Response to Reviewer 2 Comments

Review of Pang et al. (2026) 'ITMSL: an improved ice thickness inversion model integrating basal sliding dynamics for High Mountain Asia (v1.0.0)'

Summary

1. This paper presents a new ice-thickness-inversion model called ITMSL, and explores its performance across a dataset of 16 glaciers in High Mountain Asia compared to two existing thickness datasets inverted using different methods. The novelty of ITMSL is that it includes explicit consideration of glacier sliding, unlike most previous regional- or global-scale inversion methods that rely on the shallow ice approximation (SIA) and therefore neglect sliding entirely. The authors show ITMSL performs better than the reference datasets on the dataset included in this paper.

   Response: Thank you very much for your summary and evaluation of our paper. Following your valuable comments and those of the other reviewers, we have systematically revised and improved the manuscript. The revisions include:

   (1) supplementing the discussion on the ITMIX framework,

   (2) refining the parameter sensitivity analysis, standardizing the error metrics,

   (3) adding point-by-point comparisons against measured GPR data, and presenting a more objective description of the model's applicability and limitations. We thank you again for your constructive review.

2. I am not convinced by this paper as it stands. I have questions about the dataset used in this study, as well as engagement with the wider literature, and I do not believe that the study shows conclusively what it purports to show (see below for specific details). I also have some major concerns about the model parameters and the presentation of the results. Fundamentally, the paper requires very substantial work to meet the required standards, to the extent that I feel I have to recommend rejection, as I do not think it will be achievable within a major revisions timeframe. In particular, an almost entire re-write to follow the ITMIX protocol would be the easiest way to resolve many of my concerns, but at this point, we're talking about an almost entirely separate paper, rather than a revised version of this one.

   Page and line numbers refer to those in the clean version of the submitted manuscript.

   Response: We are sorry that our unclear presentation, insufficiently detailed glacier selection criteria, and inadequate model parameter calibration have left you with such an impression. We have carefully read and fully respect your review conclusions. The issues you raised—concerning the dataset, literature engagement, model parameters, and presentation of results—indeed reveal deficiencies in the methodological rigor and argumentative thoroughness of our paper. We acknowledge that there are indeed some shortcomings, and we appreciate your pointing them out. We have made every effort to respond to all your comments. Specifically, the introduction section has been almost completely rewritten to clarify the ITMIX framework, the positioning of this work, and the rationale for glacier selection. Regarding model setup and parameter calibration, we have conducted additional experiments and analyses based on your review comments. Furthermore, we have made detailed modifications and additions to the language and figures/tables throughout the paper, and have placed more results in the appendix to fully present the relevant findings of this study.

In response to the core issues you identified, we have made the following substantive revisions point by point:

(a) **Dataset and literature engagement:** We have added more detailed metadata descriptions, clarifying data sources, preprocessing steps, and potential uncertainties. We have also systematically reviewed the latest literature in the field of ice thickness inversion (particularly ITMIX-related studies), and clearly positioned our work in comparison with existing studies.

(b) **Model parameters and result presentation:** Following the benchmark testing protocol recommended by the ITMIX community, we have recalibrated the model parameters and conducted sensitivity analyses. We have also re-presented the results using standardized error statistics (e.g., MAE, RMSE, percentile bias, etc.) to ensure comparability and reproducibility.

(c) **Strength of argumentation:** We have toned down the overly absolute conclusions presented earlier, more objectively demonstrated the applicability and limitations of our model, and added point-by-point comparison plots against measured GPR data to quantitatively demonstrate the effectiveness of our method.

We understand that you consider these revisions to require "almost a complete rewrite" and that they may exceed the typical scope of a major revision. Nevertheless, we believe that after such in-depth revisions, the new manuscript will meet the publication standards of the journal.

Major Comments

1. Engagement with the literature: as pointed out below, the authors' use of terminology is curious. Couching the paper in terms of the SIA rather than laminar-flow theory would make it much more obvious how it engages with existing glaciological literature. As it is, it feels as if the authors haven't really understood where their own paper fits in the wider debate, nor how to position it, as it's written in a very non-standard way for a paper on modelling glacier sliding.

Response: Thank you very much for your valuable suggestion. The use of the term "laminar flow theory" in this paper to refer to the core equation of ice thickness inversion (Equation 1) is indeed potentially confusing. We adopted this terminology because some studies refer to it as the "laminar flow equation," while others call it the SIA (shallow ice approximation). To address your question, we have revised all occurrences of “laminar flow theory” in the main text to either “SIA” or “laminar flow equation” to facilitate reader understanding.

$$u_s = u_b + \frac{2A}{n+1}\tau_b^n H \tag{1}$$

Literature that refers to the laminar flow equation as "laminar flow":

[1] Gantayat P, Kulkarni A V, Srinivasan J. Estimation of ice thickness using surface velocities and slope: case study at Gangotri Glacier, India [J]. Journal of Glaciology, 2014, 60(220): 277-82.

[2] Gopika J S, Kulkarni A V, Prasad V, et al. Estimation of glacier stored water in the Bhaga basin using laminar flow and volume-area scaling methods [J]. Remote Sensing Applications: Society and Environment, 2021, 24.

Literature that refers to the laminar flow equation as the "shallow ice approximation (SIA)":

[1] Millan R, Mouginot J, Rabatel A, et al. Ice velocity and thickness of the world’s glaciers [J]. Nature Geoscience, 2022, 15(2): 124-9.

2. ITMIX: As a related point, at no point in the paper do the authors mention ITMIX, the Ice Thickness Model Intercomparison Experiment, which is the gold standard in glaciology for evaluating the performance of thickness-inversion models. It is referenced in the discussion, but the actual acronym never appears. This is a curious omission, and again makes it seem as if the authors aren’t really aware of the literature on the subject. Especially because, if the authors want to show how well ITMSL performs compared to other inversion models, reproducing the full set of ITMIX experiments or at least a subset of them would be by far the best way of doing so. It would make it much more obvious whether ITMSL is actually adding something or not, and clearly show where it performs better or worse than other approaches. Currently, the authors sort-of half-reproduce ITMIX in Section 5.4, but in a rather odd way that appears to show ITMSL isn’t really doing anything much better than other existing models. I would urge the authors to rethink their paper comprehensively, and adopt the ITMIX protocol for a revised version. At the very least, there needs to be substantially more engagement with the two ITMIX papers in order to strengthen the paper’s conclusions.

Response: When designing the experiments and writing the initial draft, we only considered that the proposed method is based on the laminar flow equation. Therefore, for model validation and comparison, we only selected ice thickness models based on the same approach, namely Gantayat and Millan. However, ITMIX and ITMIX2 are two important studies that cannot be overlooked in the field of ice thickness inversion modeling, yet we did not highlight them prominently in the Introduction. We recognize that this reflects an insufficient understanding of the existing literature, and we have therefore supplemented both the Introduction and Discussion sections accordingly.

(a) Additions to the Introduction (P.2-3, L56-82):

To date, approximately 20 ice thickness models have been proposed, including H-F, OGGM, GlabTop2, and ice velocity-based approaches (Huss and Farinotti, 2012; Frey et al., 2014; Gantayat et al., 2014; Farinotti et al., 2019; Maussion et al., 2019; Millan et al., 2022). To evaluate the accuracy and limitations of ice thickness inversion models, ITMIX systematically assessed 17 models that infer ice thickness from glacier surface characteristics (Farinotti et al., 2017). These models encompass different approaches, including minimization approaches, mass conservation approaches (Huss and Farinotti, 2012), shear stress-based approaches (Frey et al., 2014), ice velocity-based approaches (Gantayat et al., 2014), and convolutional neural network approaches (Jouvet et al., 2021). Different models have varying input data requirements, typically requiring two or more types of data from digital elevation models (DEMs), glacier outlines, surface velocity fields, and mass balance data (Farinotti et al., 2017; Farinotti et al., 2021). Among them, minimization approaches offer strong physical consistency and can handle complex glacier dynamics (Farinotti et al., 2021); mass conservation approaches feature a solid physical foundation and good stability (Farinotti et al., 2009); shallow ice approximation (SIA) approaches are robust and computationally fast (Ramsankaran et al., 2018); and ice velocity-based methods are particularly effective for sliding-dominated glaciers (Wu et al., 2020). ITMIX revealed that the maximum discrepancy in ice thickness estimates among models can be on the order of the actual glacier thickness itself. Substantial disparities exist among different models in their thickness estimates for the same glacier, with uncertainties reaching tens to even hundreds of meters. Weighted ensemble averaging of multiple models can effectively offset systematic biases inherent in individual models, thereby ameliorating the accuracy of ice thickness simulations (Farinotti et al., 2017). The ITMIX2 experiment evaluated the influence of the number and location of in-situ ice thickness observations on model calibration and accuracy, and found that models respond differently to data scenarios, with no single model performing best across all scenarios. At the same time, the experiment highlighted the critical role of sparse in-situ data and recommended prioritizing measurements in the thickest location of glaciers (Farinotti et al., 2021). Against this backdrop, refinements to individual ice thickness models can help improve the accuracy of the multi-model ensemble average.

(b) Additions to the Discussion (P.22, L451-462):

Taking the CTSG glacier as an example, we compare the composite mean ice thickness (i.e., the ice thickness distribution obtained by averaging, Figure 11a) with the ice thickness spread (i.e., the spread of all model results within a pixel, Figure 11b). Figures 11c and 11d present the maximum and minimum ice thickness composites, respectively, illustrating the composition of the composite results. The models producing the most extreme results are shown in Figures 11e and 11f. For the CTSG glacier, the minimum ice thickness is predominantly provided by the OGGM model (62.2%), while the minimum values from GlabTop2 are mainly distributed over the glacier's tributaries. In contrast, the maximum ice thickness is primarily contributed by ITMSL (32.7%), Millan (20.2%), Gantayat (19.8%), and H-F (16.2%). This pattern is consistent with the trends observed in the ITMIX results. Specifically, the maximum ice thickness from ITMSL is concentrated along the glacier margins; that from Millan is concentrated in the lower reaches and the tongue of the glacier; that from Gantayat is relatively evenly distributed; and that from the H-F model is concentrated in the upper reaches.

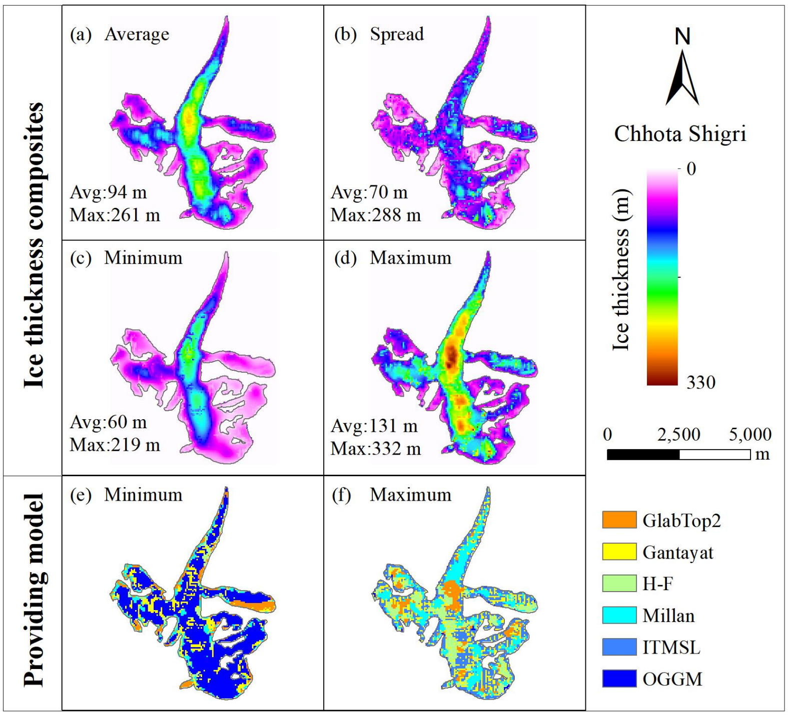


Figure 11: Comparison of simulated ice thickness among models. The first four panels present composite results from the models: (a) average, (b) spread, (c) minimal, and (d) maximal ice thickness distribution. The models corresponding to the minimum and maximum ice thickness at each pixel are shown in (e) and (f), respectively.

