https://doi.org/10.1038/s41558-023-01909-9

Earth system models must include permafrost carbon processes

Christina Schädel, Brendan M. Rogers, David M. Lawrence, Charles D. Koven, Victor Brovkin, Eleanor J. Burke, Hélène Genet, Deborah N. Huntzinger, Elchin Jafarov, A. David McGuire, William J. Riley & Susan M. Natali

Accurate representation of permafrost carbon emissions is crucial for climate projections, yet current Earth system models inadequately represent permafrost carbon. Sustained funding opportunities are needed from government and private sectors for prioritized model development.

Permafrost carbon emissions are one of the largest uncertainties in future climate projections and therefore need to be accurately represented in Earth system models (ESMs). Quantifying the potential of additional carbon emissions from the permafrost region is of high urgency given that the region is warming up to four times faster than the rest of the globe. Despite steady improvement of land model process representation, permafrost carbon remains either inadequately represented, or not represented at all, in current ESMs. Incorporation of permafrost carbon feedbacks into ESMs is of unique urgency given the exceptional warming in the Arctic and the threat to global climate mitigation goals.

Carbon budget estimates need to include permafrost emissions

Terrestrial feedbacks are critical for understanding future changes in the global coupled climate system. Of these, the permafrost carbon feedback is considered one of the most important biogeochemical feedbacks that can influence the trajectory of future climate. Vast amounts of carbon, roughly double the amount that is currently in the atmosphere[1], are stored in terrestrial permafrost (permanently frozen ground) regions, and exceptional warming in the Arctic is already causing permafrost to thaw and previously frozen organic matter to be released to the atmosphere. Despite advances in understanding of permafrost dynamics and carbon processes over recent decades, substantial uncertainty remains regarding how much carbon will be released, in what form (CO_2 versus CH_4) and at what timescales[1,2].

Given the potentially large amount of future emissions from permafrost degradation (22–524 billion metric tons of CO_2 by 2100 across a wide range of scenarios[3]), estimates of the 'remaining carbon budget' of anthropogenic emissions to constrain warming to 1.5 °C or 2 °C must consider permafrost carbon emissions. The recent IPCC Sixth Assessment Report (AR6) states there is 'high confidence' that permafrost will continue to thaw and will lead to carbon release to the atmosphere. However, the report gave a 'low confidence' rating to the timing, magnitude and ratio of CO_2 versus CH_4 emissions. This low confidence is due to the wide range of empirical and modelled estimates of the permafrost carbon feedback in the literature, coupled with the fact that most global-scale ESMs poorly represent essential permafrost physical and permafrost carbon processes, and in many models, some permafrost processes are entirely missing (Fig. 1). AR6 includes permafrost carbon emissions in its assessment of remaining carbon budgets, but it is based on upscaled field and laboratory studies, not on ESMs. The use of incomplete or inaccurate biospheric emissions estimates poses the danger of overestimating the remaining carbon budget consistent with keeping global warming at or below agreed levels[4].

Meaningful projections of the permafrost carbon feedback can only be made if important processes and features of permafrost ecosystems are accurately represented in models used for climate projections. For example, in AR6, only 2 of 11 ESMs included a representation of permafrost carbon. Both of these models used the same land component (version 5 of the Community Land Model (CLM5)), thereby providing little diversity in model response, and little ability to assess uncertainties or biases in the representation of these processes. Moreover, none of the ESMs included important processes such as abrupt thaw (for example, thermokarst, and other thermo-erosional processes) or interactions between permafrost and vegetation cover change or wildfire, even though these interactions are known to be major drivers of permafrost carbon cycling (Fig. 1). Despite progress in the Coupled Model Intercomparison Project Phase 6 (CMIP6) over CMIP5, which did not include permafrost carbon dynamics at all, confidence in current model estimates remains low[5].

Multiple challenges for model improvement

The permafrost region is large and spatially heterogeneous, and changes are not occurring uniformly. For example, thawing and degradation of near-surface permafrost creates complex landscape patterns of wet and dry ecosystems due to the spatial distribution of ground ice and subsidence patterns that can occur when that ground ice melts. This heterogeneous response has consequences for carbon release as drier conditions favour CO_2 emissions whereas waterlogged, anoxic soils promote emissions of CH_4, which has a higher global warming potential than CO_2.

