permafrost.woodwellclimate.org
arcticpolicy@woodwellclimate.org
@woodwellarctic

ARCTIC PERMAFROST CARBON & GLOBAL CLIMATE MODELS

A POLICY-RELEVANT REVIEW OF THE LATEST IN EARTH SYSTEM MODEL DEVELOPMENT

As the Arctic rapidly warms, loss of permafrost (*i.e.*, continuously frozen ground that underlies roughly 15% of the exposed land surface in the Northern Hemisphere and which contains an estimated 1.5 trillion tons of carbon) could release greenhouse gas (GHG) emissions (carbon dioxide and methane) at levels rivaling the highest-emitting countries. Accounting for these potential emissions is necessary to inform time-bound, tailored, and ambitious mitigation strategies that avoid the worst climate scenarios. Unfortunately, Earth System Models (ESMs), which are used to understand planetary responses and feedbacks to future climate scenarios, currently do not include complete representation of the permafrost-carbon cycle*; consequently, the global carbon budget underestimates potential GHG emissions from permafrost thaw and related feedbacks. Improved representation of permafrost carbon dynamics in ESMs will ultimately ensure that policy, innovation, and research are consistent with a 1.5°C climate threshold and other climate commitments (pursuant to national ambition and the Paris Agreement).

❝ 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. ❞

See Schädel, C., Rogers, B.M., Lawrence, D.M. et al., *Earth system models must include permafrost carbon processes,* Nature Climate Change (2024), synthesizing challenges undermining ESM development and offering concrete steps for improvement, as summarized below. *https://doi.org/10.1038/s41558-023-01909-9*.

PRIORITY POLICY ACTION: INCREASED FUNDING FOR MORE EXPANSIVE MODEL DEVELOPMENT RESEARCH GRANTS

There is sufficient knowledge, expertise, and computational capacity to improve permafrost carbon representation in models. The major limiting factor in achieving such improvement is the *current funding landscape*, as typical research grants are neither sufficiently expansive in scope nor duration to enable integration of permafrost processes within an ESM. Both public and private investments in ESM development (multiple millions per model) may be necessary to facilitate model advancements on a policy-relevant timescale.

US-based funding targets: Within the US, there are only a handful of targets for model development: (1) The Department of Energy (DOE) Earth System Model Development program's Energy Exascale Earth System Model (E3SM) project; (2) The National Center for Atmospheric Research (NCAR) Community Land Model (CLM) Community Earth System Model (CESM); and (3) The National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) models. Each of these efforts are well-positioned to better include permafrost processes, provided they receive an influx of directed funding. Increasing funding for agency solicitations to the research community, via the National Science Foundation (NSF), would also expedite ESM development, as it would open the door for inputs from the greater modeling community.

Extending research grant periods: Most grant-funded science projects have a duration of *three years*, *i.e.,* a cycle that is proven too short for early-career researchers to complete meaningful ESM development and research before transitioning to a new project or position. Increasing model complexity will require longer-term investments in training members of the ESM and modeling community. Longer-term grants will also provide the time needed for additional benchmarking and evaluation that is required to trace performance of more complex models.

Adjusting funding approaches: Government agencies traditionally prefer to fund research projects that *directly* answer big science questions; on its face, ESM development does not constitute such a project. Rather, model development grants are generally non-hypothesis driven and aim to achieve many intermediate steps. Nevertheless, ESM development is a prerequisite to answering many of these big science questions. A tonal shift in how projects are selected for funding is required to ensure that government agencies, like NSF, are soliciting and funding ESM development proposals, particularly those that seek to incorporate global climate feedbacks such as permafrost thaw.

