communications earth & environment

A Nature Portfolio journal

Article

Article in Press

https://doi.org/10.1038/s43247-026-04111-9

Emulating absent land processes reduces carbon budgets in CMIP6 models

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The Transient Climate Response to cumulative Emissions (TCRE) is the cornerstone of estimates of carbon emissions budgets to future warming targets, characterising the near-linear relationship between the increase in global mean temperature and cumulative emissions of CO_2. TCRE is derived from highly sophisticated Earth System Models (ESMs) - some, however, lack important processes known to have a large impact on TCRE. Here, we use multiple configurations of UKESM, a full-complexity ESM, to estimate how TCRE of 11 ESMs that participated in Coupled Model Intercomparison Project 6 would change if each included six terrestrial carbon cycle related processes present in UKESM, such as nitrogen limitation of photosynthesis and fire-vegetation interactions. We find that accounting for processes not included in the models increases their TCRE by an average of 21.4% implying a reduction of 16.0% ± 0.8% in the carbon budget for the transition from 1.5 °C to 2 °C.

The Transient Climate Response to cumulative Emissions (TCRE) is a metric characterising the near-linear relationship between the change in global mean temperature and cumulative CO_2 emissions, which first appeared in the literature in 2009[1–3]. The magnitude of the TCRE is influenced by a broad range of physical, chemical, and biological Earth system processes that combine to facilitate the absorption of anthropogenic carbon dioxide from the atmosphere, buffering the planet from more severe climate change. This near-linear relationship means that, to first order, climate change is dependent on the total amount of CO_2 emitted, with the emission rate being of secondary importance. Effectively, the TCRE tells us how much warming to expect per unit of emitted CO_2; the higher the TCRE, the more warming per tonne of anthropogenic CO_2 released to the atmosphere, so the greater the need to limit future emissions.

Hence, the TCRE forms the foundation of estimates of remaining carbon budgets to future warming levels: estimates of TCRE from Earth System Model (ESM) simulations are combined with inferences from observed historical warming and emissions rates to inform climate policy on necessary future emissions caps[4–6]. The ESMs from which TCRE is diagnosed are complex models that simulate the evolving state of the atmosphere, oceans and the land surface from the exchanges of heat, moisture and carbon between them. ESMs exhibit significant diversity in architecture and complexity – in the components of the Earth system they include, in the couplings between them and the specific processes represented, as well as in their spatial and temporal resolution. As in the real world, the TCRE is an emergent property of an ESM, dependent on the sensitivity of the model's climate to CO_2 as well as its carbon cycle response to changing CO_2 concentration, each of which is shaped by the many processes represented within the model.

Uncertainty in the land carbon response to both climate and CO_2 dominated that of the oceans in ESMs that participated in the 5th and 6th phases of the Coupled Model Intercomparison Project (CMIP5[7] and CMIP6[8,9]) respectively. This is due to the greater diversity in the representation of land carbon cycle processes within ESMs compared to the ocean carbon cycle[9]. Ocean-atmosphere carbon exchange is driven primarily by well-understood CO_2 dissolution processes in seawater, leading to a comparatively narrow spread in global ocean carbon uptake amongst ESMs. Land carbon uptake is shaped by the many different subcomponents, processes and parametrisations which make up the land surface component of the ESM. These include the diversity of vegetation types represented, formulation of photosynthesis and plant respiration, nutrient limitation, soil decomposition rates, dynamic or fixed vegetation distribution, anthropogenic land use change processes, fire-vegetation interactions, and carbon loss from permafrost thaw and drying wetlands.

To elucidate the influence of individual processes on TCRE, we performed an extensive set of experiments[10] with eight different configurations of the UK's full-complexity Earth System Model, UKESM1.1. This 'process ensemble' consists of a control configuration of the model and six experimental configurations that differ from the control by the inclusion or exclusion of one process, while the final configuration includes all six processes. Due to the diversity in terrestrial carbon cycle behaviour amongst ESMs, we focused primarily on vegetation and soil processes. These consist of a) nitrogen limitation of plant productivity; b) fire-vegetation

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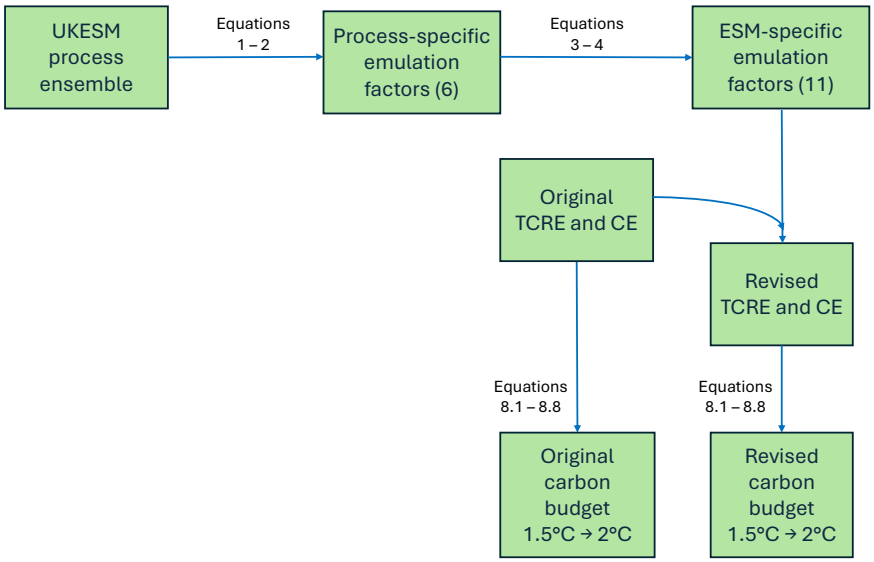


Fig. 1 | Schematic of the emulation framework. Equations 1 and 2 are applied to the TCRE and cumulative emissions to 2xCO_2 values diagnosed from the UKESM process-ensemble, generating six process-specific emulation factors. The process-specific emulation factors are combined in Eqs. 3 and 4 as a function of the processes absent from each model, generating eleven ESM-specific emulation factors. These are used to generate the revised TCRE and CE_{2xCO2} values. Equations 8.1 to 8.8 calculate the carbon budget from 1.5 °C to 2 °C from the original and revised TCRE values. The original TCRE and CE values are from Arora et al (2020)[9].