Model improvement and development require data products derived from observational, experimental and synthesis sources that effectively constrain and benchmark model processes. However, for many model parameters, spatially distributed datasets are either not available (for example, disturbance datasets), are known to be insufficient (for example, ground-ice distribution maps) or large regional gaps exist (for example, in Siberia). In other cases, available datasets are underutilized[6] or not yet integrated into models[7,8], partially due to the challenges of model development outlined in this Comment. Good data products with spatial and temporal coverage are required to make advances towards credible projections of the permafrost

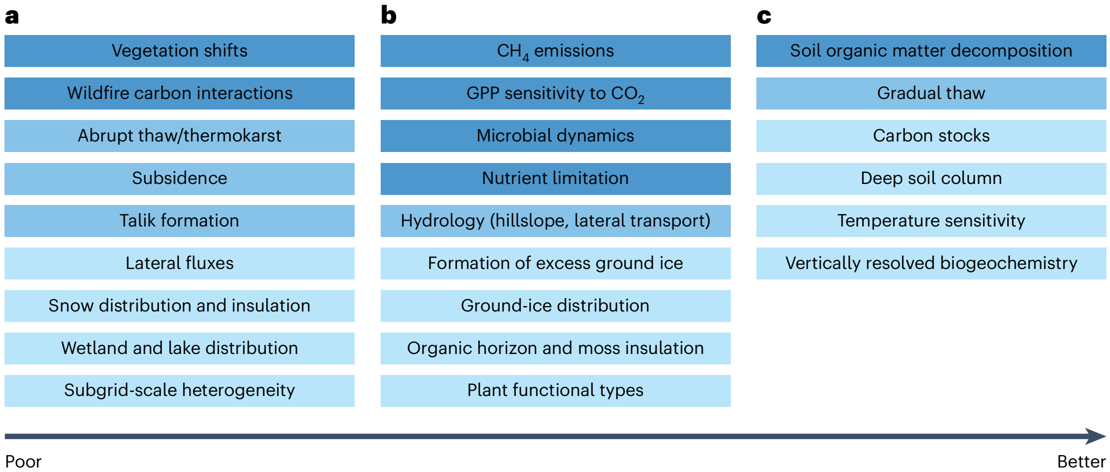

Fig. 1 | Model components and processes relevant to modelling permafrost carbon dynamics. a–**c**, Model components and processes are grouped by how well they are represented: poor (**a**), intermediate (**b**) and better (**c**). Dark blue boxes represent biogeochemical processes, medium blue boxes represent physical processes and light blue boxes represent model components. Processes are on decadal timescales. GPP, gross primary productivity.

carbon–climate feedback, and model development needs to proceed simultaneously with improvement of input datasets.

Another major challenge is rooted in the increasing complexity of the ESMs, and the need for concomitant increases in resources to support continued model improvement. Increased model complexity also provides challenges for model benchmarking and evaluation as it gets harder to trace model performance to specific model choices and process representation.

Consequently, increased model complexity requires larger investments in training new members of the modelling community. Most grant-funded science projects have a duration of three years, which gives little time for early-career researchers to complete meaningful ESM development and research before transitioning to a new project or position. In addition, model development and improvement often consist of many intermediate steps that do not directly address big science questions, and hence are unlikely to attract traditional funding. The grand challenge of improving permafrost processes in ESMs requires highly skilled domain and numerical methods experts with sufficient time to focus on model improvement. Funding agencies should recognize the changing landscape and prioritize these long-term model development needs.

Model development needs

Several important permafrost components and processes (Fig. 1) would provide a stronger basis for prediction of the permafrost carbon–climate feedback if better represented in ESMs.

Physical processes affecting the carbon cycle. Currently, ESMs that consider permafrost thaw treat it as a gradual top-down process where warming air thaws the ground uniformly across the landscape. However, in areas with ice-rich permafrost, the loss of ground support when ground ice melts can result in subsidence, erosion and slumping, which can further accelerate thaw rates and have substantial consequences on local hydrology. Inventory approaches indicate that abrupt thaw processes (that is, thermokarst) could increase carbon emissions from permafrost by up to 40% (ref. 9), thereby effectively doubling the radiative impact of permafrost thaw due to the relatively high fraction of emissions from abrupt thaw processes being CH_4 emissions. This increase in carbon emissions due to abrupt thaw, a process that is entirely missing in current ESMs (Fig. 1), may be high even under relatively low amounts of warming and is thus particularly important within the context of ambitious climate stabilization targets.

