Response to RC1

We sincerely thank Referee #1 for dedicating time and effort devoted to reviewing our manuscript. We are highly encouraged by your positive assessment of our approach and the potential value of the dataset. Your constructive comments have been invaluable in improving the quality and clarity of the paper, particularly regarding the theoretical limitations of our mathematical framework. All of your concerns have been carefully addressed in the revised manuscript.

Below, your original comments are provided in **blue,** our responses are given in **black,** and the corresponding revisions added to the main text are highlighted in **red.**

This manuscript presents a highly relevant and novel approach to mapping solum thickness on the Qinghai-Tibet Plateau (QTP). By departing from the purely empirical and machine-learning paradigms that currently dominate national-scale soil mapping, the authors implement a physically consistent mass balance model. This work addresses a critical bottleneck in Earth system modeling: the structural bias of observational data in remote, high-altitude regions. Overall, this is a worthy effort that offers a robust, physics-driven alternative to pervasive data-driven methods, offering a promising path forward for data-scarce environments. I believe this paper makes a strong contribution to the field. However, several methodological assumptions require deeper discussion before publication.

We sincerely thank the reviewer for this highly positive and encouraging assessment of our manuscript. We greatly appreciate your recognition of our efforts to transition from purely empirical paradigms to a physics-driven mass balance model to address the structural biases inherent in data-scarce, high-altitude regions like the QTP. We also completely agree with your assessment that our methodological assumptions warrant a much more rigorous discussion. In the revised manuscript, we have expanded our uncertainty analyses and theoretical discussions to address these important points, as detailed in our point-by-point responses below.

1) The core of the mathematical solution fundamentally relies on the assumption of a geomorphic steady state. The QTP, however, is a highly transient landscape. While the authors acknowledge this limitation in the discussion, relying on adjustable weighting coefficients to mathematically force a balance may inadvertently mask true mass imbalances across the region. I hope that the authors expand the discussion to

thoroughly explore how this mathematical workaround affects the final outputs and the interpretation of the underlying geomorphic mechanisms.

We thank the reviewer for this critical and insightful comment. To address this concern comprehensively, we have implemented a two-fold revision:

1 Quantitative sensitivity analysis: We conducted a One-At-A-Time sensitivity analysis (added as a new sub-section in Section 4). Based on calibrated 1 km baseline map, we applied a relative perturbation of ±20% to the α, β, and γ coefficients. We then evaluated the sensitivity by calculating the absolute change (Δh), relative percentage change ($\%\Delta h$), and elasticity (the ratio of relative change in thickness to relative change in the coefficient). The results of this analysis map exactly where and to what extent the coefficient calibration influences the simulated thickness. We applied ±20% perturbations to the erosion weighting coefficients following the reviewer's suggestion to vary key parameters by ±20–50%. We consider this range appropriate because the calibrated coefficients in most clusters are already small; even under this perturbation the resulting elasticities remain very low, confirming model robustness.

As demonstrated in the figures and table below, the sensitivity is strongly partitioned by regional geomorphic regimes. For instance, in the extreme relief of the Hengduan Mountains (Cluster 1), the model exhibits the highest sensitivity to gravitational weights (γ elasticity = -0.05), while in the interior permafrost zones (cluster 7), sensitivity is dominated by aeolian weights (β elasticity = -0.19). However, the plateau wide elasticities remain robustly low (α = -0.01, β = -0.02, γ = -0.08). These results confirm a highly stable model structure that is relatively insensitive to reasonable parameter perturbations, while still capturing local geomorphic extremes. The low sensitivities partly result from the calibration process assigning small weighting coefficients in most clusters, which effectively down-weights the empirical RUSLE and RWEQ erosion rates.