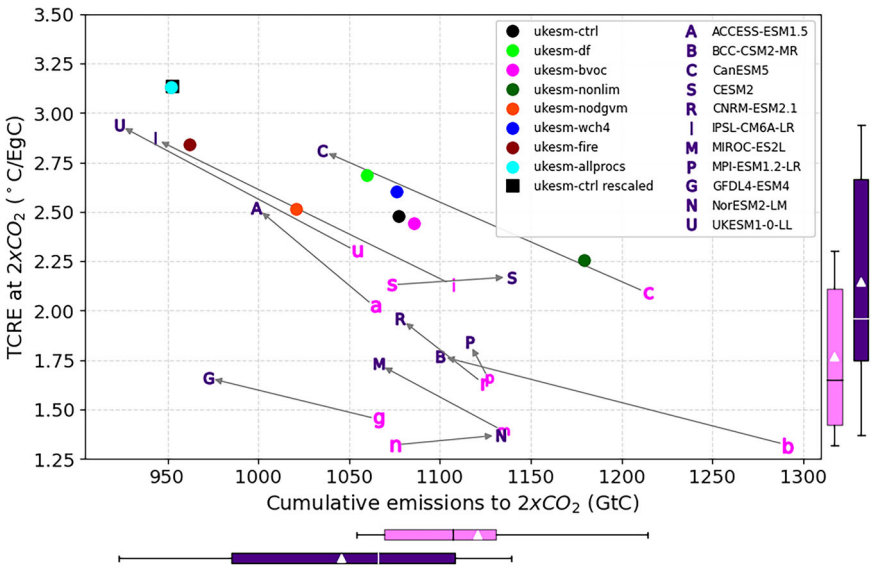


Fig. 2 | TCRE (Transient Climate Response to cumulative CO_2 Emissions) at 2xCO_2 vs cumulative emissions to 2xCO_2 for the UKESM process ensemble (coloured circles) and 11 CMIP6 ESMs (letters). Lowercase (magenta) letters are the original CMIP6 ESM values; uppercase (purple) letters are the values generated by rescaling the CMIP6 ESMs' TCRE using Eqs. 3 and 4 (Methods) to account for the processes absent from each ESM. Connecting arrows join the two, indicating the direction of travel after rescaling. Box-and-whisker plots show the minimum and maximum values (whiskers) of the CMIP6 ESMs' TCRE, with the median and upper and lower quartile values indicated by the box, and the mean represented by the white triangle: lilac and purple boxes represent the original and rescaled values, respectively. The black square represents the *ukesm-ctrl* configuration rescaled to account for the four processes absent from it, with the cyan circle representing *ukesm-allprocs*. Other coloured circles represent the six individual process configurations of UKESM.

interactions; c) spatially varying vegetation distribution; d) emissions of biogenic volatile organic compounds (BVOCs) affecting atmospheric composition; e) coupling of methane emissions from wetlands to atmospheric methane concentration; and f) diffuse radiation effects on photosynthesis.

This study is the third examination of the role of these processes in the Earth system to come from the UKESM process ensemble. In Liddicoat et al. (2026a)[10] we show how the processes individually and collectively impact the carbon-concentration and carbon-climate feedback parameters (β and γ respectively), used by the carbon cycle community for more than two decades to characterise carbon cycle behaviour within ESMs[11,12]. Liddicoat et al. (2026b)[13] examine the mechanisms underlying the influence of each process on TCRE, resolving it into contributions from the process' perturbation to the carbon cycle response and to the climate response.

Here we present a framework, summarised in Fig. 1, in which we derive emulation factors from the UKESM process ensemble that quantify the influence of each process on the TCRE and cumulative emissions. We then apply those emulation factors to 11 CMIP6 ESMs to estimate how their TCRE and cumulative emissions might change if each ESM included all six processes. We find that selectively emulating the processes absent from the models increases their TCRE by an average of 21.4%. We go on to estimate how the 11 ESMs' carbon emissions budget for the transition from global warming levels 1.5 °C–2 °C above pre-industrial might change if all six processes were included in each ESM: the 21.4% increase in TCRE equates to a reduction of 16.0% ± 0.8% in the carbon budget for this transition. We end with a discussion on the potential implications for the TCRE and remaining carbon budgets determined from CMIP7 ESMs, in which processes like nitrogen, interactive wetland methane emissions and fire will likely be represented more widely than they were in CMIP6.

Results

The TCRE plotted against cumulative emissions to 2xCO_2 for the UKESM process ensemble (circles) is shown in Fig. 2, along with the CMIP6 ESMs, before and after emulating their absent processes (letters). The TCRE increases for every ESM; the rise in mean from 1.77 to 2.15 °C/EgC is a robust, statistically significant ($p < 0.001$, paired *t*test) increase of 21.4% ± 11.4% (Supplementary Table 2).

