

Author's Responses to RC3's comments on "*Ensemble numerical simulation of permafrost over the Tibetan Plateau from Flexible Permafrost Model: 1950–2023*"

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The authors would like to thank the reviewer for their constructive feedback and thorough assessment of our manuscript. Below, we provide a point-by-point response to each comment, reviewer comments are given in black, responses are given in blue. Additionally, we have included details of how we intend to address these changes in a potential revised submission. Revised figure/table are presented at the end of our responses.

The manuscript presents a new simulation framework for large scale numerical simulation of permafrost dynamics, and apply it to the quantification of permafrost metrics (ALT, MAGT, extent) of the permafrost cover over the Tibetan Plateau from 1950 to 2023. The presented simulations are suffering of strong assumptions regarding soil water content and snow cover (both 'static'), which in my opinion hampers the possibility of temporal evolution analysis. The bibliography of the permafrost modelling landscape is also incomplete.

I do not think that the manuscript may be published in TC in its present form. A significant work for better discussing the limitations of the simulations and put them in the context of permafrost modelling across scales is needed. Thus I recommend a major revision prior to reconsider whether or not it may be published in TC.

Responses: We fully agree that the model will significantly benefit from implementing a better described snow and hydrology schemes as we've discussed in Sec. 6.2 Model limitations. In the revision, the snow compaction algorithm from Verseghy (1991) will be introduced to replace the static snow density (Eq. 1), and the uncertainties of the static soil moisture will be better quantified based on the ensemble spread. Below are our detailed clarifications to the concerns regarding snow density and soil moisture, along with the corresponding changes made to the possible revision.

$$\rho_{sn}^{t+\Delta t} = (\rho_{sn}^t - \rho_{sn}^{max}) \cdot \exp(-0.24\Delta t) + \rho_{sn}^{max} \quad (1)$$

where ρ_{sn}^{max} is assumed to be 300 kg m^{-3} , and Δt is the simulation time step in day. The fresh snow density was set as 100 kg m^{-3} .

Snow density

The significant influences of snow cover on soil thermal regime have been well documented (Zhang, 2005). The required degree of model complexity depending on the intended applications. Over the Tibetan Plateau (TP), snow cover is minor, with a mean snow depth of about 1 cm (Dec–Feb) according to ground observations from a network of 87 stations (Cao et al., 2019). Consequently, the snow insulation effects are relatively minor in this region. To address the possible uncertainties using the static snow density of 250 kg m^{-3} , additional three simulation experiments were conducted and discussed here, and the snow compaction algorithm from Verseghy (1991) will be used in the revision.

Additional three simulation experiments with different snow schemes:

- (1) static snow density of 225 kg m^{-3} (as -10% of 250 kg m^{-3});
- (2) static snow density of 275 kg m^{-3} (as $+10\%$ of 250 kg m^{-3});
- (3) the snow compaction algorithm following Verseghy (1991), with the fresh snow density of 100 kg m^{-3} and the maximum snow density of 300 kg m^{-3} .

Our simulation results indicate that:

- (1) a smaller (225 kg m^{-3}) static snow density generally leads to a deeper ALT and warmer MAGT, but the difference is very small. The ALT difference in about 71% cells are found $< 0.05 \text{ m}$, and the overall MAGT difference at 15 m depth was about 0.18°C (Fig. R1a and b);

- (2) Similar to (1), a larger (275 kg m^{-3}) static snow density generally leads to a shallower ALT and colder MAGT, but the difference is small as well (Fig. R1c and d);
- (3) the mean snow density derived from dynamic snow density scheme was about 252.9 kg m^{-3} during Dec–Feb, which is very close the typical value we used in preprint;
- (4) the overall difference of ALT using snow compaction algorithm (compared to the static snow density of 250 kg m^{-3}) was not remarkable with about 62% cells $< 0.05 \text{ m}$ and 76% cells $< 0.1 \text{ m}$. The overall difference of MAGT at 15 m depth was about $-0.15 \text{ }^{\circ}\text{C}$. The most significant differences are in the southeastern TP where snow is more prevalent.
- (5) **Please note that above differences as well as the simulated snow influences are very likely artificial amplified.** This is because the snowfall in ERA5(-Land) was reported to be significantly overestimated over the TP (Orsolini et al., 2019). In other words, above simulations are derived based on overestimated input snow cover.

