Response to Referee 1

We sincerely thank the referee for the careful evaluation of our manuscript and for the constructive comments. We appreciate the recognition of the effort involved in modifying and evaluating a land surface model. We also agree that the scope, physical interpretation, and robustness of the proposed developments should be more clearly presented. Below, we respond to each comment in detail.

General comments

Comment

Yang et al. present modifications to the LPJ-GUESS model by introducing a deeper and more discretized soil column and accounting for the influence of soil ice content on water percolation. The model is evaluated at a limited number of sites within a small region. I appreciate the effort involved in modifying and testing a land surface model, and I recognize the challenges associated with implementing new processes and conducting validation.

However, I have several concerns regarding the scope, robustness, and physical interpretation of the proposed developments.

First, the extent of the model development appears relatively limited. While incorporating the effect of soil ice on percolation is a useful step, it does not fully justify the designation of a "Cryo" version of LPJ-GUESS. Freeze–thaw processes typically influence multiple aspects of land surface dynamics, including soil thermal properties, hydraulic conductivity, and carbon transport. In its current form, the model seems to account for only a subset of these processes, and the representation of freeze–thaw impacts on coupled water–heat dynamics remains incomplete.

Second, the evaluation is conducted over a relatively small region with a limited number of observational sites. This raises questions about the robustness and general applicability of the proposed modifications. It would be important to demonstrate whether the model improvements hold across a broader range of environmental conditions.

Third, the manuscript lacks a sufficiently detailed physical interpretation of the results. For instance, the impact of increased soil layering and freeze–thaw processes on hydrological and thermal dynamics, as well as their implications for vegetation, are not fully explained. Given the relatively modest model modifications, it is unclear whether the model is capable of supporting such mechanistic interpretations.

Response: We thank the referee for this important and constructive assessment. We agree that the original manuscript did not sufficiently constrain the scope of the model developments, nor clearly separate the respective contributions of soil vertical discretization and freeze–thaw-related hydrological processes. We have substantially revised the manuscript to clarify these aspects and to avoid overstating the current model capability.

First, we agree that the previous terminology ("LPJ-GUESS-Cryo") could imply a more comprehensive cryosphere representation than is currently implemented. In response to this concern, we no longer use the term "LPJ-GUESS-Cryo" in the revised manuscript. Instead, we refer to the modified framework more generally as an improved LPJ-GUESS configuration with enhanced representation of soil hydrothermal processes in permafrost-affected ecosystems. This revised terminology more accurately reflects the actual scope of the developments presented in this study and avoids implying a comprehensive cryosphere modelling framework. We also clarified throughout the manuscript that the present developments focus on selected soil hydrothermal processes relevant to permafrost environments rather than a fully coupled cryosphere representation.

Specifically, we replaced the previous description in Section 2.2 (former P4, Line 91), which stated:

" ***In this study, we further refined the soil module of LPJ-GUESS v4.1 by implementing a cryosphere-oriented soil freeze–thaw scheme to improve the representation of soil hydrothermal processes in permafrost-affected regions. To distinguish simulations produced by the original and the modified model configurations, we hereafter refer to the default model as LPJ-GUESS and to the modified version as LPJ-GUESS-Cryo.***"

with the following revised description (P6, Line 158):

"***In this study, we improved the soil module of LPJ-GUESS v4.1 to better represent soil hydrothermal processes in permafrost-affected ecosystems. The improvements primarily include a deeper vertically discretized soil column and the incorporation of freeze–thaw constraints on soil water percolation. Throughout the manuscript, the default model configuration is referred to as LPJ-GUESS, while the modified configuration is referred to as the improved LPJ-GUESS configuration.***"

In addition, we systematically revised the terminology throughout the manuscript to ensure that the wording consistently reflects the actual scope of the implemented developments and avoids overstating the model capability. Specifically:

- ***"original model" was replaced with "LPJ-GUESS", "original LPJ-GUESS", or "default LPJ-GUESS configuration";***
- ***"LPJ-GUESS-Cryo" was replaced with "improved LPJ-GUESS configuration" or "improved configuration";***
- ***"Cryo modification" was replaced with "improved representation of soil hydrothermal processes";***
- ***"Cryo version" was replaced with "improved configuration".***

The current model developments primarily focus on improving soil hydrothermal representation through two process-level modifications: (i) increasing soil vertical resolution to better represent vertical thermal and hydrological gradients, and (ii) introducing a freeze–thaw-related constraint on downward liquid water percolation under frozen or partially frozen soil conditions. We acknowledge that several important freeze–thaw-related processes remain outside the scope of the present study, including dynamic soil thermal properties, vertically resolved soil carbon decomposition, cryoturbation, talik dynamics, and explicit permafrost carbon emissions. We have revised the manuscript to clarify these limitations and to avoid overstating the scope of the current model developments (P21 L500).

"In addition, the present developments focus primarily on selected soil hydrothermal processes relevant to permafrost environments rather than a comprehensive representation of coupled permafrost–carbon feedbacks. To maintain computational efficiency and regional applicability in large-scale DGVM simulations, the current framework prioritizes process-level improvements expected to exert first-order controls on subsurface hydrothermal dynamics. Several important processes, including vertically resolved soil carbon decomposition, talik dynamics, and explicit permafrost carbon emissions, remain unresolved in the current framework."

Second, we agree that the current evaluation remains spatially limited. The present study focuses on boreal forest ecosystems in Northeast China, where discontinuous permafrost degradation and rapid warming strongly influence ecosystem processes. Although this region provides a useful test case for evaluating the proposed developments, we agree that broader validation across pan-Arctic environmental gradients is still required before generalizing model applicability. We now explicitly acknowledge this limitation in the revised manuscript and discuss the need for future large-scale evaluations under broader permafrost and climatic conditions (P21 L510).