Conversely, mean cumulative emissions to 2xCO_2 decrease after rescaling, from 1121 to 1046 GtC (Supplementary Table 2), a reduction of 6.7% ± 7.3%, which is not statistically significant: CE_{2xCO2} reduces in 9 of the

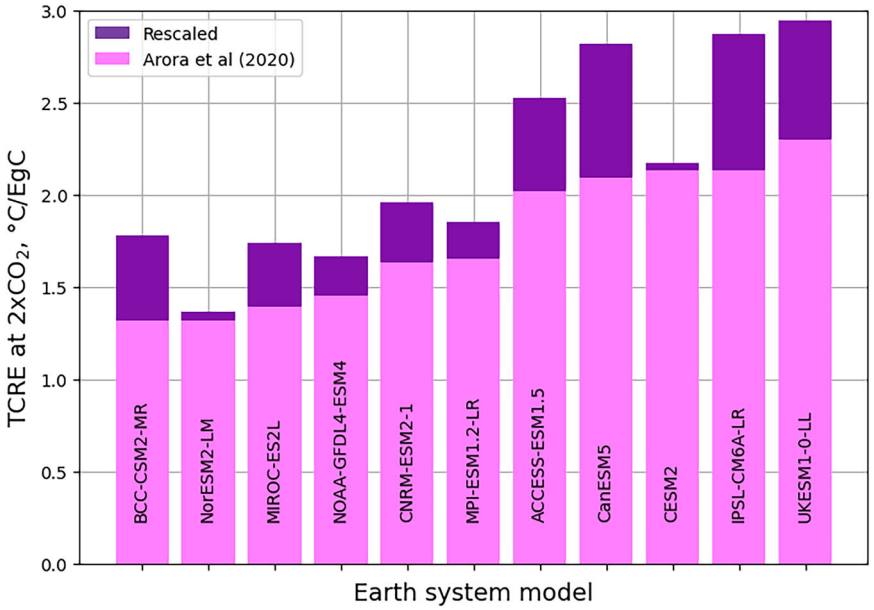


Fig. 3 | Bar chart showing the change in TCRE of 11 CMIP6 ESMs before and after emulating absent processes. Lower (lilac) bars show the original TCRE values from Arora et al (2020)[9]; upper (purple) bars show the increase in TCRE resulting from the application of Eqs. 3 and 4 to emulate the processes absent from each ESM. ESMs are ordered by original TCRE, from lowest to highest.

11 ESMs, but increases in CESM2 and NorESM2-LM. These two ESMs share a common land surface model[9]: both already include fire and nitrogen limitation, which suppress land carbon uptake, but have fixed vegetation distribution. When applying their emulation factors, therefore, the greatest influence comes from dynamic vegetation, which enhances land carbon uptake, thereby lowering the airborne fraction of emitted carbon and increasing compatible emissions. Both models exhibit an increase in TCRE primarily due to emulation of the climate impacts of wetland methane emissions[13].

Rescaling to account for absent processes in the CMIP6 ESMs—increasing commonality of process representation—might be expected to reduce the spread in TCRE, but this is not the case. Some models lacked all four processes which increase the TCRE, so applying the emulation factors increased their TCRE considerably, while other ESMs lacked fewer processes and increased to a much lesser extent (Fig. 3).

The UKESM control configuration, *ukesm-ctrl*, excludes four of the six processes. Applying the emulation factors for those four processes to *ukesm-ctrl*'s TCRE and CE_{2xCO2} transforms the black circle in Fig. 2 up to the black square at (952 GtC, 3.14 °C/EgC): this coincides almost exactly with the cyan circle at (952 GtC, 3.13 °C/EgC) representing the configuration which does indeed contain all six processes, *ukesm-allprocs*. The rescaled *ukesm-ctrl* values represent a deviation of 0.3% in TCRE, and 0.0% in CE_{2xCO2} from those of *ukesm-allprocs*.

Carbon budget sensitivity to processes

We now investigate how the process-sensitivity of TCRE influences carbon budgets calculated from it. Starting with a simple inverse relationship between TCRE and carbon budgets (Eq. 8.1), adding the adjustment terms in various combinations (Eqs. 8.2 – 8.8), we find that when using the rescaled TCRE to account for processes absent from the CMIP6 ESMs, the carbon budget from 1.5 °C to 2.0 °C reduces by a similar proportion in all eight methods of calculation, ranging from 15.0% to 17.0%, with a mean and standard deviation of 16.0% ± 0.8% (Supplementary Table 3).

The relationship between $CB_{1.5_2.0}$ and TCRE represented by Eqs. 8.1 to 8.8 is shown for the CMIP6 cohort in Fig. 4. Panels (a) to (h) show $CB_{1.5_2.0}$ calculated from the original (lilac letters) and rescaled TCRE (purple letters) on the y-axis, against the respective TCRE values (x-axis) with an arrow connecting the pair of data points corresponding to each ESM. The inverse nature of the relationship between the two, which forms the foundation of all eight equations ($CB_{1.5_2.0} \propto 1/\text{TCRE}$) is evident. Inter-model spread is greater when the equation used to calculate $CB_{1.5_2.0}$ includes the model-specific T_{ZEC} term, the same *ESF* and T_{nonCO2} values being applied to all ESMs.

Supplementary Fig. 1 illustrates the insensitivity of the change in multi-model mean $CB_{1.5_2.0}$ to the adjustment terms—T_{ZEC}, T_{nonCO2} and *ESF*—included in its calculation, with the lilac bars illustrating the 15.0% to 17.0% reduction across Eqs. 8.1 to 8.8. Incorporating any combination of T_{nonCO2}, T_{ZEC} and *ESF* into the calculation beyond the simple inverse relationship (Eq. 8.1) has negligible impact on the extent to which the carbon budget reduces for the 21.4% increase in TCRE. Indeed, $CB_{1.5_2.0}$ resulting from the simplest formulation where no adjustment terms are accounted for (Eq. 8.1), and that from the most complex which includes all three (Eq. 8.8) are almost indistinguishable, providing the two central estimates of the spread in $CB_{1.5_2.0}$ in Supplementary Fig. 1.

