earlier attempts at quantifying the permafrost-induced reduction in emission budgets were also made^{11,13}, albeit without applying any of the budget-calculation approaches we use. They simply subtracted cumulative emissions caused by permafrost thaw from cumulative anthropogenic emissions, at an arbitrary point in time. Such an approach is not suitable for accurately estimating budget reductions (Supplementary Figure 7) since it overlooks the dynamical response of the coupled system. It was not retained in the fifth IPCC assessment report⁶. Additionally, these earlier studies did not find path-dependency, either because only one scenario was investigated¹¹ or because path-independency was assumed¹³.

The OSCAR v2.2.1 model with its new permafrost carbon emulator estimates future carbon release from thawing permafrost within the range of existing studies (Table 1). A cumulative 60 [11–144] Pg C is projected to be released by 2100 under RCP8.5, slightly lower than the 37–174 Pg C reviewed by Schuur et al.¹⁴, and close to the 28–113 Pg C obtained with a data-constrained model by Koven et al.³⁰. Uncertainties in permafrost-related processes and their response to climate change remain very high, however, and there are elements that suggest our results are conservative. Deep (e.g. Yedoma) and seabed permafrost thaw is not modelled. Should these carbon stocks be mobilized, budgets would be further reduced. Changes in nitrogen cycling caused by permafrost thaw are also ignored. They could lead to emission of N₂O (ref.³¹) but also changes in the ecosystems' net carbon balance³².

We also assume a constant fraction of permafrost carbon is emitted as CH₄, while the value and future evolution of this fraction are uncertain^{14,33,34}. With this constant value, we simulate an emission of 3.7 [0.7–10.5] Tg CH₄ per year over the 1980–2012 period, in line with a recent review³⁵. This methane contributes a non-negligible fraction of the reduction in emission budgets (Figure 4). This contribution is also path-dependent, contrary to what was obtained in earlier studies^{13,33} by using a fixed global warming potential (GWP). It is, however, a well-known caveat of GWPs (or any other emission metric) that they are linear and constant while the actual Earth system behaves in a complex, dynamical and non-linear fashion³⁶⁻³⁹, **and that they cannot be naively used in combination with emission budgets**⁴⁰.

Because of all these uncertainty sources, we assume that no probabilistic distribution of the permafrost-induced effect can yet be drawn from our results, and we provide its full range. Reducing

this uncertainty, by fostering observation- and model-based research on permafrost and other tipping processes of the Earth system, is key to knowing if and when the world will enter an overshooting climatic regime. Meanwhile, permafrost adds to the uncertain context under which climate policy decisions must be taken⁴¹⁻⁴³. Careful policy-making might entail taking the pessimistic end of our estimates.

Nevertheless, we have shown that accounting for tipping elements of the Earth system breaks the apparent linear behaviour of the carbon-climate system, which equates to making emission budgets path-dependent. This renders manipulating budgets more delicate than previously thought, as budget users have to make assumptions regarding the long-term target, but also the shorter-term target (e.g. risk of overshooting) and even the reliance on certain technologies (as we have demonstrated for net negative emissions).

Furthermore, we have quantified a substantial permafrost-induced reduction in remaining budgets for low-warming targets. It ranges from ~5% to as much as ~40% for 2°C, and from ~10% to more than 100% for 1.5°C, under present-day non-CO₂ forcing and for ~50% chance of meeting the temperature targets. [Whether the world has already breached the budget for 1.5°C remains elusive, however. It depends on many factors including](#) the uncertainty on past anthropogenic emissions^{44,45}, the amount of forcing by non-CO₂ species that will be mitigated in the near future^{12,46,47}, and a possible bias in the models' simulated present-day global temperature⁷⁻¹⁰ [\(not accounted for in this study\)](#). [Irrespective of these uncertainties, it appears that the attainability of the Paris agreement is more compromised than suggested by an existing literature that largely ignores tipping or irreversible feedbacks of the Earth system.](#)

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Author contributions

T.G. designed the study. T.G. developed the permafrost emulator with inputs from P.C. and M.K. T.K. provided JSBACH data. Y.H., D.Z. and P.C. provided ORCHIDEE data. E.J.B. and A.E. provided JULES data. T.G. and M.K. set up the simulations with OSCAR, processed the outputs, and created the figures. T.G., M.K., P.C. and M.O. discussed preliminary results. T.G. wrote the manuscript with contributions from all authors.