3. Choice of dataset: At no point do the authors explain why they select the 16 glaciers in their dataset out of all the possible glaciers in HMA. What is particularly curious is that, based on the information in the paper, it seems very likely that 7/16 of them are barely flowing or sliding, in which case using a velocity-based inversion approach is fundamentally flawed (and the scale of the application is not sufficient to defend it based on the need to have a uniform approach across hundreds or thousands of glaciers). The scientific rationale behind this choice needs to be explained.

Response: Thank you for your valuable comments. We admit that some unclear expressions in the initial version of our manuscript may have caused confusion, and we apologize for that. We have now added the main text with the reasons for selecting these 16 glaciers to validate the effectiveness of our method. Model validation relies on observational data, which serve as the gold standard for performance evaluation. Since only these 16 glaciers have publicly available GPR measurements in High Mountain Asia, and these data are real and reliable, we chose them as the validation set. If more GPR data become available, we would be glad to include them. In the future, we plan to conduct research using over 4,000 glaciers from the GlaThiDa database to further assess the regional applicability and effectiveness of the proposed method. We sincerely hope to receive more of your valuable suggestions **(P.5, L118-120)**.

"We applied ITMSL to 16 glaciers across HMA, comparing its performance with two other models (Gantayat and Millan) that are also based on the laminar flow equation. These 16 glaciers were selected because in-situ ice thickness observations are publicly available for them in HMA."

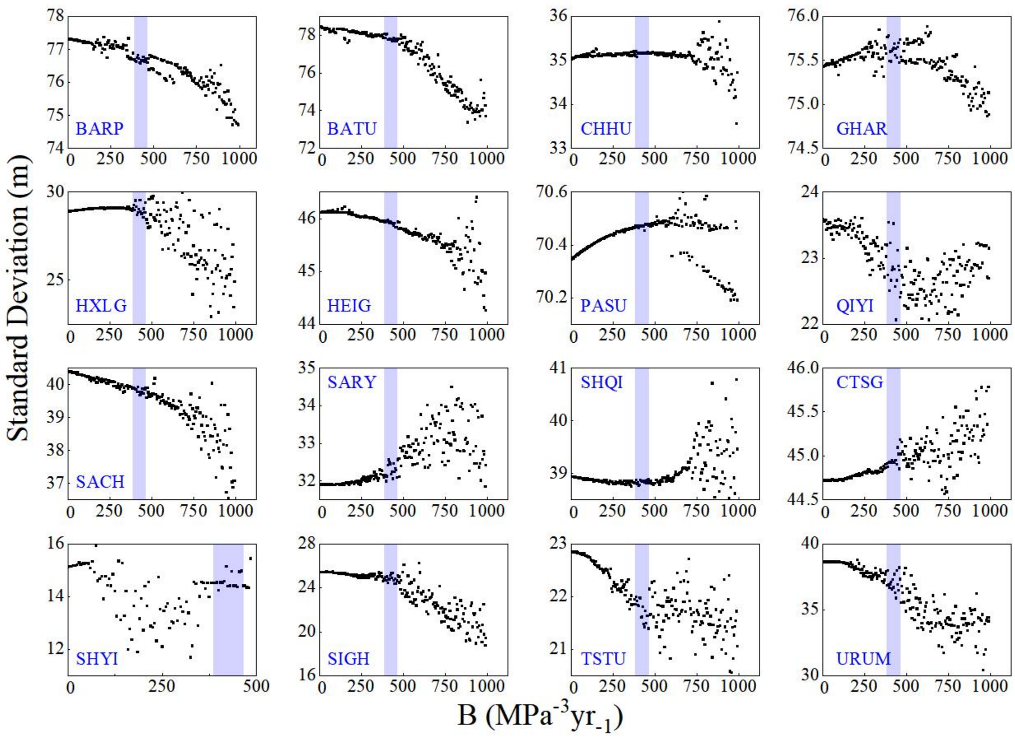
4. Choice of models: Why do the authors pick specifically the Millan and Gantayat models as their comparators? Again, this is never explained. Why not some of the other models in ITMIX? Why not all the models in ITMIX? This feels like cherry-picking or convenience, but I have no information to work out what's going on at the moment. In particular, if I accept the paper at face value, proving that ITMSL works better than the Millan approach, which was designed to work at a global scale, on only 16 glaciers isn't all that impactful. This aspect would be greatly improved by adopting the ITMIX protocol.

   Response: The ITMIX experiment involves 17 ice thickness models from five categories. The focus of this study is on how to determine the basal sliding parameter in ice-velocity-based ice thickness models. Within the ITMIX framework, models such as Gantayat, RAAJgantayat, Gantayat-v2, and Rabatel all assume that the basal sliding velocity is a fixed proportion of the surface velocity; therefore, we selected Gantayat as one of the comparison targets. In the Millan model, the basal sliding parameter is established through the ratio between surface velocity and subglacial topography, resulting in a spatially variable basal-to-surface velocity ratio across the glacier. Consequently, we chose Gantayat and Millan for comparison for two reasons: first, both are based on the same laminar flow equation; second, both have shortcomings in determining the basal sliding parameter. To address this, we developed the ITMSL ice thickness model and validated its effectiveness by comparing it with Gantayat and Millan. Additionally, following the ITMIX framework, we added a pixel-by-pixel comparison with results from other models in the Discussion section.

5. Model parameters: See specifics below, but I find Figure 3 extremely unconvincing as to the B values for each glacier the authors select being the optimal values. The other model parameters are then entirely skated over, so it's

very difficult to get any real sense of whether what the authors have done is sensible.

Response: We understand your concern. We had originally expected to see a parabolic pattern in Figure 3, but the results did not show such a trend. This indicates that the selection of the B value still has limitations. Furthermore, following your suggestion, we extended the range of B from 430±40 MPa^{-3}·yr^{-1} to 5–1000 MPa^{-3}·yr^{-1}, sampled at intervals of 5 MPa^{-3}·yr^{-1}, performed ice thickness inversion for each value, and evaluated the accuracy of the derived ice thickness using GPR data (see figure below; the purple shaded area indicates the original range of 430±40 MPa^{-3}·yr^{-1}). As shown in the figure, with increasing B values, the accuracy of the simulated ice thickness for some glaciers becomes progressively more scattered—a curious phenomenon worth noting. Therefore, we are cautious about expanding the range of B values arbitrarily, as the lack of supporting references could lead to erroneous conclusions.



Nevertheless, your suggestion remains highly professional. We have added a supplementary explanation in the main text, hoping that this issue will attract the attention of experts in the field and stimulate further research **(P.13, L293-301)**.

"These calibrated parameters provide reference values for regional ice thickness inversions in unmeasured HMA glacier (Table 2). It should be noted that the 16 glaciers investigated in this study are mainly distributed in the Tien Shan and Karakoram regions, with limited validation in the Indian monsoon-dominated Himalaya and southeastern Tibetan Plateau. Moreover, as shown in Figure 3, the RMSE for some glaciers decreases monotonically with increasing B values, whereas other glaciers display irregular fluctuations. This indicates that the B value range is not universally suitable for all glaciers, potentially due to differences in glacier characteristics and climatic conditions. Therefore, caution is required when applying B=465 $\mathrm{MPa^{-3}yr^{-1}}$ to study glacier thickness and volume in these regions."

Regarding the other parameters, they mainly fall into two categories: one includes constants such as ice density; the other includes parameters such as the valley shape factor, bedrock roughness, and basal shear stress, which are iteratively updated during the model run and therefore have not been calibrated **(P.12, L271-282)**.

"This study presents an ITMSL ice thickness model. To evaluate its performance, the model was applied to 16 HMA glaciers. In this study, the model parameters can be divided into two categories: those derived from glacier surface characteristics, such as shape factor and glacier width, and those derived from subglacial topography, including bed roughness, bed obstacle wavelength, and bed slope. Specifically, glacier width is calculated from glacier outline, while the shape factor is computed using both the glacier width and the initial ice thickness (Ramsankaran et al., 2018). Bed roughness is determined from subglacial topography (Berti et al., 2013), and the obstacle wavelength is obtained by applying a Fourier transform to the subglacial topography. These parameters are iteratively updated during the cyclic operation of the ITMSL model based on the results of the previous simulation. The sliding parameter A_s is calculated based on bed roughness, bed obstacle wavelength, and ice fluidity parameters (O. et al., 2007). The ranges of the ice fluidity parameter B ($430 \pm 40MPa^{-3}yr^{-1}$) are taken from the literature (Louis and Lliboutry, 1987)."

6. Presentation: For a paper that is about showing how well a new approach does in inverting glacier thickness, there is a stunning lack of figures that show ice thickness or useful information (ice velocity, say) more generally. There are a lot of tables, often with some not hugely relevant numbers in them, but very little in the way of the sorts of figures I'd expect to see. To the extent that it feels as if the authors are deliberately obfuscating their results (I'm not saying this is the case, but, if that's not the reason, it's a baffling oversight).

Response: As you pointed out, we should not have singled out the Chhota Shigri glacier while providing only a single value for the other glaciers—this was an oversight on our part. Following your suggestion, we have added the mean surface velocity for each glacier in Table 3, and have also included in the appendix the two-dimensional results of ice thickness, subglacial topography, basal sliding velocity, and the ratio of basal sliding to surface velocity for each glacier **(P.17, L352)**.

Table 3: The ice thickness and motion characteristics of the 16 glaciers are mean values calculated from inversion results extracted at the GPR point locations.