Soil moisture

We agree the influences of soil moisture on soil thermal regime can be significant as soil moisture affect the thermal dynamics via multiple ways (Göckede et al., 2017; Zwieback et al., 2019). Although four vertical water distribution schemes were implemented in FPM to reduce the uncertainties associated with static soil moisture, this estimate is subject to large uncertainty. Keep this in mind, we introduced the possible wetter and drier variants of the default soil moisture parameters to allow the propagation of this uncertainty into model results. This is achieved via the 45-member ensemble simulation that qualitatively accounted the possible soil moisture spread in root and vadose zones (Table 2).

We recognized that the uncertainties of static soil moisture lack sufficient discussion. To better quantify the possible uncertainties using the static soil moisture, we will add a new subsection to discuss the simulation spread raised from static soil moisture based on the 45-member ensemble simulation (see the Sec. Simulation spread below).

In fact, the use of static soil moisture models is common practice for investigating long-term permafrost changes among permafrost researchers. Below are a few examples:

1. **CryoGrid 2:** Westermann et al., 2013 derived permafrost conditions in Southern Norway for the period 1958 to 2009.
2. **CryoGridLite:** Langer et al., 2024 simulated the Arctic permafrost for 1750–2000.
3. **GIPL2:** Qin et al., 2017 simulated the active layer thickness over the TP for 1980–2013; Jafarov et al., 2012 conducted the numerical modeling of permafrost dynamics in Alaska for 1989–2100.
4. **Moving-Grid Permafrost Model:** Sun et al., 2020 modeled permafrost change on the Tibetan Plateau from 1966 to 2100; Sun et al., 2022 simulated the permafrost changes at the three sites along the Qinghai-Tibet Engineering Corridor from 1966 to 2018.
5. **Bayesian Inverse Algorithm:** Groenke et al., 2023 investigated the thermal state of permafrost with Bayesian inverse modeling of heat transfer for 2000–2021.

Sec. Simulation spread

"Soil moisture can significant affect the dynamics of the soil thermal regime through evapotranspiration and by altering soil thermal properties (Göckede et al., 2017; Zwieback et al., 2019). However, in the permafrost regions of the TP, soil moisture exhibits marked heterogeneity and is difficult to accurately represent in models. This challenge stems from uncertainties in soil datasets and climate forcing, as well as the inherent complexities of the rugged terrain. Although four vertical water distribution schemes were implemented in FPM to reduce the uncertainties associated with static soil moisture, this estimate is subject to large uncertainty. To allow the propagation of this uncertainty into model results, we introduced both wetter and drier variants of the default parameters."

"The ensemble simulation indicated that the variation in soil moisture translated into considerable influences on simulated permafrost characteristics (Fig. R2), with the overall mean standard deviation was about 0.4 m in ALT and about $0.33 \text{ }^{\circ}\text{C}$ in MAGT. In fact, the spread of input soil moisture inputs themselves were significant with the mean standard deviation of $0.11 \text{ m}^3 \text{ m}^{-3}$ in root zone and $0.14 \text{ m}^3 \text{ m}^{-3}$ in vadose zone (Fig. R3). The propagation of input uncertainties into significant permafrost simulation bias thus highlights the essential role of obtaining more reliable soil moisture datasets for advancing our capacity to simulate permafrost changes."