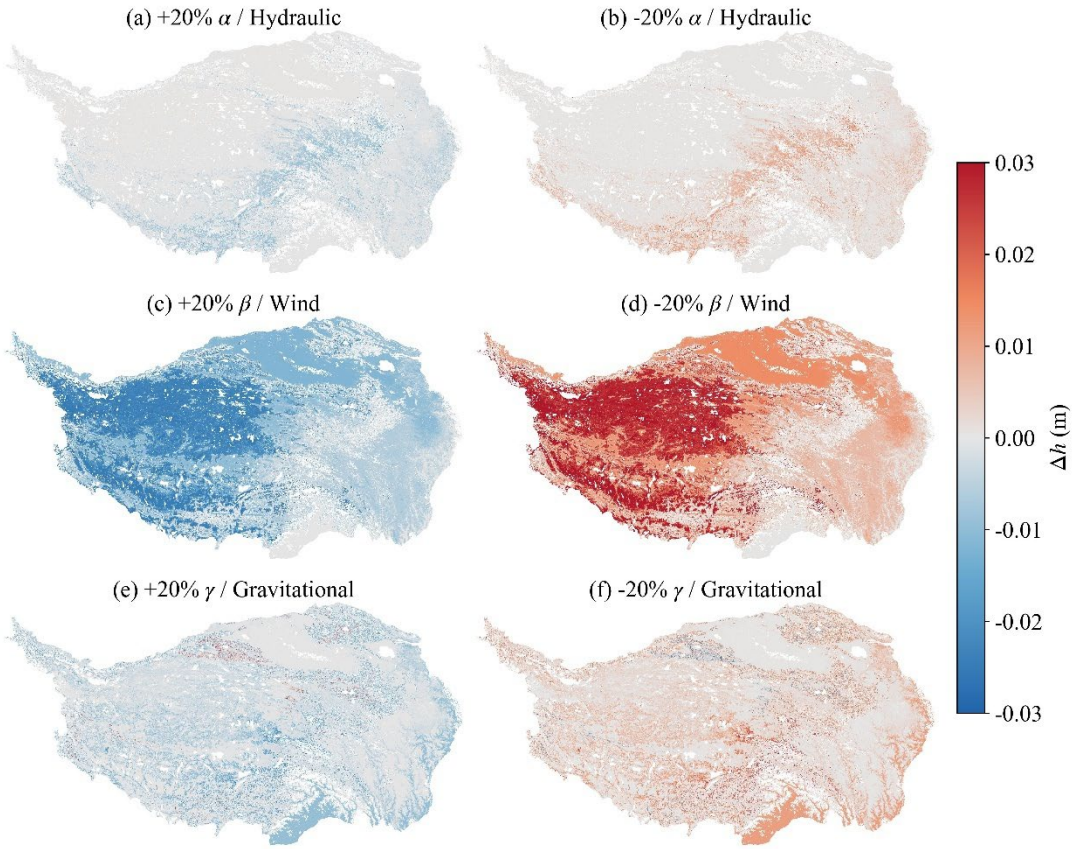


Figure R1. Spatial distribution of solum thickness sensitivity to ±20% perturbations in erosion weighting coefficients. The legend shows 98% range of values.

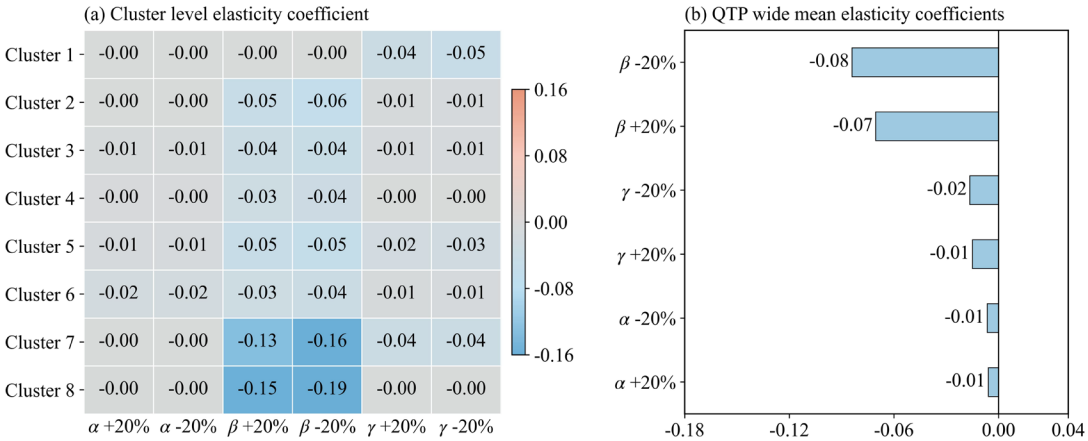


Figure R2. Elasticity coefficients of simulated solum thickness. (a) Cluster-level elasticity coefficients showing the relative sensitivity of solum thickness to ±20% perturbations of α, β, and γ for each environmental cluster. (b) QTP-wide mean elasticity coefficients summarizing the overall sensitivity of solum thickness across the

plateau. Elasticity is negative for both +20% and –20% perturbations because solum thickness responds inversely to erosion rate (Eq. 9).

Table R1. Summary statistics of the OAT sensitivity analysis, detailing mean absolute and relative changes, mean elasticity and area with >10% change per cluster and across the entire QTP.

Parameter	Scenario	Cluster	Mean Relative Change (%)	Mean Elasticity	Area with >10% Change (%)
α	-20%	1	0.00	0.00	0
	-20%	2	0.03	0.00	0
	-20%	3	0.11	-0.01	0
	-20%	4	0.08	0.00	0
	-20%	5	0.19	-0.01	0.14
	-20%	6	0.37	-0.02	0
	-20%	7	0.03	0.00	0
	-20%	8	0.07	0.00	0
	-20%	Plateau wide	0.13	-0.01	0.01
α	+20%	1	0.00	0.00	0
	+20%	2	-0.03	0.00	0
	+20%	3	-0.10	-0.01	0
	+20%	4	-0.08	0.00	0
	+20%	5	-0.19	-0.01	0.14
	+20%	6	-0.32	-0.02	0
	+20%	7	-0.03	0.00	0
	+20%	8	-0.06	0.00	0
	+20%	Plateau wide	-0.12	-0.01	0.01
β	-20%	1	0.00	0.00	0
	-20%	2	1.16	-0.06	0
	-20%	3	0.89	-0.04	0
	-20%	4	0.71	-0.04	0
	-20%	5	1.08	-0.05	0.90
	-20%	6	0.74	-0.04	0
	-20%	7	3.12	-0.16	0

	-20%	8	3.73	-0.19	0
	-20%	Plateau wide	1.68	-0.08	0.07
β	+20%	1	0.00	0.00	0
	+20%	2	-0.96	-0.05	0
	+20%	3	-0.75	-0.04	0
	+20%	4	-0.59	-0.03	0
	+20%	5	-0.95	-0.05	0.61
	+20%	6	-0.63	-0.03	0
	+20%	7	-2.63	-0.13	0
	+20%	8	-3.06	-0.15	0
	+20%	Plateau wide	-1.41	-0.07	0.05
γ	-20%	1	0.92	-0.05	0
	-20%	2	0.14	-0.01	0
	-20%	3	0.21	-0.01	0
	-20%	4	0.04	0.00	0
	-20%	5	0.54	-0.03	0.72
	-20%	6	0.13	-0.01	0
	-20%	7	0.77	-0.04	0
	-20%	8	0.00	0.00	0
	-20%	Plateau wide	0.33	-0.02	0.06
γ	+20%	1	-0.76	-0.04	0
	+20%	2	-0.12	-0.01	0
	+20%	3	-0.19	-0.01	0
	+20%	4	-0.04	0.00	0
	+20%	5	-0.46	-0.02	0.68
	+20%	6	-0.12	-0.01	0
	+20%	7	-0.72	-0.04	0
	+20%	8	0.00	0.00	0
	+20%	Plateau wide	-0.30	-0.01	0.05

2 Theoretical clarifications: We have revised Section 4.3 to explicitly state that the weighting coefficients act as “effective scaling factors”. They absorb multiple

uncertainties, including empirical erosion biases, unresolved transient dynamics, and scale mismatches, rather than serving as direct proxies for true mass imbalances.