Discussion

We have extended the experimental framework of Liddicoat et al. (2026b)[13] in which we isolated the influence on the Transient Climate Response to cumulative CO_2 Emissions of six Earth system processes within UKESM and examined underlying mechanisms. In the present study, we emulate the influence of the processes on TCRE and cumulative emissions of 11 CMIP6 ESMs to estimate how they might change if each model accounted for all six processes. We find that TCRE increases in every model, with a robust rise of 21.4% ± 11.4% ($p < 0.001$) in the multi-model mean. The change in cumulative emissions to $2xCO_2$ is less certain: while the multi-model mean reduced by 6.7%, emulating dynamic vegetation in two ESMs—which already included the three processes that suppress land carbon uptake—led to an increase in their CE_{2xCO2}, inflating uncertainty across the ensemble such that the sign of the change in mean is uncertain (−6.7% ± 7.3%).

A greater proportion of the CMIP7 ESMs will likely include nitrogen limitation (Supplementary Note), fire[22,23] and interactive wetland methane emissions[24,25], three of the four processes which have the greatest impact on TCRE within UKESM. Our results therefore help to bridge the gap between the CMIP6 ESMs and their CMIP7 counterparts, by indicating the likely 'direction of travel' of TCRE well before completion of CMIP7, and in advance of the second Global Stocktake in 2028[26]. Since four of the six processes raised TCRE in UKESM, it tended to increase to a greater extent in the ESMs that represent fewer of the processes. Emulating the two to three processes absent from NorESM2-LM and CESM2 increased their TCRE by 2–4%, while the three models that lack all six processes saw an increase of 34.8%.

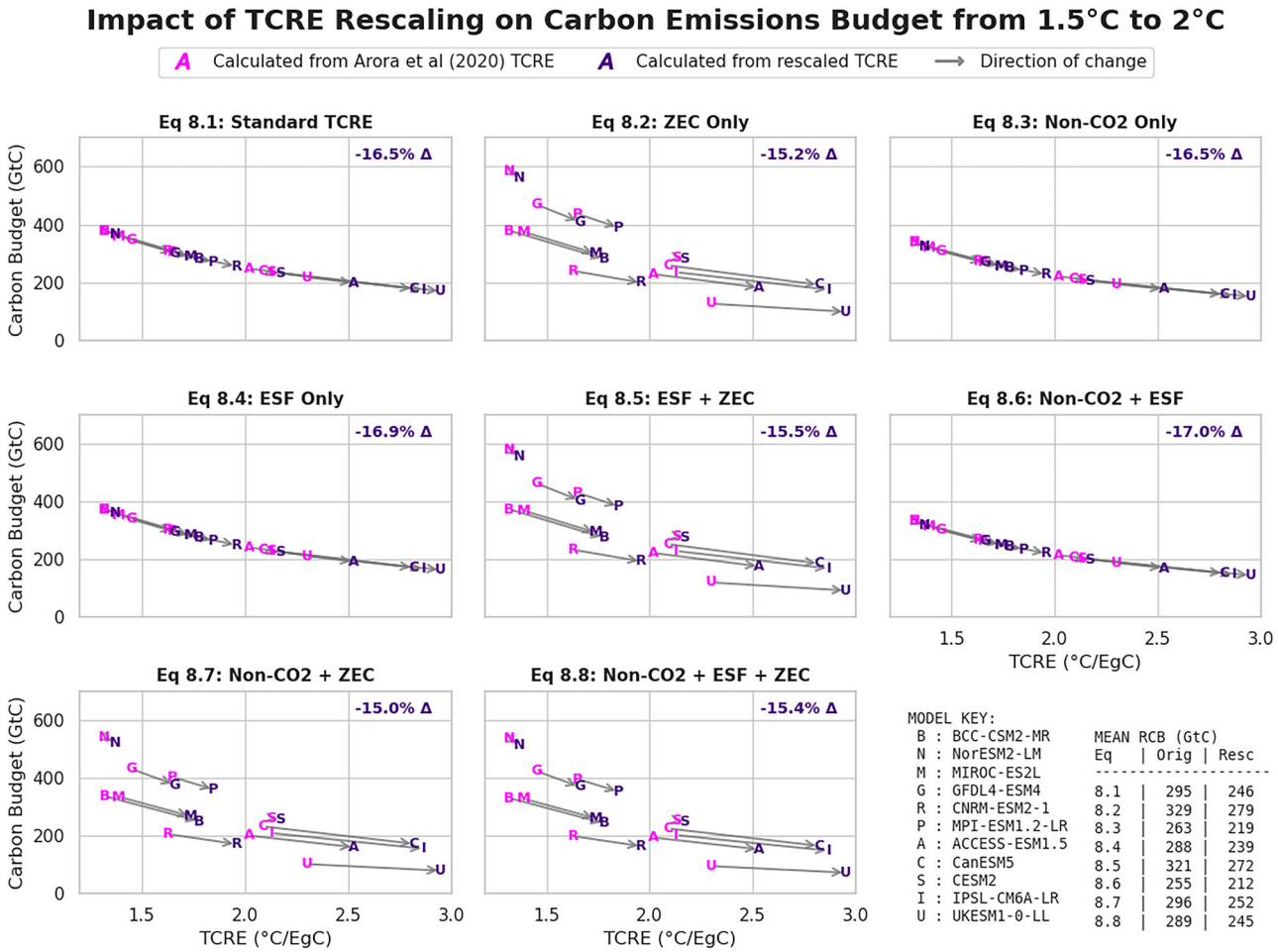


Fig. 4 | Carbon budget from 1.5 °C to 2 °C against TCRE for each CMIP6 Earth System Model. On the y-axis is the carbon emissions budget for the transition from 1.5 °C to 2 °C calculated from the original[9] (magenta letters) and rescaled (purple letters) TCREs (x-axis). Letters indicate the ESM according to the key (lower right panel), straight lines connect the original and rescaled data points. Panels a) to h) use Eqs. 8.1 to 8.8 to calculate the carbon emissions budget, using the terms indicated by the title: the panels which use the ESM-specific ZEC from MacDougall et al (2020)[17] exhibit greater variability than those for which ZEC is set to zero. Inset percentages show the change in multi-model mean carbon budget after rescaling the TCRE. The table lower right shows the original and rescaled carbon emissions budget from 1.5 °C to 2 °C in GtC, calculated by Eqs. 8.1 to 8.8 as indicated, averaged across the 11 CMIP6 ESMs.