"More broadly, the present evaluation remains regionally constrained to the permafrost-affected forests of Northeast China. Although this region represents a climatically sensitive transition zone characterized by rapid warming and discontinuous permafrost degradation, broader validation across pan-Arctic environmental gradients and permafrost regimes is still required before generalizing model applicability at the circumpolar scale. Future work should therefore combine improved process representation with broader pan-Arctic evaluations and long-term observations to better assess ecosystem carbon dynamics under continued climate warming."

Third, we agree that the original manuscript did not sufficiently explain the respective roles of enhanced soil vertical discretization and freeze–thaw-related hydrological constraints. Because the original LPJ-GUESS configuration uses a two-layer soil structure and does not provide vertically resolved outputs comparable to the 30-layer simulations, a fully depth-resolved factorial sensitivity analysis was not feasible. We therefore combined two complementary analyses: first, a site-level configuration comparison against observations to evaluate the overall effect of enhanced vertical discretization; and second, a process-oriented paired experiment within the 30-layer framework to isolate the influence of the ice impedance formulation.

Accordingly, we evaluated the contribution of increased soil vertical discretization using site-level validation against the original LPJ-GUESS configuration, and further isolated the influence of the ice impedance formulation within the revised multilayer framework.

Specifically, we compared:
(1) a 30-layer soil configuration without freeze–thaw-related percolation constraints, and(2) a 30-layer configuration including the ice impedance formulation.

The sensitivity experiments showed that the introduction of the enhanced soil vertical discretization produced the largest improvement in soil temperature simulations, particularly at deeper soil layers. This indicates that improved vertical discretization is the dominant factor improving subsurface thermal representation. In contrast, the additional contribution of the ice impedance scheme to soil temperature RMSE was comparatively modest. However, this result is physically consistent because the ice impedance formulation primarily regulates vertical liquid water redistribution rather than thermal diffusion itself.

Importantly, the soil water content sensitivity analysis demonstrated that the original LPJ-GUESS configuration substantially overestimated lower-layer soil water content, often approaching near-saturation conditions. The revised configuration substantially reduced this bias, while the inclusion of the ice impedance formulation further improved lower-layer soil water content at several sites by constraining excessive downward percolation under frozen conditions. These results suggest that enhanced soil vertical discretization mainly improves subsurface thermal representation, whereas the ice impedance formulation primarily contributes to improving the physical realism of freeze–thaw-controlled hydrological processes.

Specifically, to further evaluate the hydrological influence of freeze–thaw-related hydraulic constraints within the revised multilayer framework, we added a new subsection entitled "***Sensitivity analysis of revised soil representations***" in the Methods section.

The following text was added to the revised manuscript:

"To further isolate the relative effects of the revised soil representations, a process-oriented sensitivity analysis was conducted using two multilayer soil configurations: (1) a multilayer soil scheme without freeze--thaw-related hydraulic constraints, and (2) the same multilayer soil configuration including the ice impedance formulation.

Daily soil temperature and soil water content outputs from all soil layers were extracted for the period 2017--2022 at the representative permafrost site. Vertical soil thermal and hydrological dynamics were evaluated using depth--time contour analyses to compare seasonal propagation of thermal signals and vertical redistribution of soil water between the two experiments. To further quantify the influence of the ice impedance formulation, difference analyses were performed by calculating the deviations between the two simulations for soil temperature and soil water content throughout the soil profile.

In addition, mean vertical difference profiles were calculated to summarize the average influence of the ice impedance formulation on subsurface thermal and hydrological conditions across the entire simulation period. These analyses were used to evaluate the relative and interactive effects of increased soil vertical discretization and freeze--thaw-related hydraulic constraints on subsurface heat transfer and soil water redistribution.
”

In addition, we added a new summary figure entitled ***“Process-oriented sensitivity analysis of revised soil representations.***” (Fig. 4) to summarize the relative effects of increased soil vertical discretization and the ice impedance formulation on deep-soil temperature simulations and lower-layer soil water content. Detailed sensitivity analysis results for all sites and soil depths were additionally included in the Supplementary Material.