"...These coefficients should be interpreted as effective scaling factors rather than direct proxies for deviations from geomorphic equilibrium. They absorb multiple sources of uncertainty, including biases in the empirical erosion estimates (E_{water} and E_{wind}), unresolved transient dynamics, and scale mismatches between processes. Therefore, they do not explicitly resolve true non-steady-state mass imbalances or indicate whether a location is undergoing net accumulation or net denudation. The simulated solum thickness should therefore be viewed as a physically constrained, quasi-steady representation of regional conditions under contemporary environmental forcing, rather than as a full reconstruction of transient landscape evolution."

2) The model uses the Effective Energy and Mass Transfer framework to estimate potential weathering rates, which relies strictly on Mean Annual Temperature (MAT) and Mean Annual Precipitation (MAP). Consequently, the model largely overlooks the specific mechanics of freeze-thaw cycles and active layer dynamics. While I recognize the immense difficulty of implementing these complex cryogenic components into the current model structure, the authors must provide a more thorough and critical discussion of this limitation.

We thank the reviewer for highlighting this important point. We agree that the EEMT framework, being derived primarily from MAT and MAP, does not explicitly model the specific thermodynamics of freeze-thaw cycles and active layer dynamics. However, we wish to clarify that the effects of freeze-thaw processes are not entirely absent from our modeling framework.

Physically, freeze-thaw primarily acts as a weathering mechanism that generates loose detrital material through frost shattering. The subsequent mass loss that determines solum thickness is executed by three modelled transport processes (gravitational, wind, and water erosion). In our framework, the cluster-calibrated weighting coefficients (α, β, γ) scale these transport fluxes to match the observed local solum thickness. Consequently, these coefficients implicitly account for the net effects of cryogenic weathering by adjusting the empirical erosion terms, even though an explicit freeze-thaw production term is not included.

To rigorously address this concern, we have made two major revisions:

1 Theoretical clarification: We expanded the discussion (Section 4.3) to explicitly explain the mechanism described above.

"... Furthermore, the use of the EEMT framework relies on MAT and MAP, which does not explicitly parameterize the mechanics of freeze-thaw cycles or active layer dynamics. In our framework, the effects of cryogenic weathering are implicitly captured by the subsequent transport processes, scaled by the calibrated weighting coefficients. However, as demonstrated in our LHS uncertainty analysis, relying on empirical erosion models originally developed for temperate zones introduces spatial uncertainty, particularly in the plateau's permafrost core."

2 Global uncertainty and sensitivity analysis: Because this implicit approach relies on baseline empirical erosion inputs derived from RUSLE and RWEQ, which were not specifically designed for permafrost environments, we performed a comprehensive global uncertainty and sensitivity analysis by adding a new subsection in Section 4. For the uncertainty analysis, the empirical water and wind erosion inputs were independently perturbed within ±40% of their baseline values using Latin Hypercube Sampling, generating 150 ensemble simulations. This ±40% range is justified by the known limitations of these temperate-derived empirical models when extrapolated to high-altitude permafrost environments, where uncertainties are typically reported in the 30–60% range.

Based on these simulations, we quantified the spatial uncertainty in simulated solum thickness using the coefficient of variation (CV), standard deviation, 5th–95th percentile range, and the relative difference between the ensemble mean and the baseline simulation (Fig. R3 a-d). For the sensitivity analysis, to identify the dominant sources of uncertainty, we performed a separate Sobol total-order sensitivity analysis. The required samples were generated using the Saltelli sampling scheme, with E_{water} and E_{wind} sampled within ±40% of their baseline values. A total of 512 model evaluations were used to calculate the Sobol total-order indices. These indices quantify the overall contributions of E_{water} and E_{wind} to output uncertainty, including both their direct effects and interaction effects (Fig. R3 e, f).