Representing the distribution of (excess) ground ice and modelling excess ice melt influences the thaw rate and resulting carbon emissions. Thaw-induced changes in surface hydrology are not accurately represented in ESMs. For example, most models predict a drying landscape after thaw[10]; however, both experimental and observational data show that permafrost degradation can result in inundation, ponding and the formation of new lakes when drainage is limited, altering plant and microbial processes and climate feedbacks[1]. At the same time, permafrost thaw can open up new flow channels, leading to soil drying and lake drainage in some regions. Whether permafrost regions in the future will be wetter or drier is an urgent question for climate projections, as atmospheric feedbacks to changed permafrost hydrology could affect climate far beyond permafrost areas.

Snow regulates permafrost temperatures due to the insulation it provides. The complex vertical snowpack structure with the formation of insulative depth hoar and dense wind-affected layers are snow processes that are not fully represented, and models struggle to correctly represent the insulative capacity of the Arctic snowpack and associated future changes.

Biogeochemical processes. The representation of both soil organic matter decomposition and vegetation changes are crucial processes for accurately modelling permafrost carbon dynamics, and both are not adequately refined in ESMs. Most ESMs use first-order kinetics to characterize soil organic matter decomposition but do not explicitly include microbial processes even though soil carbon turnover prediction is strongly improved when including a microbial model[11]. Vegetation type and amount is critical to represent carbon inputs in permafrost systems (Fig. 1); yet, despite the rapid changes in Arctic vegetation distributions, most ESMs lack appropriate Arctic plant functional types and do not represent changing Arctic vegetation types over time.

Moreover, many current ESMs predict a strong increase in plant carbon uptake with increasing atmospheric CO_2 concentrations and relaxed nutrient limitations associated with increased nutrient release from thawing permafrost[2]. Experimental data from non-Arctic ecosystems, however, suggest that plants will not continuously benefit from elevated CO_2 concentrations, and models do not properly represent the underlying processes of plant productivity under increased CO_2. For example, nutrient interactions and limitations on plant productivity remain poorly represented in ESMs and are not well constrained by observations.

Finally, increased wildfires in the Arctic and boreal domains emit carbon directly and accelerate carbon release from permafrost ecosystems[12]. Yet both fire consumption of soil organic matter and wildfire–permafrost interactions are not well represented in ESMs.

Improving physical and biogeochemical process representation in models would not only improve permafrost modelling but also generally be beneficial for a better understanding of the terrestrial carbon cycle in models.

Substantive funding opportunities as a solution

More attention should be given to ESM development for permafrost processes, particularly those that impact carbon cycling (Fig. 1). Many of the building blocks needed to improve modelling of permafrost processes are in place (for example, computational resources, skilled modellers and scientific expertise), and increased and targeted funding can help solve the longstanding challenges of permafrost modelling. Substantial funding, of the order of multiple millions of (US) dollars per ESM, is needed to provide the necessary infrastructure and support needed for model development (including improvement of input datasets). To considerably advance models and speed improvement, highly skilled people are needed, including software engineers and programmers.

The key advantage of using ESMs is that they are capable of a self-consistent quantification of the feedbacks shaping the climate response to human-induced greenhouse gas emissions, which can directly inform policy-relevant tools such as the IPCC remaining carbon budget. We envision a path forward that includes a core set of land models within ESMs that can be run in land-only mode in a large variety of configurations and resolutions, and then can be readily coupled to an ESM. Land models within ESMs tend to have comprehensive, flexible and constantly evolving code bases. We suggest that the ESM community strives towards more shareable modules using existing structural representations of permafrost and carbon processes from currently available ESMs. Another component of model progress entails the incorporation of parameterization knowledge obtained from advancing small-scale highly detailed models (for example, the Arctic Terrestrial Simulator (ATS)[13] or Ecosys[14]). In addition, intermediate complexity ESMs (for example, Uvic ESCM[15]) and emulators (for example, OSCAR[3]) could be used to gain a better understanding of feedbacks on the climate, although they would not be used for process-based model development. We also propose that model development would be most successful if it was coordinated among groups and in parallel with robust and shared tools for model evaluation and assessment against a wide range of observations.