No competing financial interests.

Reference	2100	2200	2300	notes
<i>High-emission scenarios: RCP8.5 or SRES A2</i>				
<i>This study</i>	59 [11–143]	150 [34–297]	212 [55–376]	–
Koven et al. ³⁰	57 [28–113]	–	–	data-constrained modeling
MacDougall et al. ¹²	226	611	–	CO ₂ -only simulations
Schuur et al. ¹⁴	37–174	–	ca. 100–400	review compiling several studies
Schaefer et al. ¹³	37–347	–	–	review compiling several studies
<i>Medium-high stabilization scenarios: RCP6.0 or SRES A1B</i>				
<i>This study</i>	42 [8–102]	99 [23–203]	145 [39–265]	–
MacDougall et al. ¹²	166	–	–	CO ₂ -only simulations
Schaefer et al. ¹¹	–	190 ± 24	–	uncertainty is 1-sigma
<i>Medium-low stabilization scenario: RCP4.5</i>				
<i>This study</i>	35 [7–83]	64 [16–130]	89 [26–163]	–
Koven et al. ³⁰	21 [12–33]	–	–	data-constrained modeling
MacDougall et al. ¹²	156	–	–	CO ₂ -only simulations
Schaefer et al. ¹³	27–100	–	–	review compiling several studies
<i>Low-emission scenario: RCP2.6</i>				
<i>This study</i>	27 [6–62]	39 [11–82]	47 [15–93]	–
MacDougall et al. ¹²	103	153	169	CO ₂ -only simulations

Table 1. Comparison of cumulative permafrost carbon release estimated in 2100, 2200 and 2300 (in Pg C; 1 Pg C = $\frac{44}{12}$ Gt CO₂). Uncertainties show the full range of simulations or studies, unless noted otherwise. A more comprehensive comparison also including ref.^{26,48,49} is provided in Supplementary Table 3.

Figure captions

Figure 1. Illustration of the three budget-calculation approaches used in this study. Exceedance budgets (red) are the amount of CO₂ that can be emitted before exceeding a given temperature target. Avoidance budgets (blue) are the amount of CO₂ that can be emitted while staying below the target. Capture budgets (yellow) are the amount of CO₂ that need be captured when the target temperature is overshoot by a given level. Capture budgets are combined with avoidance budgets to give net overshoot budgets. See Methods and Supplementary Figure 1 for technical details on how these budgets are calculated.

Figure 2. Change in emission budgets caused by permafrost carbon release. The temperature targets of 1.5°C, 2°C, 2.5°C and 3°C are shown on the *x*-axis. Coloured symbols are for different budget-calculation approaches, including different levels of overshoot and the avoidance budgets based on two subgroups of scenarios: without net negative emissions (“NetNegEm0”) and with large amount of them (“NetNegEm+”). Uncertainty bars show the full range and symbols show the average, across all permafrost models and scenarios. **(a)** Absolute reductions in emission budgets. **(b)** Relative reductions in remaining budgets, [calculated by assuming 2240 Gt CO₂ \(ref.⁴⁴\) has been emitted between 1870 \(the preindustrial reference year\) and 2017 \(see Methods\)](#). To better isolate the effect of permafrost carbon in (b), we present values under a constant [present-day non-CO₂ radiative forcing](#) (other non-CO₂ backgrounds are available in Supplementary Table 1).

Figure 3. Path-dependency of the permafrost-induced budget reductions. Reductions in avoidance and overshoot budgets (on the *x*-axis) are compared to reductions in exceedance budgets (reference case of 100%). Each type of budget represents a different archetype of pathway, and they are roughly sorted by increasing intensity of the permafrost effect. Coloured symbols are for the four temperature targets, [and uncertainty bars show the full range of our results](#). Values >100% mean that emission budgets are more largely reduced than in the exceedance case. If the permafrost effect were path-independent, all points would be close to 100%.

Figure 4. Contribution of CH₄ released by permafrost thaw to the budget reductions. It is expressed in **(a)** absolute and **(b)** relative terms with regard to the values shown in Figure 2a. [Uncertainty bars show the full range and symbols show the average, across all permafrost models and scenarios.](#)

Methods

OSCAR v2.2.1

OSCAR is a compact Earth system model whose modules are calibrated to emulate the behaviour of more complex models¹⁸. Of particular interest to this study, OSCAR features a module for the terrestrial carbon-cycle calibrated on TRENDY and CMIP5 data^{50,51}, a module for the oceanic carbon-cycle adapted from ref.⁵² to embed CMIP5 data⁵¹, a climate response module calibrated on CMIP5 models⁵³, and an atmospheric chemistry module for the CH₄ tropospheric lifetime taken from ref.⁵⁴.

