We express our sincere gratitude to your insightful and constructive comments. Please find below our point-by-point replies. All the comments are presented in black text and the corresponding replies are highlighted in blue.

Overall:

This study "aims to fill these gaps using an Earth system model of intermediate complexity to systematically assess the permafrost response and feedback under temperature stabilization or overshoot scenarios achieving various GWLs. " I think it is an interesting paper and recommend publication, but I also think it could make some clearer points, as I discuss below.

Based on that stated aim, I expected to see one or more figures with total permafrost carbon losses plotted as a function of the GWL for both the stabilization and overshoot cases. I.e., is the permafrost carbon loss linear? Are there thresholds or tipping points? Figure 6a shows the areal loss as a function of global warming level, but why are carbon variables not quantified in this way? Does the permafrost carbon feedback strength (in units of Pg C / degree Celsius warming) show a similar nonlinearity as the SPAW shown in f.g 6a with maximum losses per unit warming in the 1.5-2 degree C range? Figure 3b seems to show that the highest sensitivity is in the ~3 degree warming range, but it is difficult to see quantitatively. Likewise it would be interesting to se the radiative forcing as well. So I'd recommend an additional figure with panels along the lines of 6a that allows the reader to trace how the (non-)linearity of each of these permafrost metrics as a function of global warming levels for the stabilization and overshoot cases changes between permafrost area, permafrost carbon, and permafrost radiative forcing.

Thank you for your insightful suggestion. We fully agree that using global warming levels (GWLs) as the horizontal axis to present key permafrost metrics helps reveal their linear or nonlinear behavior. In response, we have added a new figure (Figure 8) to the revised manuscript, which includes three panels showing (a) permafrost area change, (b) permafrost carbon loss, and (c) permafrost radiative forcing, all plotted as a function of GWLs. Colored dashed lines represent stabilization scenarios, colored solid lines represent overshoot scenarios, and the black solid line denotes the SSP5-8.5 scenario.

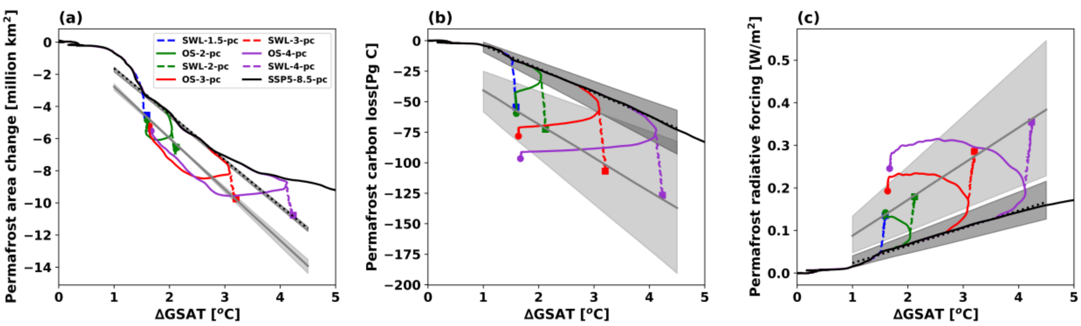


Figure 8. Relationship between global warming levels and three permafrost metrics: (a) permafrost area change, (b) permafrost carbon loss, and (c) permafrost radiative forcing in the overshoot (colored solid lines) and stabilization (colored dashed lines) scenarios at 1.5 °C (blue), 2.0 °C (green), 3.0 °C (red) and 4 °C (purple) GWLs, along with the SSP5-8.5 scenario (black). Square

and circle markers indicate values in the year 2300 for the stabilization and overshoot scenarios, respectively. Grey solid lines show linear fits of permafrost metrics to GWLs in stabilization scenarios by 2300, while black dashed lines show corresponding fits for the SSP5-8.5 scenario. Note that in panel (a), both the stabilization scenarios and the corresponding SSP5-8.5 points included in the linear fit are limited to GWLs between 1.5 °C and 3.0 °C, whereas in panels (b) and (c), the fits include points with GWLs ranging from 1.5 °C to 4.0 °C. For stabilization scenarios, only the results from the year 2300 are used for fitting, while for the SSP5-8.5 scenario, all results within the specified GWL ranges are used for fitting. Shaded regions represent the 5th to 95th percentile ranges across 250 ensemble simulations.