Glacier	GPR (m)	Gantayat (m)	Millan (m)	ITMSL (m)	u_b (m/yr)	u_b/u_s
BARP	120.95	143.86	191.74	163.90	42.35	0.350
BATU	127.06	142.37	211.63	157.94	36.35	0.342
CHHU	103.93	113.63	142.55	127.08	44.92	0.391
GHAR	152.94	114.62	153.15	138.11	31.08	0.366
HXLG	43.96	83.91	42.60	83.47	4.25	0.457
HEIG	114.87	94.88	68.75	106.43	9.65	0.385
PASU	145.55	156.36	185.24	163.58	59.89	0.368
QIYI	77.81	63.58	53.26	59.14	3.34	0.401
SACH	121.79	123.40	185.03	131.01	16.56	0.388
SARY	75.52	77.80	81.28	77.68	3.32	0.415
SHQI	38.68	71.31	80.88	71.16	7.92	0.354
CTSG	172.88	104.90	98.39	114.63	5.53	0.399
SHIY	39.47	49.18	30.09	52.83	2.95	0.398
SIGH	68.93	71.99	42.28	72.0	2.63	0.399
TSTU	51.63	64.63	63.55	60.21	1.78	0.422
URUM	40.05	78.45	45.61	83.85	7.67	0.415

S1 Ice thickness results derived from model inversion

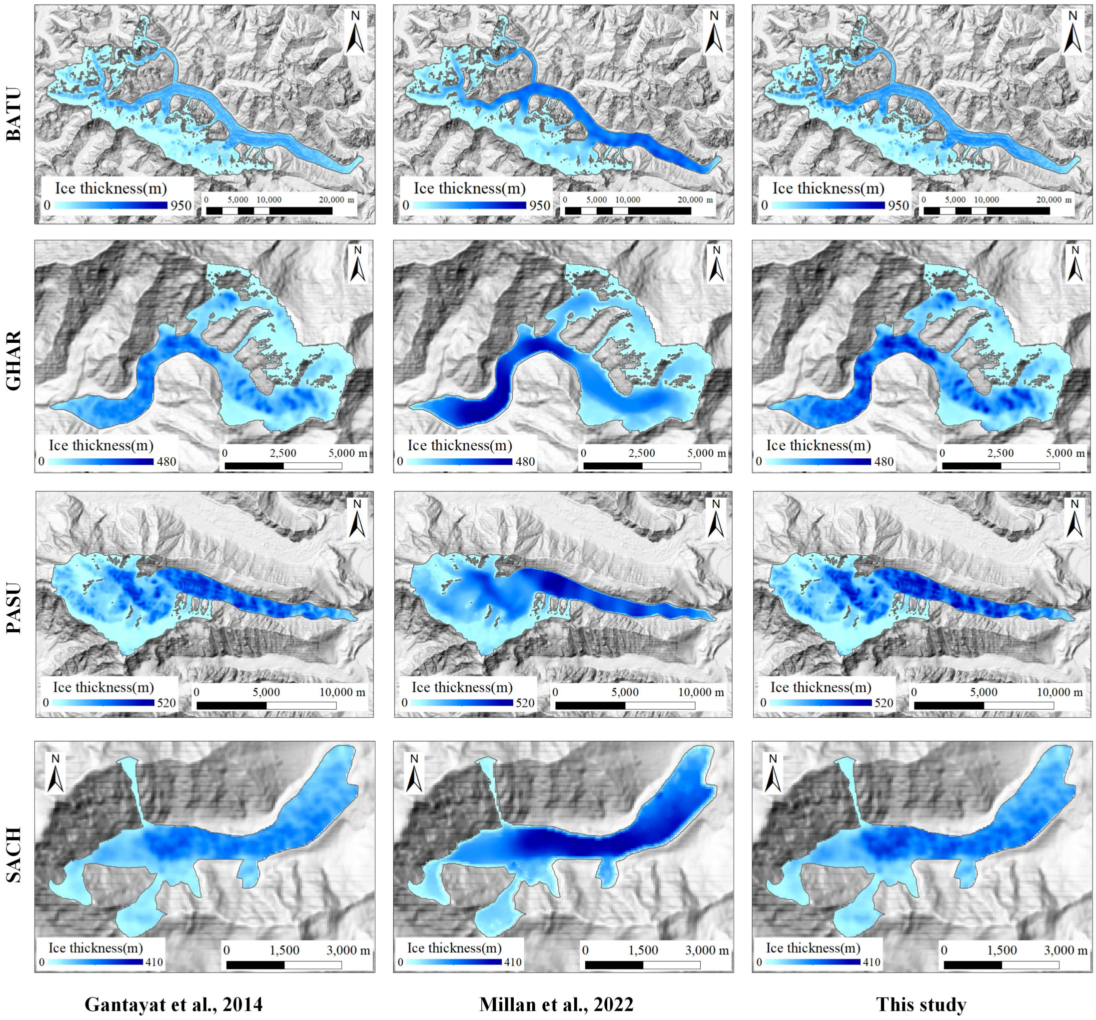


Figure S1: Glacier thickness inverted by the Gantayat, Millan, and ITMSL models.

S2 Difference between simulated ice thickness and GPR measurements

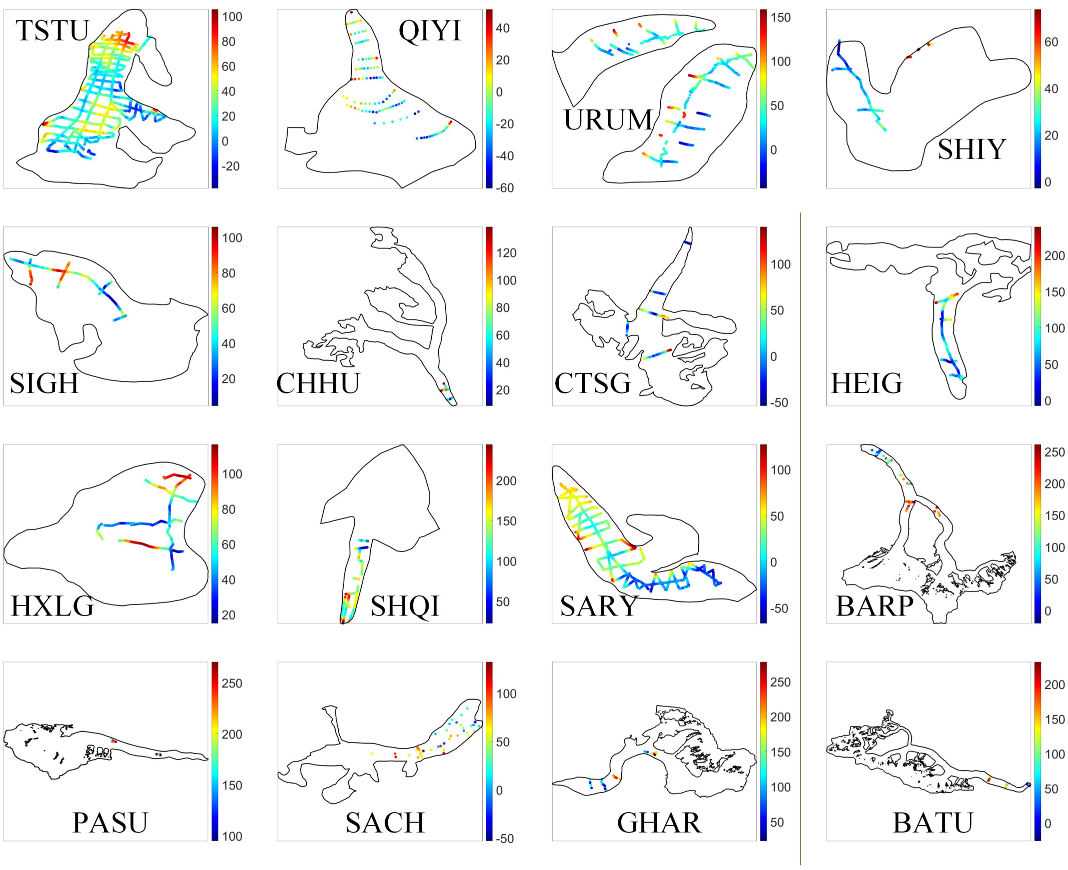


Figure S4: Glacier thickness inverted by ITMSL (unit: m).

S3: Bed topography

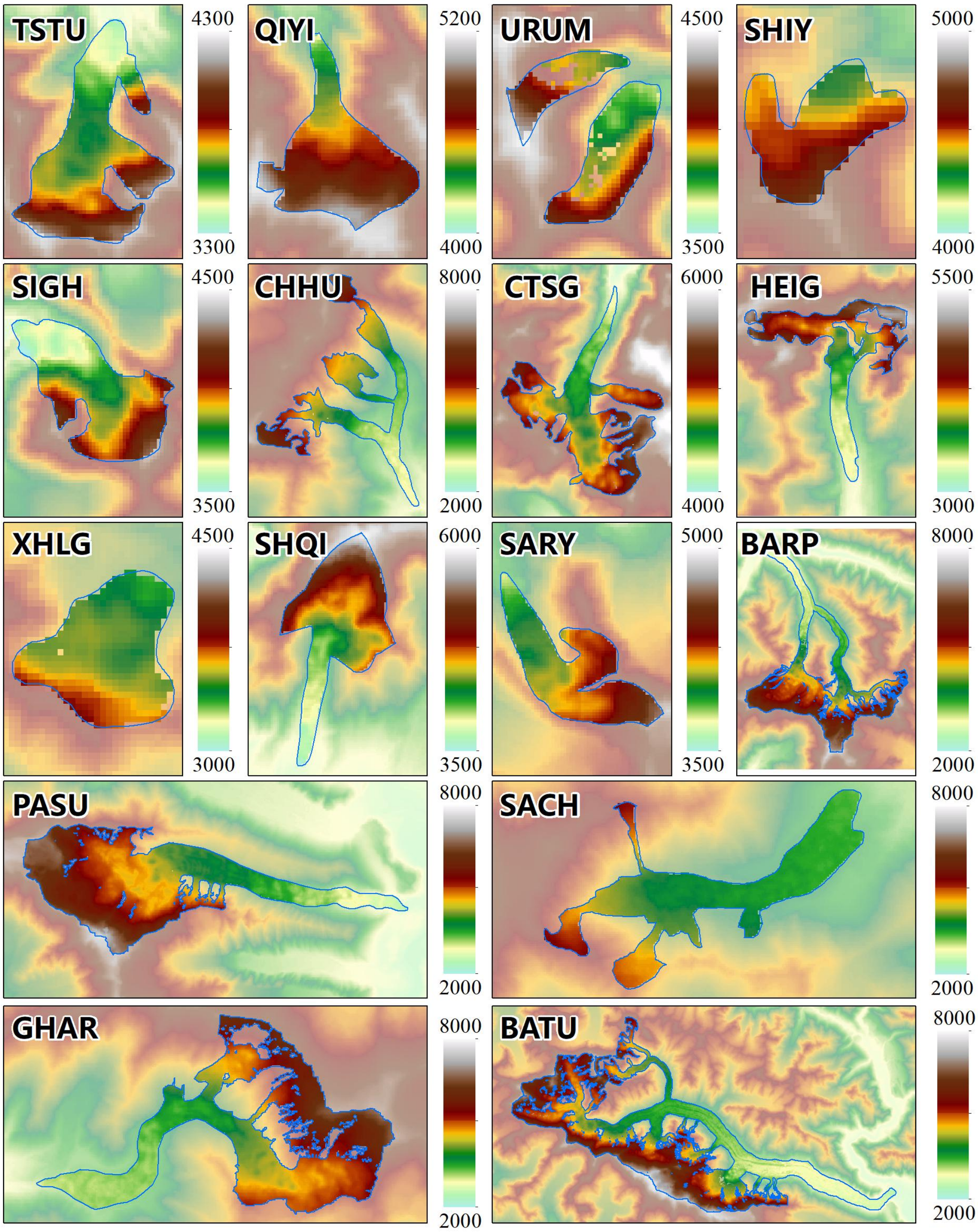


Figure S5: Subglacial topography simulated by the ITMSL model.