We use OSCAR v2.2.1 that is a minor update of v2.2. The only change between the two versions that affects this study is a minor correction of the carbonate chemistry in the surface ocean. This correction implies a better behaviour of the model for high-warming scenarios. All equations remain the same as in the description paper¹⁸.

We use the global RCP data²³ to drive the model over the data set's historical period (1765–2005) and following the four extended RCP scenarios (2006–2500). Concentrations of all greenhouse gases but CO₂ and CH₄ are prescribed to the model. Radiative forcings (RFs) of all near-term climate forcers (ozone and aerosols) and albedo effects (black carbon on snow and land-cover change) are also prescribed. Therefore, the model is run in an emission-driven fashion only for fossil CO₂ and CH₄ emissions. However, to ensure that we obtain the same atmospheric concentrations of CO₂ and CH₄ as those of the RCPs when permafrost thaw is turned off, we first run a concentration-driven simulation which we use to back-calculate the anthropogenic emissions of CO₂ and CH₄ that are compatible with these atmospheric concentrations^{28,55}. These compatible anthropogenic emissions are then used to drive the model, instead of the original RCP emissions. Land-use and land-cover change data comes from the LUH1.1 data set⁵⁶ until 2100. After that year, land-cover change is assumed to be zero, and land-uses (wood harvest and shifting cultivation) are assumed to be constant.

We also introduce the CST and STOP scenarios. In CST, concentrations of all greenhouse gases but CO₂, radiative forcings of all near-term climate forcers and albedo effects, and fossil CO₂ emissions are kept constant after 2005. In STOP, all these values are set to their preindustrial value after 2005. In both CST and STOP, land-cover change is assumed to be zero after 2005. Land-uses are assumed to be constant after 2005 in CST, and to be zero in STOP.

The above protocol is further adjusted so that, when atmospheric CH₄ concentration deviates from that of the original RCP because of CH₄ emission from permafrost thaw, OSCAR also calculates the associated change in radiative forcing from stratospheric H₂O and tropospheric O₃ (ref.^{18,36}).

In this study, OSCAR is not run in a probabilistic fashion: we use the default configuration of the model to save computing time. This implies that the full uncertainty of the Earth system is not sampled in this study, and only that of the permafrost system is, under a close-to-median configuration

of the rest of the model. The default configuration has an equilibrium climate sensitivity for CO₂ doubling of ~3.2°C. A comparison of the default and median results for key variables of the model is provided in Supplementary Figure 8, for our six scenarios and in the case without permafrost thaw. The median results are obtained by running an unconstrained Monte Carlo ensemble of 2,000 elements, as in ref.¹⁸. Supplementary Figure 8 shows that the default and median atmospheric CO₂ and global temperature simulated variables remain close, with a normalised root-mean square error (nRMSE) <5%. Two noticeable biases are identified, however. First, the default configuration gives a lower atmospheric CH₄ than the median, which suggests that our results underestimate the additional effect of CH₄ emission caused by permafrost thaw. Second, for RCP2.6 (a peak-and-decline scenario) and to a lesser extent for RCP4.5 (a stabilizing scenario), the default configuration warms more than the median, indicating that our capture budgets are likely overestimated (which may partly compensate for the protocol-induced underestimate described in main text).

Permafrost carbon emulator

We couple a permafrost emulator to OSCAR v2.2.1, calibrated on four land surface models: JSBACH (see dedicated section), ORCHIDEE-MICT (ref.¹⁹), and JULES (ref.²⁰) following the two different versions “DeepResp” and “SuppressResp” (ref.²¹). The calibration of the parameters defined hereafter is done using outputs of the complex models for integrations over 1850–2300 of the RCPs 8.5, 4.5 and 2.6. In this emulator, we calibrate and separately run the permafrost system of two aggregated regions of the globe: North America and Eurasia. In these models, we call “permafrost carbon” the carbon that was frozen (and therefore inactive) during preindustrial times. All parameter values are given in Supplementary Table 4.