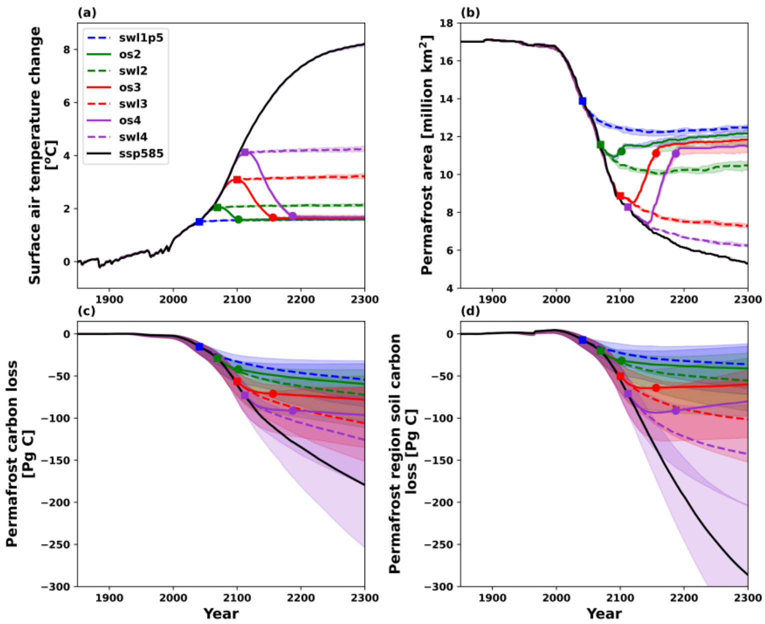
Our results show permafrost area change shows a strongly nonlinear relationship with GWLs greater than 1 °C. However, there is a quasilinear relation between them for the GWLs between 1.5 °C and 3 °C. The decreasing sensitivity of permafrost area to GWLs above 3 °C is evident in both the stabilization scenarios and SSP5-8.5 scenario (Figure 8a). In contrast, permafrost carbon loss and associated radiative forcing exhibit a nearly linear response to increasing GWLs, especially above 1.5 °C, for both stabilization and SSP5-8.5 scenarios (Figures 8b,c). Meanwhile, the sensitivities of permafrost area to global warming (SPAW), permafrost carbon feedback, and associated radiative forcing under stabilization scenarios are all stronger than those under the SSP5-8.5 scenario. Specifically, based on the simulated permafrost area in the year 2300 under stabilization scenarios with GWLs between 1.5 °C and 3 °C, the SPAW is -3.19 [-3.01 to -3.36] million km^2 $°C^{-1}$. In comparison, a linear fit of permafrost area against GWLs over the same temperature range in the SSP5-8.5 scenario yields a SPAW of -2.85 [-2.77 to -2.89] million km^2 $°C^{-1}$。 Similarly, the sensitivity of permafrost carbon feedback, derived from a linear fit based on the total permafrost carbon loss in the 2300 year under stabilization scenarios, is -27.6 [-16.5 to -38.2] PgC $°C^{-1}$. In contrast, the corresponding value under the SSP5-8.5 scenario, estimated from a linear fit over the 1.5 °C to 4.0 °C warming range, is -19.3 [-15.7 to -24.1] PgC $°C^{-1}$. Applying the same approach, the associated radiative forcing per degree of warming is estimated to be 0.08 [0.05 to 0.12] W m^{-2} $°C^{-1}$ for the stabilization scenarios and 0.04 [0.03 to 0.05] W m^{-2} $°C^{-1}$ for the SSP5-8.5. These differences between the stabilization and SSP5-8.5 scenarios are mainly attributable to the differing response time scales represented by the two scenarios: SSP5-8.5 reflects a typical transient response, while the stabilization scenarios maintain stabilized temperatures over extended periods and thus approximate a quasi-equilibrium response of the climate-carbon system. Furthermore, the smaller sensitivity of permafrost radiative forcing under the SSP5-8.5 can be partially attributed to its higher background atmospheric CO_2 concentration compared to the stabilization scenarios. The same amount of CO_2 emissions would produce smaller additional radiative forcing under higher background atmospheric CO_2 concentration, due to the logarithmic relationship between CO_2 concentration and radiative forcing (Etminan et al., 2016). Our results are consistent with the conclusions of Nitzbon et al. (2024), who reported that the accumulated response of Arctic permafrost to climate warming remains approximately quasilinear. Moreover, the permafrost carbon feedback sensitivities derived from both the stabilization and SSP5-8.5 scenarios fall within the ranges reported in existing literature, namely -18 [-3 to -41] PgC $°C^{-1}$ from Nitzbon et al. (2024) and -21 [-4 to -48] PgC $°C^{-1}$ from Canadell et al. (2021).