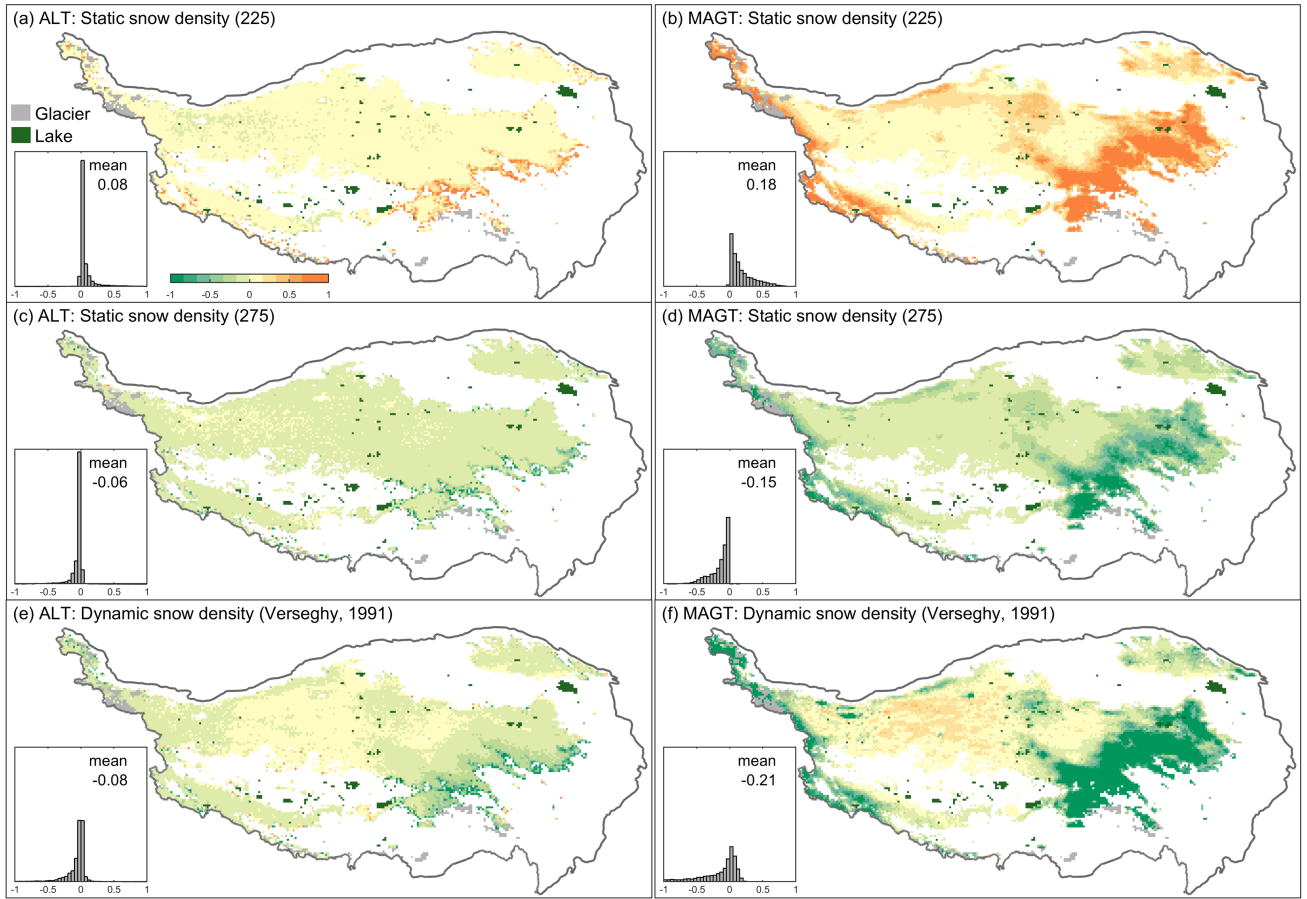


Figure R1: The difference of simulated active layer thickness (ALT) and permafrost mean annual ground temperature (MAGT, 15 m) between using the static snow density of 250 kg m⁻³ and 225 kg m⁻³ (a, b), 275 kg m⁻³ (c, d), and a empirical-based dynamic snow compaction parameterization from Verseghy (1991) (e, f). The differences derived as the simulation with static density of 250 misused by the new simulation.

