



Incorporating pan-Arctic excess ground ice across structurally distinct Land Surface Models: Community Land Model (CLM5.1) and Common Land Model (CoLM2014)

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Abstract. Accurately representing permafrost thaw processes in Earth System Models (ESMs) is critical for predicting future climate-carbon feedbacks. While gradual top-down thaw schemes are standard in most of the CMIP6 models, large-scale land surface models increasingly incorporate excess ground ice physics to capture abrupt thaw and subsequent land subsidence. These parameterizations, however, are typically developed and evaluated within single-model frameworks making it difficult to understand how underlying model structure influences the model performance. This study integrates an identical excess-ice ground ice physics into the Common Land Model (CoLM, version 2014) and evaluates it against the Community Land Model (CLM, version 5.1). Using paired historical sensitivity experiments (1901–2014) with and without excess ice across the pan-Arctic, we investigate the effects of excess ice on physical and biogeochemical properties. In this study, we evaluate three configurations: CLM, standard CoLM, and CoLM coupled with a dynamic global vegetation model (CoLM-DV). Our results show that while all configurations capture key physical processes of excess ice such as subsurface latent heat buffering and progressive ice loss under warming, the magnitude and spatial distribution of these responses diverge substantially. The CoLM simulates a much higher sensitivity to warming than CLM, undergoing widespread excess ice loss than the CLM. Biogeochemical responses diverge even more i.e. excess ice melt suppresses regional GPP in CLM (by -40 to -70 TgC yr⁻¹) and standard CoLM (by -5 to -20 TgC yr⁻¹) due to warming anomalies maintained by latent heat absorption. On the other hand, CoLM-DV simulates a positive GPP response ($+15$ to $+25$ TgC yr⁻¹) driven by localized warming and wettening that stimulates shrub and grass expansion over bare soil. This inter-model divergence demonstrates that identical physical parameterizations create significantly different climate-carbon feedback trajectories depending on



host-model structure and vegetation feedbacks. This work highlights cross-model benchmarking as a vital tool for robust parameterization development across the permafrost modeling community.

35 1 Introduction

Permafrost is a critical component of Earth's climate system, covering approximately 15–24% of the Northern Hemisphere's land surface (Obu et al., 2019; Ran et al., 2022). In particular, permafrost soils are estimated to store 1,300–1,700 Pg of carbon (Schuur et al., 2015; Hugelius et al., 2014). Under the current projections of global scale warming, widespread permafrost degradation is expected, with the potential to release large amounts of greenhouse gases and potentially
40 amplifying climate warming through a positive feedback loop (Koven et al., 2011; Schuur et al., 2022). Consequently, accurately representing permafrost processes in Earth System Models (ESMs) is essential for understanding future climate change and carbon-climate feedbacks.

Despite considerable progress over the past couple of decades to better represent permafrost thaw processes, there still remains a critical gap in ESMs to represent abrupt thaw processes (Burke et al., 2020). Abrupt thaw, driven primarily by
45 melting excess ground ice and subsequent land surface subsidence, results in physical and biogeochemical changes that gradual thaw schemes cannot capture. Land surface subsidence in the lowlands can lead to waterlogged environments forming thermokarst lakes, degrading ice-wedge polygons, and collapsing peat plateaus (Jorgenson et al., 2006; Liljedahl et al., 2016; Turetsky et al., 2020). This subsidence-driven inundation alters local hydrology by raising the water table and extending the duration and spatial extent of saturated soil conditions (Grosse et al., 2011; Olefeldt et al., 2016). However,
50 these changes to hydrology can go both ways depending on topographic and subsurface characteristics; while ice melt frequently induces localized waterlogging in poorly drained lowlands, it can also breach structural barriers and open up new vertical or lateral drainage pathways, leading to a general drying of the local environment. The shift in hydrological environments affect balance between aerobic and anaerobic decomposition pathways: well-drained, aerobic conditions may result in emissions dominated by CO₂ production, whereas waterlogged, anaerotic conditions may result in emissions
55 dominated by CH₄ with 30 times greater global warming potential (Turetsky et al., 2020; Schuur et al., 2022). Therefore, the absence of abrupt thaw processes in ESMs may lead to a systematic underestimation in projecting permafrost-carbon climate feedbacks.

Recent efforts to address this gap have incorporated excess ground ice physics into large-scale models. The presence of excess ice exerts a strong control on the rate and characteristics of permafrost thaw, in part because of the substantial latent
60 heat required to melt it (Lee et al., 2014). Additionally, excess ice melt triggers abrupt, nonlinear thawing processes such as abrupt thawing and ground subsidence (Jorgenson et al., 2006; Liljedahl et al., 2016; Turetsky et al., 2020). These processes are fundamentally distinct from the gradual top-down thaw that current ESMs simulate, and lack of such process likely leads to a systematic underestimation of permafrost carbon feedbacks (Schädel et al., 2024; Webb et al., 2025). Since the first global-scale representation of excess ice in the Community Land Model (CLM4.5, Lee et al. 2014), incorporating excess



65 ground ice into large-scale land surface models has been an area of active development over the past decade. Notwithstanding this progress, most of these developments have been evaluated in offline or single-model configurations, leaving the question of how excess ice influences permafrost simulations across different ESMs largely unaddressed.

The importance and benefit of cross-model comparison and coordinated model development has been emphasized by several synthesis efforts. Targeted investment in ESM co-development such as sharing process parameterizations, evaluation
70 frameworks, and code developments across modeling groups will be essential to accelerate the incorporation of key permafrost processes (Schädel et al., 2024). Such collaborative approaches can help identify how the same physical process responds differently depending on the broader model architecture, soil column depth, timestep, and coupling configuration in which it is embedded, thereby offering insights that are transferable across the modeling community. This type of co-development is particularly valuable given that different ESMs share land components or common physical structure.

75 This study aims to incorporate excess ground ice into the Common Land Model (hereafter CoLM) by integrating the excess-ice physics scheme based on Lee et al. (2014). By conducting paired sensitivity experiments with and without excess ice, we quantify and compare the physical responses of pan-Arctic permafrost affected land surface to excess ice across two structurally distinct land surface models. Specifically, our experimental design evaluates three model configurations i.e. CLM, standard CoLM, and CoLM coupled with a dynamic global vegetation model (hereafter CoLM-DV). This allows us to
80 isolate how differences in host model architecture and vegetation representation modulate the impacts of excess ice melt. Through this multi-model setup, we track the downstream consequences of sub-surface ice degradation on active layer dynamics, soil thermal and hydrological regimes, and regional gross primary production (GPP). This comparison demonstrates how choices in model structure and parameterization shape the simulated response to excess ground ice. In doing so, we expect to provide diagnostic insights for further co-development across the modeling community.

85 **2 Model description and simulation setup**

2.1 Community Land Model (CLM)

The CLM serves as the land component of several earth system models, including NorESM (Seland et al., 2020) and CESM (Danabasoglu et al., 2020). In this study, we use version 5.1, which is an updated version of CLM5 described by Lawrence et al. (2019). It includes up to 20 hydrologically active soil layers on top of 5 bedrock layers going down to a total depth of
90 about 50 m. The depth to bedrock is spatially varying, between 0.4 (5 layers) and 8.5 m (20 layers). The model includes up to 12 snow layers, with explicit representation of many snow related processes like fractional snow cover (Swenson and Lawrence, 2012), wind and temperature dependent fresh snow density and compaction of snow due to destructive metamorphism, overburden pressure and snow drift (van Kamenhout et al., 2017). The model is run with fixed vegetation distribution represented by default 17 natural plant functional types including bare ground, and includes representation of
95 snow and rain interception by canopy. Heat and moisture transport is fully coupled in the hydrologically active layers, where thermal and hydrological properties are influenced by liquid and frozen water. Excess ground ice is represented in



permafrost regions as described by Lee et al. (2014) allowing ground subsidence, changing soil structure and release of soil water as the excess ground ice melts. Other aspects of the model are described in Lawrence et al. (2019) and the continuously updated online documentation (CLM tech node: <https://escomp.github.io/CTSM/>).

100 2.2 Common Land Model (CoLM)

The Common Land Model (CoLM; Dai et al., 2003) is the land component of CAS-ESM2.0, which originated from the synthesis of three earlier land surface schemes: BATS (Dickinson et al., 1993), IAP94 (Dai and Zeng, 1997), and the NCAR LSM (Bonan, 1996; 1998). The initial version of CoLM served as the land component of BNU-ESM (Ji et al., 2014). Since its inception, CoLM has undergone substantial restructuring, and the current version differs fundamentally from its initial
105 release. In this study, we use version CoLM2014.

