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. Our responses to the referee's comments are shown in blue font, while revised manuscript text is shown in bold italic blue font.

Comment 1

I am still concerned about the interpretation of the limited temperature response to the ice-impedance formulation in permafrost-affected soils. The authors explain that this formulation mainly affects liquid water redistribution and therefore has only an indirect effect on soil temperature. While this may be true for the current implementation, in permafrost-affected areas, ice and freeze-thaw processes can directly affect soil heat transfer through changes in thermal conductivity, heat capacity, and latent heat effects. Therefore, the weak simulated temperature response should be presented as a limitation of the current model formulation, rather than as evidence that ice-related processes have little influence on soil thermal dynamics. Please revise the relevant text accordingly and more clearly acknowledge this limitation.

Response:

We thank the referee for this important clarification. We agree that our previous interpretation of the weak temperature response was too broad and could be misinterpreted as suggesting that ice-related processes have only a limited influence on soil thermal dynamics. This was not our intention. In the current model framework, soil ice and phase changes already influence the thermal calculations through changes in soil thermal properties and latent heat effects. However, the newly implemented freeze--thaw-related hydraulic constraint itself acts directly on layer-to-layer liquid water transport rather than introducing an additional modification to the soil thermal parameterization. Therefore, the relatively weak temperature response in the sensitivity experiment should be interpreted as the incremental thermal response to this newly introduced hydraulic constraint, rather than as evidence that ice-related processes are of limited importance for soil thermal dynamics.

We have revised the relevant text in the Discussion section to clarify this distinction and avoid overinterpreting the weak temperature response. We have also added a further clarification at the end of Sect. 4.1 to explicitly define the scope of the newly implemented hydraulic constraint and the interpretation of the sensitivity experiment.

The revised text in the Discussion section is provided below (P18, L398-L407):

"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 should be interpreted specifically as the incremental response to the newly introduced hydraulic constraint. In the current implementation, this constraint directly modifies layer-to-layer liquid water transport, whereas soil thermal dynamics continue to be governed by the existing thermal scheme, in which soil water and ice states affect thermal properties and phase-change energetics. Therefore, the limited additional temperature response does not imply that ice-related processes exert only a minor influence on soil thermal dynamics, but rather reflects the primarily hydraulic scope of the newly implemented process."

In addition, the following clarification was added to the P19 L430-435:
"The experiment isolating the freeze-thaw-related hydraulic constraint should also be interpreted within the scope of this specific model development. The newly implemented constraint directly modifies frozen-soil water transport and does not introduce an additional parameterization of soil heat transfer. Its influence on soil temperature therefore arises through changes in soil water and ice states propagated through the existing thermal scheme. Accordingly, the comparatively weak additional temperature response should not be interpreted as a complete assessment of the thermal effects associated with soil ice and freeze-thaw processes."

Comment 2
In response to my previous comment on the simulation protocol, the authors added the spin-up length and simulation period. Please also provide the names, sources, references, and access links for the forcing datasets used in the simulations.

Response:
We thank the referee for this suggestion. We have revised the Model setup and simulations section to provide additional information on the forcing datasets used in this study, including dataset names, data providers, relevant references, and access information. Specifically, we have added details for the ERA5-Land meteorological forcing dataset, NOAA atmospheric CO_2 dataset, and Harmonized World Soil Database used for soil properties. The corresponding data sources and access links are also provided in the Data availability section.

The following text was added in the revised manuscript (P7, L163-172):
"All simulations were driven by the ERA5-Land reanalysis dataset provided through the Copernicus Climate Data Store (CDS) for the period 1980–2024 at a spatial resolution of 0.1° × 0.1° (Muñoz-Sabater et al., 2021). Daily air temperature,

total precipitation, and surface shortwave radiation were extracted as climatic forcing variables for soil thermal–hydrological processes and vegetation dynamics in both model configurations. Atmospheric CO_2 concentrations were prescribed using the annual global mean CO_2 dataset from the NOAA Global Monitoring Laboratory (Masarie and Tans, 1995). Soil physical properties required by the model were derived from the Harmonized World Soil Database version 2.0 (HWSD v2.0), provided by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) (Sinitambirivoutin et al., 2024)."