S4: Basal sliding

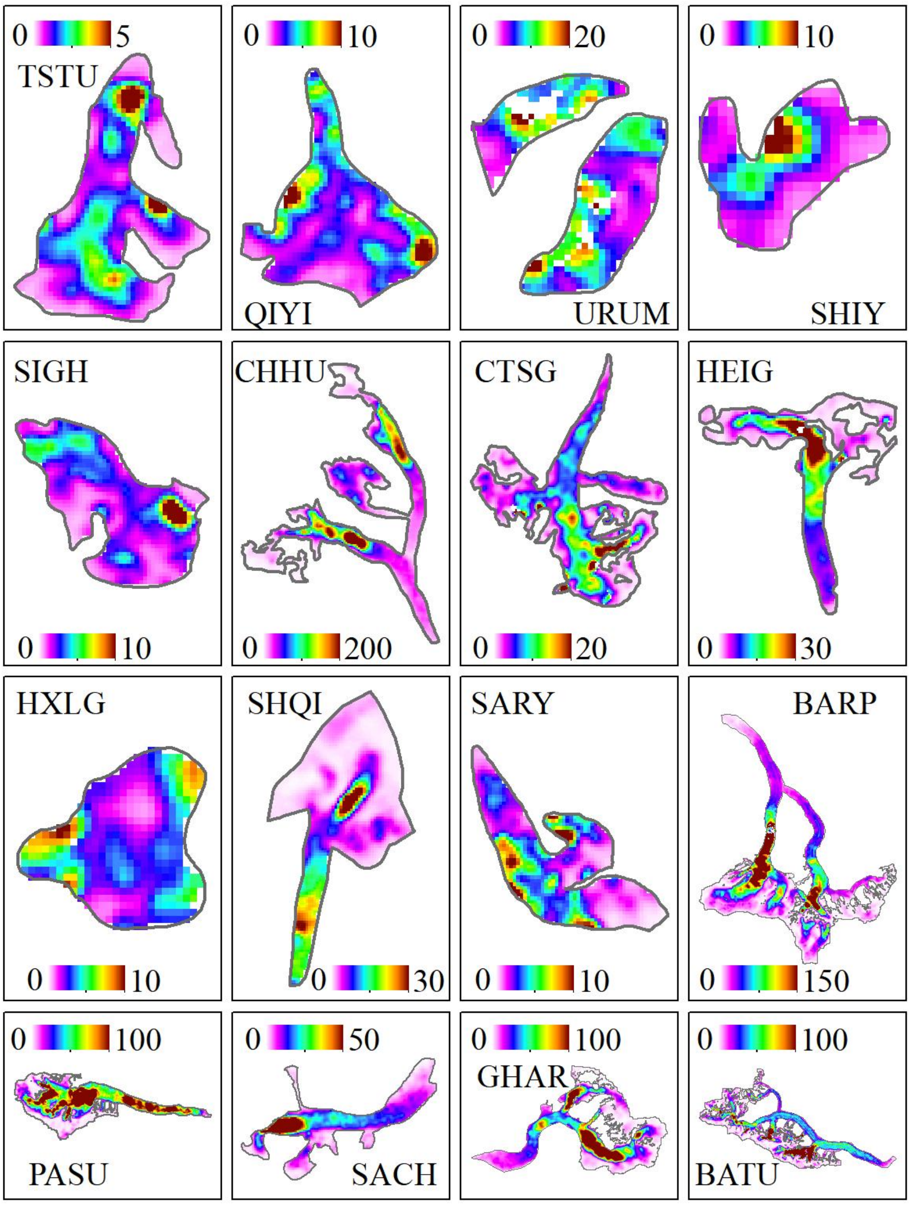


Figure S6: Basal sliding simulated by the ITMSL model.

S5: Ratio of basal sliding to surface velocity

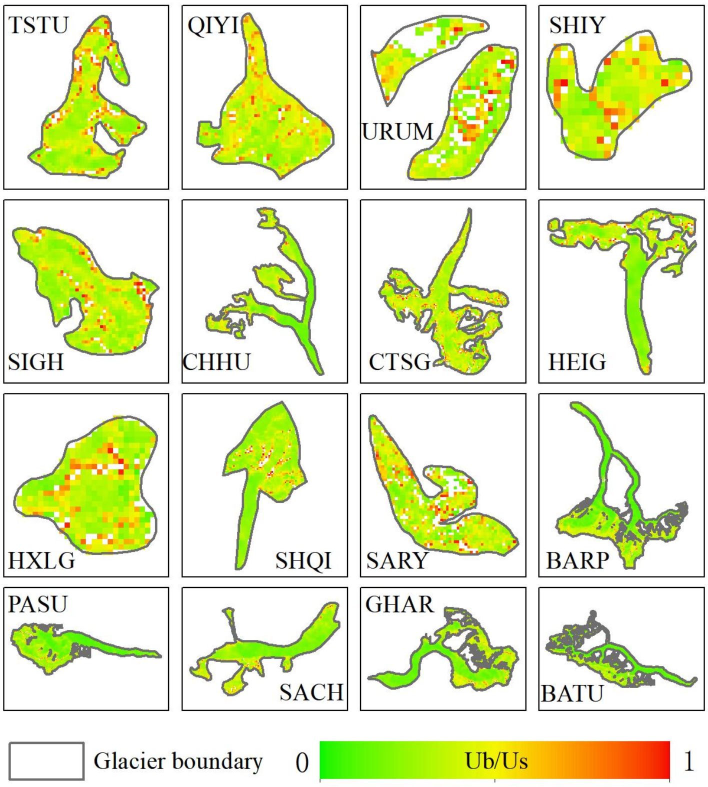


Figure S7: Ratio of basal sliding to surface velocity simulated by the ITMSL model.

Minor Comments

1. Terminology: throughout, the authors talk about laminar-flow theory. In a glaciological modelling context, though, this is more commonly encountered as part of the shallow ice or shallow shelf approximations, so I think it would be worth adding a sentence somewhere in the introduction just clarifying the different terms and how they relate for the purposes of this paper. In a sense, all ice- flow models are laminar, because that's how ice flows – it's not turbulent – and I think what the authors really mean is that they've got a better version of the SIA that incorporates some consideration of sliding rather than neglecting it entirely. So, I'm wondering if there needs to be some more thorough re-writing to make it clearer what's going on

   Response: Thank you for your suggestion. the theoretical basis of this paper is the shallow ice approximation (SIA). In some literature it is referred to as the "laminar flow equation", while in others it is directly called the "shallow ice approximation". To avoid confusion for readers, we have revised and supplemented the Introduction accordingly, and have uniformly replaced all instances of "laminar flow theory" in the manuscript with either "laminar flow equation" or "SIA". Because the changes to the Introduction are extensive—amounting to a near rewrite—we kindly ask you to refer to the revised manuscript for the specific modifications.

2. p.1, l.27-28: GV14 and GV22 are codes purely used in this paper and not the names of the respective models used or anything that would be recognisable to someone who hasn't already read the paper. Which isn't ideal in the abstract. I'd just take the codes out and give only the references.

   Response: We have replaced GV14 and GV22 with Gantayat and Millan, respectively, throughout the manuscript to make them more immediately understandable to readers.

3. p.2, l.50-51: 'requiring substantial manpower and material resources'?

   Response: We have revised this sentence **(P.2, L51-53)**.

   "However, due to the harsh high-altitude environments and logistical difficulties, in-situ methods typically require substantial manpower and material resources."

4. p.3, l.61: I think there needs to be an 'and' after the brackets to make the sentence make sense

   Response: Thank you for your suggestion; we have added "and" **(P.4, L93-98)**.

   "However, basal sliding is a complex process influenced by subglacial topography, basal shear stress, and ice overburden pressure (Weertman, 1957; Schoof, 2005; Cuffey and Paterson, 2010; Zoet and Iverson, 2020; Helanow et al., 2021), and the ratio of basal sliding to surface velocity exhibits significant spatial and temporal variability within glaciers, with observed values ranging widely from 0.03 to 1 (Engelhardt and Kamb, 1998; Cuffey and Paterson, 2010; Echelmeyer and Zhongxiang, 1987)."

5. p.3, l.67: The implication here is that there's an alternative to using some sort of sliding law to represent sliding in a model, which there...isn't? Even using some version of laminar flow is assuming a sliding law. Might be worth rephrasing this a little more definitively.

   Response: We have rewritten this sentence to emphasize the important role of the basal sliding law **(P.4, L105-107)**.

   "In glacier dynamics, simulating the basal sliding process must rely on a basal sliding law, which is the only way to describe this process (Zekollari et al., 2022; Schoof, 2005; Joughin et al., 2019; Zoet and Iverson, 2020)."

6. p.3, l.79: 'the theoretical basis'?

   Response: We have revised this sentence **(P.5, L122-125)**.

   "In the subsequent sections, we will present the theoretical basis (Section 2), implementation workflow of the model (Section 3), evaluate its inversion results against existing ice thickness models (Section 4), discuss certain limitations and possible improvements (Section 5), and conclude with a summary (Section 6)."

7. p.4, l. 88: 'dynamics'

Response: We have revised this sentence **(P.5, L131-132)**.

"These climatic regimes drive pronounced spatial heterogeneity in glacier distribution, mass balance, and dynamics (Hugonnet et al., 2021; Miles et al., 2021; Millan et al., 2022; Wang et al., 2023)."

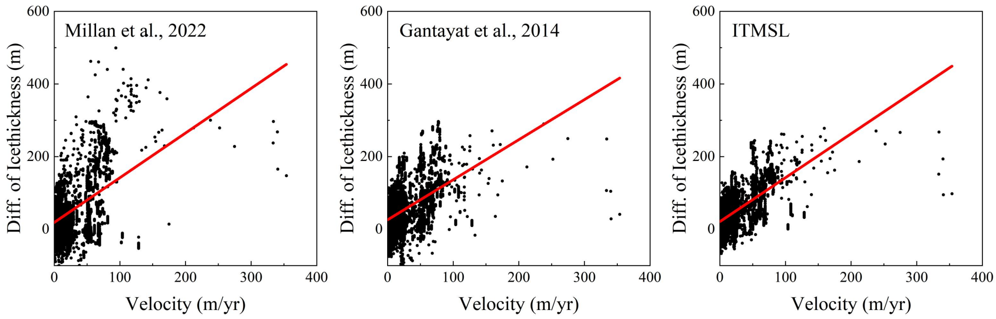
8. p.4, l.89-93: What's the rationale behind this glacier selection? I don't doubt there was one, but it's exceedingly obscure as written. The Himalayas seem rather under-represented compared to the Tian Shan, for instance, so there needs to be some explanation of why this selection was made. Also, a decent chunk of the dataset seems to be rather small glaciers: is there any sliding actually happening on them? Otherwise, why bother including them, given the whole point of the paper is to integrate basal sliding dynamics? Have the authors considered a range of glacier velocities, for instance?

Response: **(a)** We admit that some unclear expressions in the initial version of our manuscript may have caused confusion, and we apologize for that. We have now added the main text with the reasons for selecting these 16 glaciers to validate the effectiveness of our method. Model validation relies on observational data, which serve as the gold standard for performance evaluation. Since only these 16 glaciers have publicly available GPR measurements in High Mountain Asia, and these data are real and reliable, we chose them as the validation set. If more GPR data become available, we would be glad to include them. In the future, we plan to conduct research using over 4,000 glaciers from the GlaThiDa database to further assess the regional applicability and effectiveness of the proposed method **(P.5, L118-120)**.

"We applied ITMSL to 16 glaciers across HMA, comparing its performance with two other models (Gantayat and Millan) that are also based on the laminar flow equation. These 16 glaciers were selected because in-situ ice thickness observations are publicly available for them in HMA."