Under overshoot scenarios, permafrost area responds nearly reversibly and presents an almost closed loop (Figure 8a). In contrast, permafrost carbon loss exhibits an open loop with respect to

GWLs, that is, permafrost carbon loss does not reverse as temperatures decline, indicating irreversible permafrost radiative forcing. Among the three metrics investigated here, only permafrost area exhibits strong reversibility under the overshoot scenarios. This also explains why, in Figure 6a (figure number according to the original manuscript), the permafrost area sensitivity derived from the SSP5-8.5 scenario can be used, when multiplied by additional warming, to reasonably reconstruct permafrost area loss in the stabilization and overshoot cases.

Further, given the possibility of perturbing parameters due to the relatively low cost of running UVic-ESCM, I had expected to see if any of those parameters introduced nonlinearities or substantially changed the magnitude of the results. But I just see median lines. So it is hard to know how important the uncertainty is. I suggest showing the uncertainty via translucent colored plumes in all figures.

We sincerely appreciate your valuable suggestion. We previously attempted to display uncertainty via translucent colored plumes. However, results from different scenarios overlapped significantly (see Figure below), making the visualization overly cluttered and difficult to interpret.



Nevertheless, we fully acknowledge the importance of showing the uncertainty to accurately convey the results. Therefore, we have represented the 5th to 95th percentiles of all ensemble simulations for the year 2300 in all figures to help readers better understand the uncertainty associated with those parameters. For example, the following figures include uncertainties:

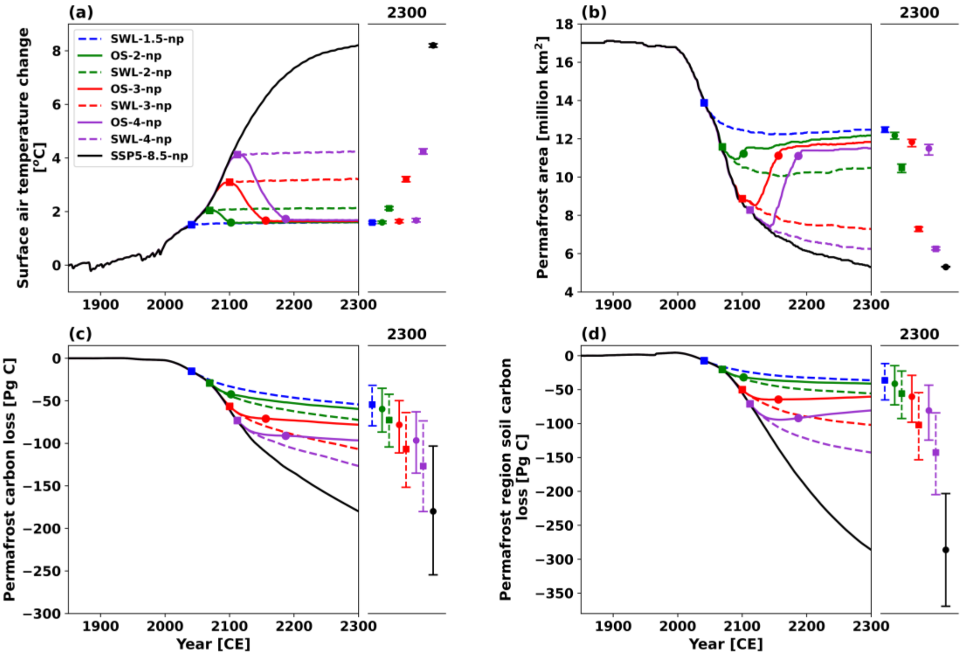


Figure 3. Timeseries of annual mean (a) GSAT changes, (b) permafrost area, (c) permafrost carbon loss and (d) permafrost region soil carbon loss under overshoot (solid lines) and stabilization (dashed lines) scenarios at 1.5 °C (blue), 2.0 °C (green), 3.0 °C (red), and 4 °C (purple) GWLs, as well as the SSP5-8.5 scenario. Square markers indicate the time points when the temperature overshoot reaches its peak or stabilized warming begins, while circle markers indicate when the temperatures return to 1.5 °C in the overshoot scenarios. All changes are relative to the pre-industrial period (1850-1900). Results represent the ensemble median of 250 simulations. Dots on the right panels represent values in the year 2300, with uncertainty ranges estimated as the 5th to 95th percentiles.

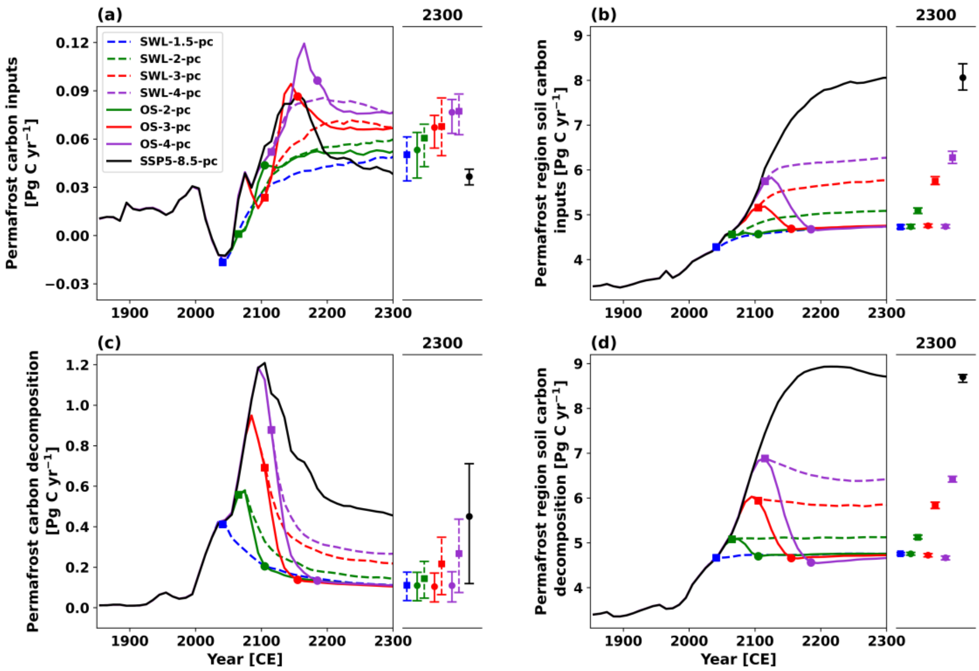


Figure 5. Timeseries of (a) permafrost carbon inputs, (b) permafrost region soil carbon inputs, (c) permafrost carbon decomposition and (d) permafrost region soil carbon decomposition, under the overshoot (solid lines) and stabilization (dashed lines) scenarios at 1.5 °C (blue), 2.0 °C (green), 3.0 °C (red) and 4 °C (purple) GWLs, along with the SSP5-8.5 scenario (black). Square markers indicate the time points when the temperature overshoot reaches its peak or stabilized warming begins, while circle markers indicate when the temperatures return to 1.5 °C in the overshoot scenarios. Results represent the ensemble median of 250 simulations. Dots on the right panels represent values in the year 2300, with uncertainty ranges estimated as the 5th to 95th percentiles.