The footnote of ¹ and ² mean the ensemble mean and standard deviation (std.) of five remote-sensing-based soil moisture in Table 1.

Table 2: Soil moisture (m³ m⁻³) parameters selected for ensemble simulations. The dry and wet variants indicate the parameter ensemble range, and default indicates the standard choice used in model simulation.

Soil layer	Root layer	Vadose layer
Symbol	θ_R	θ_v
Default	ensemble mean ¹	$\frac{\theta_{sat} + \theta_{fc}}{2}$
Dry	-std. ²	$-0.1(\theta_{sat} - \theta_{fc})$
Wet	+std.	$+0.1(\theta_{sat} - \theta_{fc})$
Step	$\frac{std.}{4}$	$0.05(\theta_{sat} - \theta_{fc})$

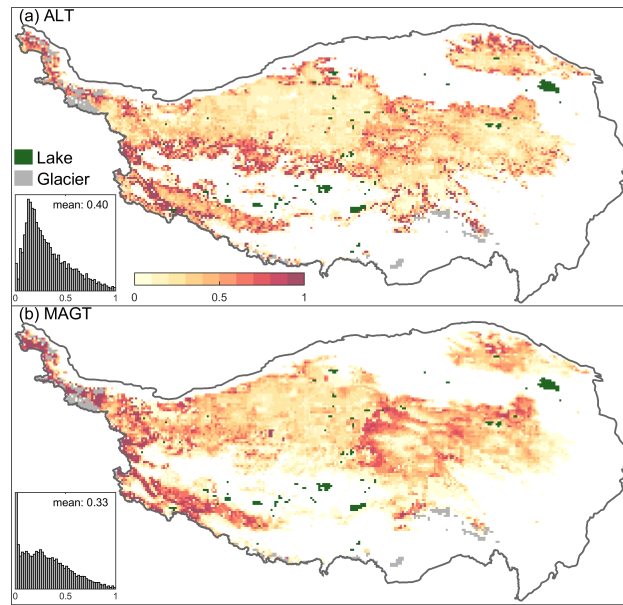


Figure R2: The standard deviation of simulated active layer thickness (ALT) and mean annual ground temperature (MAGT) based on the 45-member ensemble simulations which accounted the soil moisture spread in root and vadose zones.

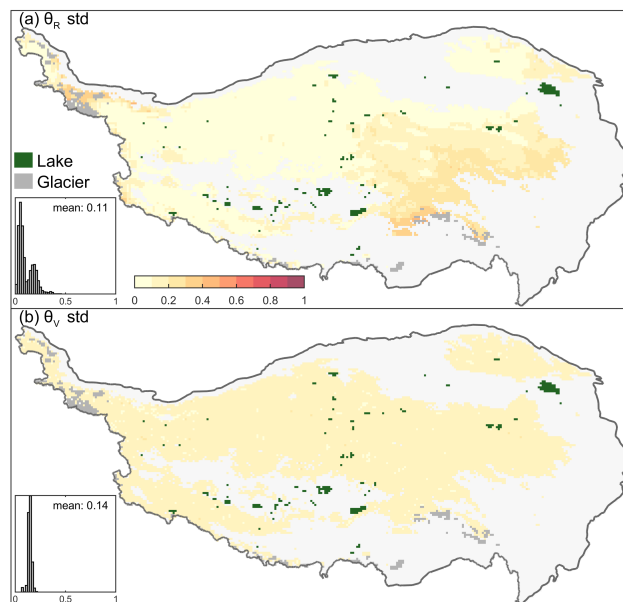


Figure R3: The standard deviation of the soil moisture spread in root (a) and vadose (b) zones.