Our methodology relies on the differences in behaviour of the experimental configurations relative to *ukesm-ctrl*, analysed in detail by Liddicoat et al (2026a)[10]: from these relationships, we derived multiplicative factors rather than additive correction terms to apply the influence of each process to other ESMs. Since UKESM has the highest TCRE of the 11 CMIP6 ESMs, a correction term derived from UKESM would be disproportionately large when applied to an ESM with a smaller baseline TCRE. Emulating the influence of an absent process through a multiplying factor, however, applies a correction proportionate to the magnitude of each model's TCRE, consistent with its own internal climate and carbon cycle sensitivity. This approach ensures that the framework relies on the relative influence of the processes on TCRE, rather than on its magnitude, within UKESM.

The outcome of our emulation framework when applied to another ESM should be considered a first-order estimate, rather than a precise prediction, of how its TCRE and CE would change, were the ESM to be developed to include the process. The precise impact of any new process depends on the structural changes and parametrisations of its implementation and how they alter the model's sensitivity to changing CO_2 and climate. Nevertheless, we can be confident in the overall direction of travel predicted by our emulation framework because our findings are consistent with theoretical prediction of the behaviour of the land carbon sink, and, by extension, cumulative emissions and TCRE. For example, fire is known to have a large impact on land carbon uptake through reduction in above-ground biomass and therefore photosynthetic potential[27–29], so $F_{fire} > 1$ and $G_{fire} < 1$ are expected outcomes. Accounting for nitrogen availability weakens the land carbon sink as CO_2 rises[30], consistent with $G_{nlim} < 1$ and $F_{nlim} > 1$. The dynamic vegetation scheme within UKESM results in realistic simulated vegetation distributions[31], and allows the vegetation to migrate and adapt to changing climatic conditions under rising CO_2 levels. This optimisation of photosynthetic uptake aligns with our results that $G_{dv} > 1$ and $F_{dv} < 1$. Finally, consistent with $F_{wch4} > 1$, wetland methane emissions are expected to rise under future scenarios with increasing CO_2, resulting in additional warming[32].

Our experimental design focuses on isolating the impacts of processes individually. Many further *1pctCO2* simulations pairing the processes in various combinations would be required to quantify the extent to which their collective influence on TCRE deviates from the linear sum of their individual contributions. It is reassuring, however, that TCRE and CE_{2xCO2} of the *ukesm-allprocs* configuration can be predicted so precisely by combination of the individual terms; we are confident, therefore, that interactions between the processes will not alter our conclusions fundamentally.

The framework we have presented can be extended to quantify explicitly, and simply, the impact of thawing permafrost on TCRE and carbon budgets as the relevant processes become fully coupled within ESMs. Similarly for other processes, such as carbon loss from peat reserves,

Table 1 | Summary of the 8 configurations of UKESM

Configuration	Nutrient limitation	Vegetation distribution	Diffuse fraction of Photosynthetically Active Radiation	Methane cycle	Fire-vegetation interactions	BVOCs
ukesm-ctrl	Nitrogen	Dynamic	0.4	Concentration driven	-	Prescribed
ukesm-nodgvm	Nitrogen	Fixed	0.4	Concentration driven	-	Prescribed
ukesm-nonlim	-	Dynamic	0.4	Concentration driven	-	Prescribed
ukesm-df	Nitrogen	Dynamic	Calculated from local conditions	Concentration driven	-	Prescribed
ukesm-bvoc	Nitrogen	Dynamic	0.4	Concentration driven	-	Interactive
ukesm-fire	Nitrogen	Dynamic	0.4	Concentration driven	Included	Prescribed
ukesm-wch4	Nitrogen	Dynamic	0.4	Emissions driven with interactive wetland emissions	-	Prescribed
ukesm-allprocs	Nitrogen	Dynamic	Calculated from local conditions	Emissions driven with interactive wetland emissions	Included	Interactive

phosphorus limitation of plant uptake and thermal acclimation of photosynthetic capacity, which are starting to be incorporated into land surface[33–35] and Earth system models[36].

While the magnitude of the carbon budget from 1.5 °C to 2 °C is sensitive to the choice of TCRE adjustment terms—zero emissions commitment, non-CO_2 forcing and unsimulated Earth system feedbacks—included in its calculation, the extent to which it reduces after the TCRE is rescaled is not, having a very small uncertainty range. Averaged across the eight different carbon budget calculation methods, the 21.4% increase in the CMIP6 multi-model mean TCRE after emulating processes absent from the ESMs led to a reduction in carbon budget of 16.0 ± 0.8%.

Our results make clear the significant impact that differences in process representation within ESMs have on TCRE and carbon budgets calculated from it. This process-based approach complements top-down studies such as the Global Carbon Budget 2025[18] and Cox et al. (2024)[37], which use observations-based evidence to constrain remaining carbon budgets across the CMIP6 ESMs' historical and Shared Socioeconomic Pathway experiments, sampling uncertainty in multiple drivers of climate change (greenhouse gases, aerosols and land use forcing). By contrast, we provide evidence of structural uncertainty arising from the process differences embedded within the models. Furthermore, our results suggest that because many models lack important processes such as nitrogen limitation and fire-vegetation interactions known to limit long-term land carbon storage, such estimates of remaining carbon budgets may be overly optimistic.

Methods

UKESM process ensemble

The UKESM process ensemble is described in detail in Liddicoat et al. (2026a)[10]. We briefly summarise the eight configurations here.