Several developments are particularly relevant to cold-region processes addressed in this study. The vertical discretization employs 15 soil layers extending to a depth of 42.1 m, with up to five snow layers. This deep soil column, combined with thermal insulation by soil organic matter, is essential for realistically simulating permafrost extent and active layer thickness at northern high latitudes (Lawrence and Slater, 2008). A frozen soil parameterization based on the supercooled soil water
110 concept (Niu and Yang, 2006) allows liquid water to coexist with ice across a wide subzero temperature range via the freezing-point depression equation; vertical water fluxes account for fractional permeable area within each model layer, with total soil moisture used to compute matric potential and hydraulic conductivity. Frost and thaw front dynamics are explicitly represented through a dedicated front-tracking scheme (Gao et al., 2016; 2019). A multilayer soil organic carbon scheme captures cryoturbation and bioturbation effects, enabling surface-derived carbon to be mixed into deeper, colder soil
115 horizons (Koven et al., 2009). Additional developments include an improved two-stream canopy radiation transfer model with separate treatment of sunlit and shaded leaf fractions, a photosynthesis-stomatal conductance scheme resolving CO₂ and water vapor exchange for sunlit and shaded leaves (Dai et al., 2004), and a carbon-nitrogen interaction scheme based on LPJ-DyN (Xu and Prentice, 2008). CoLM is coupled with the IAP-DGVM dynamic global vegetation model (Zhu et al., 2018), which classifies natural vegetation into 12 plant functional types and includes a shrub submodel (Zeng et al., 2008; Zeng,
120 2010), a process-based fire parameterization (Li et al., 2012), and an establishment scheme enabling realistic reproduction of major terrestrial ecosystem distributions (Song et al., 2016).

2.3 Simulation set up

Simulations with CLM has been performed following the setup in (Lawrence et al., 2019) with BGC and GSWPv3 atmospheric forcing. Model was initialized from a spun-up state with the two key differences. First, the simulation was
125 performed in the resolution on a 1.9° latitude by 2.5° longitude grid. Second, starting from equilibrium 1850 conditions, we perform an additional 300 year spinup (same procedure as “normal mode” spinup in Lawrence et al., 2019) for both EXICE and DEFAULT simulations until the EXICE simulation reaches a new equilibrium state. At the start of the additional spinup in EXICE simulation we add excess ground ice concentration bilinearly interpolated from Brown et al. (1997). If



interpolated concentration is greater than zero for a given gridcell, it is applied to every soil layer deeper than previous year's maximum active layer depth and up to the shallowest bedrock layer if soil temperature for that layer is lower than freezing temperature of water. We consider EXICE simulation to reach a thermal equilibrium state when global maximum difference between two consecutive 20 year rolling mean excess ice volume less than 1% and same global maximum difference for soil temperature at 3 m depth is less than 0.1°C. After this additional spinup we continue simulation as historical with transient 1850–2014 forcing.

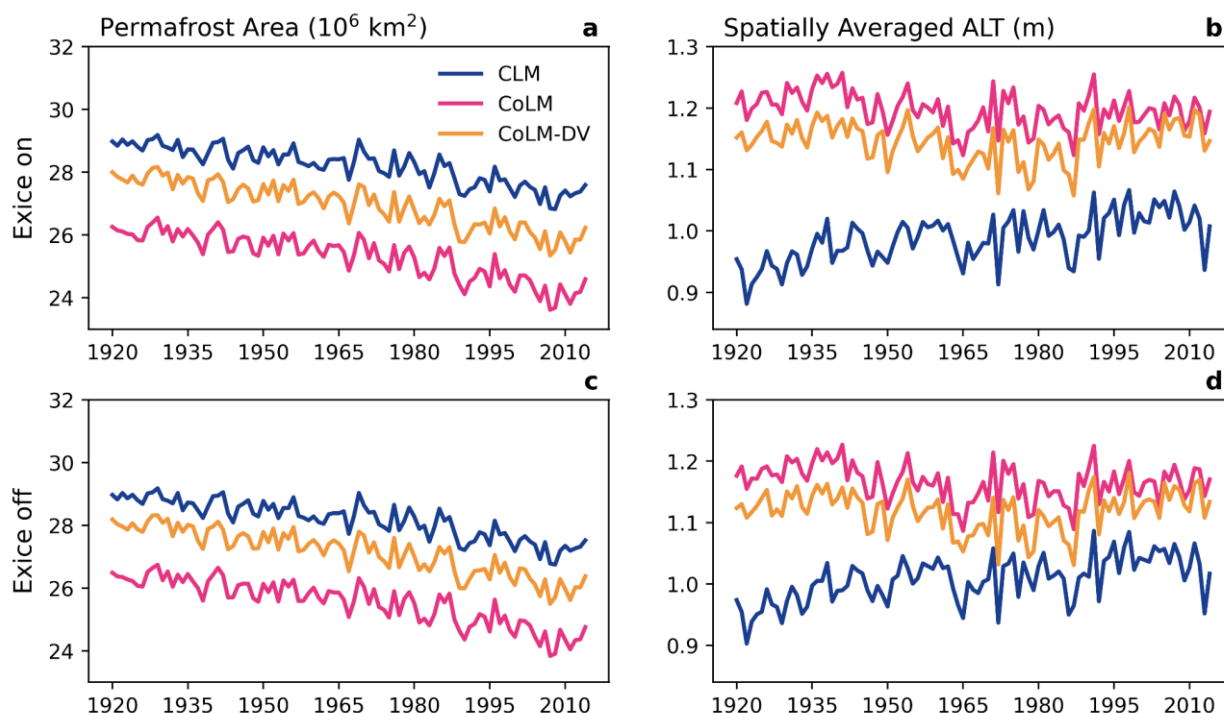
The CoLM conducted similar simulations as the CLM. Two sets of CoLM simulations were conducted to assess the influence of dynamic vegetation and excess ground ice. The first set enabled the dynamic vegetation module (CoLM-DV), whereas the second set used prescribed vegetation without dynamic vegetation processes (CoLM). Within each set, paired experiments were performed with and without excess ground ice, resulting in a total of four simulations.

For model spin-up, the excess-ground-ice experiments were first driven by a repeated cycle of the 1901–1920 GSWPv3 meteorological forcing for 100 years to allow the land surface and permafrost states to reach equilibrium. Following the spin-up, all simulations were integrated using transient GSWPv3 forcing from 1901 to 2014.

3 Results and discussion

3.1 Physical properties

Over the simulation period, all three model configurations (CLM, CoLM, and CoLM-DV) exhibit 1.7–2.1 × 10⁶ km² decline in pan-Arctic permafrost area, ranging from approximately 29–30 × 10⁶ km² in the early twentieth century to around 27–28 × 10⁶ km² by 2014. Among the three configurations, CoLM simulates the smallest area, declining from roughly 28 × 10⁶ km² to below 25 × 10⁶ km² (Figure 1). The representation of present day permafrost area is within acceptable range compared to other LSMs used in CMIP6 simulations (Steinert et al., 2024) and observations (Obu et al., 2019, Brown et al., 1997). There is an overall 0.01–0.08 m deepening of the active layer thickness (ALT) for CLM. This is consistent with the long-term warming trend in the historical forcing. But CoLM shows no significant increase in ALT. The difference in ALT is more pronounced when Exice is turned on because the two host models differ structurally in soil layer discretization and thermal conductivity, which control how much the latent heat of excess ice melt buffers subsurface warming. This difference is dampened once excess ice and its buffering effect is removed.



155 **Figure 1. Annual evolution of the permafrost area (a, c) and spatially averaged active layer thickness (ALT; b, d) across the pan-**
Arctic region from 1920 to 2014 for three configurations. Panels (a) and (b) show the results from the 'Excess Ice On' simulation,
while panels (c) and (d) show the 'Excess Ice Off' simulation.

By 2014, all three model configurations show deepening of the active layer across the domain, with the southern boundaries undergoing the most change (Figure 2). Both CoLM and CoLM-DV show particularly strong deepening in northeastern
160 Siberia and Alaska, with active layer values in these regions increasing by 0.5–1.0 m or more over the simulation period, while CLM shows a more heterogeneous change, but still a larger area in the continuous permafrost zone with shallower ALT.