L1: "Permafrost remains a largely subsurface phenomenon" Clumsy. Permafrost is a subsurface phenomenon. I guess the authors want to point out the difficulty of direct observation of this subsurface phenomena as the reason why its understanding largely relies on numerical simulations. First sentence to be rephrased.

Responses: Yes, details are given in Sec. Introduction (L26–30: *Despite permafrost's importance, direct permafrost measurements, such as borehole temperature, are rare due to harsh environments and high costs (Biskaborn et al., 2015). This is especially true on the Tibetan Plateau (TP), where complex terrain and high altitudes impose further constraints on permafrost research (Cao et al., 2017b, 2019b)... Therefore, process-based simulation is an increasingly important tool for transient assessment of permafrost conditions and dynamics.*).

In the revision, the sentence will be changes as

"Permafrost is a subsurface phenomenon that is difficult to be measured directly, and understanding its dynamics as well as influences under a warming climate depends critically on numerical simulations."

L31-43 : An important part of the permafrost modelling landscape is overlooked in the bibliographical survey given in the introduction: the cryohydrogeological simulators (e.g.: Grenier et al., 2018, Hu et al., 2023). These mechanistic models are based on the numerical resolution of the equations on the continuum mechanics, and thus have a much bigger predictive potential than conceptual, calibrated models. I think that, for the sake of completeness, this type of model should also be included in the survey.

Responses: We agree the cryohydrogeological simulators is not involved here. Given the numerical resolution (both the temporal and spatial ones), this kind of the cryohydrogeological simulators with more realistic and therefore complex processes are generally applied in very fine-scale (meters to several hundreds meters) studies based on very small simulation step (seconds) as given in Grenier et al., (2018) and McKenzie et al., (2007). This is because such simulations are data-intensive, computational costs and require additional boundary conditions. In other words, cryohydrogeological simulators may be challenging to be applied for the large-scale simulations as presented in this study.

On the other hand, Referee #2 suggested to review the hydrological models. In the revision, the following part will be added to clarify.

"Significant efforts have been made to understand the permafrost changes over the TP based on simulations. A significant portion of these contributions comes from the hydrological community, employing models originally designed to simulate hydrological processes in permafrost-affected regions. However, many of the models implemented detailed representations of hydrological processes (e.g., water mass balance) while simplifying the surface energy balance and soil thermal processes. For instance, the DHTC model (Linmao et al., 2024) parameterizes ground heat conduction as a linear function of net radiation, and the FLEXTopo-FS model (Gao et al., 2022) uses the Stefan equation rather than a numerical solution for heat conduction. Beyond such hydrological models, the process-based models used for recent transient permafrost simulation over the TP can be generally divided into geothermal numerical models (i.e., GIPL model) and the common land surface models (i.e., CLM and Noah-MP). The geothermal numerical models typically have rich permafrost-specific processes, such as suitable numerical solver in heat transfer with soil phase changes (Nicolsky et al., 2007; Tubini et al., 2021), deep soil column (tens to hundreds of meters), and well-defined lower boundary, but lack representation of land-atmosphere interactions (i.e., Qin et al., 2017, Sun et al., 2023). On the other hand, the land surface models benefits from the consideration of land-atmosphere processes, and therefore outperform in describing the responses and influences of permafrost to climate warming (i.e., Guo et al., 2018, Wu et al., 2018, Zhang et al., 2021, Cao et al., 2022). Recently, a few permafrost-specific land surface scheme models—combining the advantages of these two types of models—were proposed. The stand-alone models yield promising potential for application to cross-scale permafrost processes (Fiddes et al., 2015, Westermann et al., 2016). However, dedicated stand-alone permafrost models remain scarce for the TP. Most existing simulations rely on distributed hydrological models that have been enhanced with permafrost process representations (e.g., Gao et al., 2018; Song et al., 2020). Although these models generally offer more realistic and detailed simulations of permafrost-influenced hydrological processes, they are typically confined to site or regional scales and short time periods due to their demand for extensive spatial data and high computational cost (e.g., Pan et al., 2016; Zhang et al., 2017; Zheng et al., 2020)."