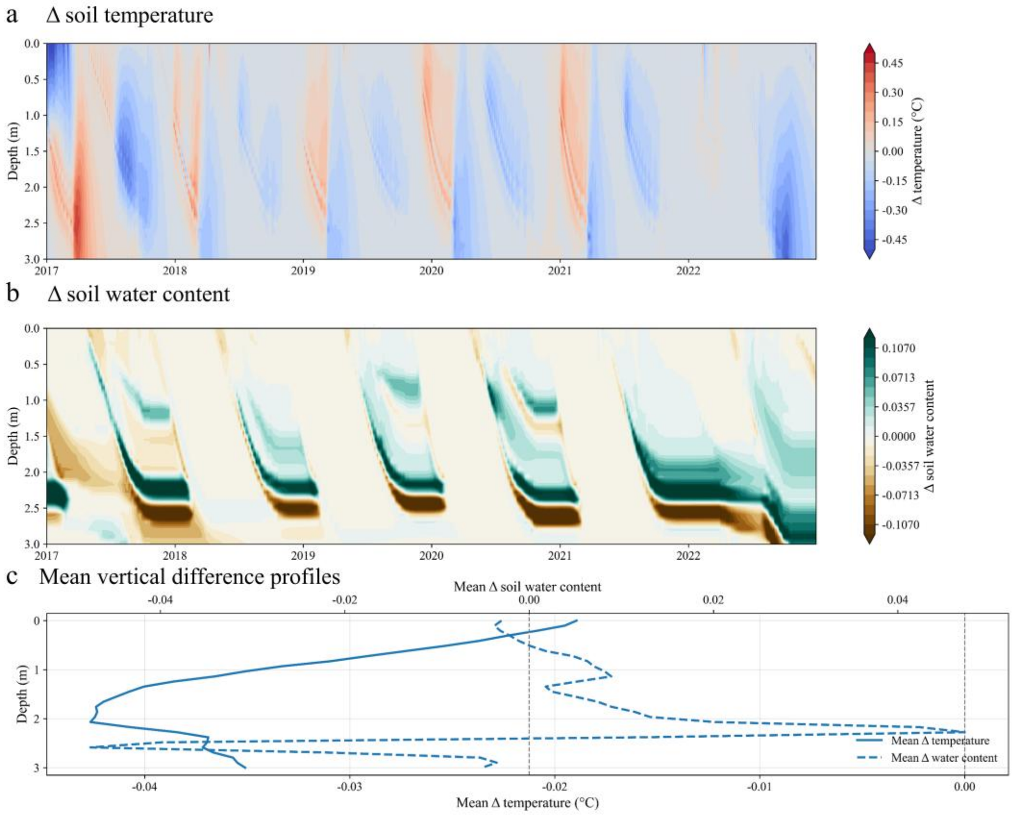


Figure 4. Process-oriented sensitivity analysis of revised soil representations. (a) Differences in soil temperature (∆ST, ◦C) between the multilayer soil configuration including the ice impedance formulation and the multilayer configuration without ice impedance. (b) Differences in soil water content (∆SWC, m3 m−3) between the two simulations. Positive values indicate higher soil temperature or soil water content in the simulation including the ice impedance formulation. (c) Mean vertical profiles of ∆ST and ∆SWC averaged over the entire simulation period (2017–2022).

We further revised the Results section ***(“3.1 Performance of soil thermal and hydrological simulations”***) to explicitly describe the sensitivity analysis results and clarify the respective contributions of the two process-level modifications. The following text was added (P14, L335):

“To further evaluate the relative effects of the revised soil representations, a process-oriented sensitivity analysis was conducted using two multilayer soil configurations: a multilayer soil scheme without the ice impedance formulation and the same multilayer configuration including freeze–thaw-related hydraulic constraints. The sensitivity analysis showed that both simulations reproduced similar large-scale patterns of seasonal soil thermal propagation, with thermal signals progressively attenuating with depth (Fig. 2). The difference analysis further indicated that the inclusion of the ice impedance formulation resulted in relatively small changes in the bulk soil thermal regime, with a mean soil temperature difference of only −0.034 °C across the soil profile. Most soil temperature differences remained within ±0.5 °C and were mainly concentrated around seasonal thawing and refreezing fronts (Fig. 2a), suggesting that freeze–thaw-related hydraulic constraints exerted comparatively limited direct influence on overall subsurface heat propagation.

In contrast, substantially larger differences were observed in soil water redistribution after incorporating the ice impedance formulation (Fig. 2b). Although the mean difference in soil water content was relatively small (0.003), local differences reached up to ±0.2, particularly within the active freeze–thaw transition zone and deeper soil layers below approximately 1.5 m depth. The vertical difference profiles further showed that the strongest hydrological responses occurred in deeper soil layers, whereas temperature differences remained comparatively weak throughout most of the soil column (Fig. 2c). These results indicate that the ice impedance formulation primarily influenced subsurface hydrological dynamics by constraining vertical liquid water movement under frozen and partially frozen conditions, while its effects on soil thermal dynamics were secondary and mainly localized around thawing and freezing fronts.”

To strengthen the physical interpretation of the revised simulations, we additionally revised the Discussion section to clarify the respective roles of increased soil vertical discretization and the ice impedance formulation in controlling thermal and hydrological dynamics. Specifically, we added the following interpretation (P17, L400):

"The process-oriented sensitivity analysis helped clarify the distinct but interacting roles of the two model developments. Increased soil vertical discretization primarily improved the representation of subsurface thermal propagation by allowing seasonal thermal signals to diffuse more gradually through the soil profile and by reducing artificial layer-scale discontinuities associated with the vertically coarse soil scheme. As a result, the multilayer structure enhanced the realism of depth-dependent soil thermal dynamics and restored more continuous vertical hydraulic connectivity throughout the soil column.

By contrast, the ice impedance formulation mainly affected subsurface hydrological dynamics during freeze--thaw transitions. The strongest responses were concentrated around thawing and refreezing fronts, indicating that freeze--thaw-related hydraulic constraints primarily regulate transient vertical redistribution of liquid water under frozen and partially frozen conditions. Physically, partial ice occupation within soil pores reduces effective hydraulic conductivity, thereby modifying the timing and depth of seasonal infiltration and subsurface water redistribution. The comparatively weak thermal response further suggests that the influence of ice impedance on soil temperature is largely indirect and mainly occurs through hydrological regulation rather than through direct modification of heat transfer processes."

Together, these revisions substantially improve the physical interpretation of the proposed developments and clarify the respective roles of enhanced soil layering and freeze–thaw-related hydraulic constraints in the simulated hydrothermal responses.

Specific comments

Comment 1

The relative contributions of increased soil vertical resolution (e.g., 2 layers vs. 30 layers) and freeze–thaw processes are not clearly separated. It would be useful to quantify their individual and combined effects on soil thermal and hydrological dynamics.