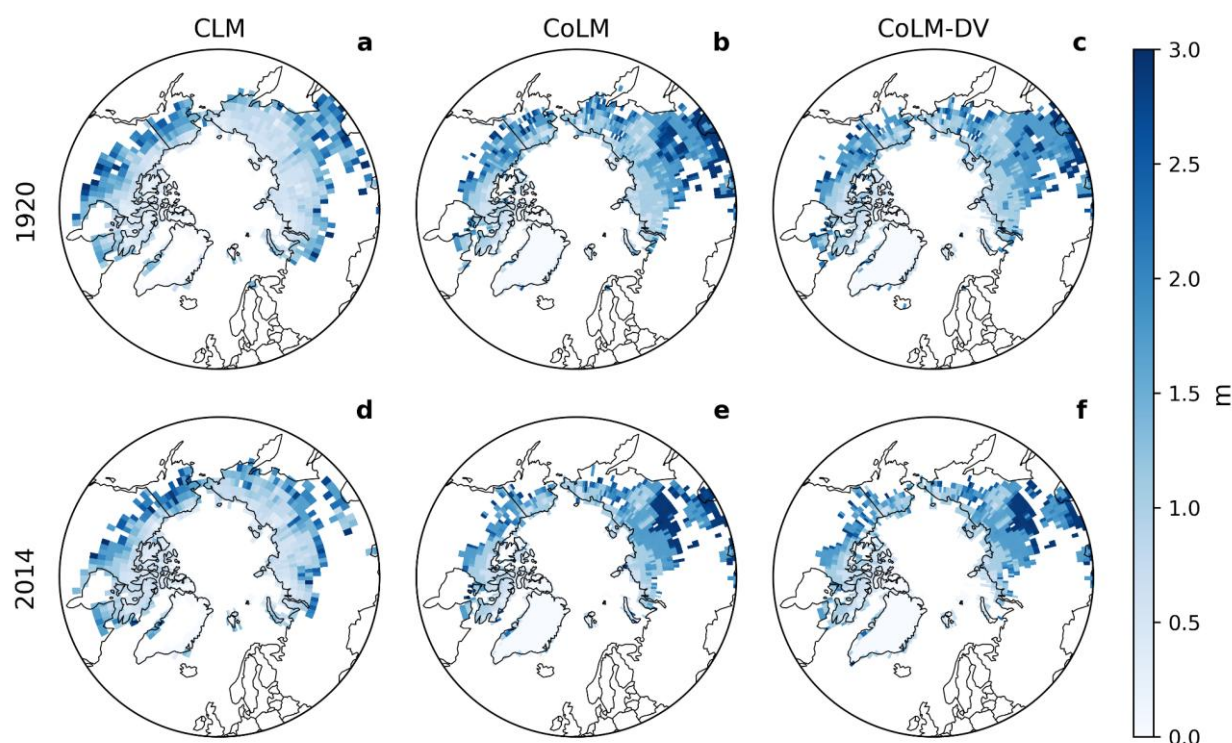


Figure 2. Annual mean active layer thickness (ALT) in the pan-Arctic region ($\geq 50^\circ\text{N}$) at the beginning (1920) and end (2014) of the 'Excess Ice Off' simulation.

In the model, excess ice is initialized as a fixed proportion of the soil thickness and operates as a melt-only tracer (Lee et al., 2014). This creates some discrepancies between its absolute and relative volume changes. Regardless of the metric used, excess ice melts the least in CLM and the most in CoLM, with the latter showing a sharp decline in the last 20 years of the simulation period (Figure 3). Excess ice loss in CoLM-DV falls directly between CLM and CoLM, which is likely due to the insulating feedback of expanding surface vegetation during the late-century warming phase. Despite sharing an identical initialization based on the Brown et al. (1997) dataset, the three model configurations simulate drastically different pan-Arctic excess ground ice between 1920 and 2014 (Figure 4). While CLM holds a nearly unchanged spatial distribution of excess ice, CoLM undergoes widespread excess ice melting up to 50 kg m^{-2} across northeastern Siberia, Alaska, and northwest Canada. Ultimately, these differences expose a significant structural gap: although the underlying excess ice physics scheme is identical, host-model choices regarding vertical layer discretization, thermal conductivity, and static versus dynamic vegetation parameters fundamentally dictate the thermal threshold and sensitivity of the permafrost state.

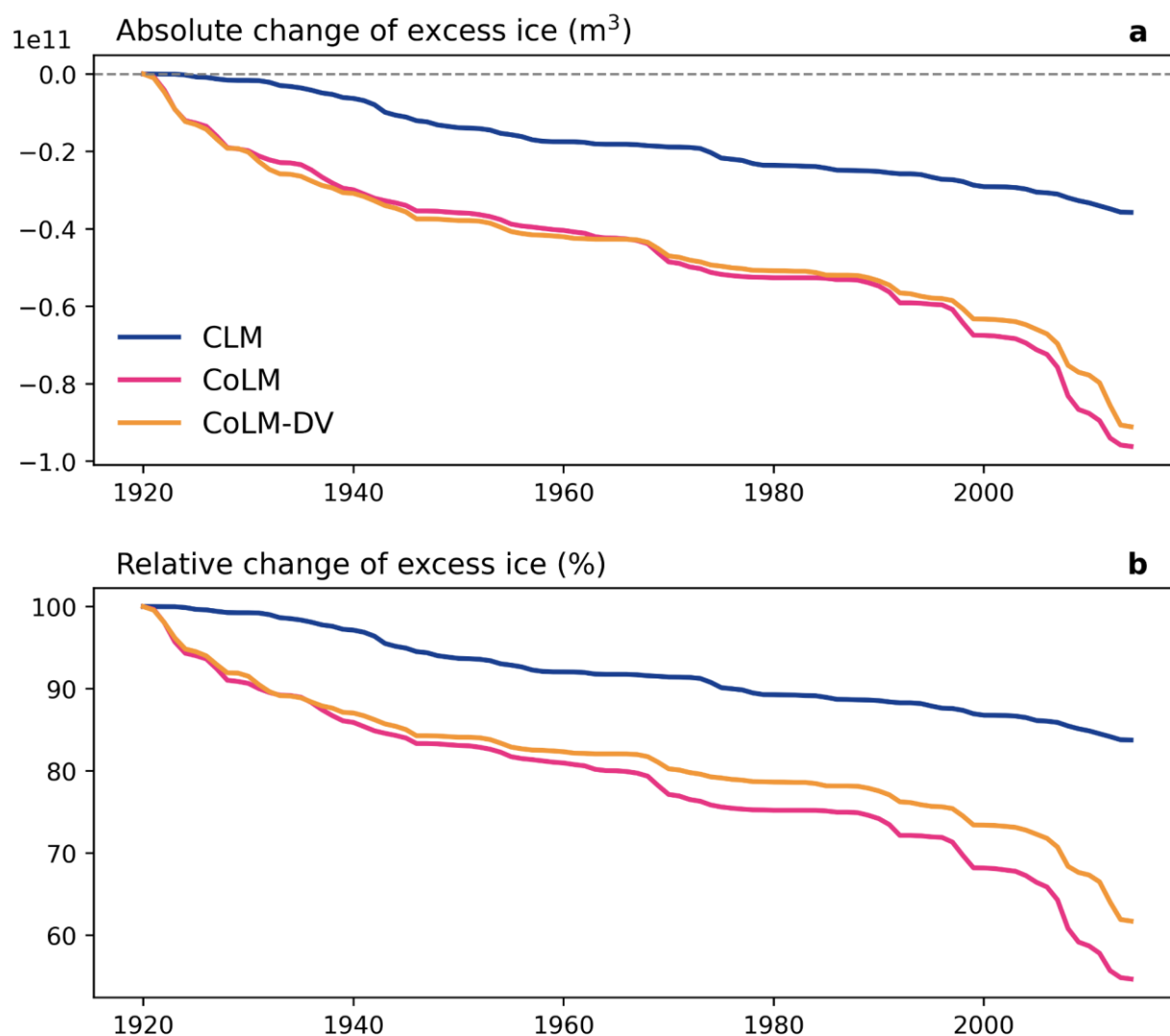


Figure 3. Temporal evolution of column-integrated excess ice within the upper 1.04 m from 1920 to 2014. (a) Absolute change in excess ice volume (m^3) for CLM (yellow), CoLM (navy), and CoLM-DV (light blue). (b) Relative change in excess ice (%) compared to the initial state in 1901.