In addition, detailed access links for these datasets have been provided in the Data availability section (P23, L560).

"Data availability. Meteorological forcing data were obtained from the ERA5-Land reanalysis dataset (1980–2024) at a spatial resolution of 0.1° × 0.1°, available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). Atmospheric CO_2 concentration data were obtained from the NOAA Global Monitoring Laboratory (https://gml.noaa.gov/ccgg/trends/). Soil physical parameters were derived from the Harmonized World Soil Database (HWSD v2.0), available at https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v20. Site-level soil hydrothermal observations and flux tower data used for model evaluation were obtained from previously published datasets (Li et al., 2024; Yan et al., 2023)."

Comment 3

The explanation for the discrepancy in 1 m soil temperature at the HuZhong site remains insufficient. Please briefly describe the QC procedure applied to the observations and clarify the reason of the remaining mismatch.

Response:

We thank the referee for this further comment. We agree that the explanation of the remaining discrepancy in simulated 1 m soil temperature required further clarification. We have now added a more detailed description of the quality-control procedure applied to the HuZhong observations and expanded the discussion on the potential causes of the remaining mismatch.

Specifically, the 1.0 m soil temperature observations were screened using four criteria prior to model evaluation: (1) removal of extreme values exceeding 15 °C; (2) removal of isolated daily spikes with abrupt changes exceeding 3 °C relative to both adjacent days; (3) removal of values deviating by more than 3 °C from a 7-day moving median; and (4) removal of records showing unrealistic vertical inconsistency with concurrent 0.5 m soil temperature observations (>5 °C difference). These criteria were based on the temporal and vertical consistency of the observations and were applied independently of the model simulations.

After quality control, isolated observational anomalies were substantially reduced, but a systematic mismatch remained at 1.0 m depth. In particular, the model underestimated the seasonal temperature amplitude, remaining too warm in winter and too cool in summer. Because this pattern persisted after QC, we do not attribute the remaining discrepancy solely to observational anomalies. Instead, the smoother simulated seasonal cycle suggests excessive damping of the thermal signal as it propagates downward through the simulated soil profile. We therefore clarified in the Discussion that a likely contributor is uncertainty in the effective thermal diffusivity of the deeper soil layers, which in the model depends on prescribed soil composition together with simulated liquid water and ice fractions. Detailed site-specific vertical profiles of these thermal properties are not available for HuZhong, and differences between the prescribed and actual site conditions may therefore contribute to the excessive attenuation of the seasonal thermal signal at 1.0 m depth.

The following text has been added to the revised manuscript (P8, L185):
"**Because the 1.0 m soil temperature observations contained occasional isolated spikes and abrupt short-term excursions that were inconsistent with the temporal continuity of the series and the concurrent 0.5 m observations, additional quality control was applied specifically to this depth prior to model evaluation. Specifically, the QC procedure excluded extreme values exceeding 15 °C, isolated abrupt daily fluctuations (>3 °C relative to both adjacent days), deviations exceeding 3 °C from a 7-day moving median, and records differing by more than 5 °C from concurrent 0.5 m soil temperature observations. The remaining observations were used for model evaluation**"

In addition, we expanded the Discussion to clarify the characteristics and likely origin of the remaining mismatch at 1.0 m depth (P18, L417–427):
"Some discrepancies nevertheless remain. More generally, 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. At the HuZhong site, the residual mismatch at 1.0 m depth is characterized mainly by an underestimated seasonal temperature amplitude, with the model remaining too warm in winter and too cool in summer. Because this pattern persists after quality control, it is unlikely to result solely from isolated observational anomalies. Instead, it suggests excessive damping of the seasonal thermal signal as heat propagates downward through the simulated soil profile. A likely source of this damping is uncertainty in the effective thermal diffusivity of the deeper soil layers. In the model, layer-specific thermal conductivity and heat capacity are determined from prescribed soil composition together with simulated liquid water and ice fractions, whereas detailed site-specific vertical profiles of these thermal properties are not available for HuZhong. Consequently, differences between the prescribed and site-specific depth-dependent soil composition and water--ice conditions may cause the simulated thermal signal to attenuate too strongly before reaching 1.0 m depth."