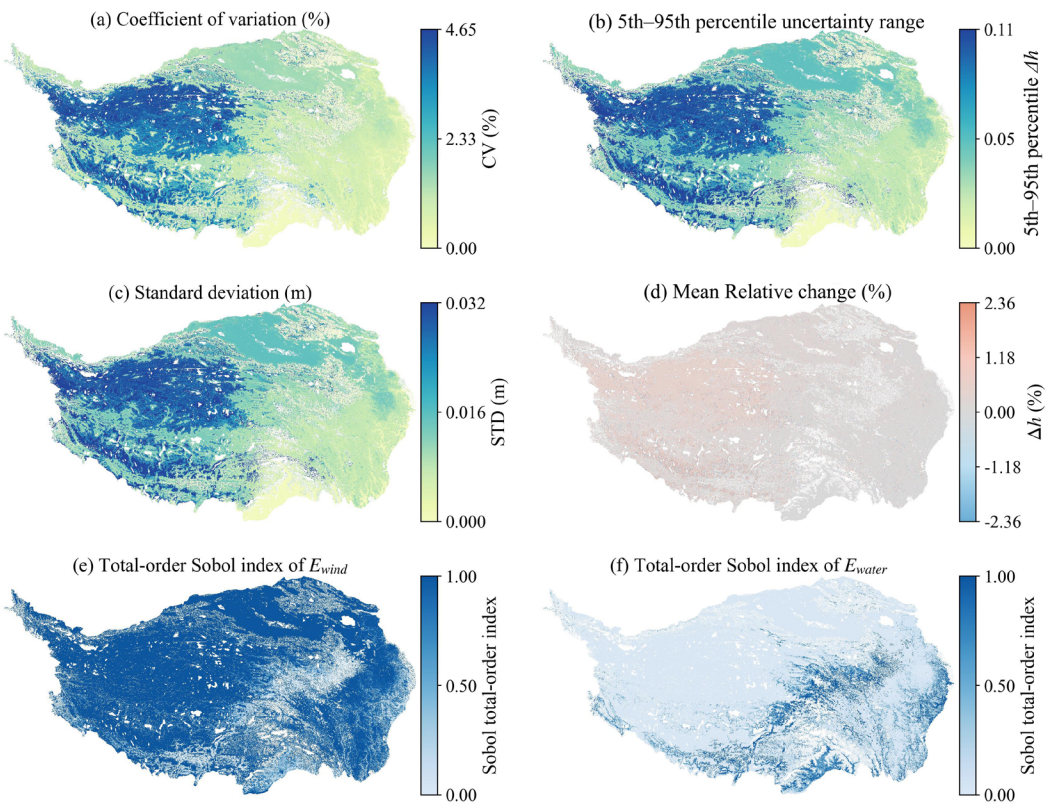


Figure R3. Spatial distribution of uncertainty and sensitivity in the simulated solum thickness across the QTP due to uncertainties in the empirical wind and water erosion inputs (RUSLE and RWEQ). (a) Coefficient of variation (CV, %), (b) 5th–95th percentile range. (c) Standard deviation of the 150 ensemble simulations. (d) Relative difference between ensemble mean and baseline. (e-f) Sobol total-order sensitivity indices for E_{wind} and E_{water}, respectively.

This CV map explicitly quantifies how the uncertainty of using these erosion models in permafrost-dominated zones propagates into our final solum thickness estimates. Notably, the uncertainty is highest in the plateau's permafrost core, directly highlighting where aeolian and cryogenic interactions deviate most from the empirical baselines.

Crucially, we have added a new paragraph to the discussion to discuss this uncertainty as a critical diagnostic feature for the Earth system modeling community, rather than merely a model limitation:

"Rather than viewing this spatial uncertainty purely as a limitation, it serves as a critical diagnostic of the current state of Earth system modeling on the QTP. Traditional mapping approaches often provide deterministic values that mask the underlying uncertainty of applying temperate-derived empirical models to cryogenic environments. By explicitly mapping the CV, this study provides essential structural bounds for hydrological and ecological modelers. Furthermore, the concentration of high uncertainty in the Qiangtang Plateau quantitatively exposes the structural inadequacies of the standard empirical frameworks in permafrost-dominated zones, highlighting the urgent need for the community to develop permafrost-specific erosion and weathering parameterizations."

3) The model is driven by several external inputs, including a global machine-learning Depth-to-Bedrock product and high-resolution outputs from the Revised Universal Soil Loss Equation and the Revised Wind Erosion Equation. Because these are fundamentally empirical products, they often also fail to capture the complex sediment transport dynamics specific to alpine meadows, freeze-thaw eroded slopes, and discontinuous permafrost zones. The uncertainties inherent in these driving datasets will inevitably propagate into the final solum product. The authors should discuss whether there are methods to quantify, or ideally further reduce, the uncertainties introduced by these foundational inputs.

We completely agree that the uncertainties from these empirical driving datasets propagate into the final solum map. So, we performed two additional uncertainty analysis:

1 Quantifying uncertainty from empirical erosion forcing (water and wind erosion):

As the reviewer correctly points out, the empirical RUSLE and RWEQ inputs may not fully capture the complex cryogenic sediment transport dynamics of the QTP. Thus, we have introduced a comprehensive global uncertainty and sensitivity analysis using Latin Hypercube Sampling (LHS) and Saltelli sampling scheme.

We applied a conservative ±40% perturbation specifically to the empirical wind and water erosion inputs across 150 ensemble members (gravitational erosion was excluded from this perturbation, as it is an internally calculated mechanistic term driven by local topography rather than an external empirical dataset). This allowed us to generate a spatial Coefficient of Variation (CV) map (Fig. R3), which explicitly quantifies and maps the structural uncertainty propagated from the RUSLE and RWEQ datasets across different geomorphic zones. Furthermore, to distinguish the relative importance of the two empirical erosion inputs, we performed a separate Sobol total-order sensitivity

analysis. In this analysis, the empirical wind and water erosion inputs were independently sampled within ±40% of their baseline values using the Saltelli sampling scheme, resulting in 512 model evaluations. The resulting Sobol total-order sensitivity indices for E_{wind} and E_{water} were then used to identify the dominant sources of uncertainty in simulated solum thickness.

2 Quantifying the impact of the DTB constraint:

The global machine-learning DTB product (Shangguan et al., 2017) serves a different function. In our revised mass balance framework, the solum thickness (hs*) is independently derived through the steady-state balance between soil production and surface erosion (Eq. 9). The DTB dataset is only used as a boundary condition to define the maximum available regolith (as a cutoff for hs*).

Therefore, uncertainties or underestimations in the global DTB product do not propagate into our calculated solum thickness unless the independently calculated solum depth exceeds the DTB threshold. To quantify this, we analyzed the intersection of our simulated solum depth with the DTB constraint. To maintain consistency with the perturbation ranges applied to E_{wind} and E_{water}, we also applied a ±40% perturbation to the DTB input and compared the results with those from the 150 ensemble simulations. Our analysis shows that, even under the −40% DTB perturbation scenario, the calculated solum thickness reaches or is truncated by the DTB constraint in only 0.001% of the total simulated area across the plateau.