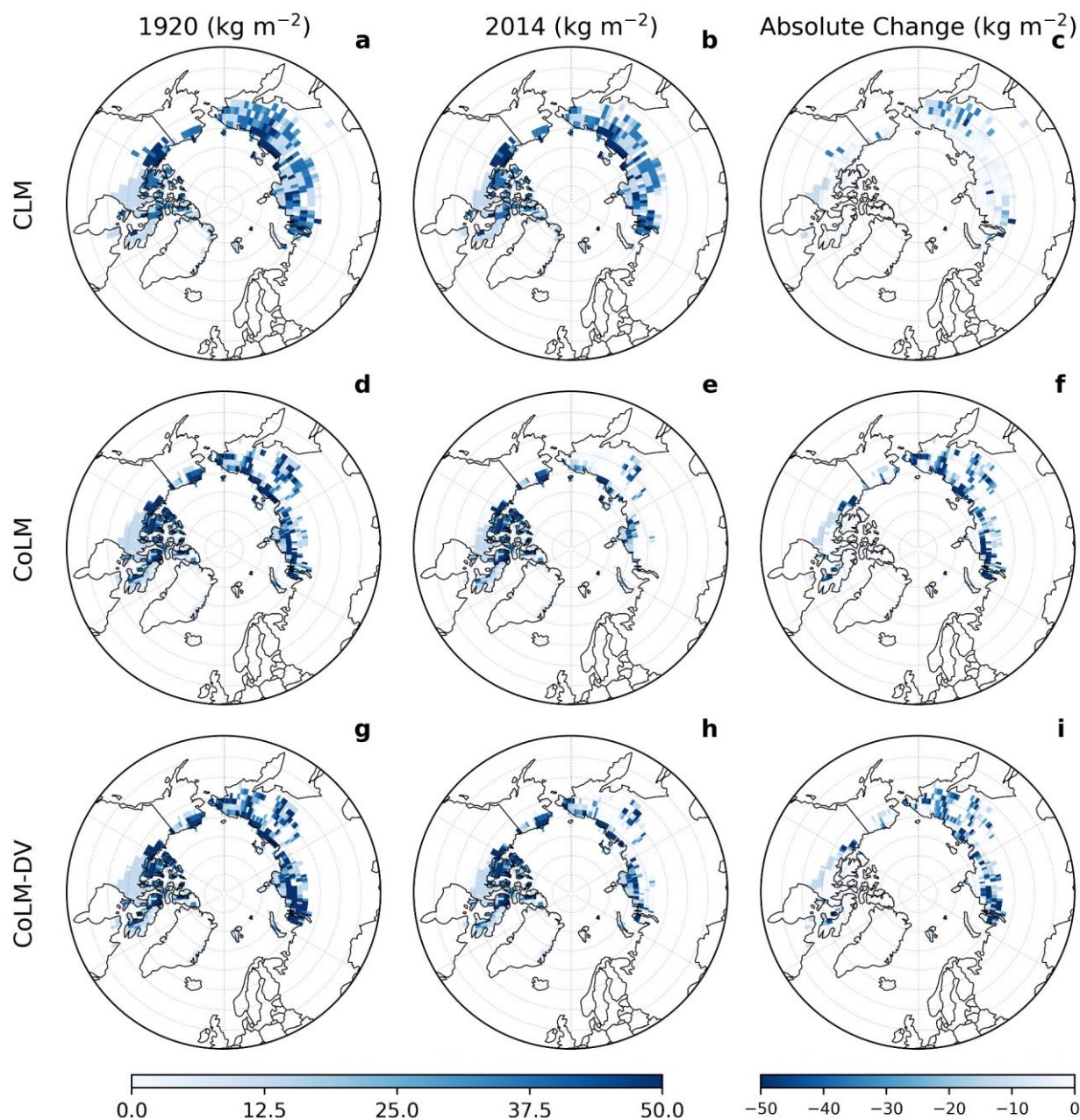
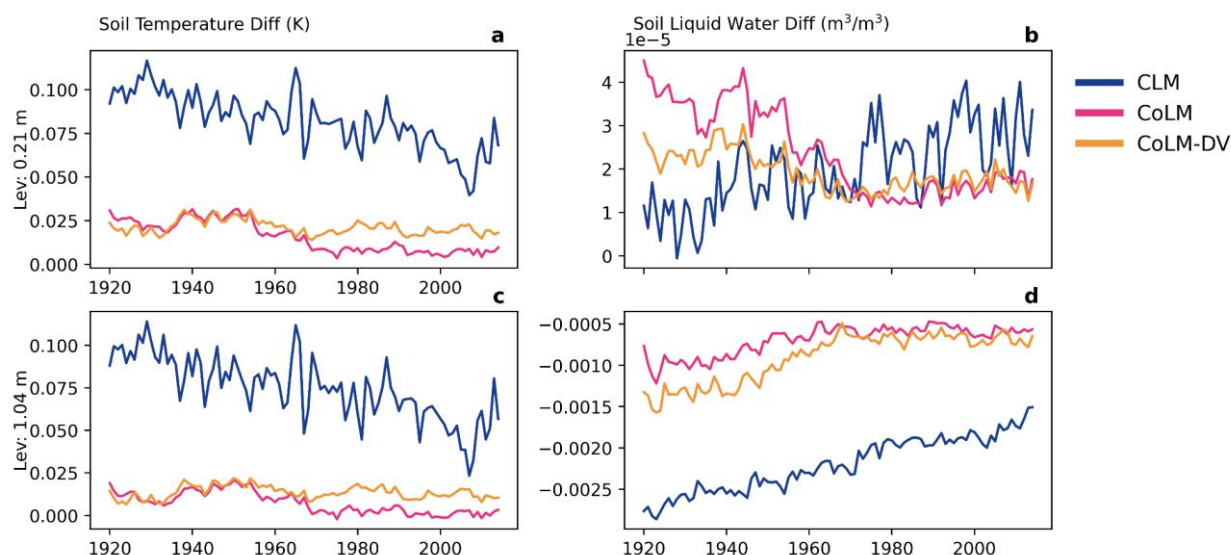


Figure 4. Simulated spatiotemporal changes in column-integrated excess ice within the top 1.04 m. The first two columns display the spatial maps for 1920 and 2014, while panels (c, f, i) show the absolute change from 1920 to 2014.

The presence of excess ground ice exerts a pronounced warming effect on soil temperatures due to the substantial latent heat required for ice melting, which effectively buffers subsurface temperatures during the thaw (Figure 5a, c). The CLM exhibits a much stronger regional soil temperature response to excess ice, with differences remaining close to 0.1 K at both depths,



190 indicating that excess ice has a more distinct thermal influence within its soil column compared to CoLM. The spatial patterns of this subsurface thermal signal confirm these model contrasts (Figure 6). The CLM shows widespread and locally intense warming anomalies, whereas CoLM and CoLM-DV show weaker and more scattered thermal shifts. This large inter-model divergence exposes a key structural gap: identical physical ice schemes will yield entirely different thermal protections depending on the host model's soil column depth, vertical layer discretization, thermal conductivity parameterization, and the vertical placement of excess ice within the soil profile.



195 **Figure 5. Temporal evolution of the simulated differences ('Excess Ice On' minus 'Off') in soil temperature (K) and soil liquid water (m³/m³) from 1920 to 2014. The values represent the spatial mean across all grid cells containing excess ice, shown specifically for the 0.21 m and 1.04 m soil depths.**

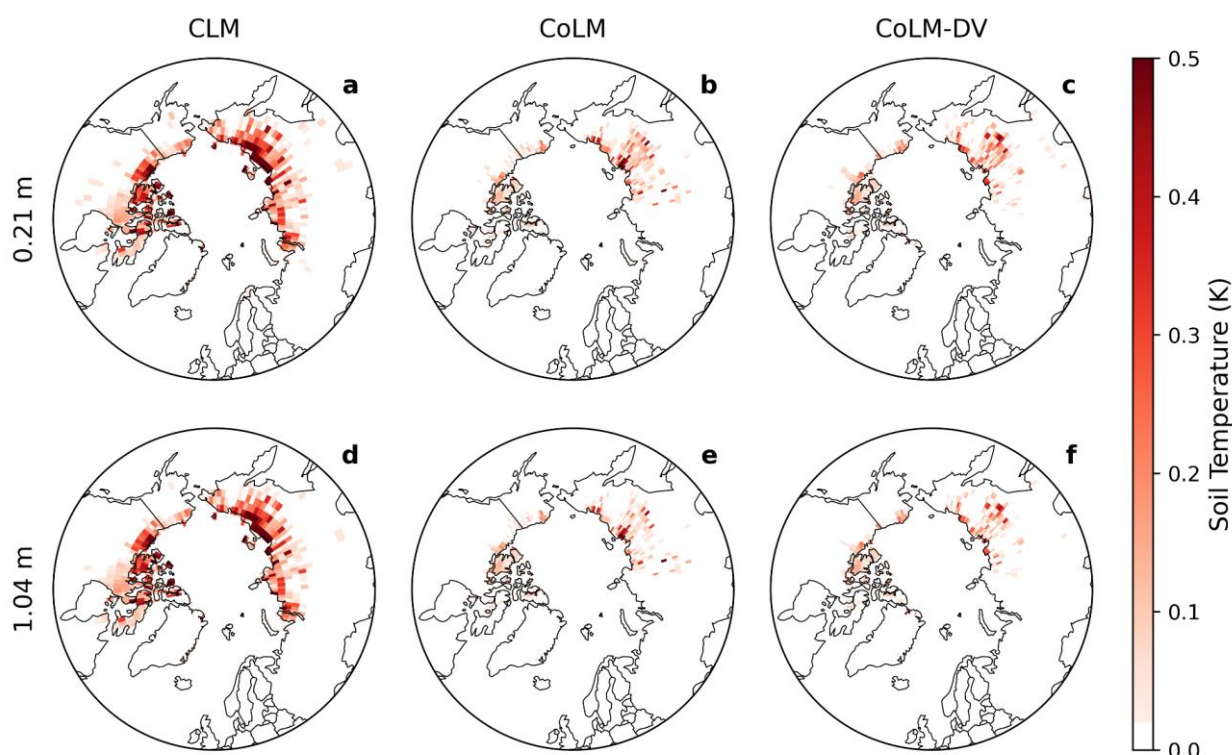


Figure 6. Spatial distribution of the simulated mean soil temperature differences ('Excess Ice On' minus 'Off') from 1920 to 2014.