First, we model the regional air surface temperature change (T^i) in each region i with a linear dependency on global temperature change (T):

$$T^i = \omega^i T \quad (1)$$

The parameters ω^i are calibrated with a linear fit between T^i and T (Supplementary Figures 9 and 10; first row). Note that this parameter represents a feature of the climate system. It does not actually come from the emulated land surface model, but rather from the climate model it uses as input. In the case of JSBACH, it is the MPI-ESM-LR model’s results for CMIP5 (ref.⁵⁷). In the case of ORCHIDEE and JULES, the detailed protocol of the simulations used is provided by ref.²¹. For JULES, we take the average of all realizations made with IMOGEN, and for ORCHIDEE we take only one realization made with IMOGEN emulating HadCM3.

Second, we calibrate the temperature-dependency of the heterotrophic respiration rate of non-permafrost carbon (r) following a Gaussian law⁵⁸:

$$r^i = r_0^i \exp\left(\gamma_1^i T^i - \gamma_2^i T^{i2}\right) \quad (2)$$

γ_1 and γ_2 are the sensitivity parameters calibrated with forced positive values (Supplementary Figures 9 and 10; second row), and r_0 is the preindustrial heterotrophic respiration rate taken as the average over 1850–1859 in the case of JSBACH, and 1850 in the case of ORCHIDEE and JULES (since IMOGEN features no inter-annual variability).

Third, we introduce the “theoretical thawed fraction” (\bar{p}) that can take values from $-p_{min}$ to 1, with a preindustrial value of 0. It corresponds to the fraction of thawed permafrost carbon for a given regional temperature change, but neglecting dynamic considerations. It is fitted by an S-shaped function:

$$\bar{p}^i = -p_{min}^i + \frac{1+p_{min}^i}{\left(1 + \left(\left(\frac{1}{p_{min}^i} + 1\right)^{\kappa_p^i} - 1\right) \exp(-\gamma_p^i \kappa_p^i T^i)\right)^{\frac{1}{\kappa_p^i}}} \quad (3)$$

p_{min} represents a hypothetical (i.e. never reached) case of fully frozen soils, κ_p is a shape parameter, and γ_p is the sensitivity parameter. The three parameters are calibrated with the same fit (Supplementary Figures 9 and 10; third row), with the additional constraint that p_{min} cannot be greater than the ratio of the model’s non-frozen soil carbon over frozen soil carbon in preindustrial times. In the case of JSBACH, because there is no re-freezing in the model, we calibrate this relationship on the scenario with the fastest warming only (i.e. RCP8.5). For ORCHIDEE and JULES, the calibration is made with all scenarios. Therefore, the exact physical meaning of \bar{p} depends on the emulated model.

Fourth, we introduce an asymmetric dynamic behaviour in the thawing/freezing process by defining the “actual thawed fraction” (p) which is lagging behind the theoretical thawed fraction \bar{p} :

$$\frac{dp^i}{dt} = v_p^i (\bar{p}^i - p^i) \quad (4)$$

with:

$$v_p^i = \begin{cases} v_{thaw}^i, & \text{if } \bar{p}^i \geq p^i \\ v_{froz}^i, & \text{if } \bar{p}^i < p^i \end{cases} \quad (5)$$

v_{thaw} and v_{froz} are the speeds of thawing and freezing, respectively. They are calibrated simultaneously with transient simulations (Supplementary Figures 9 and 10; fourth row), using equations (3), (4) and (5) driven only by the regional temperature change taken from the emulated model, i.e. not using equation (1).

Fifth, a frozen carbon pool (C_{froz}) changes with time following the thawing carbon flux (F_{thaw}) calculated as the product of the frozen pool size during preindustrial times ($C_{froz,0}$) by the speed of change in (i.e. time-derivative of) the actual thawed fraction:

$$-\frac{dC_{froz}^i}{dt} = F_{thaw}^i = \frac{dp^i}{dt} C_{froz,0}^i \quad (6)$$