"...Second, the partitioning of the regolith into solum and saprolite is constrained by the global DTB product (Shangguan et al., 2017). While this dataset is inherently limited by the scarcity of deep borehole data in the plateau's interior, it is crucial to note that the solum thickness is derived independently through the erosion-production balance (Eq. 9). To maintain consistency with the perturbation ranges applied to E_wind and E_water, we also applied a ±40% perturbation to the DTB input and compared the results with those from the 150 ensemble simulations. Our analysis shows that, even under the −40% DTB perturbation scenario, the calculated solum thickness reaches or is truncated by the DTB constraint in only 0.001% of the total simulated area across the plateau. Therefore, while any systematic underestimation in the global DTB product would compress our calculated saprolite thickness, the accuracy of the solum depth reported here remains structurally robust across the vast majority of the landscape."

4) In Section 3.3, the authors perform a Pearson correlation analysis and report MAT and elevation as the primary drivers of the regional thickness gradient. However,

because the model's core soil production function is mathematically driven by MAT and MAP in the first place, the final results are practically guaranteed to correlate strongly with MAT and elevation. I recommend reframing this section. Rather than presenting these correlations as independent scientific discoveries about the region, they should simply be framed as an internal validation confirming that the model behaves as parameterized.

We completely agree with your assessment. To address this, we have completely reframed Section 3.3. We altered the section heading and revised the text to explicitly present the correlation analysis as an internal validation exercise. The purpose is now framed to confirm that the prescribed thermodynamic relationships were successfully preserved through the steady-state solver, and that the regional climatic signal was not entirely overridden by the local geomorphic noise introduced by the multi-process erosion modules.

I show some important revised text as follows:

"3.3 Internal Validation of Environmental Drivers

To verify that the model's underlying thermodynamic parameterizations were preserved in the final steady-state solutions, we conducted a Pearson correlation analysis between the simulated solum thickness and key environmental variables (Fig. 4). Because the initial soil production function ($P_{c\to s}$) is mathematically driven by the EEMT framework, the final results are structurally expected to correlate with primary climatic inputs. As anticipated, MAT (r = 0.66) and elevation (r = -0.66) emerge as the primary correlates of the regional thickness gradient.

Rather than an independent discovery, this strong coupling serves as an internal validation of our modeling framework. It confirms that the broad, regional-scale thermodynamic forcing successfully propagates through the steady-state mass balance equations, establishing the regional baseline thickness without being excessively distorted or overridden by the local, high-frequency geomorphic noise introduced by the hydraulic, aeolian, and gravitational erosion modules. Conversely, the lack of correlation with local morphometric variables like general curvature (r = -0.01) at the plateau scale confirms that while topography drives local differentiation (as seen in Fig. 5), the regional mean state of the soil is correctly dominated by the broad climatic forcing."

Specific comments

1. Please maintain consistency in terminology. The manuscript uses "solum thickness," "solum thickness," and "solum depth" interchangeably.

In the revised manuscript, we now consistently use "solum thickness" throughout the text, figures, and tables when referring to our specific simulated and measured metric (the vertical distance from the ground surface to the C horizon interface). We have removed all instances of "solum depth" to avoid confusion. In the few instances where "soil thickness" is retained for broader readability, such as in the title or general introductory statements, we have ensured it is explicitly and immediately defined as referring to the solum thickness.

2. Lines 163–165: The text initially states that freeze-thaw erosion is not considered as a separate category, but immediately follows up by describing two main freeze-thaw erosion processes. This creates a contradiction.

We thank the reviewer for pointing out this confusing phrasing. Our intent was to clarify the physical distinction between the weathering phase (frost shattering creating loose particles) and the transport phase. To resolve this, we have revised the text to avoid the term "freeze-thaw erosion" entirely. We now explicitly define frost action as a "weathering agent," clarifying that the loose material it generates is subsequently moved by the three modeled transport fluxes (wind, water, and gravity).

We revised text to clarify this confusion in Section 2:

"Other potential mass-loss factors, such as explicit freeze-thaw driven transport and human activities, were not modeled as separate erosion categories. Physically, freeze-thaw action in this extreme environment primarily acts as a weathering agent (frost shattering) that generates loose detrital particles, rather than a distinct transport mechanism. In our mass-balance framework, this cryogenic weathering prepares the material, which is subsequently removed by the simulated fluvial, aeolian, and gravitational transport fluxes."

3. Lines 160–170: The text repeatedly states that human activities are not considered, which is excessively lengthy.

We thank the reviewer for pointing out this redundancy. We have streamlined this paragraph, condensing the justification into a single, brief sentence.

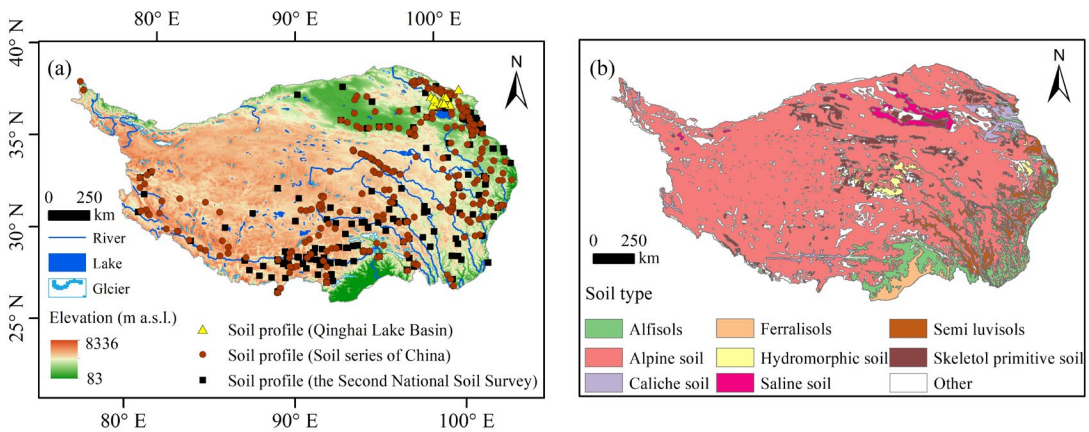
"Furthermore, given the vast area and sparse population of the QTP, the impact of direct human activities on regional-scale erosion patterns is considered negligible compared to natural forcing (Sun et al., 2020), and was therefore excluded from the model."