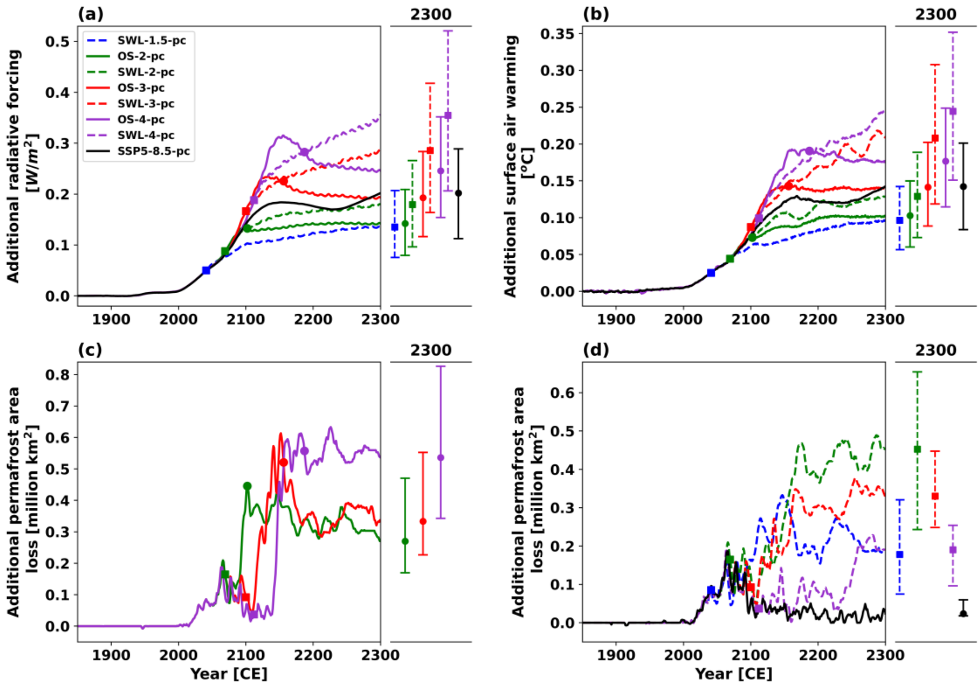


Figure 7. Additional changes in (a) radiative forcing, (b) global mean surface air warming and (c, d) permafrost area due to permafrost carbon-climate feedback in the the overshoot (solid lines) and stabilization (dashed lines) scenarios at 1.5 °C (blue), 2.0 °C (green), 3.0 °C (red) and 4 °C (purple) GWLs, along with the SSP5-8.5 scenario (black). Square markers indicate the time points when the temperature overshoot reaches its peak or stabilized warming begins, while circle markers indicate when the temperatures return to 1.5 °C in the overshoot scenarios. Results represent the ensemble median of 250 simulations. Dots on the right panels represent values in the year 2300, with uncertainty ranges estimated as the 5th to 95th percentiles. In panel (a), the additional radiative forcing is calculated using the simplified expressions (Etminan et al., 2016) based on simulated CO_2 concentrations. In panels (c) and (d), the additional permafrost area loss is smoothed using a 5-year rolling average to eliminate shorter interannual variability.

Comments

line 36: the 1.5 degree budget will be exhausted within the next few years, but not the 2 degree budget. Please clarify.

Thank you for your suggestion. We have revised the sentence for greater clarity:

"If current emission rates persist, the remaining carbon budgets compatible with the 1.5 °C target will be critically tight and likely exhausted within the next few years (Rogelj et al., 2015; Goodwin et al., 2018; Masson-Delmotte et al., 2018; Forster et al., 2023; Smith et al., 2023)."

Paragraph starting line 142: This is great that you were able to perturb these key parameters. But I don't see any uncertainty plumes in any of the figures, only the median values. I think it would be informative to the reader to see the partameter uncertainty plumes plotted on all figures.

Thank you for your suggestion. We have incorporated the 5th to 95th percentiles of all ensemble simulations for the year 2300 in figures to better represent the uncertainty associated with these key perturbed parameters.

fig. 2b: Why doesn't the permafrost area recover all the way under the overshoot scenarios? Are there regional changes to the northern high latitude climate that are responsible for the differing permafrost amounts at a given GWL? If so, what are the drivers of that regional change? It might help to add a panel with the regional temperature difference to see whether it behaves differently from the global mean.