Inspired by Koven et al.³⁰, the thawing flux is then split between three thawed carbon pools (C_{IN}) following partitioning coefficients (π_{IN}). Note, however, that for some models we reduced the number of thawed carbon pools to avoid over-fitting (see Supplementary Table 4). Each thawed carbon pool is

then subjected to heterotrophic respiration with its own turnover time (τ_{HN}). The respiration rate is affected by regional temperature change following the same law as in equation (2), except that the sensitivities are modified by a factor κ_t . This gives:

$$\begin{cases} \frac{dC_{t1}^i}{dt} = \pi_{t1}^i F_{thaw}^i - \frac{1}{\tau_{t1}^i} \left(\frac{r^i}{r_0^i}\right)^{\kappa_t^i} C_{t1}^i \\ \frac{dC_{t2}^i}{dt} = \pi_{t2}^i F_{thaw}^i - \frac{1}{\tau_{t2}^i} \left(\frac{r^i}{r_0^i}\right)^{\kappa_t^i} C_{t2}^i \\ \frac{dC_{t3}^i}{dt} = \pi_{t3}^i F_{thaw}^i - \frac{1}{\tau_{t3}^i} \left(\frac{r^i}{r_0^i}\right)^{\kappa_t^i} C_{t3}^i \end{cases} \quad (7)$$

To ensure mass balance, we must have: $\pi_{t3} = 1 - \pi_{t1} - \pi_{t2}$. The other six parameters are calibrated simultaneously with transient simulations by fitting the respiration flux simulated by our emulator to the actual complex model's flux (Supplementary Figures 9 and 10; fifth row). To do so, we use only equation (7), driven by the complex model's thawing carbon fluxes and heterotrophic respiration rates.

Finally, the permafrost carbon emissions (E_{pf}) are deduced as:

$$E_{pf}^i = -\frac{dC_{t1}^i}{dt} - \frac{dC_{t2}^i}{dt} - \frac{dC_{t3}^i}{dt} - \frac{dC_{froz}^i}{dt} \quad (8)$$

The overall performance of the emulator is shown in Supplementary Figures 9 and 10 (sixth row), where the emulator is driven only by the emulated model's global temperature change (the only driver of our permafrost module). Overall, the performance of the emulator is very satisfying, with a normalized root-mean square error (nRMSE) for global cumulative permafrost carbon emissions of 2.8%, 5.3%, 5.7% and 7.1%, for JULES-DeepResp, JULES-SuppressResp, JSBACH and ORCHIDEE-MICT, respectively.

Effect of methane emissions

A fraction of 2.3% (ref.¹⁴) of permafrost carbon emission is assumed to be CH₄. This value is assumed to remain constant throughout the simulations, since the future response of this fraction to environmental changes (e.g. climate or CO₂) is unclear³³. In OSCAR, the atmospheric evolution of these CH₄ molecules is tracked in a separate manner, so that, when the permafrost-induced CH₄ is oxidized in the atmosphere, we add the newly formed CO₂ to the atmospheric CO₂ pool. Therefore, the long-term addition of CO₂ to the atmosphere caused directly by permafrost thaw does not depend on the CH₄ fraction. The transient warming and ensuing feedbacks in the system, however, are a function of this fraction.

To investigate this effect, two additional series of simulations are performed: one without and one with doubled methane emission (i.e. fractions of 0% and 4.6%, respectively). The methane effect shown in Figure 4 is equal to the difference between the budgets obtained in the main simulations with 2.3% of methane and those obtained in the simulations with 0%. We also find that the difference between the 4.6% and 2.3% simulations is approximately the same as that between 2.3% and 0% (not shown), which suggests the absolute contribution of methane is roughly linear in this domain.

Exceedance budgets protocol

To obtain the exceedance budgets, we run our six scenarios with the permafrost module turned off and with its four alternative configurations. This is a total of $6 \times 5 = 30$ simulations. By definition, for each of these simulations, the exceedance budget is the maximum cumulative amount of anthropogenic CO₂ that is emitted up to the time when the given temperature target is exceeded²². So the exceedance budgets are calculated as:

$$B_{exc} = \max_{\tau} \int_{t_0}^{\tau} E_{FF}(t) + E_{LUC}(t) dt \quad (9)$$

for $T(\tau) \leq T_{target}$ and where B_{exc} is the exceedance budget, E_{FF} is the yearly fossil-fuel CO₂ emission, E_{LUC} is the yearly CO₂ emission from land use change, t_0 the year the simulation starts, T the simulated temperature change, and T_{target} the target temperature change.

Fossil-fuel CO₂ emission pathways

For the avoidance budgets, we require a set of varied CO₂ emission pathways that cover a wide range of possible futures. We create these emission pathways as the sum of one positive emission pathway and one negative: $E_{FF} = E_{FF+} + E_{FF-}$.