4. Figure 1: Increase the font size to ensure clarity, and review the formatting of all remaining figures and tables to ensure consistency with the journal's requirements.

We have redrawn Figure 1 to significantly increase the font sizes of all labels, coordinates, and legends, ensuring clear legibility.

Furthermore, we have conducted a comprehensive review of all remaining figures and tables in the revised manuscript to verify that their layouts, resolutions, and text sizes are fully consistent with ESSD's publication guidelines.

Revised Figure 1



5. Table 2: What is the basis for the range of each parameter in Table 2? Please add supporting references.

We thank the reviewer for pointing out this omission. In the revised manuscript, we have updated Table 2 to include a "Basis / References" column. The ranges for the kinetic and transport parameters were established based on classic geomorphological compilations and previous applications of the EEMT framework.

The soil diffusion coefficient (D) is bounded based on established empirical ranges for hillslope transport (e.g., Roering, 2008), soil bulk density (ρ_s) is constrained according to the commonly reported range for mineral soils summarized by Rühlmann et al. (2006), the characteristic soil depth (h_0) and EEMT coefficients (a, b) are bounded based on the foundational works of Pelletier and Rasmussen (2009a) and Pelletier et al. (2013), and the weighting coefficients (α, β, γ) are mathematically constrained between 0 and 1 as they represent relative dimensionless scaling factors.

6. Lines 272–274: The description of the distribution of cluster 6 is inaccurate.

We thank the reviewer for pointing out this geographical inaccuracy. We have carefully re-examined the spatial distribution of the clusters in Figure 2b and agree that grouping Clusters 5 and 6 together as broadly "northeastern and northern" was imprecise. While Cluster 5 is predominantly located in the northeastern QTP, Cluster 6 extends much further south, primarily occupying the central and eastern-central portions of the plateau (which encompasses the Three Rivers Source Region).

We have corrected this description in the revised manuscript to accurately reflect the distinct spatial footprints of these two clusters.

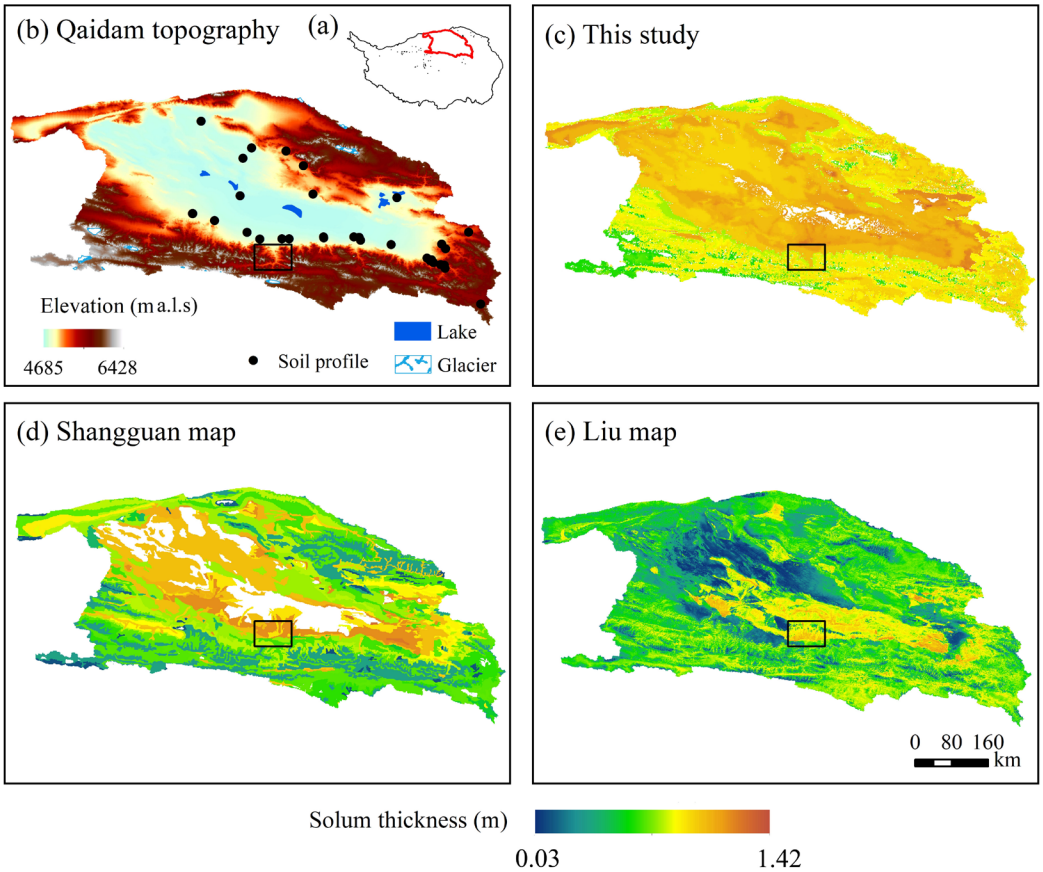
7. Figure 7: Insert the corresponding legend for soil thickness.