The soil liquid water response to excess ice appears more complex and depth dependent (Figure 7). In all three configurations the dominant pattern is that the upper soil layers (here showing 0.21 m) show mostly a wetting trend when excess ice is turned on, while the somewhat deeper soil (here showing 1.04 m) is mainly dryer in the excess ice runs. In both cases the absolute numbers are small, but reveals an interesting vertical dynamics. The increased soil liquid water near the surface in excess ice runs likely comes from a combination of water coming from the melting excess ice and a reduced infiltration to deeper soil layers when excess ice is present. The reduced infiltration when there is more ground ice can also explain why the lower layers (and the upper layers in some of the coldest regions in CLM) show reduced soil liquid water. However, it is worth noting that the annual mean soil liquid numbers presented here will also be affected by the timing of the spring thaw in the different layers, and the change in total soil water could therefore deviate somewhat from this.

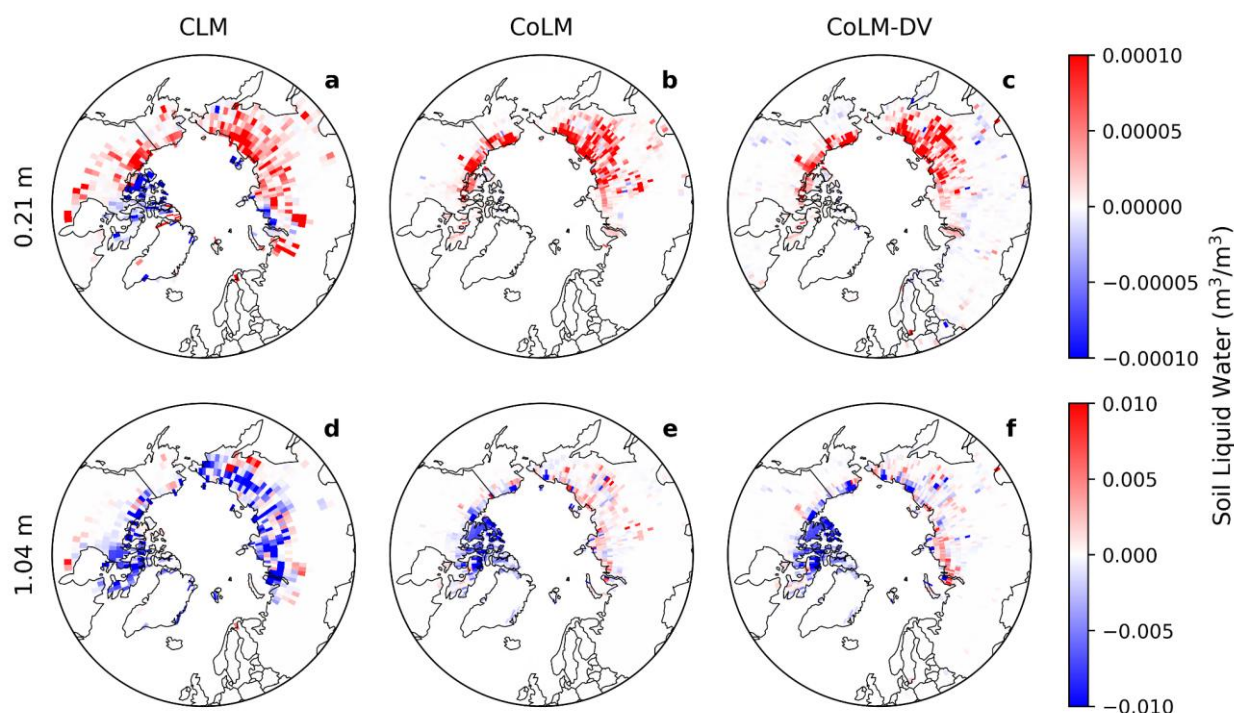
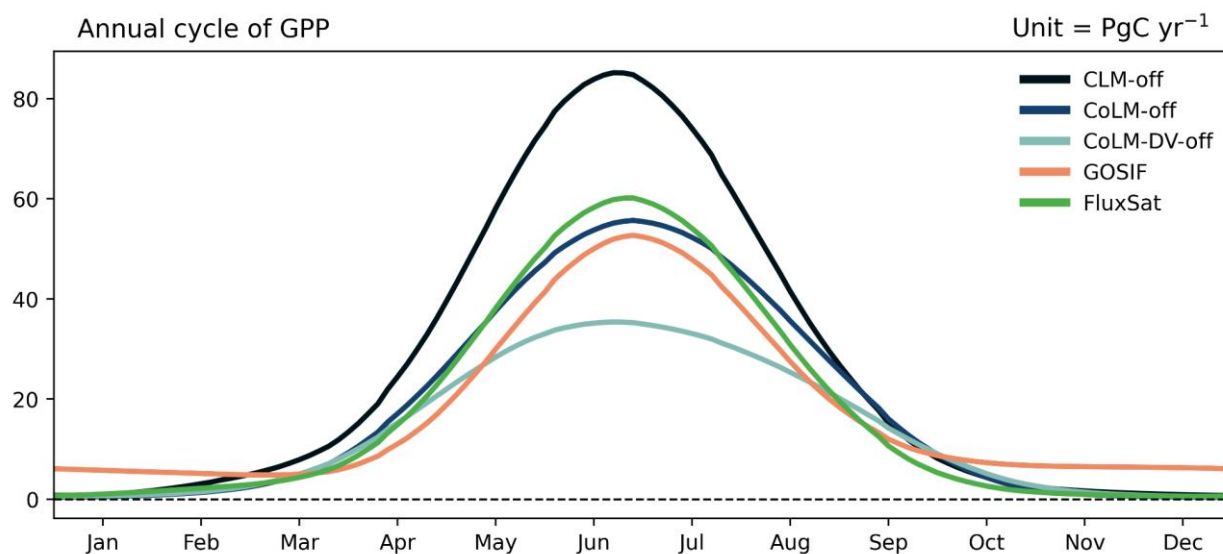


Figure 7. Spatial distribution of the simulated mean soil liquid water differences ('Excess Ice On' minus 'Off') from 1920 to 2014.

3.2 Biogeochemical properties

We first evaluated the baseline performance of the three model configurations without excess ice against observational products (Figure 8). The climatological mean seasonal cycle of pan-Arctic GPP over 2001–2014 shows that CLM substantially overestimates summertime productivity relative to both the GOSIF and FluxSat datasets. CoLM performs within the range of observational products, while CoLM-DV simulates a substantially lower peak of around 35 PgC yr^{-1} . Spatially, CLM produces high GPP values across much of the boreal and sub-Arctic domain, while CoLM shows a spatially smoother and more moderate GPP field that compares more favorably in spatial pattern to GOSIF and FluxSat (Figure 9). The CoLM-DV, on the other hand, shows systematically lower GPP across the pan-Arctic domain, suggesting that the dynamic vegetation configuration may be suppressing plant cover and productivity in these regions relative to reality.



220 **Figure 8. Climatological mean seasonal cycle of Gross Primary Production (GPP) averaged over the pan-Arctic region ($\geq 50^\circ\text{N}$) for the period 2001–2014.**