Response: We thank the referee for this helpful suggestion. We agree that the original manuscript did not sufficiently distinguish the respective contributions of enhanced soil vertical discretization and freeze--thaw-related hydraulic constraints.

In response to this concern, we conducted additional process-oriented sensitivity analyses based on the revised multilayer soil configuration and substantially revised the corresponding Methods, Results, and Discussion sections. Specifically, we compared two multilayer soil configurations: (1) a 30-layer soil configuration without the ice impedance formulation and (2) the same 30-layer configuration including the ice impedance formulation. These analyses were designed to isolate the specific influence of freeze--thaw-related hydraulic constraints on subsurface thermal and hydrological dynamics.

The sensitivity analyses showed that the ice impedance formulation exerted comparatively limited influence on the bulk soil thermal regime, whereas its effects on vertical soil water redistribution were substantially stronger, particularly during seasonal freeze--thaw transition periods and within deeper soil layers. Combined with the site-level validation results comparing the original LPJ-GUESS configuration and the revised multilayer configuration, the analyses further suggested that improved subsurface thermal representation was primarily associated with enhanced soil vertical discretization, whereas the ice impedance formulation mainly influenced freeze--thaw-related hydrological redistribution processes.

Accordingly, we added a new sensitivity analysis subsection and an additional process-oriented sensitivity analysis figure in the revised manuscript to further clarify the respective influences of enhanced soil vertical discretization and freeze--thaw-related hydraulic constraints on simulated soil thermal and hydrological dynamics.

Detailed descriptions of the newly added sensitivity analyses, corresponding figure, and related revisions to the Methods, Results, and Discussion sections are provided in our response to the General Comments above.

Comment 2
The functional relationship used to represent ice inhibition of percolation should be illustrated (e.g., with a curve or schematic), to better understand its behavior.
Response: We thank the reviewer for this helpful suggestion. In the revised manuscript, we added a new figure illustrating the functional relationships used to represent freeze–thaw-related inhibition of vertical water percolation in the revised model.

The added figure shows how the ice impedance factor varies as a function of soil ice fraction and soil temperature under different soil textures. Specifically, the figure illustrates the continuous reduction in hydraulic permeability with increasing ice fraction and decreasing soil temperature, as well as the stronger inhibition effects represented for clay-rich soils compared to sandy soils.

We also expanded the description of the ice impedance formulation in the Methods section to more clearly explain the physical meaning of the scaling functions, the role of the key parameters, and the behavior of the formulation under frozen, partially frozen, and unfrozen soil conditions.

This addition improves the transparency and interpretability of the freeze–thaw-related hydrological parameterization implemented in the revised model.

Specifically, we added the following description and schematic figure in Section 2.3.2 ***(“Physical reconstruction of soil infiltration incorporating permafrost-specific hydrological effects”)*** (P6, L150):

“Figure 2 illustrates the functional behavior of the freeze–thaw-related ice impedance formulation under different soil textures and thermal conditions. The ice-fraction-dependent scaling function progressively reduces hydraulic permeability with increasing volumetric ice fraction, with stronger inhibition effects represented for finer-textured soils. The temperature-dependent scaling function provides a smooth transition between unfrozen and frozen hydrological states around the freezing point, thereby avoiding abrupt threshold behavior in vertical liquid water transport.”

In addition, the newly added figure explicitly illustrates both the ice-fraction-dependent inhibition function and the temperature-dependent transition function, thereby providing a more intuitive representation of how freeze–thaw conditions regulate vertical liquid water percolation in the improved LPJ-GUESS configuration.

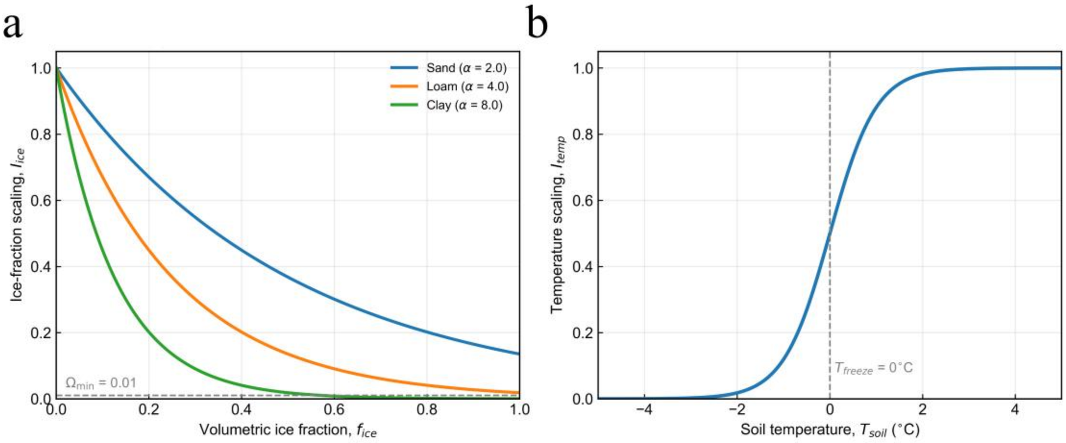


Figure 2. Functional behavior of the freeze–thaw-related ice impedance formulation used to regulate vertical liquid water percolation in the improved LPJ-GUESS configuration.(a) Ice-fraction-dependent inhibition function (Iice) under different soil textures, illustrating progressively stronger hydraulic impedance with increasing volumetric ice fraction and finer soil texture.(b) Temperature-dependent scaling function (Itemp), showing the smooth transition between unfrozen and frozen hydrological conditions around the freezing point (0 °C).