We thank the reviewer for pointing this out. In the original manuscript, the legend for solum thickness was located within panel (e). To maintain a clean and uncluttered visual layout, we prefer not to repeat the identical legend across subplots (c), (d), and (e). However, we agree that its previous placement may not have clearly indicated that the scale applied to all three maps.

To resolve this, we have redrawn Figure 7. We extracted the solum thickness color bar from the individual panel and enlarged it into a single, prominent, unified legend positioned to clearly serve the spatial maps in panels (c), (d), and (e).

Note to Reviewer: The same unified legend formatting has also been applied to Figure 8 for consistency.

Revised Figure 7

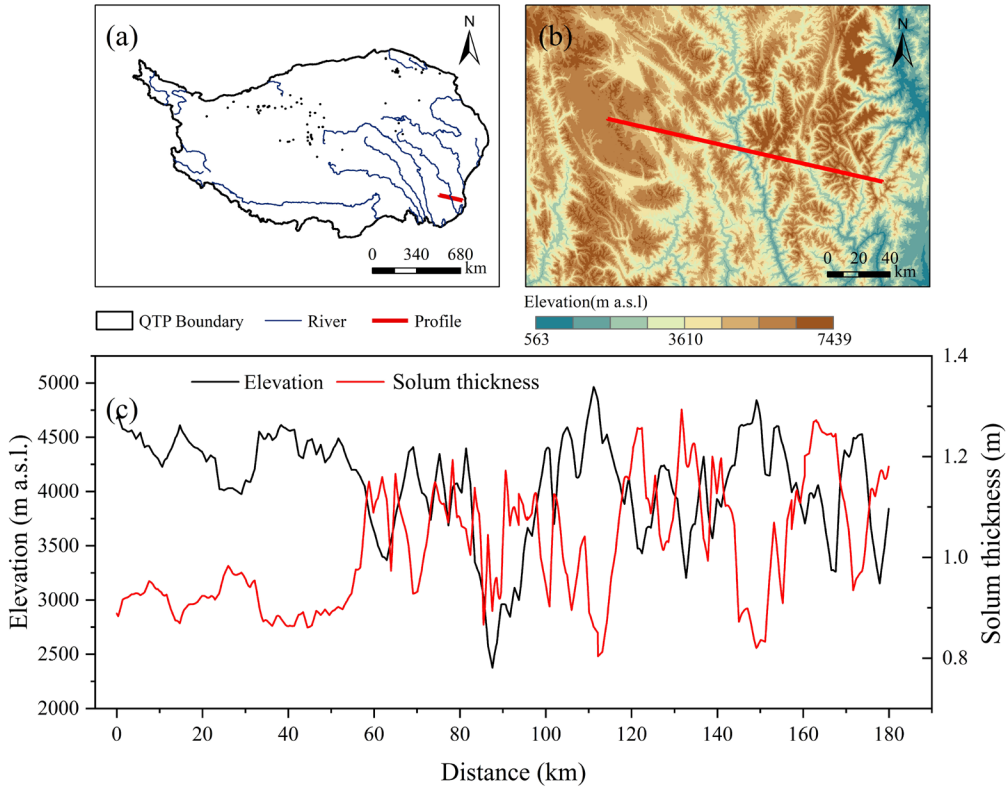


8. Figure 5-8: Please add legend to Fig. 5 and carefully review the captions for Figs. 6–8.

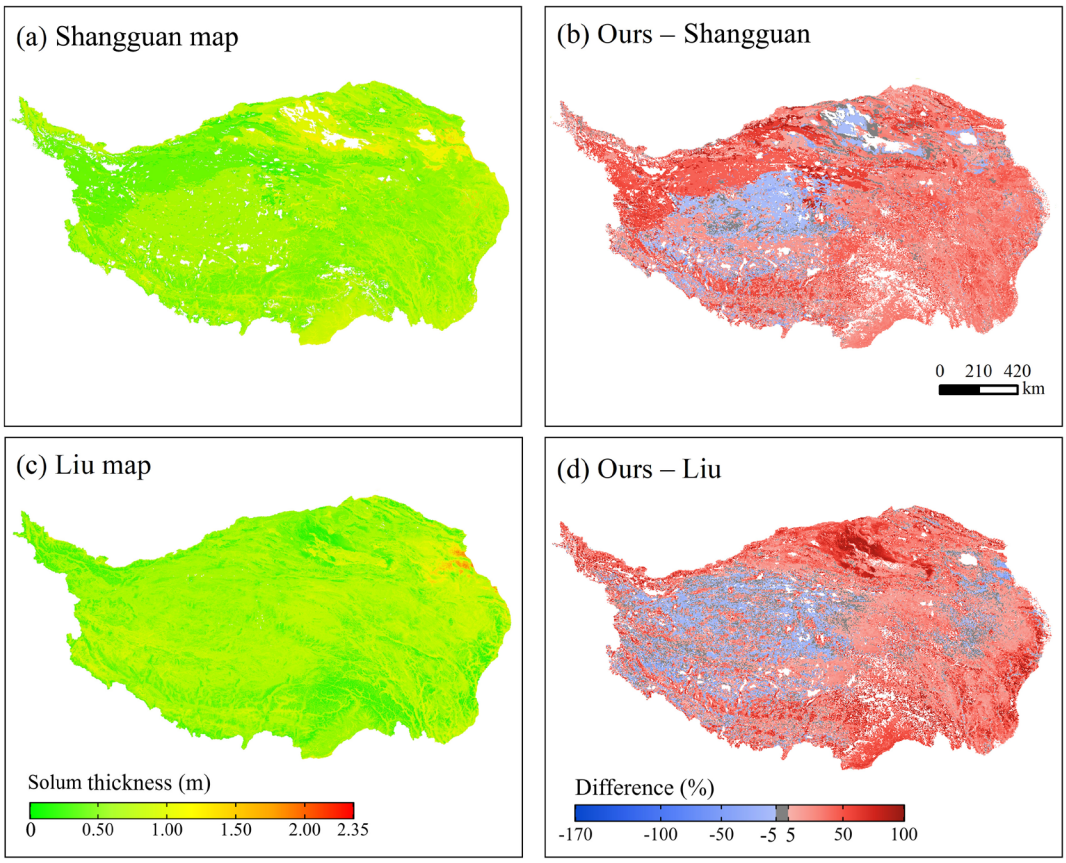
We thank the reviewer for their careful attention to the figures. We agree that the omission of the elevation legend in Figure 5b made the topographic transect difficult to interpret. In the revised manuscript, we have updated Figure 5 to include a clear legend in panel (b).