(b) Indeed, as you pointed out, some small glaciers may not exhibit basal sliding. However, when we selected from the 16 glaciers with available GPR data, we might have—consciously or unconsciously—chosen those that perform better. While this approach helps evaluate the performance of the ITMSL model, we acknowledge that it is not comprehensive. In reality, we cannot predetermine which glaciers have basal sliding and which do not. Therefore, we conducted simulations and analyses for all 16 glaciers. If you believe that certain glaciers should be removed, we kindly ask for your explicit guidance, and we will recalculate and revise the results accordingly. We sincerely hope to receive more of your valuable suggestions.

(c) For the 16 glaciers investigated in this study, we compared the ice flow velocity and the deviation of ice thickness simulated by three models from the GPR measurements. Based on the laminar flow equation, it can be inferred that the inverted ice thickness increases with increasing sliding velocity, which is consistent with physical expectations, and the results indeed confirmed our inference. Therefore, no additional analysis has been added to the main text, and we kindly ask for your understanding.



9. p.5, l.110: Sure, the average error for the Millan velocities might be 10 m/a, but there is an error map provided with the data and is it 10 m/a on average for these 16 glaciers? Some more clarity here would be useful.

Response: Millan's ice velocity dataset includes standard deviations in the east-west and north-south directions, which can be used to calculate the standard deviation distribution for each glacier. We have clarified this in the main text **(P.6, L155-156)**.

"Moreover, this dataset includes the standard deviations of ice velocity in the east-west and north-south components, which enables the computation of the standard deviation of ice velocity for each glacier."

10. p.5, l.117: Yes, I agree for most of them, but maybe not for the one where the GPR measurements are from 1980…? I would expect there to have been some substantial thickness changes in 45 years … . This should be at least acknowledged as a slight inaccuracy here.

Response: Yes, the GPR measurements on the Qiyi Glacier were acquired nearly half a century ago, and this temporal difference should indeed be noted and distinguished from the other glaciers. It is also expected that the deviation between GPR-derived and simulated ice thickness may be larger for this glacier than for others. We have added a clarification to this effect in the manuscript **(P.7, L164-166)**.

"However, the GPR measurements for the Qiyi Glacier date back to 1980. After more than half a century of change, the difference between the simulated ice thickness and the GPR measurements should be viewed with this long-term evolution in mind."

11. Table 1: I would really like to see the mean glacier velocity or some other measurement of how much it's moving included here, as well as mean measured ice thickness or similar in order to assess how representative of glacier sliding this dataset might actually be. Elevation extent, by contrast, seems like it could be safely deleted – I don't feel it's telling the reader anything useful for the purposes of this paper.

Response: Following your suggestion, we have removed the glacier elevation range from Table 1 and moved the mean velocity of each glacier from Table 4 to Table 1. The ice thickness data have been placed in Table 3. In addition, incorporating comments from other reviewers, we have supplemented each glacier with its RGI- ID and the number of GPR measurement points. The revised Table 1 and Table 3 are shown below **(P.7, L167)**:

Table 1: Glaciers from RGI 6.0, survey years, and GPR data sources.

RGI-ID	Glacier (abbreviation)	Area (km^2)	u_s (m/yr)	GPR Survey Year	number of GPR points	GPR source
RGI60-14.00032	Barpu (BARP)	104.952	125.70	2015~2018	60	(Zou et al., 2021)
RGI60-14.02150	Batura (BATU)	311.419	101.34	2015~2018	23	
RGI60-14.20030	Chhungphar (CHHU)	15.136	108.40	2015~2018	17	
RGI60-14.04590	Gharko (GHAR)	30.318	81.06	2015~2018	29	
RGI60-14.03123	Pasu (PASU)	62.145	162.08	2015~2018	9	
RGI60-14.19344	Sachen (SACH)	10.307	40.90	2015~2018	55	
RGI60-13.47247	Haxilegen No.51 (HXLG)	1.099	10.70	2010	584	(Welty et al., 2020)
RGI60-13.48211	Heigou No.8 (HEIG)	6.074	24.97	2009	906	
RGI60-13.45335	Urumqi No.1 (URUM)	1.579	20.51	2014	1385	
RGI60-13.32330	Qiyi (QIYI)	2.530	8.65	1980	105	
RGI60-13.08055	Sary-Tor (SARY)	2.927	8.82	2013	1352	
RGI60-13.43165	Shenqi Peak (SHQI)	6.591	21.63	2008	823	
RGI60-13.31537	Shiyi (SHIY)	0.495	7.78	2010	294	
RGI60-13.45233	Sigonghe No.4 (SIGH)	2.641	7.01	2009	623	
RGI60-13.08624	Tsentralniy Tuyuksu (TSTU)	2.838	4.61	2013	8353	
RGI60-14.15990	Chhota Shigri (CTSG)	13.463	15.48	2009	146	(Azam et al., 2012a)

Table 3: The ice thickness and motion characteristics of the 16 glaciers are mean values calculated from inversion results extracted at the GPR point locations.

Glacier	GPR (m)	Gantayat (m)	Millan (m)	ITMSL (m)	u_b (m/yr)	u_b/u_s
BARP	120.95	143.86	191.74	163.90	42.35	0.350
BATU	127.06	142.37	211.63	157.94	36.35	0.342
CHHU	103.93	113.63	142.55	127.08	44.92	0.391
GHAR	152.94	114.62	153.15	138.11	31.08	0.366
HXLG	43.96	83.91	42.60	83.47	4.25	0.457

HEIG	114.87	94.88	68.75	106.43	9.65	0.385
PASU	145.55	156.36	185.24	163.58	59.89	0.368
QIYI	77.81	63.58	53.26	59.14	3.34	0.401
SACH	121.79	123.40	185.03	131.01	16.56	0.388
SARY	75.52	77.80	81.28	77.68	3.32	0.415
SHQI	38.68	71.31	80.88	71.16	7.92	0.354
CTSG	172.88	104.90	98.39	114.63	5.53	0.399
SHIY	39.47	49.18	30.09	52.83	2.95	0.398
SIGH	68.93	71.99	42.28	72.0	2.63	0.399
TSTU	51.63	64.63	63.55	60.21	1.78	0.422
URUM	40.05	78.45	45.61	83.85	7.67	0.415

12. p.7, l.145: ‘though’

Response: We have corrected this typographical error **(P.9, L195)**.

“To address this limitation, Budd introduced a sliding law accounting for basal cavity evolution, though it retains a power-law form (Budd et al., 1979; Fowler and Frank, 1981).”

13. p.7, l.149: The word ‘accurately’ is doing a lot of heavy lifting here. We know that none of the existing sliding relations fully captures sliding with perfect accuracy (otherwise, why would we have so many options?). Also, this paper is not explicitly modelling subglacial hydrology and thus N, so I’m not sure claiming that this is an ‘accurate’ implementation really stands up.

Response: As you pointed out, the term "accurately" is indeed not rigorous enough, since no existing sliding relation can perfectly capture the real sliding process. We have revised this sentence to avoid making the expression too absolute **(P.4, L199-202)**.

We employ the Coulomb sliding law to characterize this complex interaction among water pressure, shear stress, and dynamics, which is given as follows (Helanow et al., 2021):

$$\frac{\tau_b}{N} = C\left(\frac{u_b}{u_b + A_s C^n N^n}\right)^{1/n} \quad (4)$$

14. Figure 2: ‘Surface Slpoe’ probably wasn’t intended … .

Response: We have corrected the errors in the figure and reorganized the flowchart to make it more concise and clear **(P.12, L267)**.

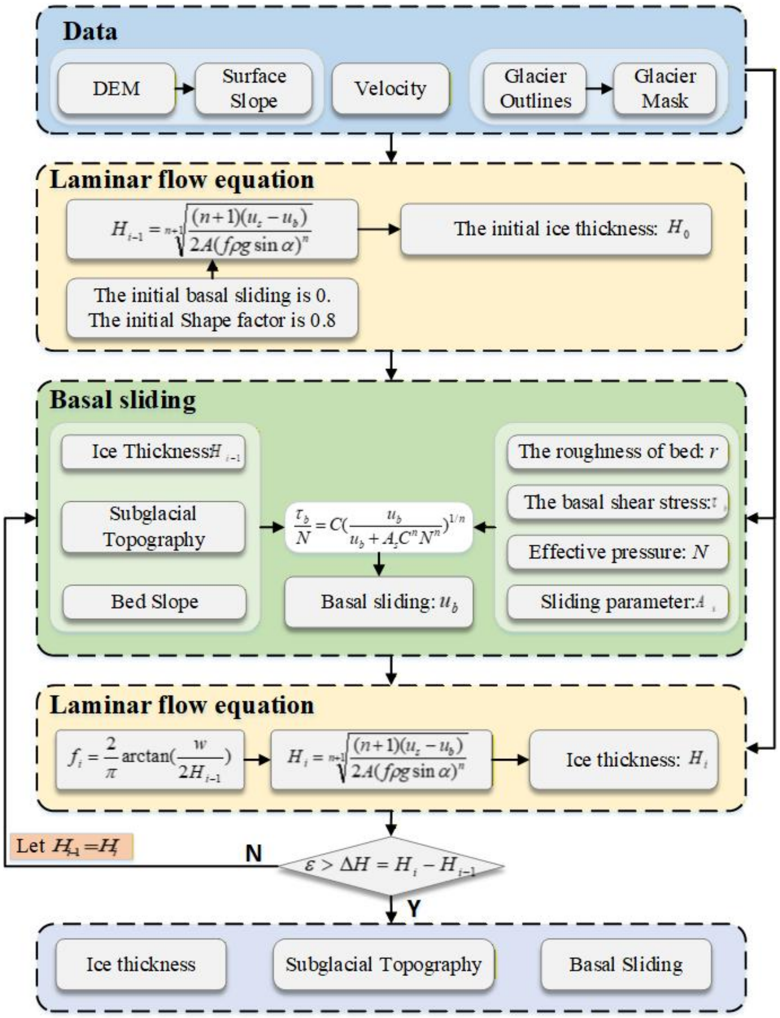


Figure 2: Flow chart of glacier thickness inversion using ITMSL model.

15. p.10, l.219-220: I think the authors need to specify which parameters were literature-derived (and their values), and which were glacier-specific (and how they were chosen). Otherwise, it's very difficult to get much sense of what's actually going on.

Response: We have reorganized this section and added relevant references to provide a detailed explanation of the justification for each parameter **(P.12, L271-282)**.

"This study presents an ITMSL ice thickness model. To evaluate its performance, the model was applied to 16 HMA glaciers. In this study, the model parameters can be divided into two categories: those derived from glacier surface characteristics, such as shape factor and glacier width, and those derived from subglacial topography, including bed roughness, bed obstacle wavelength, and bed slope. Specifically, glacier width is calculated from glacier outline, while the shape factor is computed using both the glacier width and the initial ice thickness (Ramsankaran et al., 2018). Bed roughness is determined from subglacial topography (Berti et al., 2013), and the obstacle wavelength is obtained by applying a Fourier transform to the subglacial topography. These parameters are iteratively updated during the cyclic operation of the ITMSL model based on the results of the previous simulation. The sliding parameter A_s is calculated based on bed roughness, bed obstacle wavelength, and ice fluidity parameters (O. et al., 2007). The ranges of the ice fluidity parameter B ($430 \pm 40MPa^{-3}yr^{-1}$) are taken from the literature (Louis and Lliboutry, 1987)."

16. Table 2: The more interesting question is: are these B values physically realistic? Some consideration of this in the foregoing text would be useful. Also, what's the 'Total' value in the table – the mean?

Response: Thank you for your valuable comment. **(a)** The range of B values was derived from references. Within this range, we sampled at equal intervals and calculated the RMSE of the simulated ice thickness to determine the optimal B value. We have added an explanation in the main text to clarify the source of this range, ensuring that readers understand it was not arbitrarily chosen by the authors **(P.13, L281-287)**.