Comment 3

The manuscript provides detailed information for the Huzhong flux tower site, but much less for the other four sites. A clearer description and comparison of all sites would improve the transparency of the evaluation.

Response: We thank the referee for this helpful suggestion. We agree that the original manuscript provided substantially more detailed information for the HuZhong flux-tower site than for the four additional validation sites (MG, AL, GL, and MH), which reduced the transparency of the site-scale evaluation framework.

In the revised manuscript, we added a clearer description of the four additional validation sites in the "Site-scale comparison" section. The revised text now summarizes their geographic locations, elevation, vegetation characteristics, and their role in evaluating model performance under contrasting freeze–thaw environments. Specifically, we clarified that MG and AL represent larch forest ecosystems, whereas GL and MH represent shrub wetland ecosystems within the discontinuous permafrost region of the northern Da Xing'anling Mountains.

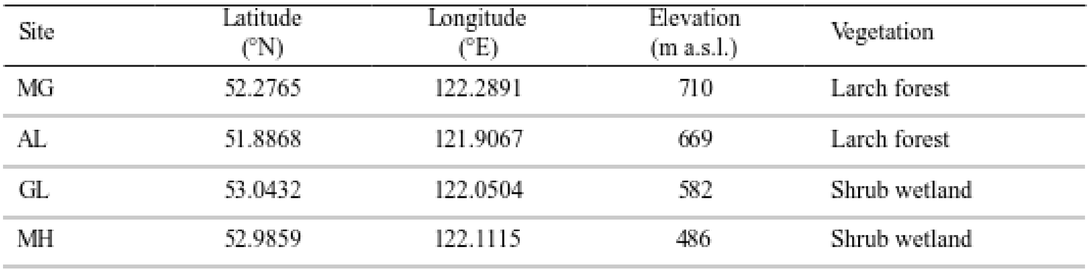
In addition, we added a new summary table (Table 1) that provides a direct comparison of the four sites, including latitude, longitude, elevation, and vegetation characteristics. This addition improves the transparency and readability of the site-scale evaluation and provides clearer context for interpreting the soil temperature and active layer thickness validation results.

Specifically, the following text was added in the revised manuscript (P8, L180):

" Table 1 summarizes the geographic locations, elevation, and vegetation characteristics of the four additional monitoring sites used for site-scale evaluation. The sites represent contrasting ecosystem conditions within the northern Da Xing'anling Mountains, including larch forest and shrub wetland ecosystems distributed across the discontinuous permafrost region."

We also added the following new table:

Table 1. Geographic and vegetation characteristics of the four additional monitoring sites used for site-scale model evaluation.



Site	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Vegetation
MG	52.2765	122.2891	710	Larch forest
AL	51.8868	121.9067	669	Larch forest
GL	53.0432	122.0504	582	Shrub wetland
MH	52.9859	122.1115	486	Shrub wetland

Comment 4

The simulation protocol is not sufficiently described. For example, what is the simulation length, and were the simulations spun up to equilibrium?

Response: We thank the reviewer for this helpful suggestion. We agree that the simulation protocol was insufficiently described in the original manuscript.

In the revised manuscript, we added a more detailed description of the simulation setup, including the spin-up procedure, simulation period, climate forcing datasets, and model initialization settings. Specifically, the model was spun up for 500 years (nyear_spinup = 500) using repeated climate forcing in order to allow vegetation and soil hydrothermal states to approach quasi-equilibrium conditions before the transient simulations were conducted.

The transient simulations used for analysis covered the period 1980–2024. We also clarified the climate forcing datasets used during both the spin-up and transient simulation periods, together with the initialization procedures used for vegetation and soil state variables.

These additions improve the transparency and reproducibility of the simulation protocol presented in the study.
Specifically, the following text was added in Section 2.4 "Model setup and simulations" (P7 L165):

"All simulations included a 500-year spin-up period using repeated climate forcing to allow vegetation and soil hydrothermal conditions to approach quasi-equilibrium states prior to transient simulations. The spin-up procedure followed the standard LPJ-GUESS framework and was applied consistently to both the original and improved model configurations. Transient simulations used for analysis covered the period 1980–2024. Both model configurations were driven using identical climate forcing, atmospheric CO_2, and soil property datasets to ensure that simulated differences primarily reflected the effects of the revised soil hydrothermal representations."

Comment 5
At L225 and Fig. A1, the simulated soil temperature at 1 m depth at the Huzhong site appears to deviate substantially from observations. This discrepancy seems larger than what could be attributed to observational uncertainty alone and deserves further discussion.
Response: We thank the reviewer for this important comment. We agree that the discrepancy between simulated and observed soil temperature at 1 m depth at the HuZhong site required further discussion in the manuscript.

In the revised analysis, we re-examined the original deep-soil temperature observations and identified several isolated short-term fluctuations that were likely associated with observational noise or sensor-related artifacts. To reduce the influence of these anomalies on the model evaluation, basic quality-control (QC) procedures were applied to the 1 m soil temperature observations prior to comparison with the simulations. The updated comparison after QC processing is presented in the revised Fig. A1 (see response to Comment 9).

After applying the QC procedure, the comparison became less affected by isolated observational anomalies, allowing a more robust evaluation of the seasonal dynamics of deep-soil temperature. Nevertheless, some discrepancies between simulations and observations remain, particularly regarding the amplitude and seasonal timing of temperature variations at 1 m depth.