Furthermore, we have thoroughly reviewed and revised the captions for Figures 6, 7, and 8. We have expanded these captions to provide more explicit context for the spatial patterns shown, and make sure the use of consistent "solum thickness" as established in our response to Specific Comment #1.

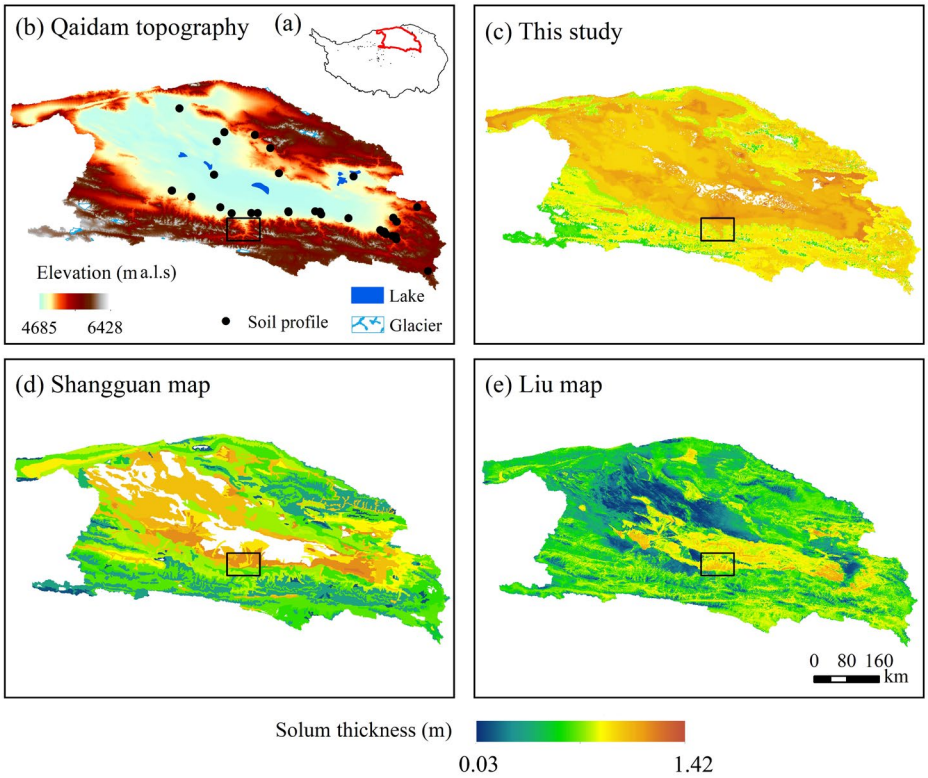
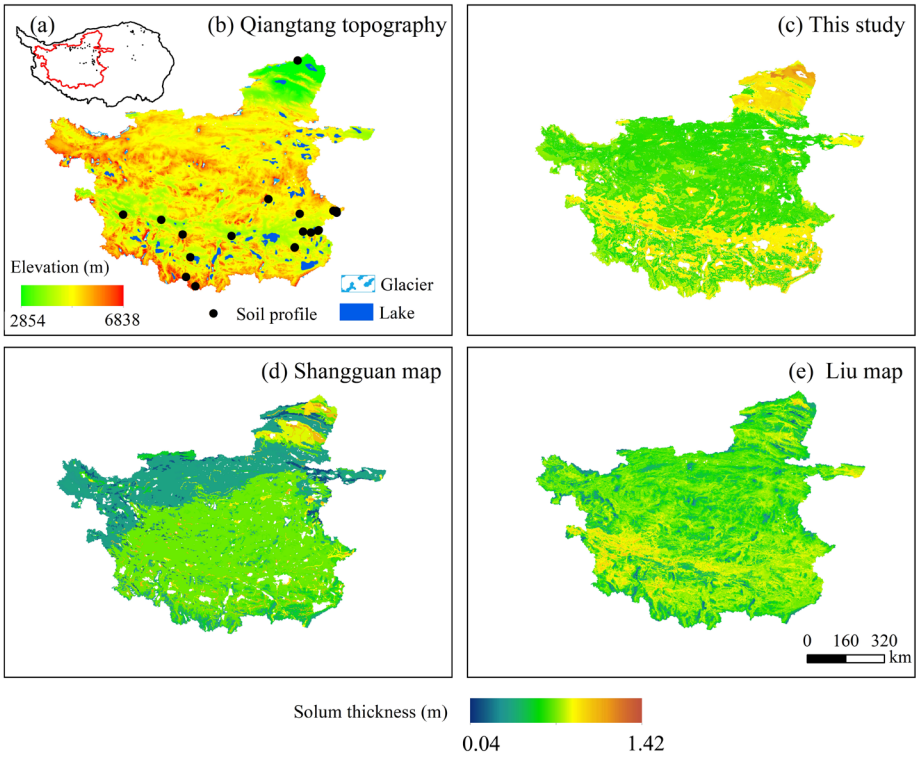
Revised Figure 5



Revised Figure 6



Revised Figure 7



Revised Figure 8