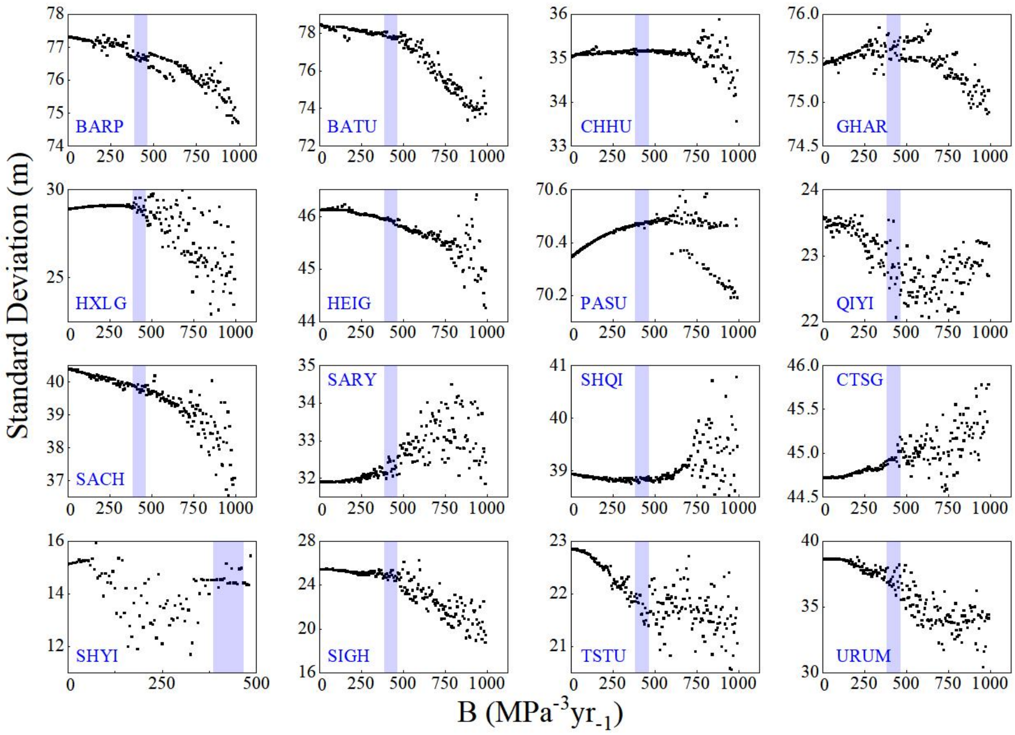
"The ranges of the ice fluidity parameter B ($430 \pm 40MPa^{-3}yr^{-1}$) are taken from the literature (Louis and Lliboutry, 1987). The ice fluidity parameter B was calibrated against GPR ice thickness measurements, with a value range of $390 - 470\mathrm{MPa}^{-3}\mathrm{yr}^{-1}$ determined based on the existing studies (Louis and Lliboutry, 1987; Cuffey and Paterson, 2010). We systematically tested B values at $5\mathrm{MPa}^{-3}\mathrm{yr}^{-1}$ interval to quantify its influence on thickness estimates, while other parameters were either literature-derived or glacier-specific. The optimal B value for each glacier was determined by minimizing RMSE between modeled and GPR measured thickness."

(b) Method for determining the overall optimal B value (Total) (P.13, L290-293):

"The Total B value for the 16 glaciers is determined by pooling all GPR measurement points together, calculating RMSE of the simulated ice thickness for different B values, and then selecting the B value that minimizes the RMSE as the global optimal value."

17. Figure 3: I was expecting to see some sort of parabola or L-curve with a clear minimum RMSE at the optimal B value for each glacier. Instead, it looks as if many of the glaciers (principally the smaller ones) have a very unstable behaviour here, and many of the glaciers have the highest or second-highest B value used chosen on a curve that's clearly still trending downwards or is so chaotic there's no guarantee it's not going to suddenly jump lower at the next value. As things stand, it feels to me that the authors have little justification for picking these B values for most of their dataset – they need to extend these curves to test B values above 480 to prove that their preferred values are actually minima, not just a local blip

Response: We share your concern. We had originally expected to see a parabolic pattern in Figure 3, but the results did not show such a trend. This indicates that the selection of the B value still has limitations. Furthermore, following your suggestion, we extended the range of B from $430\pm40\ \mathrm{MPa^{-3}\cdot yr^{-1}}$ to $5–1000\ \mathrm{MPa^{-3}\cdot yr^{-1}}$, sampled at intervals of $5\ \mathrm{MPa^{-3}\cdot yr^{-1}}$, performed ice thickness inversion for each value, and evaluated the accuracy of the derived ice thickness using GPR data (see figure below; the purple shaded area indicates the original range of $430\pm40\ \mathrm{MPa^{-3}\cdot yr^{-1}}$). As shown in the figure, with increasing B values, the accuracy of the simulated ice thickness for some glaciers becomes progressively more scattered—a curious phenomenon worth noting. Therefore, we are cautious about expanding the range of B values arbitrarily, as the lack of supporting references could lead to erroneous conclusions.



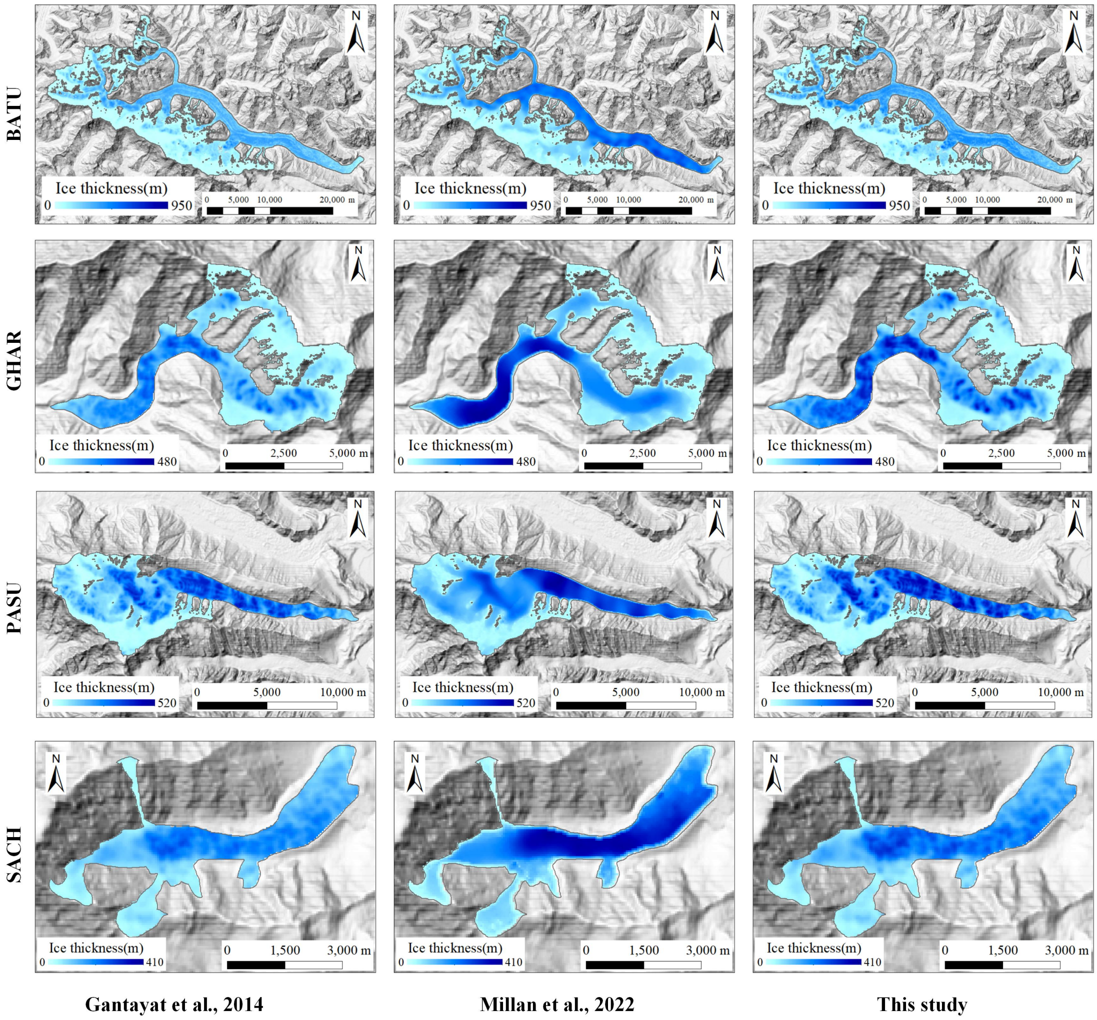
Nevertheless, your suggestion remains highly professional. We have added a supplementary explanation in the main text, hoping that this issue will attract the attention of experts in the field and stimulate further research **(P.13, L293-301)**.

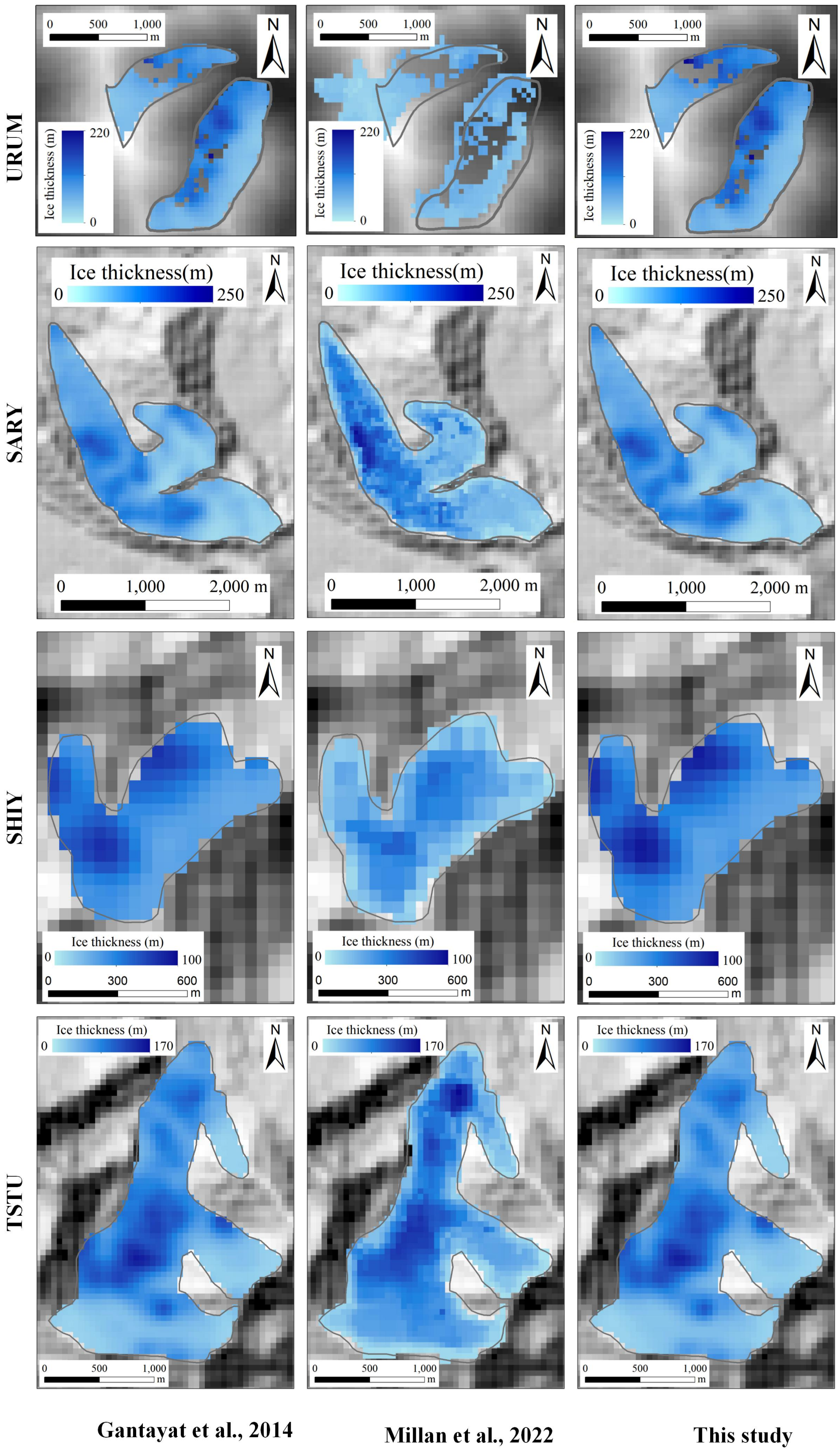
"These calibrated parameters provide reference values for regional ice thickness inversions in unmeasured HMA glacier (Table 2). It should be noted that the 16 glaciers investigated in this study are mainly distributed in the Tien Shan and Karakoram regions, with limited validation in the Indian monsoon-dominated Himalaya and southeastern Tibetan Plateau. Moreover, as shown in Figure 3, the RMSE for some glaciers decreases monotonically with increasing B values, whereas other glaciers display irregular fluctuations. This indicates that the B value range is not universally suitable for all glaciers, potentially due to differences in glacier characteristics and climatic conditions. Therefore, caution is required when applying $B=465\ \mathrm{MPa^{-3}yr^{-1}}$ to study glacier thickness and volume in these regions."