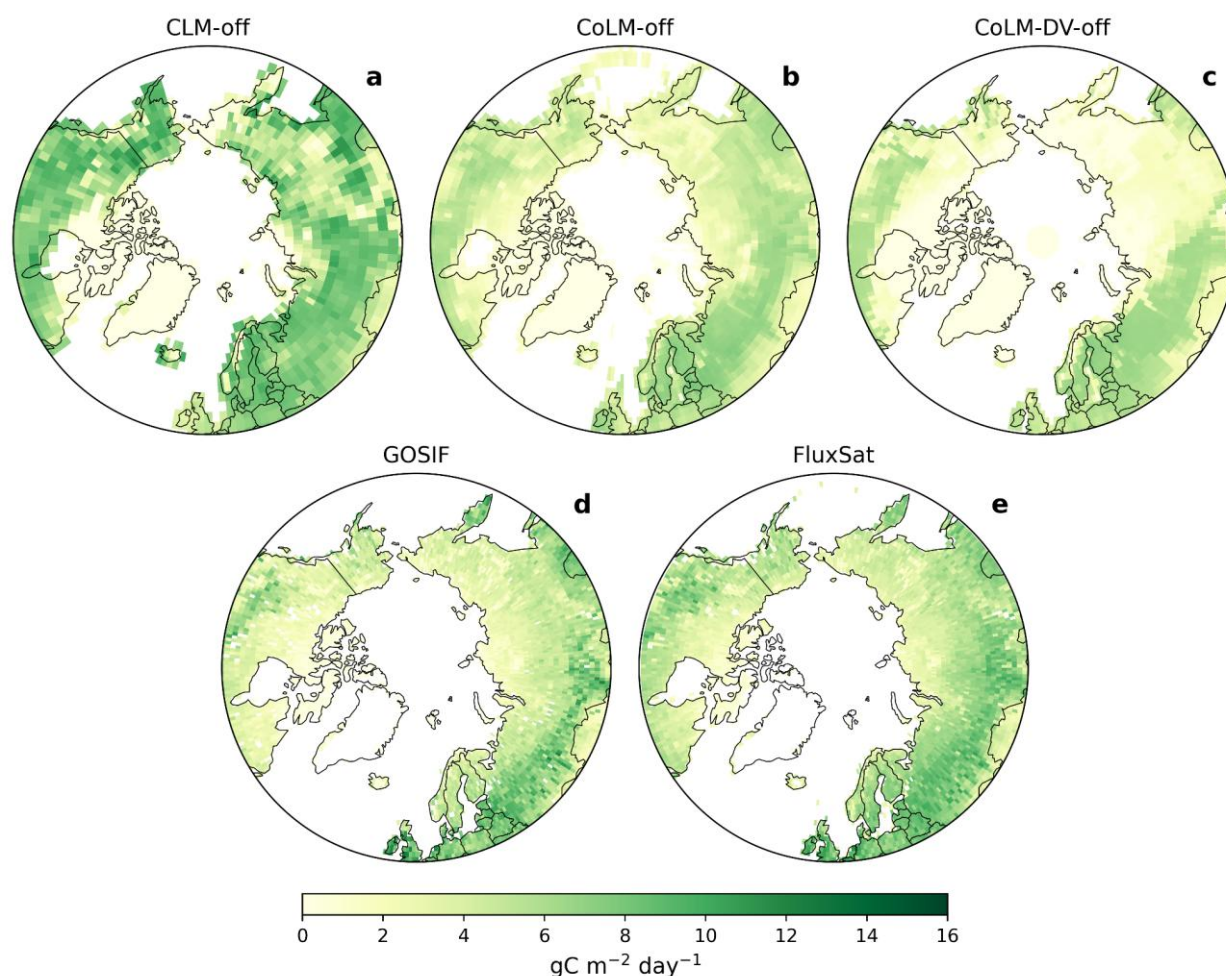


Figure 9. Spatial distribution of the climatological mean summer (JJA) Gross Primary Production (GPP) for the period 2001–2014.

The effect of excess ice on GPP differs in sign and magnitude across the three models (Figure 10). In CLM, excess ice leads to a persistent and large negative GPP anomaly throughout the simulation. There are annual mean differences around -40 to -70 TgC yr^{-1} across ice-rich grid cells (Figure 10d). This strong suppression of productivity in CLM is consistent with the soil warming effect imposed by excess ice melt, where the large latent heat consumption associated with ice thaw keeps soil temperatures lower in the 'Excess Ice On' simulation, potentially limiting photosynthesis. In CoLM, excess ice also produces a negative GPP anomaly, but of considerably smaller magnitude, with annual differences generally between -5 and -20 TgC yr^{-1} . The CoLM-DV, on the other hand, shows a positive GPP response to excess ice, with annual differences of approximately $+15$ to $+25 \text{ TgC yr}^{-1}$ (Figure 10d). This response reflects the role of the dynamic vegetation module in CoLM. The thaw of excess ground ice generates warmer and wetter environmental conditions in surface level (Figure 5), which favor plant growth and lead to increased shrub and grass cover (Figure 11). The resulting vegetation expansion enhances photosynthetic activity and consequently increases GPP. Spatially, CLM shows widespread negative GPP differences across



235 much of the boreal and sub-Arctic permafrost region (Figure 10a), while CoLM shows predominantly negative but spatially
 limited anomalies concentrated in northern Siberia and Alaska (Figure 10b). Additionally, CoLM-DV shows a more
 geographically widespread pattern of positive GPP differences particularly across the Canadian Arctic and northern Eurasia
 (Figure 10c) due to increased shrub and grass fraction over bare soil (Figure 11). Together, these vegetation shifts suggest
 that the dynamic coupling between excess ice, soil temperature and moisture, and plant community composition introduces
 240 an important addition in the biogeochemical response to permafrost thaw that static vegetation models cannot capture.

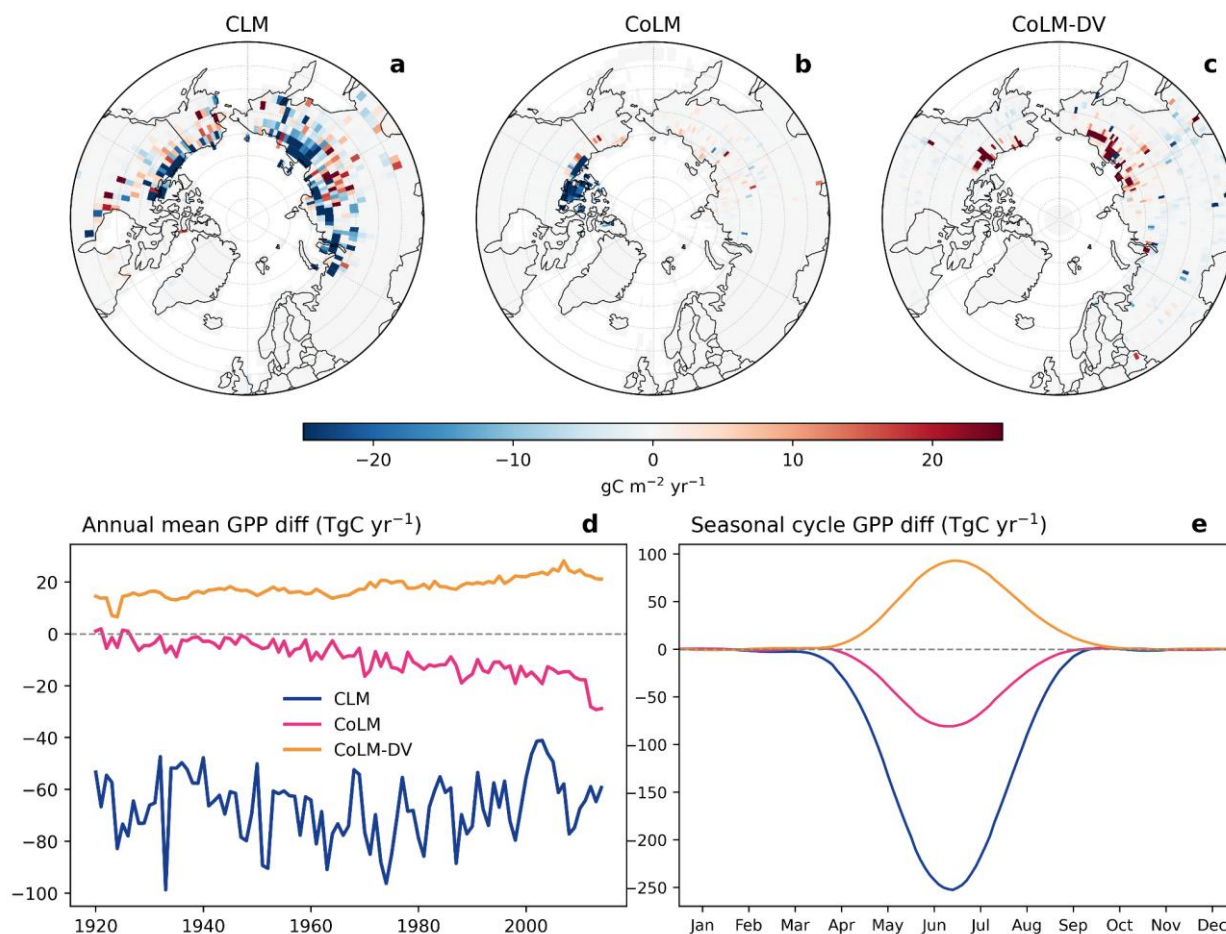


Figure 10. Simulated GPP differences induced by excess ice ('On' minus 'Off') over the 1920–2014 period. (a–c) Spatial
 distribution of the mean GPP differences in the boreal region. (d) Interannual evolution of the regionally averaged GPP
 differences across all grid cells containing excess ice for CLM, CoLM, and CoLM-DV. (e) Mean seasonal cycle of these GPP
 245 differences over the same ice-rich grid cells.