Version 1.1 of the UK Earth System Model, UKESM1.1, provides the foundation of our experimental framework. Our control configuration, *'ukesm-ctrl'*, deviates from the standard UKESM1.1 model[14] only by having non-interactive emissions of BVOCs. Six experimental configurations differ from *ukesm-ctrl* through the enabling or disabling of one process (Table 1). Two of the six processes are included in *ukesm-ctrl*: nitrogen limitation of land carbon uptake, and the ability of the vegetation distribution to adapt dynamically as the climate and CO_2 concentration change. Two experimental configurations therefore disable nitrogen limitation (*'ukesm-nonlim'*) and dynamic vegetation (*'ukesm-nodgvm'*). The other four experimental configurations add a process absent from *ukesm-ctrl*. These include fire-vegetation interactions (*'ukesm-fire'*); influence of methane emissions from wetlands on atmospheric methane concentration[15] (*'ukesm-wch4'*); influence of BVOC emissions on atmospheric composition (*'ukesm-bvoc'*); and impact of spatiotemporal variation of diffuse radiation on photosynthesis (*'ukesm-df'*). A final configuration includes all six processes together (*'ukesm-allprocs'*).

The experimental configurations are copies of *ukesm-ctrl* amended to include or exclude the process under investigation. Each configuration was spun-up independently until the net flux of CO_2 to the atmosphere was approximately zero, to provide a configuration-specific initial state for the experiments described in the next section.

Diagnosing TCRE

TCRE is defined as the change in global mean temperature divided by the total carbon emitted as CO_2, typically evaluated when CO_2 concentration has reached twice the pre-industrial level (hereafter '2xCO_2'), expressed in units of °C/1000 GtC or °C/EgC. In ESMs, the TCRE is usually diagnosed from idealised simulations in which CO_2 increases at 1% yr^{-1} for 140 years, starting from the pre-industrial CO_2 level (*'1pctCO2'*) while all non-CO_2 forcing is fixed at the pre-industrial level. In the *1pctCO2* experiments, CO_2 concentration is prescribed, and the compatible CO_2 emissions—how much anthropogenic CO_2 can be emitted without deviating from the 1% pathway—can be diagnosed from the changes in the three global carbon reservoirs: the atmosphere, the land surface, and the oceans. Since the carbon content of the atmosphere is prescribed, the magnitude of compatible emissions is dependent entirely on the response of the land and ocean carbon sinks to the CO_2 concentration pathway.

In the case of *ukesm-wch4*, the concentration of methane deviates from the pre-industrial level due to the additional coupling of wetland emissions with atmospheric methane[10]. Similarly, the aerosol concentration in *ukesm-fire* and *ukesm-bvoc* exceeds pre-industrial levels due to enhanced release of aerosols or aerosol precursors as CO_2 increases[10]. In each case, the deviation from pre-industrial conditions is a consequence of the additional process representation responding to the standard *1pctCO2* forcing in which only CO_2 varies, rather than a deviation from the *1pctCO2* forcing protocol that facilitates calculation of TCRE.

We calculate the change in global mean temperature at 2xCO_2 (in year 70) as the average of years 60 to 80 (simulated years 1910 to 1930) relative to the first 21 years of the pre-industrial control simulation run in parallel with the *1pctCO2* experiment; dividing this change in global mean temperature by the cumulative emissions to 2xCO_2, normalising to units of °C/1000 GtC, gives the TCRE. An alternative approach would be to diagnose TCRE from CO_2 emissions-driven simulations as the change in global mean temperature after 1000 GtC have been emitted, but as we are applying our emulation factors to the CMIP6 ESMs' TCRE taken from Arora et al (2020)[9], we replicate the CMIP6 protocol by using concentration-driven *1pctCO2* simulations.

Derivation of emulation factors

Performing the standard *1pctCO2* experiment with the UKESM process ensemble allows us to calculate the TCRE for each configuration and thereby quantify the impact of each process on TCRE[13] in isolation. For each process, a multiplicative factor, F_{proc}, emulating the influence on TCRE of adding the

Table 2 | Factors emulating the impact on TCRE (F_{proc}) and on cumulative emissions to 2xCO$_2$ (G_{proc}) of adding each process (*proc*) into UKESM

Process being added (*proc*)	TCRE factor, F_{proc}		CE_{2xCO2} factor, G_{proc}	
Fire-vegetation interactions (*fire*)	F_{fire}	1.146	G_{fire}	0.893
Vegetation is nitrogen limited (*nlim*)	F_{nlim}	1.097	G_{nlim}	0.913
Spatially varying diffuse fraction of PAR (*df*)	F_{df}	1.085	G_{df}	0.984
Interactive CH_4 cycle + wetland emissions (*wch4*)	F_{wch4}	1.051	G_{wch4}	0.999
Vegetation distribution is dynamic (*dv*)	F_{dv}	0.985	G_{dv}	1.055
Interactive BVOC emissions (*bvoc*)	F_{bvoc}	0.986	G_{bvoc}	1.008

PAR is photosynthetically active radiation.