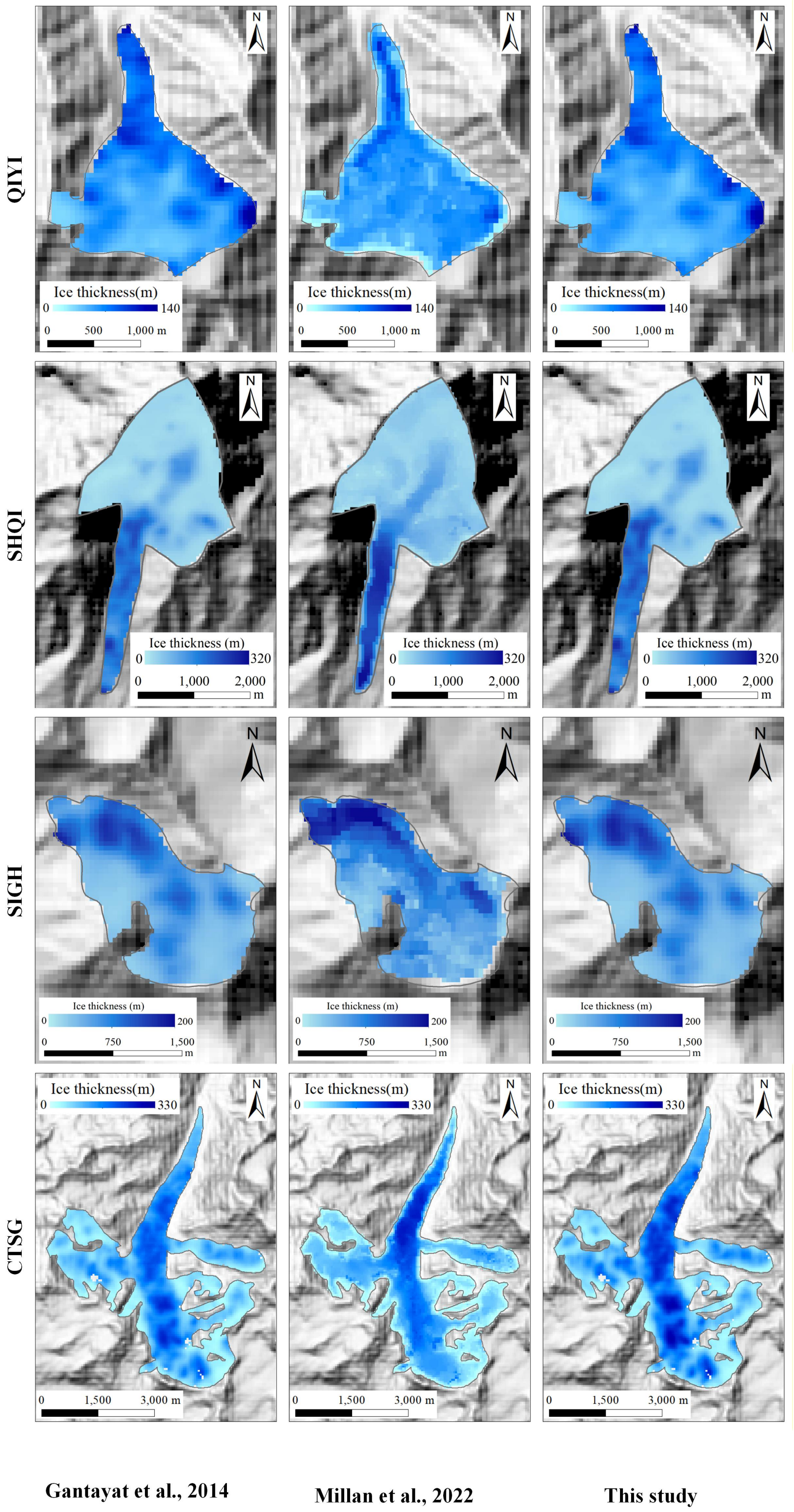
18. p.12, l.238: I think, given this paper is claiming to do ice thickness better, we really need to see the distributed fields for all 16 glaciers, not just one, and then some summary statistics in a table for the other 15. For all I know based on what's shown currently, it might be that half the glaciers have horrendous artefacts that cancel out or something going on!

Response: In the initial version of manuscript, due to space constraints, we did not present the ice thickness results for all 16 glaciers in the main text, which was indeed unreasonable. Now, we have placed the results of ice thickness, subglacial topography, basal sliding, and the ratio of basal sliding to surface velocity for all 16 glaciers in the supplement for your review.

S1 Ice thickness results derived from model inversion




URUM
SARY
SHIY
TSTU
Ice thickness (m)
220
0
Ice thickness(m)
250
Ice thickness (m)
100
Ice thickness (m)
170
0
500
1,000
m
1,000
2,000 m
300
600
N
Gantayat et al., 2014
Millan et al., 2022
This study



QIYI
SHQI
SIGH
CTSG
N
Ice thickness(m)
0
140
0 500 1,000 m
Ice thickness (m)
0
320
0 1,000 2,000 m
Ice thickness (m)
0
200
0 750 1,500 m
Ice thickness(m)
0
330
0 1,500 3,000 m
Gantayat et al., 2014
Millan et al., 2022
This study

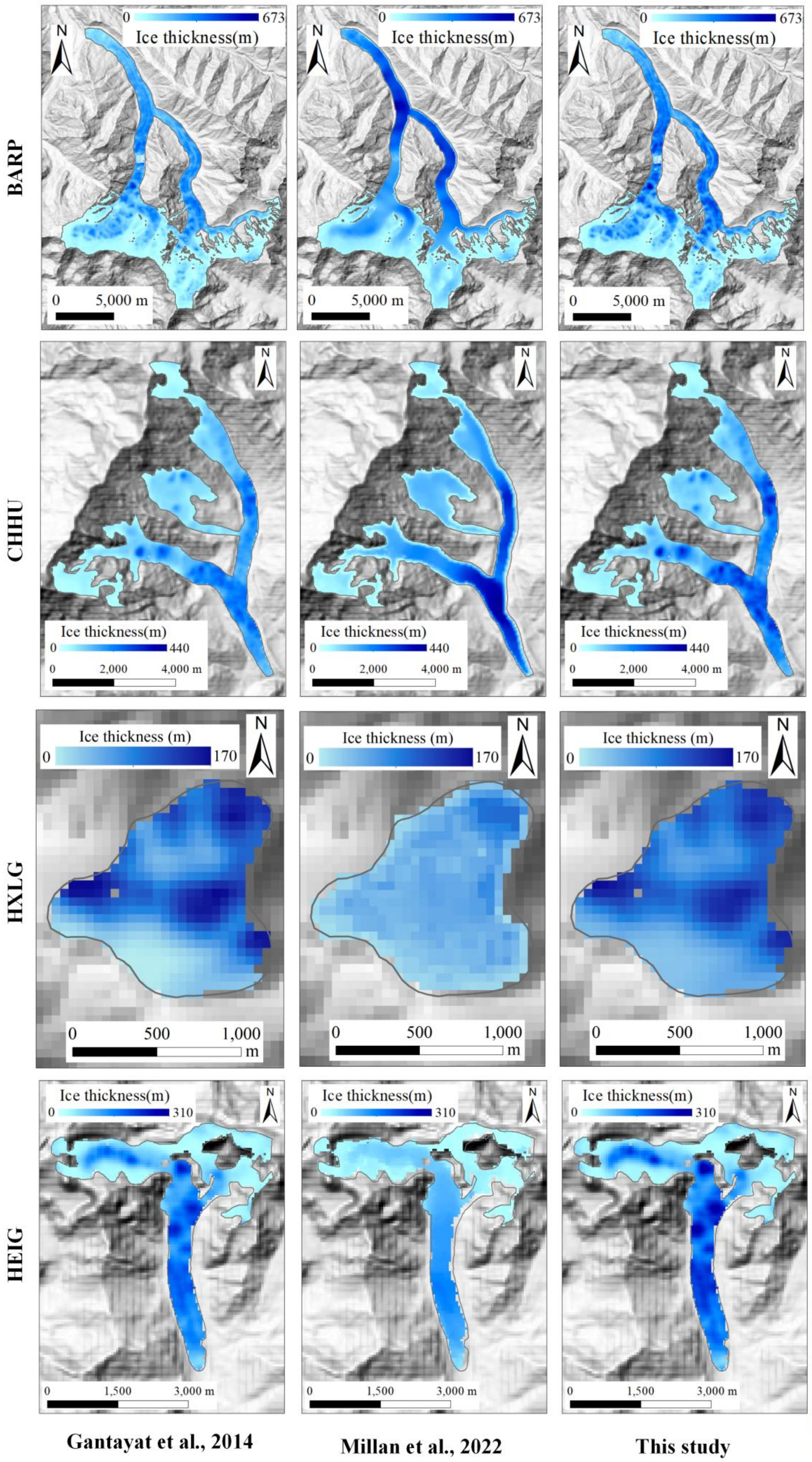


Figure S1: Glacier thickness inverted by the Gantayat, Millan, and ITMSL models.

19. Figure 4: 'Mersured' is also probably not intended … .

Response: This was our oversight, and it has now been corrected **(P.15, L329)**.