We therefore expanded the Discussion section to clarify that uncertainties in deep-soil thermal simulations likely reflect the combined effects of observational uncertainty, local hydrothermal heterogeneity, snow insulation effects, and remaining limitations in representing deep-soil thermal processes within the current model framework.

Specifically, the following sentence was added in the "Site-scale comparison" subsection (P8, L187):

"Basic quality-control procedures were applied to the deep-soil temperature observations prior to model evaluation to reduce the influence of isolated measurement spikes and physically implausible short-term fluctuations."

In addition, we expanded the Discussion section to further clarify the remaining uncertainties associated with deep-soil thermal simulations.

Comment 6

L242: repeated sentences.

Response: Thank you for pointing this out. We carefully checked the corresponding paragraph and confirmed that a sentence was inadvertently repeated in the original manuscript. The duplicated sentence has been removed in the revised version to improve clarity and readability.

Comment 7

Fig. 2 suggests that the model modifications reduce soil moisture in the upper layers while increasing it in deeper layers. This redistribution should be discussed and physically interpreted.

Response: We thank the reviewer for this helpful comment. We agree that the simulated redistribution of soil water across soil layers required clearer physical interpretation in the manuscript.

Compared with the original LPJ-GUESS two-layer configuration, the revised multilayer scheme alters vertical soil water redistribution by allowing more gradual downward water movement throughout the extended soil column. In the original configuration, the simplified two-layer structure tends to retain excessive water within the 50–150 cm layer because downward percolation below the lower soil layer is strongly limited. By contrast, the revised multilayer configuration represents water transfer progressively across individual soil layers and incorporates freeze–thaw-related hydraulic constraints on percolation under frozen and partially frozen conditions. As a result, excessive soil water accumulation within intermediate soil layers is reduced, while soil water redistribution throughout the deeper soil profile becomes more physically realistic.

Accordingly, we added additional physical interpretation of the simulated soil water redistribution in Section 3.1 "Performance of soil thermal and hydrological simulations" (P13, L318).

Specifically, the following content was added in the revised manuscript in Section 3.1 "***Performance of soil thermal and hydrological simulations***" (P13, L318):

"A snapshot analysis for October 2016 revealed that the original LPJ-GUESS

configuration frequently reached the prescribed saturation limit (1.0 m^3 m^{-3}) in the lower soil layer (50–150 cm), whereas this behavior occurred less frequently in the improved LPJ-GUESS configuration. The original two-layer soil configuration promotes bulk downward water transfer and tends to retain excessive soil water within the 50–150 cm layer under permafrost conditions. By contrast, the revised multilayer configuration allows more gradual vertical redistribution of soil water and permits continued percolation below 1.5 m depth within the extended 3 m soil column. Consequently, the revised configuration reduces excessive intermediate-layer saturation and modifies the seasonal redistribution of soil water across the soil profile, resulting in a more realistic representation of active-layer hydrology and freeze–thaw-controlled subsurface water movement. Although the soil water content observations at the four validation sites integrate both liquid and ice components, the multi-site comparison provides a consistent diagnostic evaluation of the simulated hydrothermal conditions in the improved configuration."

Comment 8

Section 4.1 would benefit from a more mechanistic discussion, including:

- the impact of increased soil layering on water and heat transport;
- the influence of freeze–thaw processes on these dynamics;
- the relative and interactive effects of these two model developments.

Given the model setup, such sensitivity analyses should be feasible.

Response: We thank the reviewer for this constructive suggestion. We agree that the original version of Section 4.1 did not sufficiently distinguish the respective roles of increased soil vertical discretization and freeze--thaw-related hydraulic constraints, nor did it fully explain their interactive effects on subsurface hydrothermal dynamics.

To address this issue, we conducted additional process-oriented sensitivity analyses within the revised multilayer framework by comparing:

(1) a multilayer (30-layer) soil configuration without freeze--thaw-related hydraulic constraints, and

(2) the same multilayer configuration including the ice impedance formulation. Based

on these analyses, we substantially revised and expanded Section 4.1 to provide a more mechanistic interpretation of the physical processes controlling soil heat transport and soil water redistribution.

Specifically, the revised discussion now more explicitly clarifies the respective influences of increased soil vertical discretization and freeze--thaw-related hydraulic constraints. The revised text clarifies that increased soil vertical discretization primarily improves the representation of vertical heat transfer and vertical hydraulic connectivity throughout the soil profile, whereas the ice impedance formulation mainly regulates transient vertical redistribution of liquid water during freeze--thaw transitions by constraining hydraulic conductivity under frozen and partially frozen conditions.

We further discuss how the interaction of these two process-level developments improves the representation of coupled subsurface thermal--hydrological dynamics in permafrost-affected ecosystems. The revised discussion also emphasizes that the multilayer soil structure provides a more physically continuous vertical framework through which freeze--thaw-related hydraulic constraints can influence seasonal subsurface water redistribution.

The revised discussion in Section 4.1 now reads:

"Based on evaluations against site-level measurements and regional data products, the improved LPJ-GUESS configuration showed improved performance in simulating soil temperature amplitude and reduced biases in soil water content, resulting in simulations that were consistently closer to observations than those of the original LPJ-GUESS. Both model configurations reproduced the seasonal phase of near-surface variability, indicating that large-scale atmospheric forcing remains the primary control on the timing of shallow-soil freeze–thaw dynamics (Koven et al., 2013; Koven et al., 2015). However, the improved configuration showed more consistent performance across sites, with improvements becoming more evident at greater depths. This depth-dependent improvement suggests that, as direct atmospheric control weakens with depth, simulated subsurface variability becomes increasingly governed by internal soil process representations, including vertical heat diffusion, water redistribution, and freeze–thaw-related hydraulic constraints (Walvoord and Kurylyk, 2016).