The pathway of positive emission is defined using a parameterized analytical formula of the peak-and-decline form on a semi-infinite interval⁵⁹:

$$E_{FF+} = \begin{cases} E_{FF+}(t), & \text{if } t \leq t_1 \\ E_{FF+}(t_1) \exp(r(t - t_1)), & \text{if } t_1 < t \leq t_m \\ F_m(1 + (r + m)(t - t_m)) \exp(-m(t - t_m)), & \text{if } t > t_m \end{cases} \quad (10)$$

where $F_m = E_{FF+}(t_1) \exp(r(t_1 - t_m))$. We also define the total cumulative positive emission (Q_+) of this pathway:

$$Q_+ = \int_{t_0}^{\infty} E_{FF+}(t) dt = Q_{t_1} + \int_{t_1}^{\infty} E_{FF+}(t) dt \quad (11)$$

Here, t_0 is the starting year of the simulation, t_1 the last year of the historical data, t_m the time at which mitigation begins, r the historical growth rate of fossil CO₂ emissions, and m the mitigation rate. The value of r is taken as the mean of the growth rate over the last ten years of the historical period ($r = 0.022623 \text{ yr}^{-1}$). The mitigation rate m is deduced from the other parameters:

$$m = \frac{F_m}{A_r} \left(1 + \sqrt{1 + \frac{A_r}{rF_m}} \right) \quad (12)$$

with $A_r = Q_+ - Q_{t_1} - \frac{F_m}{r} (1 - \exp(r(t_1 - t_m)))$. Each positive emission pathway is uniquely defined by the tuple (t_1, t_m, Q_+) .

In a similar manner, the negative emission pathways are defined following a logit-normal law on a finite interval:

$$E_{FF-} = \frac{Q_-}{x(1-x)} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\log(\frac{x}{1-x}) - \mu)^2}{2\sigma^2}\right) \quad (13)$$

with:

$$x = \frac{t - (t_m + t_{lag})}{t_f - (t_m + t_{lag})} \quad (14)$$

where t_f is the last year of the simulation, μ and σ two shape parameters, t_{lag} the time between mitigation of positive emission starts and negative emissions start, and Q_- the cumulative amount of negative emissions. Each negative emission pathway is uniquely defined by the tuple $(t_{lag}, \mu, \sigma, Q_-)$.

Using the above equations, we create 520 fossil-fuel CO₂ emission pathways by combining different values for the positive emission tuple (t_1, t_m, Q_+) and the negative emission one $(t_{lag}, \mu, \sigma, Q_-)$. A full list of these 520 combinations of parameters is provided in Supplementary Table 5. The obtained emission pathways are also represented in Supplementary Figure 4.

Avoidance budgets protocol

To calculate the avoidance budgets, we run simulations with the 520 fossil-fuel CO₂ emission pathways combined with the six scenarios we already have for all other drivers of the model (i.e. non-CO₂ forcings and land-use drivers), with the permafrost module turned off and with its four alternative configurations. This leads to a total of $520 \times 6 \times 5 = 15,600$ simulations. We note that our approach of combining two independent sets of scenarios likely lead to an overestimation of the scenario-related uncertainty, since we implicitly combine inconsistent sources of CO₂ and non-CO₂ emissions⁴⁶. It allows, however, for a systematic analysis of the effect of non-CO₂ forcing (using e.g. Supplementary Table 1).

Then, for each of these simulations (superscript i), we calculate the maximum temperature of the simulation:

$$T_{max}^i = \max_{\tau < t_f} T^i(\tau) \quad (15)$$

and its maximum cumulative CO₂ emissions:

$$B_{max}^i = \max_{\tau < t_f} \int_{t_0}^{\tau} E_{FF}^i(t) + E_{LUC}^i(t) dt \quad (16)$$

If any of these two maxima occurs at the last time step of the simulation (t_f), the simulation is discarded. With this approach, we are certain that an emission budget of B_{max} ensures that global temperature do not go above T_{max} , given the non-CO₂ and land-use forcings of the i th scenario.

However, we have no control over the individual values of T_{max} . Therefore, to deduce the avoidance budgets (B_{avo}) for an exact temperature target, we interpolate linearly in the (B_{max}^i, T_{max}^i) phase space, within the T_{max} value interval of $\pm 0.2^\circ\text{C}$ around T_{target} . We acknowledge this is not exactly the approach followed by ref⁴⁶. However, our approach does respect the philosophy of the ‘‘avoidance’’ budget in ensuring that the temperature target is indeed avoided. Obviously, for a given non-CO₂ and land-use scenario, any budget lower than the deduced B_{avo} also implies avoiding the temperature target.