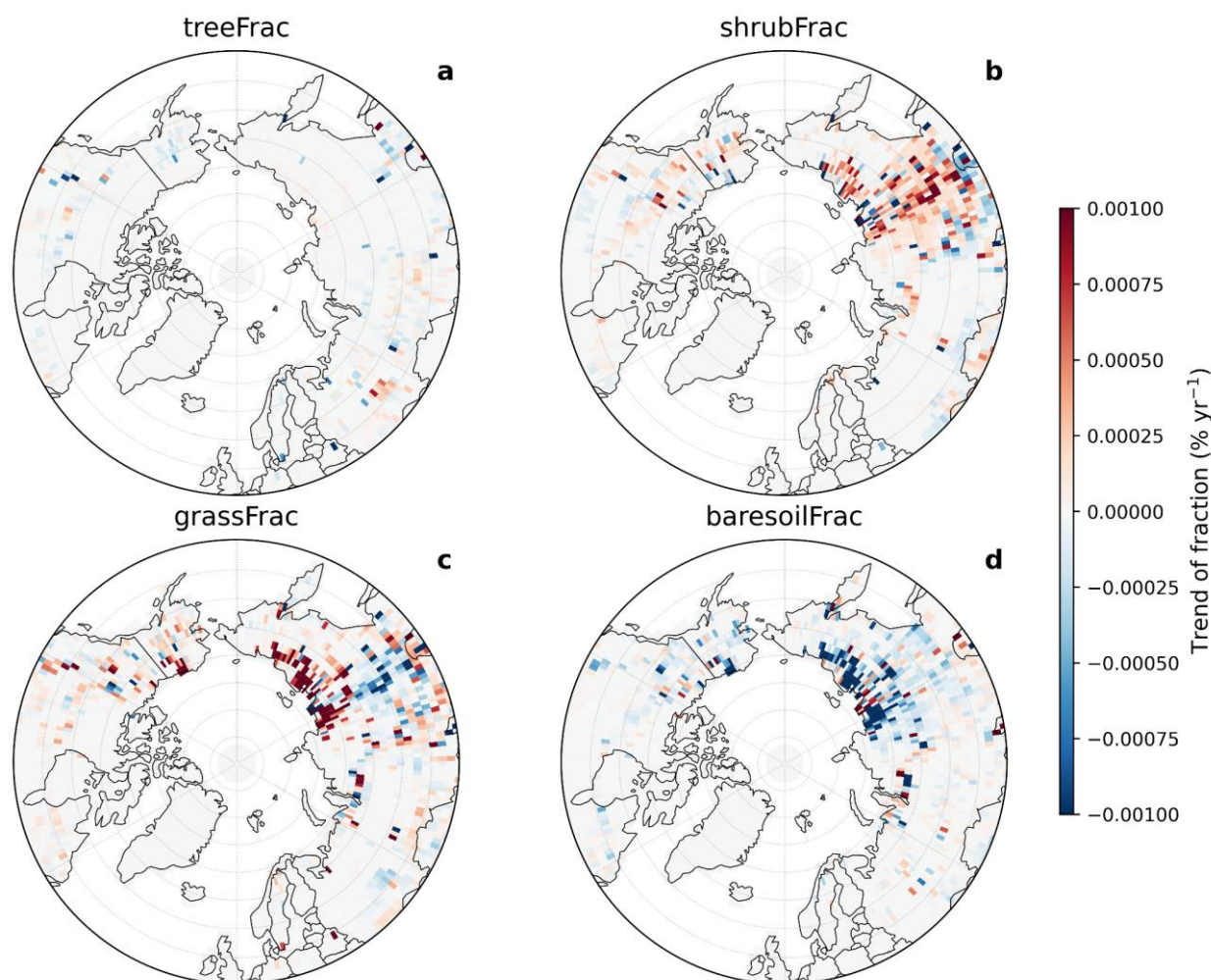


Figure 11. Long-term trends (from 1920 to 2014) in the fractional cover differences ('Excess Ice On' minus 'Off') for four major land cover types (tree, shrub, grass, and bare soil) simulated by CoLM-DV.

4 Conclusions

250 In this study, we incorporated excess ground ice physics into CoLM and conducted paired sensitivity experiments to compare the simulated response of pan-Arctic permafrost to excess ice across two structurally distinct land surface models (CLM, CoLM, and CoLM-DGVM) over the historical period. Our results demonstrate that both models capture the expected physical signatures of excess ice, including latent heat buffering of soil temperatures and progressive ice volume loss under historical warming, but differ substantially in the magnitude and spatial extent of these responses. The CoLM simulates a
 255 considerably stronger thermal and excess ice melt response than CLM, likely reflecting differences in soil column configuration, thermal parameterization, snow scheme, and the vertical placement of excess ice. The biogeochemical



responses diverge even more as a result. Excess ice suppresses GPP in both CLM and CoLM, while CoLM-DV shows the opposite response as dynamic vegetation expands shrub cover in response to the altered soil conditions, highlighting how the representation of vegetation dynamics can alter the direction of the carbon cycle response to permafrost thaw.

260 These contrasting responses underscore a central challenge in permafrost modeling that motivated this study, i.e. what happens to the same physical process, when embedded in different model architectures? We consider this not a failure of either model, but rather an inevitable consequence of the different structure present in different models. These include soil discretization, hydrological schemes, and vegetation representation. For this reason, cross-model comparison could be a valuable and necessary part of model development. When implementing a new process parameterization such as excess
265 ground ice, benchmarking against both observational products and an established model that has already incorporated the same scheme provides an interesting avenue for quality control. It allows us to distinguish responses that are physically robust and transferable across models from those that are artifacts of a particular model structure. This further identifies process understanding or necessity for parameterization refinement.

This work is part of a broader collaborative effort between the NorESM-CTSM and CAS-ESM modeling groups, and
270 reflects the kind of targeted co-development that has been called for by the permafrost modeling community to accelerate progress on representing abrupt thaw processes in ESMs (Schädel et al., 2024). As emphasized in the introduction, the absence of excess ice and abrupt thaw from most ESMs likely leads to a systematic underestimation of permafrost-carbon feedbacks under future warming. While we did not directly quantify feedbacks, our study demonstrates that incorporating excess ground ice produces physically meaningful and biogeochemically significant responses in both models. In addition,
275 the two models respond in ways that are broadly consistent in direction even where they vary in magnitude. This consistency provides confidence that the excess ice scheme is functioning as intended in the newly implemented CoLM framework, and that the cross-model differences reflect genuine structural sensitivities rather than implementation errors. Therefore, future work should extend this comparison to fully coupled ESM simulations and future climate scenarios, where the accelerating pace of Arctic warming is expected to make the role of excess ice and abrupt thaw increasingly consequential for the global
280 carbon budget.

Code and data availability

The code repository (<https://doi.org/10.5281/zenodo.23077934>, Guo, 2025) contains the Jupyter notebooks necessary to reproduce all figures in this study. The CoLM and CoLM-DV simulation output data used in this study are available at: <https://doi.org/10.5281/zenodo.20809122> (Zhu and Guo, 2026). CLM source code for performed simulations is accessible
285 from Zenodo at <https://doi.org/10.5281/zenodo.21098981> (Debol'skiy, 2026a) and the simulations output as well as setup to reproduce the simulations are available at <https://doi.org/10.5281/zenodo.21026350> (Debol'skiy, 2026b). The records and files are publicly accessible.



Author contributions

JZ conducted model development for CoLM. MD performed simulations for CLM and provided technical support for CoLM
290 development. LG performed simulations for CoLM and analyzed the data. FL and HL conceived the original idea and
acquired funding. JZ, MD, LG, KA, SW. and HL wrote the manuscript. All authors participated in revising the manuscript.

Competing interests

None.

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References

- Bonan, G. B.: A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical
description and user's guide, NCAR Technical Note NCAR/TN-417+STR, National Center for Atmospheric Research,
Boulder, CO, 1996.
- 310 Bonan, G. B.: The American Meteorological Society land surface-atmosphere experiment (LSMEX), B. Am. Meteorol. Soc.,
79, 2417–2432, 1998.