L36: Lan et al., 2025 seems to be a reference related to a reanalysis, not to a model. Reanalysis are built using models, but they are not models.

Responses: Yes, it is a reanalysis evaluation paper. Lan et al., 2025 indicated the numerical solution, i.e., decoupled energy conservation parameterization (DECP), used in many land surface models may be an issue for permafrost simulations. To clarify, the reference will be replaced by two more related references, i.e., Nicolsky et al., 2007; Tubini et al., 2021. This part will be revised as below.

"The geothermal numerical models typically have rich permafrost-specific processes, such as suitable numerical solver in heat transfer with soil phase changes (Nicolsky et al., 2007; Tubini et al., 2021), deep soil column..."

Table R1: Nomenclature and input parameters for Flexible Permafrost Model (FPM).

Symbol	Parameter	Value or range	Unit
C	apparent heat capacity		$\text{J m}^{-3} \text{K}^{-1}$
L	volumetric latent heat of fusion for ice		J m^{-3}
θ_u	volume contents of unfrozen water		$\text{m}^3 \text{m}^{-3}$
θ_i	volume contents of ice		$\text{m}^3 \text{m}^{-3}$
θ_a	volume contents of air		$\text{m}^3 \text{m}^{-3}$
θ_R	soil moisture in root zone		$\text{m}^3 \text{m}^{-3}$
θ_v	soil moisture in vadose zone		$\text{m}^3 \text{m}^{-3}$
θ_{sat}	saturated soil moisture		$\text{m}^3 \text{m}^{-3}$
θ_r	residual soil moisture		$\text{m}^3 \text{m}^{-3}$
θ_{fc}	soil field capacity		$\text{m}^3 \text{m}^{-3}$
ϕ	soil porosity		$\text{m}^3 \text{m}^{-3}$
α	surface albedo		Dimensionless
α_g	snow-free surface albedo		Dimensionless
α_{sn}	snow albedo	0.50–0.85	Dimensionless
α_{sn}^{max}	maximum snow albedo	0.85	Dimensionless
α_{sn}^{min}	minimum snow albedo	0.50	Dimensionless
T_a	near-surface air temperature		K
T	ground or/and snow temperature		K
T_{s0}	ground or snow surface temperature		K
Z	total depth of the analysis domain		m
D_h	exchange coefficients for heat		Dimensionless
S	evaporation stress factor		Dimensionless
α_{pt}	Priestly-Taylor coefficient		Dimensionless
Δ	slope of the saturation vapor pressure temperature curve		Pa K^{-1}
γ	psychrometric constant		Pa K^{-1}
e_s	snow or soil surface vapor pressure		Pa
ϵ_s	surface emissivity		Dimensionless
P_a	atmospheric pressure		Pa
u_z	wind speed		m s^{-1}
z_0	roughness length		m
ρ_{sn}	density of the snow		kg m^{-3}

L39: "and influences" I am not sure about what is meant here. To delete, or to be rephrased.

Responses: will be deleted in the revision.

L47: "Specially": Specifically

Responses: Will be revised in the revision.

L64: given the large number of symbols used, I recommend to put the table of symbols with full names and units in the beginning of the manuscript, or at least in the beginning of section 2, rather than in Appendix.

Responses: The symbols used in the main text will be moved at the beginning of Sec.2 (see Table R1)

L135-152: According to equations (16) to (19), soil water content does impacts heat transfers. Meanwhile, no information is given on how is handled hydrology in FPM. This should be discussed here.