OTHER CONSIDERATIONS

Schaedel *et al.* notes specific research gaps relevant to ESM development, *inter alia:*

- Enhanced focus on missing and underrepresented physical and biochemical processes:
  - Abrupt Thaw, Surface Hydrology, Snow. 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–much of which is not currently represented in ESMs. Inventory approaches indicate that abrupt thaw processes (*i.e.,*thermokarst) could increase carbon emissions from permafrost by up to 40%, thereby effectively doubling the radiative impact of permafrost thaw due to the relatively high fraction of emissions from abrupt thaw processes being CH4 emissions. Whether permafrost regions in the future will be wetter or drier, and the insulative capacity of the Arctic snowpack are also urgent questions for climate projections and could affect climate far beyond permafrost areas.
  - Wildfires, Soil Decomposition, Vegetation Changes: Increased wildfires in the Arctic and Boreal domain that emit carbon directly and accelerate carbon release from permafrost ecosystems are currently underrepresented in ESMs. Soil organic matter decomposition and vegetation changes that inform plant-carbon uptake are also crucial processes for accurately modeling permafrost carbon dynamics, but have not been sufficiently refined in existing models.

- Continued development of spatially distributed datasets for the Arctic region: Because the permafrost region is large and spatially heterogeneous, landscape changes, including thawing and degrading permafrost, are not occurring uniformly. Credible projections of the permafrost carbon-climate feedback require datasets that reflect this heterogeneity; yet spatially distributed datasets are currently either not available (*e.g.,* disturbance datasets), are insufficient (*e.g.,* ground ice distribution maps), or large regional gaps exist (*e.g.,* in Siberia). Obtaining good data products with spatial and temporal coverage is possible, but the improvement of these inputs via new satellites and measurements, data analysis, and pan-Arctic data sharing must simultaneously proceed with model development.

*Catalyzing ESM development improvements are key to ensuring that future climate assessments feature a higher degree of certainty (and accuracy) with respect to the implications of permafrost thaw on various emission scenarios– and thus, inform better climate policy outcomes. Note that current climate policies are heavily informed by findings of the IPCC 6th Assessment Report (AR6), published in 2021, which found with *high confidence* that permafrost will continue to thaw and will lead to carbon release to the atmosphere. Unfortunately, only 2 of 11 models (which used the same component of the Community Land Model (CLM5)) included representation of permafrost carbon; neither model included important processes such as abrupt thaw or interactions between permafrost and vegetation cover change or wildfire. Improving representation of permafrost carbon dynamics in ESMs will reduce uncertainty as to the timing, magnitude, and characteristics (CO2 vs. CH4) of future emissions in global climate assessments and ultimately improve policy responses.

ADDITIONAL RESOURCES

Natali, S. M., Bronen, R., Cochran, P., Holdren, J. P., Rogers, B. M., and Treharne, R.: Incorporating permafrost into climate mitigation and adaptation policy, Environ. Res. Lett., 17, 091001, https://doi.org/10.1088/1748-9326/ac8c5a, 2022.

Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., and MacDonald, E.: Permafrost carbon feedbacks threaten global climate goals, Proceedings of the National Academy of Sciences, 118, e2100163118, https://doi.org/10.1073/pnas.2100163118, 2021.

Schädel, C., Bader, MF., Schuur, E. *et al.* Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nat. Clim. Change., 6 (10), 950–953 . https://doi.org/10.1038/nclimate3054, 2016.

Schädel, C., Rogers, B. M., Lawrence, D. M., Koven, C. D., Brovkin, V., Burke, E. J., Genet, H., Huntzinger, D. N., Jafarov, E., McGuire, A. D., Riley, W. J., and Natali, S. M.: Earth system models must include permafrost carbon processes, Nat. Clim. Chang., 1–3, https://doi.org/10.1038/s41558-023-01909-9, 2024.

Treharne, R., Rogers, B. M., Gasser, T., MacDonald, E., and Natali, S.: Identifying Barriers to Estimating Carbon Release From Interacting Feedbacks in a Warming Arctic, Frontiers in Climate, 3, https://doi.org/10.3389/fclim.2021.716464, 2022.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., and McGuire, A. D.: Carbon release through abrupt permafrost thaw, Nat. Geosci., 13, 138–+, https://doi.org/10.1038/s41561-019-0526-0, 2020.

For more information, please contact:
Melissa Shapiro, Arctic Policy Lead, mshapiro@woodwellclimate.org