process into UKESM, can be calculated as TCRE of the configuration including the process, divided by TCRE of the configuration excluding it. For example, the greatest change in TCRE, a 14.6% increase from 2.478 °C to 2.839 °C, was caused by the introduction of fire-vegetation interactions[13], hence F_{fire} = 2.839 °C /2.478 °C = 1.146. The factors emulating the impact on TCRE of dynamic vegetation (F_{dv}), nitrogen limitation (F_{nlim}), interactive BVOCs (F_{bvoc}), interactive wetland methane emissions (F_{wch4}) and spatially varying diffuse fraction of photosynthetically active radiation (F_{df}) can be defined in a similar manner, yielding Eq. 1a to 1 f:

$$Fnlim = TCRE_{ctrl}/TCRE_{nonlim} \tag{1a}$$

$$Fdv = TCRE_{ctrl}/TCRE_{nodgvm} \tag{1b}$$

$$Fbvoc = TCRE_{bvoc}/TCRE_{ctrl} \tag{1c}$$

$$Fwch4 = \frac{TCRE_{wch}4}{TCRE_{ctrl}} \tag{1d}$$

$$Fdf = TCRE_{df}/TCRE_{ctrl} \tag{1e}$$

$$Ffire = TCRE_{fire}/TCRE_{ctrl} \tag{1f}$$

where $TCRE_{config}$ is the TCRE of configuration *ukesm-config*: for example $TCRE_{fire}$ refers to *ukesm-fire*. Note that for F_{nlim} and F_{dv}, *ukesm-ctrl* is the configuration containing the process under consideration, which is disabled in the associated experimental configuration, and therefore $TCRE_{ctrl}$ forms the numerator.

Similarly, following the same subscript convention as Eq. 1a to 1 f, the factors, G_{proc}, which emulate the influence of a process on cumulative emissions to 2xCO$_2$ (CE_{2xCO2}) are defined by Eq. 2a to 2 f (here CE_{2xCO2} is abbreviated to CE for clarity):

$$Gnlim = CE_{ctrl}/CE_{nonlim} \tag{2a}$$

$$Gdv = \frac{CE_{ctrl}}{CE_{nodgvm}} \tag{2b}$$

$$Gbvoc = \frac{CE_{bvoc}}{CE_{ctrl}} \tag{2c}$$

$$Gwch4 = CE_{wch}4/CE_{ctrl} \tag{2d}$$

$$Gdf = \frac{CE_{df}}{CE_{ctrl}} \tag{2e}$$

$$Gfire = CE_{fire}/CE_{ctrl} \tag{2f}$$

The values of F_{proc} and G_{proc} for each process are shown in Table 2.

For an ESM lacking an individual process, the influence of that process on TCRE and CE can be estimated by multiplying the ESM's TCRE by the appropriate F_{proc} and its CE by G_{proc}. However, the CMIP6 ESMs all lack at least two of the processes, with all six being absent from three models (Supplementary Table 1). To combine the TCRE (CE) emulation factors for all processes absent from an ESM, we use Eqs. 3 and 4, where Φ_{proc} (Ψ_{proc}) is equal to 1 if an ESM includes the process, or is equal to F_{proc} (G_{proc}) from Table 2, if not:

$$TCRE' = [1 + (\Phi_{nlim} - 1) + (\Phi_{dgvm} - 1) + (\Phi_{fire} - 1) + (\Phi_{wch4} - 1) + (\Phi_{df} - 1) + (\Phi_{bvoc} - 1)]TCRE \tag{3}$$

$$CE' = [1 + (\Psi_{nlim} - 1) + (\Psi_{dgvm} - 1) + (\Psi_{fire} - 1) + (\Psi_{wch4} - 1) + (\Psi_{df} - 1) + (\Psi_{bvoc} - 1)]CE \tag{4}$$

where *TCRE'* and *CE'* are the rescaled *TCRE* and *CE* respectively. For example, in the case of ACCESS-ESM1-5, which includes nitrogen limitation but none of the other five processes, Eqs. 3 and 4 yield Eqs. 5 and 6:

$$TCRE' = [1 + (F_{dgvm} - 1) + (F_{fire} - 1) + (F_{wch4} - 1) + (F_{df} - 1) + (F_{bvoc} - 1)]TCRE \tag{5}$$

$$CE' = [1 + (G_{dgvm} - 1) + (G_{fire} - 1) + (G_{wch4} - 1) + (G_{df} - 1) + (G_{bvoc} - 1)]CE \tag{6}$$

Note that this framework relies on multiplicative emulation factors rather than additive correction terms, which assumes that the impacts of omitted processes are independent and combine linearly. We present our justification for this approach in the Discussion, with reference to the particular case in which we use the framework to emulate the impact on TCRE and CE of the four processes absent from *ukesm-ctrl*.

Carbon budget from 1.5 °C to 2 °C

Having calculated how TCRE changes due to the influence of processes absent from the CMIP6 ESMs, we can take a step further and see how this influence extends to carbon budgets calculated from the TCRE. To first order, a simple inverse relationship connects TCRE and the remaining carbon budget (RCB) from a starting temperature (T_0) to a target temperature (T_{lim}), Eq. 7:

$$RCB = (Tlim - T0)/TCRE \tag{7}$$

However, additional factors which impact future warming and the release of CO_2 to the atmosphere also need to be accounted for. Following Equation (1) of Rogelj et al (2019)[5], Eq. 8 includes three additional terms: T_{ZEC}, the 'Zero Emissions Commitment' (ZEC), which is warming that occurs after CO_2 emissions have reduced to zero; T_{nonCO2}, future temperature change due to non-CO_2 forcing; and *ESF*, future emissions arising from Earth system feedbacks not accounted for in the derivation of TCRE, such as carbon release from permafrost thaw.

$$RCB = (T_{\lim} - T_0 - T_{nonCO2} - T_{ZEC})/TCRE - ESF \tag{8}$$

Rather than calculating the remaining carbon budget to 1.5 °C or 2 °C, we calculate the emissions budget for the transition from 1.5 °C to 2 °C (T_0 = 1.5 °C and T_{lim} = 2.0 °C). This removes uncertainty around the present global warming level, which is rapidly approaching 1.5 °C: the World

Meteorological Organisation states[16] that the three-year average 2023–2025 global mean warming level relative to the 1850−1900 average is 1.48 °C ± 0.13 °C. As we are calculating emissions from one future global warming level, rather than from the present day to another, we use the term 'carbon budget', rather than 'remaining carbon budget'.