Net overshoot budgets protocol

Net overshoot budgets (B_{net}) are the combination of two budgets: an emission budget to reach peak temperature (B_{peak}) and a capture budget consisting of the cumulative amount of negative emission required to go back to the targeted temperature ($B_{cap} < 0$): $B_{net} = B_{peak} + B_{cap}$. Therefore, net overshoot budgets are defined for a given temperature target and a given level of overshoot (T_{over}), with peak temperature then being given by: $T_{peak} = T_{target} + T_{over}$.

To calculate B_{peak} and B_{cap} , we use the same ensemble of scenarios as for the avoidance budgets. In each case, we take only the subset of scenarios whose maximum temperature is $\pm 0.2^\circ\text{C}$ of the chosen T_{peak} and then declines by at least T_{over} . For each of these scenarios (superscript j), we calculate T_{max}^j and B_{max}^j exactly as we do for the avoidance budgets in equations (15) and (16). We also calculate B_{neg}^j :

$$B_{neg}^j = \min_{\tau} \int_{t_1}^{\tau} (E_{FF}^j(t) + E_{LUC}^j(t)) [E_{FF}^j(t) + E_{LUC}^j(t) \leq 0] dt \quad (17)$$

for $T^j(\tau) \geq T_{max}^j - T_{over}$ and using Iverson brackets in the notation. (They take a value of 1 iff the logical test in the brackets is true, and 0 otherwise.)

Then, just as with the avoidance budgets, we linearly interpolate B_{peak} and B_{cap} in the (B_{max}^j, T_{max}^j) and $(B_{neg}^j, T_{max}^j - T_{over})$ phase spaces, respectively. The net overshoot budget B_{net} is deduced by summation of B_{peak} and B_{cap} . We note again that this protocol, being somewhat similar to the exceedance protocol in its formulation, ignores everything that may occur after the temperature goes back below the targeted value. It therefore provides a lower-bound estimate of future capture requirements.

Extra data processing

To be consistent with IPCC (ref.⁶), we adjust our budgets for a preindustrial year of 1870. To do so, before actually calculating any budget, global temperatures (T) are offset by a value equal to the average over 1861–1880, and cumulative CO₂ emissions (B) are reduced by the cumulative amount of CO₂ emitted over 1765–1870. Budgets are rounded to the nearest 10 Gt CO₂ in the tables and main text. We also discard estimates of B_{avo} and B_{peak} for which the coefficient of determination (R^2) of the linear fit is less than 0.50.

Remaining budgets calculation

Remaining budgets (ΔB) are calculated as $\Delta B = B - B_{hist}$, where B can be B_{exc} , B_{avo} or B_{net} , and B_{hist} is the historical cumulative CO₂ emission from anthropogenic activities (fossil-fuel burning, industry- and land-related). We take $B_{hist} = 2240$ Gt CO₂ (ref.⁴⁴). In Figure 2b, we show the relative reduction in remaining budgets caused by permafrost carbon release, that is: $\Delta B_1 / \Delta B_0 - 1$, where the subscript “1” is for a case with permafrost carbon processes, and “0” one without. In Figure 3, we show reductions in budgets relative to those in the exceedance case: $\Delta B / \Delta B_{exc}$.

Permafrost in JSBACH

The earlier CMIP5 version of the Max Planck Institute Earth System Model land surface scheme JSBACH (ref.^{60,61}) is extended with a multilayer hydrology scheme⁶², a representation of permafrost physical processes⁶³, as well as the improved soil carbon model YASSO (ref.⁶⁴). For permafrost carbon stocks, we represent carbon cycling in the active layer by the YASSO model, while we prescribe frozen carbon stocks below the active layer from the Northern Circumpolar Soil Carbon Database (NCSCD) version 2 (ref.⁶⁵). When the active layer thickness changes, we transfer carbon from the prescribed frozen carbon stocks into the active YASSO carbon pools.

Data availability

RCP scenarios are available at: <http://www.pik-potsdam.de/~mmalte/rcps/>. The data that support the findings of this study are available from the corresponding author upon request.

Code availability

The source code of OSCAR is available at: <https://github.com/tgasser/OSCAR>. The code used to generate all the results of this study is available from the corresponding author upon request.

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