- Brown, J., Ferrians, O., Heginbottom, J. A., and Melnikov, E.: Circum-Arctic map of permafrost and ground-ice conditions, National Snow and Ice Data Center, Boulder, CO, 1997.
- Burke, E. J., Zhang, Y., and Krinner, G.: Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change, *The Cryosphere*, 14, 3155–3174, <https://doi.org/10.5194/tc-14-3155-2020>, 2020.
- Dai, Y., Zeng, Q.: A land surface model (IAP94) for climate studies part I: Formulation and validation in off-line experiments. *Adv. Atmos. Sci.* 14, 433–460, 1997. <https://doi.org/10.1007/s00376-997-0063-4>
- Dai, Y., Zeng, X., Dickinson, R. E., Baker, I., Bonan, G. B., Bosilovich, M. G., Denning, A. S., Dirmeyer, P. A., Houser, P. R., Niu, G., Oleson, K. W., Schlosser, C. A., and Yang, Z. L.: The Common Land Model, *B. Am. Meteorol. Soc.*, 84, 1013–1024, 2003. <https://doi.org/10.1175/BAMS-84-8-1013>
- Dai, Y., R. E. Dickinson, Wang, Y.: A Two-Big-Leaf Model for Canopy Temperature, Photosynthesis, and Stomatal Conductance, *J. Climate*, 17, 2281–2299, 2004. [https://doi.org/10.1175/1520-0442\(2004\)017<2281:ATMFCT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2281:ATMFCT>2.0.CO;2).
- Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Lawrence, D. M., Medeiros, B., Jochum, M., ... and Strand, W. G.: The Community Earth System Model version 2 (CESM2), *J. Adv. Model. Earth Sy.*, 12, e2019MS001916, <https://doi.org/10.1029/2019MS001916>, 2020.
- Debol'skiy, M.: mvdebol'skiy/CTSM: Excess_ice_simulations_v0.0.0 (ctsm5.1.135_exice), Zenodo [software], <https://doi.org/10.5281/zenodo.21098981>, 2026a.
- Debol'skiy, M.: Output from historical simulations for evaluating excess ice parameterization CLM5.1 (v0.0.0), Zenodo [data set], <https://doi.org/10.5281/zenodo.21026350>, 2026b.
- Dickinson, R. E., Henderson-Sellers, A., and Kennedy, P. J.: Biosphere-Atmosphere Transfer Scheme (BATS) version 1e as coupled to the NCAR Community Climate Model, NCAR Technical Note NCAR/TN-387+STR, National Center for Atmospheric Research, Boulder, CO, 1993.
- Gao, M., Dai, Y., and Wang, Z.: A front-tracking scheme for the simulation of soil freezing and thawing, *J. Hydrol.*, 539, 432–445, 2016.
- Gao, M., Dai, Y., and Wang, Z.: Improving the numerical simulation of frost front dynamics in land surface models, *J. Geophys. Res.-Atmos.*, 124, 1025–1043, 2019.
- Guo, L.: Analysis code for "Incorporating pan-Arctic excess ground ice across structurally distinct Land Surface Models: Community Land Model (CLM5.1) and Common Land Model (CoLM2014)", Zenodo [code], <https://doi.org/10.5281/zenodo.23077934>.
- Grosse, G., Romanovsky, V., Walter Anthony, K., Jones, B. M., Jorgenson, M. T., and Marchenko, S. S.: Vulnerability of high-latitude soil organic carbon in a changing climate, *Ecosphere*, 2, 1–23, 2011.
- Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P.:



- 345 Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and regional distributions, *Biogeosciences*, 11, 6573–6593, <https://doi.org/10.5194/bg-11-6573-2014>, 2014.
- Ji, D., Wang, L., Feng, J., Wu, Q., Cheng, H., Zhang, Q., ... and Moore, J. C.: Description and basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1, *Geosci. Model Dev.*, 7, 2039–2064, <https://doi.org/10.5194/gmd-7-2039-2014>, 2014.
- 350 Jorgenson, M. T., Shur, Y. L., and Pullman, E. R.: Abrupt increase in permafrost degradation in Arctic Alaska, *Geophys. Res. Lett.*, 33, L02503, <https://doi.org/10.1029/2005GL024939>, 2006.
- Koven, C. D., Friedlingstein, P., Ciais, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: On the radio-carbon date structure of deep permafrost carbon pools and its implications for climate feedback, *Biogeosciences*, 6, 2389–2403, <https://doi.org/10.5194/bg-6-2389-2009>, 2009.
- 355 Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Crill, P., Burke, E. J., Chen, G., Schneider von Deimling, T., Riley, W. J., and Davidson, E. A.: Permafrost carbon-climate feedbacks accelerate global warming, *P. Natl. Acad. Sci. USA*, 108, 14769–14774, <https://doi.org/10.1073/pnas.1103910108>, 2011.
- Lawrence, D. M. and Slater, A. G.: Incorporating leaves, snow, and organic matter into a bedrock-to-atmosphere land surface model: Consequences for permafrost simulation, *J. Geophys. Res.-Earth*, 113, F02007, <https://doi.org/10.1029/2007JF000883>, 2008.
- 360 Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., ... and Zeng, X.: The Community Land Model version 5 (CLM5): Description of new features, regional, and global applications, *J. Adv. Model. Earth Sy.*, 11, 2545–2587, <https://doi.org/10.1029/2018MS001583>, 2019.
- Lee, H., Swenson, S. C., Lawrence, D. M., Alexeev, V. A., Nicolsky, D. J., and Marchenko, S. S.: Effects of excess ground ice on projections of permafrost in a warming climate, *Environ. Res. Lett.*, 9, 124006, <https://doi.org/10.1088/1748-9326/9/12/124006>, 2014.
- 365 Li, F., Zeng, X. D., and Levis, S.: A process-based fire parameterization of intermediate complexity in a Dynamic Global Vegetation Model, *Biogeosciences*, 9, 2761–2780, <https://doi.org/10.5194/bg-9-2761-2012>, 2012.
- Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. V., Grosse, G., ... and Zona, D.: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology, *Nat. Geosci.*, 9, 312–318, <https://doi.org/10.1038/ngeo2674>, 2016.
- 370 Niu, G. Y. and Yang, Z. L.: Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale, *J. Hydrometeorol.*, 7, 937–952, <https://doi.org/10.1175/JHM538.1>, 2006.
- Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., ... and Zou, D.: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale, *Earth-Sci. Rev.*, 193, 299–316, <https://doi.org/10.1016/j.earscirev.2019.04.023>, 2019.
- Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., ... and Turetsky, M. R.: Circumpolar distribution and carbon storage of thermokarst landscapes, *Nat. Commun.*, 7, 13043, <https://doi.org/10.1038/ncomms13043>, 2016.



- Ran, Y., Li, X., Cheng, G., Che, J., Wu, J., Luo, D., ... and Yang, Y.: New estimates of permafrost distribution on the Tibetan Plateau from 2000 to 2016, *Earth Syst. Sci. Data*, 14, 525–540, <https://doi.org/10.5194/essd-14-525-2022>, 2022.
- Schädel, C., Schuur, E. A. G., Bracho, R., Elberling, B., Knoblauch, C., Lee, H., ... and Wilkinson, M.: A synthesis of permafrost thaw and carbon cycle responses across Earth System Models, *Nat. Commun.*, 15, 2468, 2024.
- Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., and Vonk, J. E.: Climate change and the permafrost carbon feedback, *Nature*, 520, 171–179, 2015.
- Schuur, E. A. G., Bracho, R., Celis, G., Grieco, A. K., Hutchings, J., Ledman, J., ... and Webb, E. E.: Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic, *Annu. Rev. Env. Resour.*, 47, 343–371, <https://doi.org/10.1146/annurev-environ-012220-011847>, 2022.
- Seland, Ø., Bentsen, M., Olivie, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., ... and Schulz, M.: Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 simulations, *Geosci. Model Dev.*, 13, 6165–6200, <https://doi.org/10.5194/gmd-13-6165-2020>, 2020.
- Steinert, N. J., Debolskiy, M. V., Burke, E. J., Garcia-Pereira, F., Nitzbon, J., Turetsky, M., Chadburn, S. E., and Krinner, G.: Evaluating permafrost definitions for global permafrost area estimates in CMIP6 climate models, *Environ. Res. Lett.*, 19, 014033, <https://doi.org/10.1088/1748-9326/ad10d7>, 2024.
- Swenson, S. C. and Lawrence, D. M.: A new fractional snow cover parameterization for the Community Land Model and its effect on the state of the ground, *J. Geophys. Res.-Atmos.*, 117, D21107, <https://doi.org/10.1029/2012JD018178>, 2012.
- Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., ... and McGuire, A. D.: Carbon release frequently underestimated by gradual permafrost thaw models, *Nat. Geosci.*, 13, 138–143, 2020.
- van Kampenhout, L., Lenaerts, J. T. M., Lipscomb, W. H., Sacks, W. J., Lawrence, D. M., Slater, A. G., and van den Broeke, M. R.: Improving the representation of polar snow in the Community Land Model, *J. Adv. Model. Earth Sy.*, 9, 2383–2400, 2017.
- Webb, E. E., Schuur, E. A. G., Natali, S. M., and Schädel, C.: Quantifying the abrupt thaw feedback of Arctic carbon cycles under warming scenarios, *Global Change Biol.*, 31, e16842, 2025.
- Xu-Ri and Prentice, I. C.: Terrestrial nitrogen cycle simulation with a dynamic global vegetation model, *Global Change Biol.*, 14, 1745–1764, 2008.
- Zeng, X. D.: A new formulation of plant geographic distribution logic for dynamic global vegetation models, *Adv. Atmos. Sci.*, 27, 1253–1266, 2010.
- Zeng, X. D., Zeng, X., and Barlage, M.: Growing shrub fraction on the bare soil horizon: Implementation in a dynamic global vegetation model, *J. Geophys. Res.-Biogeo.*, 113, G03004, <https://doi.org/10.1029/2007JG000574>, 2008.
- Zhu, J., Dai, Y., and Song, X.: Development and evaluation of the IAP Dynamic Global Vegetation Model (IAP-DGVM), *J. Adv. Model. Earth Sy.*, 10, 1532–1550, 2018.

<https://doi.org/10.5194/egusphere-2026-4332>

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Zhu, J. and Guo, L.: CoLM and CoLM-DV simulation output: excess-ice on/off experiments, Zenodo [data set], <https://doi.org/10.5281/zenodo.20809122>, 2026.