The process-oriented sensitivity analysis helped clarify the distinct but interacting roles of the two model developments. Increased soil vertical discretization primarily improved the representation of subsurface thermal propagation by allowing seasonal thermal signals to diffuse more gradually through the soil profile and by reducing artificial layer-scale discontinuities associated with the vertically coarse soil scheme. As a result, the multilayer structure enhanced the realism of depth-dependent soil thermal dynamics and restored more continuous vertical hydraulic connectivity throughout the soil column.

By contrast, the ice impedance formulation mainly affected subsurface hydrological dynamics during freeze–thaw transitions. The strongest responses were concentrated around thawing and refreezing fronts, indicating that freeze–thaw-related hydraulic constraints primarily regulate transient vertical redistribution of liquid water under frozen and partially frozen conditions. Physically, partial ice occupation within soil pores reduces effective hydraulic conductivity, thereby modifying the timing and depth of seasonal infiltration and subsurface water redistribution. The comparatively weak thermal response further suggests that the influence of ice impedance on soil temperature is largely indirect and mainly occurs through hydrological regulation rather than through direct modification of heat transfer processes.

The improved performance of the revised configuration is therefore likely associated with the alleviation of two interacting structural limitations in the original model. First, the shallow lower boundary (1.5 m) and vertically coarse "bucket"-type hydrology of the standard LPJ-GUESS configuration can artificially constrain downward water movement when the active layer extends beyond the simulated soil domain (Gerten et al., 2004). Extending the soil profile to 3.0 m restores vertical hydraulic continuity and allows more realistic redistribution of soil water throughout the soil column. Second, the incorporation of phase-change-dependent hydraulic impedance introduces a physically motivated constraint on liquid water movement under frozen and partially frozen conditions, consistent with the reduced hydraulic conductivity characteristic of permafrost soils (Walvoord and Kurylyk, 2016). Together, these process-level modifications improve the representation of coupled subsurface thermal and hydrological dynamics, particularly during freeze–thaw transitions and within deeper soil layers where internal hydrothermal processes become increasingly important.

Some discrepancies nevertheless remain. These may arise from uncertainties in precipitation forcing, snow insulation, soil organic-layer properties, unresolved lateral flow, and local heterogeneity in soil texture and drainage conditions. In addition, the current model soil column remains shallower than the active layer depth observed in parts of the study region, limiting the interpretation of simulated thaw depth or active-layer thickness. For this reason, the present sensitivity analysis focused primarily on soil thermal propagation and vertical soil water redistribution rather than directly interpreting active-layer thickness changes. Despite these limitations, the revised soil representation provides a more physically consistent baseline for simulating subsurface hydrothermal states. This improvement is essential for interpreting ecosystem-scale responses because freeze–thaw status and soil water availability in the rooting zone regulate vegetation phenology, plant water stress, and soil carbon respiration in permafrost-affected boreal forests under a warming climate (Kimball et al., 2006; Treat et al., 2022; Schaphoff et al., 2026)."

Comment 9

Fig. A1: The legend appears to have reversed colors for “Observation” and “LPJ-GUESS.” In addition, the impact of the Cryo modification on simulated soil temperature appears limited. Could the authors clarify this point? Also, please clarify what the two lines in panel (d) represent.

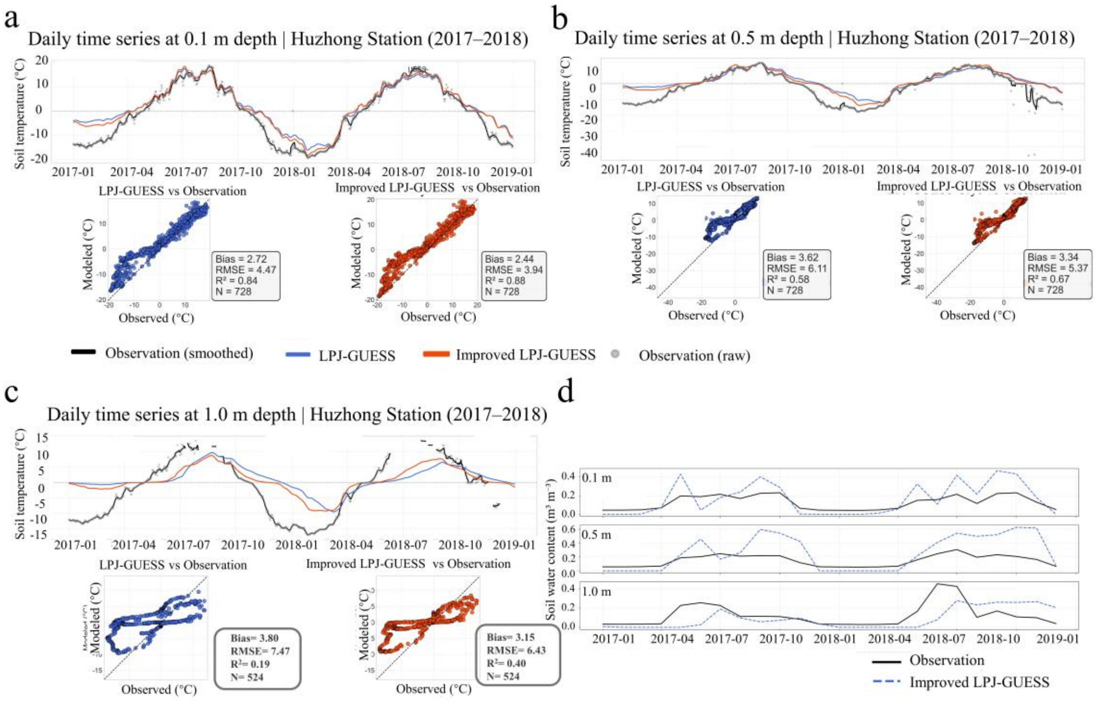
Response: We thank the referee for carefully checking Fig. A1. The referee is correct that the legend colors for “Observation” and “LPJ-GUESS” were incorrectly assigned in the original figure. We apologize for this oversight. In the revised manuscript, the figure legend was corrected to ensure consistency between the plotted lines and legend labels.