In conclusion, ESMs can provide information on societally relevant impacts such as predictions of carbon emissions from permafrost; yet, in most cases, model predictability is limited by deficient (for example, vegetation shifts, nutrient limitation) and entirely missing (for example, abrupt thaw, wildfire carbon interactions) processes, creating large uncertainties in permafrost carbon emissions predictions. Substantive and targeted funding is required to prioritize model development and to work collaboratively among modelling centres and in partnership with data owners.

Christina Schädel[1] ✉, **Brendan M. Rogers**[1], **David M. Lawrence**[2], **Charles D. Koven**[3], **Victor Brovkin**[4], **Eleanor J. Burke**[5], **Hélène Genet**[6], **Deborah N. Huntzinger**[7], **Elchin Jafarov**[1], **A. David McGuire**[6], **William J. Riley**[3] & **Susan M. Natali**[1]

[1]Woodwell Climate Research Center, Falmouth, MA, USA. [2]National Center for Atmospheric Research, Boulder, CO, USA. [3]Climate and Ecosystem Sciences Division, Lawrence Berkeley National Lab, Berkeley, CA, USA. [4]Max Planck Institute for Meteorology, Hamburg, Germany. [5]Met Office Hadley Centre, Exeter, UK. [6]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK, USA. [7]School of Earth and Sustainability, Northern Arizona University, Flagstaff, AZ, USA.

✉e-mail: cschaedel@woodwellclimate.org

Published online: 18 January 2024

References

1. Schuur, E. A. G. et al. *Annu. Rev. Environ. Resour.* **47**, 343–371 (2022).
2. McGuire, A. D. et al. *Proc. Natl Acad. Sci. USA* **115**, 3882–3887 (2018).
3. Gasser, T. et al. *Nat. Geosci.* **11**, 830–835 (2018).
4. Natali, S. M. et al. *Proc. Natl Acad. Sci. USA* **118**, e2100163118 (2021).
5. Burke, E. J., Zhang, Y. & Krinner, G. *Cryosphere* **14**, 3155–3174 (2020).
6. Schädel, C. et al. *Glob. Change Biol.* **20**, 641–652 (2014).
7. Olefeldt, D. et al. *Earth Syst. Sci. Data* **13**, 5127–5149 (2021).
8. Virkkala, A.-M. et al. *Earth Syst. Sci. Data* **14**, 179–208 (2022).
9. Turetsky, M. R. et al. *Nat. Geosci.* **13**, 138–143 (2020).
10. Andresen, C. G. et al. *Cryosphere* **14**, 445–459 (2020).
11. Wieder, W. R., Bonan, G. B. & Allison, S. D. *Nat. Clim. Change* **3**, 909–912 (2013).
12. Holloway, J. E. et al. *Permafr. Periglac. Process.* **31**, 371–382 (2020).
13. Painter, S. L. et al. *Water Resour. Res.* **52**, 6062–6077 (2016).
14. Mekonnen, Z. A. et al. *Environ. Res. Lett.* **17**, 094037 (2022).
15. MacDougall, A. H., Avis, C. A. & Weaver, A. J. *Nat. Geosci.* **5**, 719–721 (2012).

Acknowledgements

C.S. and D.N.H. received funding from the US Department of Energy (DOE) grant DE-SC0022116. C.S., B.M.R., E.J., H.G. and S.M.N. received funding from Permafrost Pathways through the TED Audacious Project. C.D.K., W.J.R. and D.M.L. acknowledge support from the DOE RGMA Program via the RUBISCO SFA.

Author contributions

C.S. conceptualized the article, created Fig. 1 and wrote the initial draft. B.M.R., D.M.L. and C.D.K. contributed to the conceptualizing and writing of the paper. H.G., W.J.R. and S.M.N contributed to the conceptualizing and editing of the paper. All authors provided insights and edits to the paper.

Competing interests

The authors declare no competing interests.

Additional information

Peer review information *Nature Climate Change* thanks Andrew MacDougall, Jan Nitzbon and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.