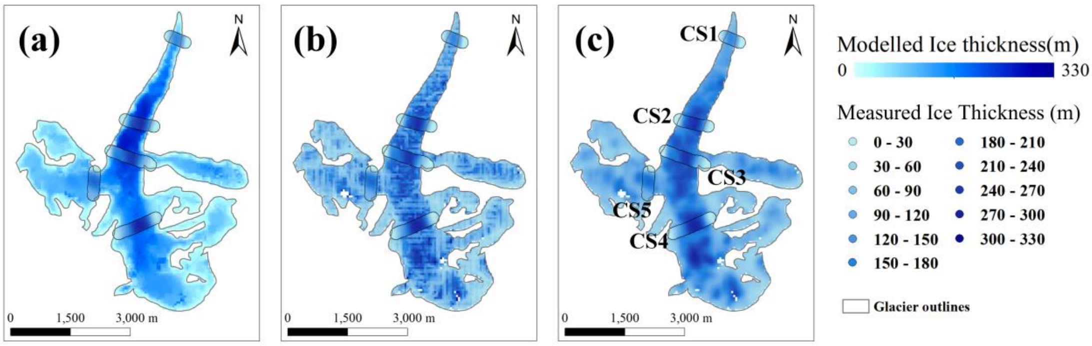


Figure 4: CTSG glacier thickness estimated by the three models. (a) Millan et al., 2022, (b) Gantayat et al., 2014, (c) ITMSL.

20. p.13, l.258: And what's that as a percentage of total glacier velocity? Is that a large contribution of sliding to total motion, or negligible?

Response: Basal sliding accounts for 39.9% of the glacier surface velocity, a proportion that cannot be ignored. We have changed the decimal value 0.399 to a percentage expression in the text.

21. p.13, l.258-261: Frankly, I'd be extraordinarily surprised if sliding velocity didn't correlate well with surface velocity. I think we can take that as read without it needing to be reported. I also think we can safely say the entire glaciological community knows sliding matters for accurate glacier modelling, otherwise we wouldn't have spent an awful lot of time over the last 80 years trying to quantify it. The reason it's often left out of regional- or global-scale models is because many smaller glaciers don't really slide, and it's complicated, so it's easier to approximate it some other way or neglect it entirely. I think I might just delete these lines entirely … .

Response: Your comment is really professional. We acknowledge that the original sentence was indeed somewhat redundant, and we have therefore deleted it following your suggestion.

~~"This velocity exhibits a strong spatial correlation with surface velocity (R = 0.799), with a mean ratio of 0.399 (u_b/u_s). These findings demonstrate that basal sliding affects ice thickness distribution in laminar flow theory, necessitating explicit representation of sliding dynamics for accurate glacier simulations."~~

22. Figure 5: I would replace panel d with the modelled ice thickness from ITMSL and then produce that four-panel figure for all the other glaciers too. Possibly, some of this might need to end up in the supplementary material.

Response: In the initial draft, due to concerns about excessive length, we presented detailed results for only one glacier in the main text, while summarizing the results for the remaining glaciers in a simple table. This treatment was indeed not rigorous or complete. Furthermore, the purpose of panel (d) is to illustrate the spatial relationship between basal sliding velocity and surface velocity, which is why it was placed there. We kindly ask for your understanding. Meanwhile, following your suggestion, we have placed the results of ice thickness, subglacial topography, basal sliding velocity, and the ratio of basal sliding to surface velocity for all glaciers in the supplementary material for your review.

23. p.14, l.270: There's no 'suggests' about it – we know it misses things.

Response: We have revised this sentence **(P.16, L347-348)**.

"This bias arises from inherent limitations in laminar flow equation parameterization."

24. Table 4: OK, so five of the glaciers in the dataset have a surface velocity so low that I'm almost certain that the velocity observations are likely to be very unreliable. Another two seem likely to barely be getting above the noise-to-signal ratio, so that's nearly half the dataset that's moving so slowly that the velocities provide very little in the way of a useful constraint and where I would be very surprised if there was any measurable basal sliding … . I come back to my previous point: why these 16 glaciers?

Response: Thank you for your valuable comments. We admit that some unclear expressions in the initial version of our manuscript may have caused confusion, and we apologize for that. We have now supplemented the main text with the reasons for selecting these 16 glaciers to validate the effectiveness of our method. Currently, only these 16 glaciers have publicly available GPR measurements in High Mountain Asia. If more GPR data become available, we would be glad to include them. In the future, we plan to conduct further research using over 4,000 glaciers from the GlaThiDa database to assess the regional applicability and effectiveness of the proposed method **(P.5, L118-120)**.

"We applied ITMSL to 16 glaciers across HMA, comparing its performance with two other models (Gantayat and Millan) that are also based on the laminar flow equation. These 16 glaciers were selected because in-situ ice thickness observations are publicly available for them in HMA."

25. p.17, l.311-325: I think this can be summed up as 'these glaciers are way too small to have any reliable velocity observations or basal sliding'. So, again, why include them as targets to demonstrate the importance of including basal sliding in a model?

Response: Your summary is very accurate: these glaciers are indeed too small to allow reliable velocity observations or basal sliding studies. As you pointed out, some small glaciers may not exhibit basal sliding at all. If we deliberately selected only the better-performing ones, although that would help evaluate the performance of the ITMSL model, we believe such an approach would not be comprehensive, nor would it help reveal the true limitations of ITMSL. Therefore, we have revised the relevant statement to make it more logical **(P.20, L404-405)**.

"While sharing comparable elevation, velocity, and slope characteristics with other glaciers, their small size exacerbates four key limitations."

26. p.18, l.329: Established glaciological what? Theory?

Response: We have rewritten this sentence **(P.20, L419-420)**.

"This study combines the basal sliding law with the laminar flow equation to develop the ITMSL model (Schoof, 2005; Gantayat et al., 2014; Zoet and Iverson, 2020; Millan et al., 2022)."

27. p.18, l.329-336: This pretty much comes down to the model incorporating basal sliding performs better where sliding is a meaningful proportion of total velocity and doesn't where it isn't, which is perhaps to be expected? Again, it seems strange to pick a substantial proportion of small, non-sliding glaciers to demonstrate the importance of sliding, and it still hasn't been explained.

Response: As you noted, when basal sliding accounts for a relatively high proportion of surface velocity, the model that includes a sliding mechanism performs better; when the proportion is low, the model ' s performance becomes less satisfactory. This is precisely the improvement made in this study to address the uncertainty introduced by assuming a fixed ratio (e.g., 25%) between basal sliding and surface velocity. The analysis of small glaciers is also intended to clarify the limitations and shortcomings of the ITMSL model. We have added a corresponding explanation in the main text **(P.20, L411-412)**.

"Consequently, the thickness results obtained from these four small glaciers also highlight the limitations and applicable conditions of the ITMSL."

28. p.18, l.341-342: Well, yes, obviously ITSML is more sensitive to basal sliding because the others ignore it? Not sure that's terribly relevant to showing ITSML is better, just that, as a model, it's sensitive to its own inputs, which would be extremely shocking if the reverse were true.

Response: Thank you for pointing out this logical issue. You are right: any model that explicitly includes a sliding parameter will naturally be sensitive to its inputs, and simply stating that "ITMSL is more sensitive to basal sliding" does not demonstrate that it is better. The original wording in our manuscript was indeed misleading. In response, we have revised the relevant sentences to shift the emphasis **(P.21, L433-435)**:

"ITMSL can reasonably capture the spatial variation of basal sliding and thereby improve the physical consistency of ice thickness estimates, whereas other models that ignore sliding cannot reflect this key dynamical process."

29. Section 5.3: This a) isn't anything to do with ITSML and b) everyone already knows that using higher-resolution inputs is going to give you a more accurate representation of the glacier and better results. I think I would just delete this section – it's adding nothing to the paper's main argument

Response: You are absolutely right that higher - resolution input data can characterize glaciers more accurately and yield better simulation results. The purpose of this section was to explain why we selected the GLO-30 DEM as input for ice thickness modeling. Following your suggestion, we have removed this section.

30. Section 5.4: The authors appear to be reinventing ITMIX here. But inadequately. And also proving that ITSML isn't adding much to the existing range of thickness-inversion processes. Which is probably not the intention, but is very much what I'm getting.

Response: Following the ITMIX framework, we have added a comparative analysis of ice thickness results from multiple models in the main text to discuss the performance of different models **(P.22, L456-462)**.
"Taking the CTSG glacier as an example, we compare the composite mean ice thickness (i.e., the ice thickness distribution obtained by averaging, Figure 11a) with the ice thickness spread (i.e., the spread of all model results within a pixel, Figure 11b). Figures 11c and 11d present the maximum and minimum ice thickness composites, respectively, illustrating the composition of the composite results. The models producing the most extreme results are shown in Figures 11e and 11f. For the CTSG glacier, the minimum ice thickness is predominantly provided by the OGGM model (62.2%), while the minimum values from GlabTop2 are mainly distributed over the glacier's tributaries. In contrast, the maximum ice thickness is primarily contributed by ITMSL (32.7%), Millan (20.2%), Gantayat (19.8%), and H-F (16.2%). This pattern is consistent with the trends observed in the ITMIX results. Specifically, the maximum ice thickness from ITMSL is concentrated along the glacier margins; that from Millan is concentrated in the lower reaches and the tongue of the glacier; that from Gantayat is relatively evenly distributed; and that from the H-F model is concentrated in the upper reaches."

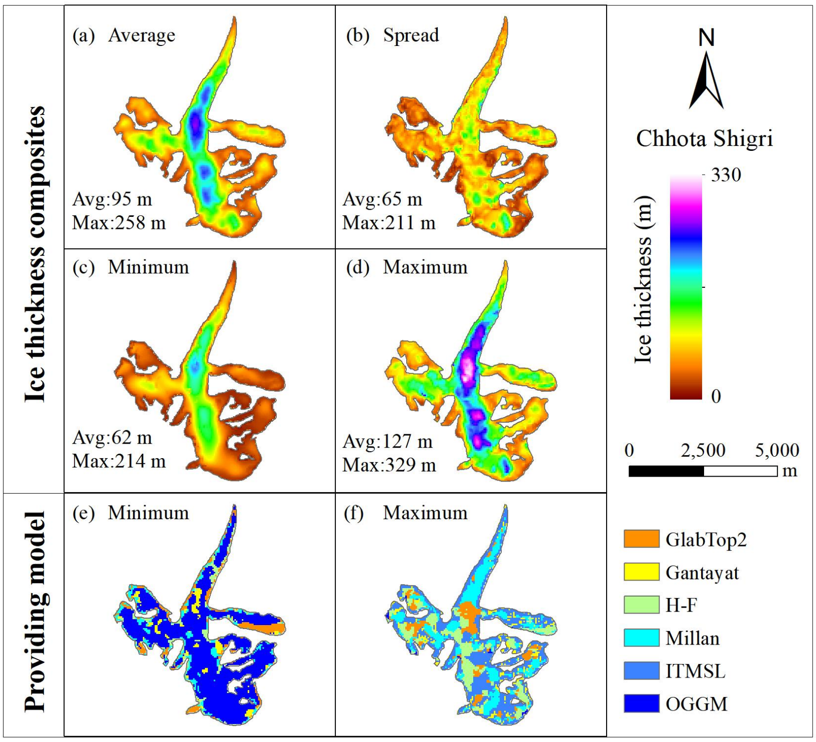


Figure 11: Comparison of simulated ice thickness among models. The first four panels present composite results from the models: (a) average, (b) spread, (c) minimal, and (d) maximal ice thickness distribution. The models corresponding to the minimum and maximum ice thickness at each pixel are shown in (e) and (f), respectively.