Responses: While the current version of FPM does not consider the water mass balance, we specify the vertical water distribution within the soil column. We distinguished four hydrological layers, including the : 1) root zone; 2) vadose layer; 3) saturated layer; and 4) bedrock layer. In the root layer, the water content θ_R ($\text{m}^3 \text{m}^{-3}$) is estimated as the ensemble mean of five remote sensing-based products (Table 1, details see Sec. 3.3). The water content for the vadose layer θ_v ($\text{m}^3 \text{m}^{-3}$) is determined based on field capacity θ_{fc} ($\text{m}^3 \text{m}^{-3}$) and soil porosity ϕ ($\text{m}^3 \text{m}^{-3}$), and an ensemble range is used (see Sec. 3.3). Please see Appendix B for the parameterizations of soil properties. In the saturated layer, the water content ($\text{m}^3 \text{m}^{-3}$) is equal to ϕ . The water content of $0.05 \text{ m}^3 \text{m}^{-3}$ was used for the bedrock (Gubler et al., 2013).

All the above information can be found in Sec. 3.2 Soil water content.

L155-156: Why these numbers of layers and these thicknesses of grid cells? Any convergence study for justifying these choices?

Responses: We adopted the general principle for soil discretization: the grid size increases with depth. In this approach, thinner layers are used near the surface to better represent land-atmosphere interactions and to maintain numerical stability,

while thicker layers are employed in deeper soil to reduce computational cost.

L162: "the static soil moisture is used". This is an extremely strong assumption, eliminating seasonal dynamics (e.g.: wet season vs dry season) and inter-annual variability (e.g.: dry years vs wet years). Given the importance of soil water content and state for heat transfer properties, this is likely to generate important errors and biases in the result of permafrost dynamics. See for instance Clayton et al., 2021 for the impact of soil moisture distribution on active layer thickness. See also de Vrese et al., 2023 for a study of hydrology - related biases in large scale permafrost modelling. Anyway the manuscript does not give enough information for clearly understanding what is assumed here.

Responses: Regard to the static soil moisture, please see our responses to your general comments.

In fact, the related biases presented by Vrese et al., 2023 is largely due to the previous *"standard JSBACH version does not include the phase change of water in the soil, the model does not account for the above effect (ice-impedance) on the vertical movement of water through the ground..."* (see Sec. 2.1.4 from Verse et al., 2023).

According to table 1, only the 2015-2022 period has a complete set of five remote sensing products. Then what is done exactly ? Is the soil moisture in a given pixel considered to be constant equal to the mean of the five 2015-2022 multi-annual averages of each product?

Responses: The daily soil moisture data were aggregated to day-of-year for each dataset across their available coverage. Then the ensemble mean of five datasets are derived as model inputs. We will revise the Sec. 4.3 as below to clarify.

"FPM considers the influences of vegetation on permafrost via the latent heat and soil moisture etc. (Appendix A). In FPM, static vegetation is assumed and the vegetation optical depth (VOD), leaf area index (LAI), and vegetation type are required (Table 1). For snow-free periods, the ground albedo is from Jia et al. (2022).

The remote-sensing datasets vary in their temporal coverage, so we used the climatology to represent the long-term conditions. For the VOD and snow-free ground albedo, the daily measurements over the entire recording period were aggregated into a day-of-year climatology using the median, so as to reduce sensitivity to extreme values. The monthly LAI from Myneni et al. (2021) was aggregated to monthly medians. Daily θ_R values were first aggregated into monthly averages for each dataset. These monthly values from the thawing season (June to August) were then used to compute the annual mean. For each soil moisture dataset, the average over the entire recording period was derived, and an ensemble mean across the five datasets was calculated and employed as model inputs. Note that only the measurements from the thawing season (June to August) were used to derive VOD and θ_R ."

L255-256: "The simulated soil temperature was significantly improved by 2.1 °C, indicating FPM could be improved with more reliable climate forcing and soil profile (Fig. 2)." Interesting. I think that this is a direction to follow to improve the manuscript : study on how to improve LSM permafrost simulations?