For our purposes, treatment of the additional terms included in Eq. 8 is open to interpretation. For example, T_{ZEC} is found to be approximately zero (0.00 ± 0.19 °C) when averaged across 18 Earth system models of intermediate to full complexity[17], so $T_{ZEC} = 0$ could be considered a valid assumption. However, ZEC evaluated after 25, 50 and 90 years (ZEC25, ZEC50 and ZEC90) has been quantified for 9 of the 11 ESMs considered in this study[17], so alternatively these could be used where known, with $T_{ZEC} = 0$ used otherwise. The 50-year ZEC figure, ZEC50, is commonly quoted in the literature, but the 25-year timeframe is more consistent with the transition from 1.5 °C to 2 °C: the Global Carbon Budget 2025 calculates a 290 GtC remaining carbon budget from January 2026 for a 50% chance of limiting warming to 2 °C, which equates to ~25 years at 2025 anthropogenic emission rates[18].

The release of CO_2 to the atmosphere due to Earth system feedbacks not included in the calculation of TCRE is highly uncertain. We use $ESF = 7.1$ GtC, converted from the value of 26 ± 97 $GtCO_2$ provided in Lamboll et al (2023)[19]. Since the same *ESF* value is used for every model, it reduces each ESM's carbon budget by the same absolute amount; how this influences the percentage reduction when using the revised TCRE relative to the original depends on the choice of other terms used in the calculation of the carbon budget. Alternatively, since *ESF* is both small—7.1 GtC is less than the carbon emitted in one year at 2020 s emission rates—and highly uncertain, it could reasonably be omitted. Note that ESF accounts for additional CO_2 emissions due to natural feedbacks omitted from ESMs—primarily permafrost thaw, though wetland methane emissions are sometimes nominally included in such terms as a CO_2 equivalent[5]. In *ukesm-wch4*, interactive wetland methane emissions change TCRE solely via their radiative influence on climate[13], without changing land carbon uptake. The use of F_{wch4} in rescaling the CMIP6 ESMs' TCRE is therefore entirely distinct from the use of ESF to account for emissions of CO_2 from unrepresented processes, ensuring no double-counting occurs.

Warming due to non-CO_2 forcing at the crossing of the 2 °C threshold is not known for the individual ESMs. Estimates of T_{nonCO2} are provided in Lamboll et al (2023)[19] to a range of warming targets, calculated from thousands of simulations performed with climate models FaiR[20] and MagICC[21]: to 1.5 °C and 2.0 °C, T_{nonCO2} is 0.165 °C and 0.22 °C respectively, so for the transition between these temperature levels, we use T_{nonCO2} = 0.22 °C–0.165 °C = 0.055 °C. This has a greater influence on the inter-model spread than *ESF* when included, as it is multiplied by each ESM's TCRE.

Taking the different approaches described for *ESF* and T_{ZEC}, and including/excluding T_{nonCO2} in a similar way for completeness, yields Eqs. 8.1–8.8 to calculate the carbon budget from 1.5 °C to 2.0 °C ($CB^n_{1.5\text{-}2.0}$ for Eq. 8.n): where included, T_{ZEC} denotes ZEC25[17]. This approach allows us to investigate whether the change in TCRE leads to a robust change in carbon budget when the ESMs' revised TCRE values are used in place of the values from Arora et al (2020)[9], or whether the change is influenced strongly by the adjustment terms considered in the carbon budget calculation.

$$CB^1_{1.5-2.0} = 2.0\frac{^\circ C - 1.5(^\circ C)}{TCRE} \tag{8.1}$$

$$CB^2_{1.5-2.0} = 2.0\frac{^\circ C - 1.5(^\circ C - TZEC)}{TCRE} \tag{8.2}$$

$$CB^3_{1.5-2.0} = (2.0\frac{^\circ C - 1.5(^\circ C - TnonCO2)}{TCRE} \tag{8.3}$$

$$CB^4_{1.5-2.0} = (2.0\,^\circ C - 1.5\,^\circ C)/TCRE - ESF \tag{8.4}$$

$$CB^5_{1.5-2.0} = (2.0\,^\circ C - 1.5\,^\circ C - TZEC)/TCRE - ESF \tag{8.5}$$

$$CB^6_{1.5-2.0} = (2.0\,^\circ C - 1.5\,^\circ C - TnonCO2)/TCRE - ESF \tag{8.6}$$

$$CB^7_{1.5-2.0} = (2.0\frac{^\circ C - 1.5(^\circ C - TnonCO2 - TZEC)}{TCRE8.7} \tag{8.7}$$

$$CB^8_{1.5-2.0} = (2.0\,^\circ C - 1.5\,^\circ C - TnonCO2 - TZEC)/TCRE - ESF \tag{8.8}$$

Data availability

All data from which the figures are created are included in the tables in the main manuscript and Supplementary Information.

Received: 23 March 2026; Accepted: 19 September 2026;
Published online: 24 October 2026

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Acknowledgements

S.S and L.M.M. thank UK Research and Innovation (UKRI)'s NERC project Amazon-SOS (NE/X019039/1). We thank three reviewers for their thorough and constructive reviews. For the purpose of open access, the author has applied a 'Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising'.

Author contributions

S.K.L. performed the analysis, with input particularly from C.D.J., A.W. and E.R. S.K.L. wrote the manuscript with contributions from all authors, particularly from L.M.M. and S.S. There are no competing interests.

Funding

SKL, CDJ, ER and AW received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 101003536 (ESM2025 - Earth System Models for the Future), and The Met Office Hadley Centre Climate Programme, funded by UK Department for Science, Innovation and Technology. L.M.M acknowledges funding from the UK Natural Environment Research Council (NERC) TerraFIRMA project (NE/W004895/1).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-026-04111-9.

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Peer review information Communications Earth & Environment thanks all reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Zhongjing Jiang and ChenRui Diao. A peer review file is available.

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