We also clarified the meaning of the lines shown in panel (d) by revising both the figure caption and panel annotations. Specifically, the panel compares observed and simulated volumetric soil water content at depths of 0.1, 0.5, and 1.0 m.

Regarding the comparatively limited influence of the revised soil representation on simulated soil temperature, we agree that the differences between the original and improved configurations are relatively modest at some depths and sites. The additional sensitivity analyses indicate that enhanced soil vertical discretization primarily improves subsurface thermal simulations, whereas freeze--thaw-related hydraulic constraints mainly affect vertical liquid water redistribution under frozen and partially frozen conditions. Consequently, the direct influence of the ice impedance formulation on soil temperature remains comparatively limited, which is physically consistent with the intended role of the scheme.

The revised manuscript now includes additional sensitivity analyses and expanded mechanistic discussion to further clarify the respective influences of enhanced vertical discretization and freeze--thaw-related hydraulic constraints on simulated soil thermal and hydrological dynamics.

In addition, Fig. A1 was revised to improve overall clarity and consistency, including corrected legend colors, revised panel annotations, and updated figure descriptions.



"Figure A1. Validation of simulated soil hydrothermal dynamics against observations at the HuZhong flux tower site (2017–2018). Panels (a–c) show observed and simulated soil temperature at depths of 0.1, 0.5, and 1.0 m, respectively. Panel (d) shows the corresponding volumetric soil water content at the same depths. Black solid lines represent observations, whereas blue dashed lines represent simulations from the improved LPJ-GUESS configuration."

Comment 10

Fig. A4 suggests that the modifications have limited impact on soil temperature but a substantial effect on soil moisture. Are frozen and unfrozen soil water distinguished in this analysis?

Response: We thank the referee for this important question. In the revised manuscript, we clarified that the soil water content analyzed in Fig. A4 represents liquid soil water content rather than total soil water storage including frozen water components.

Under frozen soil conditions, liquid water availability decreases substantially and may approach zero during winter because water is converted into soil ice within the model framework. The ice impedance formulation therefore primarily constrains the redistribution of liquid water under frozen and partially frozen soil conditions.

This distinction helps explain why the revised soil representation exerts a substantially stronger influence on simulated soil water dynamics than on soil temperature. The model developments directly regulate vertical liquid water redistribution, whereas soil thermal dynamics remain primarily controlled by vertical heat diffusion and soil thermal properties. Consequently, the impacts on simulated soil temperature are comparatively smaller.

We also clarified that changes in liquid soil water redistribution may indirectly influence soil thermal dynamics through coupled water–heat interactions, although the direct thermal effects remain comparatively modest.

The Methods section and the Fig. A4 caption were revised accordingly to clarify the distinction between liquid and frozen soil water in the analysis.

Added in revised manuscript (P10, L250) at Section 2.6.2 "***Evaluation of soil hydrothermal simulations***":

"The soil water content analyzed in this study refers to volumetric liquid soil water content rather than total soil water storage including frozen water components."

Added in revised Fig. A4 caption:

"Soil water content shown in panels (g–i) represents volumetric liquid soil water content rather than total soil water storage including frozen water components."

Comment 11

Table B2: From LPJ-GUESS 2L to LPJ-GUESS-Cryo 30L, the correlation coefficient (R) decreases, while RMSD, bias, and MAE improve. This inconsistency should be explained.

Response: We thank the reviewer for pointing out this important issue. We agree that the interpretation of Table B2 required clearer explanation in the manuscript.

In the revised manuscript, we clarified that different evaluation metrics characterize different aspects of model performance. The correlation coefficient (R) primarily reflects the temporal co-variability between simulations and observations, whereas RMSD, bias, and MAE quantify the magnitude of absolute errors and systematic deviations. Consequently, improvements in absolute error magnitude do not necessarily correspond to higher temporal correlation.

Compared with the original LPJ-GUESS 2L configuration, the revised multilayer scheme generally improved the magnitude and vertical distribution of simulated soil water content, reducing systematic wet biases and lowering RMSD, bias, and MAE values. At the same time, the revised representation of vertical percolation and freeze--thaw-related hydrological constraints may slightly alter the temporal persistence and redistribution of soil water across soil layers, resulting in modest reductions in temporal correlation at some sites or depths.

We therefore clarified in the revised manuscript that model improvements were not uniformly reflected across all statistical metrics, and that the overall reductions in systematic errors indicate improved agreement between simulations and observations.

Added in revised manuscript:

"Although correlation coefficients decreased slightly at some depths, the revised configuration generally reduced systematic soil water biases and improved the magnitude of simulated soil water content, resulting in lower RMSD, bias, and MAE values overall. This indicates that the revised multilayer configuration primarily improved the vertical distribution and magnitude of soil water storage, while slightly modifying the temporal variability of simulated soil water dynamics."