Responses: As we presented and discussed, with more reliable climate forcing and soil profile, the simulation results rather than the model itself could be further improved. Producing better climate forcing and soil datasets will likely be an involved process requiring a broad range of knowledge, skills, and perspectives that differ from ours, and that will take time to bring together in a research project.

L274-297: Sections 5.2 to 5.4. Here temporal evolution of ALT, MAGT and permafrost extent are proposed for the period 1950-2023, with two contrasted periods, 1950-1980 and 1980-2023. I have strong concerns over the validity of any temporal evolution analysis while keeping the soil water content constant equal to an estimate based on 2015-2022 products (see my comment on l 162). At least, the way precipitation and evapotranspiration (and thus the overall water balance) have evolved during the whole considered period should be presented. Then the impact of assuming a time constant soil moisture profile should be discussed at the light of this information.

Responses: Please see our responses to the general comments.

L301-304: "In fact, permafrost simulations are hampered by reduced reanalyses quality in cold regions primarily due to inherent challenges in representing nonlinear processes involving ice, or its phase change near 0 °C (Cao and Gruber, 2025). The poorly described soil column, especially the soil organic matter, put additional uncertainty for permafrost simulations." I insist here on the key role of hydrology, and the especially of the water transfers within the soil column.

Responses: We agree. The uncertainties of assuming static soil moisture will be discussed based on the spread of ensemble simulations (see our responses to your major comments).

L309-310: "The static snow density was used to represent the overall conditions during the snow-covered period." Most likely concerns analogous to those I rose about static soil water content could be raised about considering a static snow cover. I recommend to make also a study of the evolution of properties of the snow cover over the study period, and to discuss the impacts of assuming a static snow cover on the basis of this information.

Responses: We agree the model would be more realistic with snow compaction scheme. A simulation comparison with different static snow density (225, 250, and 270 kg m⁻³) and snow compaction parameterization are presented to address

the influences. Please see the overall responses above.

L358: "Our simulations indicate that current land surface models employing shallow soil columns are inadequate for permafrost research on the Tibetan Plateau, since they have generally underestimated permafrost extent while overestimating degradation rates. Such inadequacy may also pose challenges in other regions characterized by deep active layers (i.e., > 3m); "I don't think that I saw any data or figure that give a quantitative basis for this statement, such as a comparison between good modelling results with thick soil column vs bad modelling results with shallow soil column. I do not want to say that the statement is not correct, just that it is not clearly established in the manuscript.

Responses: Figure 9 shows the difference of simulated permafrost areas using a various soil column depths, i.e., 3 m, 15 m, and 100 m. I copied related parts below

In section 3.5: *"In this study, we especially focus on the thermal state of permafrost at a depth of 3 m as the near-surface permafrost treated in most land surface models (Burke et al., 2020), and 15 m as the permafrost mean annual ground temperature (MAGT)."*

In section 5.2: *"Our results indicated that about 34.1 % of permafrost regions have an ALT greater than 3 m, highlighting that the widely used land surface models and reanalyses with shallow soil column may not be sufficient for permafrost studies over the TP."*

In section 5.4: *"Our results showed that the model with shallow soil column would significantly underestimate permafrost area but overestimated permafrost degradation. Take the top 3 m as an example, which has been widely used in the land surface model. The estimated near-surface (top 3 m) permafrost area ($7.67 \times 10^4 \text{ km}^2$) was about 33.4 % smaller compared to the ground "truth", or 33.6 % smaller than the simulations with sufficient soil column (e.g., 100 m, Fig. 9a)."*

L614-615: a manuscript cannot cite itself.

Responses: This citation refers to the simulated results of this study (publicly available via Zenodo with a DOI) rather than the manuscript itself. This citation will be revised as below to clarify.

Sun, W. and Cao, B.: Ensemble numerical simulation of permafrost over the Tibetan Plateau from Flexible Permafrost Model: 1950–2023 [data set], <https://doi.org/10.5281/zenodo.15229474>, 2025.

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