Thank you for your valuable comments. The incomplete recovery of permafrost area under the overshoot scenarios in Fig. 2b (figure number according to the original manuscript) is influenced by multiple factors: First, Figure 2b shows results from simulations with the permafrost carbon module switched on, and the persistent additional warming due to permafrost carbon feedback causes additional permafrost degradation. During stabilization phases of overshoot scenarios, the northern high-latitude permafrost regions experience additional warming compared to the SWL-1.5 scenario, with regional temperature increases of 0.01～0.14 °C by 2300. Second, the thermal inertia of deep soil layers limits the rate of permafrost recovery. Even when global temperatures return to the 1.5 °C target, residual heat accumulated in deeper soil layers during temperature overshoot period continues to inhibit permafrost refreezing, preventing full restoration to its initial state. Third, the greater soil carbon loss under overshoot scenarios has a strong impact on the soil's hydrological and thermal properties (Avis, 2012; Lawrence et al., 2008), which in turn affects the recovery of permafrost area. Moreover, irreversible shifts in vegetation composition of high-latitude terrestrial ecosystems also contribute to the incomplete recovery of permafrost area under overshoot scenarios. For instance, as two dominant vegetation types, needleleaf trees continue to expand and C3 grasses decline, even after global temperatures return to the 1.5 °C level. These irreversible changes may stabilize the carbon, water, and energy cycles over the permafrost region at different equilibria after overshoot through the interactions between physical and biophysical processes (de Vrese and Brovkin, 2021), constraining the ability of permafrost to fully recover under the overshoot scenarios.

Line 321: This paper doesn't really establish anything about the realism of the model, since there are no model-data comparisons, so suggest reword or provide citations to the papers that have shown this.

Thank you for your valuable comment. We acknowledge the need for additional clarification regarding the realism of the UVic ESCM model. To address this, we have incorporated model validation into the first paragraph of Section "3 Results". This addition provides a direct comparison between model simulations and observational data, demonstrating that the UVic ESCM model realistically reproduces historical permafrost area and permafrost carbon stocks. The added content is:

"The UVic ESCM v2.10 reliably simulates historical temperature changes, permafrost area, and the partitioning of anthropogenic carbon emissions among the atmosphere, ocean and land. During the period 2011–2020, the model estimated a GSAT increase of 1.14 [1.13 to 1.15] °C relative to preindustrial levels, which is closely aligned with the observed rise of 1.09 [0.91 to 1.23] °C (Gulev et al., 2021). For the period 1960–1990, the model simulated the northern hemisphere permafrost area at 16.8 [16.7 to 16.9] million km^2, which falls within the reconstructed range of 12.0 to 18.2 million km^2 (Chadburn et al., 2017) and the observation derived extent of 12.21 to 16.98 million km^2 (Zhang et al., 2000). Additionally, the modeled soil carbon stock in the top 3.35 m of permafrost regions for this same period was 1034 [919 to 1151] PgC, with 483 [382 to 587] PgC classified as perennially frozen carbon, accounting for 47% [42% to 51%] of the total permafrost soil carbon stock, in agreement with Hugelius et al. (2014). From 2010 to 2019, the model estimated that anthropogenic carbon emissions were distributed as follows: 5.5 [5.4 to 5.6] PgC yr^{-1} to the atmosphere, 3.0 [2.98 to 3.03] PgC yr^{-1} to the ocean, and 2.5 [2.4 to 2.6] PgC yr^{-1} to terrestrial ecosystems. These estimates are broadly consistent with the global anthropogenic CO_2 budget assessment by the Global Carbon Project (GCP) with figures of 5.1±0.02 PgC yr^{-1} for the atmosphere, 2.5±0.6 PgC yr^{-1} for the ocean, and 3.4±0.9 PgC yr^{-1} for terrestrial ecosystems (Friedlingstein et al., 2020)."

Accordingly, we have revised the statement in Line 321 to: "UVic ESCM has been validated against observational and reconstructed datasets, demonstrating its ability to reproduce historical permafrost area and permafrost carbon stocks."

Data availability: I downloaded some of the data files in Cui et al., 2024, but they aren't clearly described and don't include any further details than what is in the paper (e.g., spatial information). This strikes me as a fairly minimal data archival effort.

We appreciate your comments regarding the data archiving. We have added more detailed descriptions to the uploaded data files, including variable names, units, and associated spatial and temporal dimensions, in order to improve the clarity.

Due to the large volume of spatial model output, we have archived only the key variables necessary to support the main analyses presented in the paper (https://zenodo.org/records/15148252). Although this may not capture all details, we are happy to provide more comprehensive datasets upon request. In addition, a data description file (README.md) has been included alongside the archived model output to facilitate understanding.

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