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Sensitivity of Andean Glaciers to ice-flow parameters in the Parallel Ice Sheet Model

Ethan Lee[1], Jeremy C. Ely[1], Sarah L. Bradley[1], Tamsin L. Edwards[2], Bethan J. Davies[3]

[1] School of Geography and Planning, University of Sheffield, Sheffield, S3 7ND, UK
[2] Department of Geography, King's College London, London, WC2B 4BG, UK
[3] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

Correspondence to: Ethan Lee (ethan.lee@sheffield.ac.uk)

Abstract. Mountain glaciers are losing mass rapidly due to anthropogenic climate change. Projections of glacier evolution across the Andes under different warming scenarios have primarily been as part of global scale modelling frameworks, rather than dedicated, regionally optimised, simulations. These global-scale models use simplifications of ice flow physics that may be unsuitable for steep topography, such as that which occurs at mountain valley glaciers. More complex models are available, but with that complexity comes further sources of uncertainty. Here, we assess the sensitivity of the Parallel Ice Sheet Model to ice-flow parameters influencing the ice rheology and subglacial sliding characteristics. We find that the resistance of subglacial material has the most impact on modelled ice outputs (e.g., ice volume), followed by the exponent which relates basal shear stress to sliding, and the threshold velocity at which sliding occurs. The ice-flow rheology enhancement factors, the rate of subglacial water decay, and the maximum water thickness within a presumed subglacial drainage network, can either cause minor variations, or no effect at all, on ice outputs. Our study informs what parameters can potentially be negated in future parameter ensemble tests and provides direction on where further investigation is needed.

1 Introduction

Andean glaciers are a critical part of the region's water tower system (Immerzeel et al., 2020), particularly during droughts (Drenkhan et al., 2015) and in upland rural areas (Buytaert et al., 2017; Rabatel et al., 2013). However, they are losing mass rapidly (Dussaillant et al., 2019), placing stress on water resources, and contributing to sea level rise. Continued global warming, intensified by regional elevation-dependent warming (Byrne et al., 2024; Pepin et al., 2015), and changing precipitation regimes (Cai et al., 2020; Masiokas et al., 2020; Potter et al., 2023) heighten the need for accurate glacier projections to inform water management and sea level rise assessments.

Global-scale models of glaciers and ice caps (i.e., all land-based ice not stored in ice sheets) predict continued ice loss through to 2100 (Hock et al., 2019; Hugonnet et al., 2021; Rounce et al., 2020). While long-term sea level rise will be dominated by the Greenland and Antarctic Ice Sheets (Goelzer et al., 2020; Seroussi et al., 2024), glaciers and ice caps may contribute up to 0.35m of sea level rise by 2100 (Edwards et al., 2021; Hock et al., 2019; Marzeion et al., 2020). These global-scale experiments are designed to capture the envelope of plausible sea level rise contributions from glaciers under different emission scenarios (Fox-Kemper et al., 2023). However, global and regional scale projections of mountain glacier change are not only needed for sea level rise, but also for management of changing water resources, mountain glacier hazards, resources for tourism and recreation, and for ecological and biodiversity management.

Glacier models used in intercomparison efforts such as GlacierMIP (Hock et al., 2019; Marzeion et al., 2020; Rounce et al., 2023) provide insight at global and regional scales (Zekollari et al., 2025). However, their use may be limited for planning local resource management and mitigations due to: i) simplified ice-flow physics unsuited to steep topography (Egholm et al., 2011); ii) reliance on downscaled global climate models (GCMs), which often poorly capture mountain climate (Núñez Mejía et al., 2023); and iii) simplified mass balance schemes, often reduced to positive degree-day models (PDD; Bolibar et al., 2022).

Here we attempt to address the first issue, by using a complex ice sheet model to assess uncertainties in the parameterisation of glacier ice flow physics in areas of steep mountain topography. We use the Parallel Ice Sheet Model (PISM; Winkelmann et al., 2011), a thermomechanically coupled shallow-ice/shallow-shelf model commonly applied to both ice sheets (Johnson et al., 2023; Payne et al., 2021; Seroussi et al., 2024) and mountain glaciers (e.g., Candaş et al., 2020; Martin et al., 2022; Žebre et al., 2021). PISM incorporates subglacial hydrology and basal sediment (till) deformation (Albrecht et al., 2020; Winkelmann et al., 2011), but the added complexity increases the number of uncertain parameters. Perturbed parameter ensembles are generally used to explore this type of uncertainty (e.g., Berdahl et al., 2021; Roe and Baker, 2014), however, the number of simulations tends to increase with the number of parameters used, leading to significant computation for computationally expensive models (Archer, 2024; Rougier, 2015). Therefore, a useful precursor to such efforts is a targeted sensitivity analysis to identify which parameters meaningfully influence model outputs. This can aid in excluding parameters from a full ensemble design that show low control over model output, saving computation resources and time.

The aim of this study is to assess the sensitivity of modelled Andean glaciers to ice-flow parameters within PISM. We explore this parameter space through a suite of steady-state univariate and multivariate sensitivity experiments across selected Andean glacier catchments. We focus solely on parameters controlling internal ice deformation and glacier-bed interactions.

2 Study area

Mountain glaciers and ice caps in the Andes span 68º of latitude, from 12ºN in Columbia, to 56ºS in Chile and Argentina. Projections over Andean glaciers show they are likely to become significantly smaller, or entirely lost, in the future due to climatic warming (e.g., Zekollari et al., 2025). Rounce et al. (2023) estimates mass losses by 2100 for the Low Latitudes (RGI 16) of 69 ± 25% to 98 ± 2%, and for the Southern Latitudes (RGI 17) 38 ± 15% to 68 ± 20% for the low and very high emission

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scenarios RCP2.6 (mean projected global warming +1.6°C by 2100) and RCP8.5 (+4.3°C), respectively. Under the more recent SSP scenarios, Rounce et al., (2023) projected slightly higher losses: from 76 ± 18% to 99 ± 3% in the Low Latitudes, and from 49 ± 19% to 74 ± 22% in the Southern Andes, under SSP1-2.6 (+1.8°C) and SSP5-8.5 (+4.4°C), respectively. More recently, Zekollari et al. (2025) detailing the committed loss of glaciers after equilibrating with global warming estimates of +1.5°C and +4.0°C, the Southern Andes would lose a mean of 45% and 79% of their mass, and the Low Latitudes a mean of 46% and 96% of their mass respectively. Regionally specific in Peru, Drenkhan et al. (2015) projects area losses between 40.7% and 44.9% by 2060 under RCP2.6, and between 41.4% and 92.7% by 2100 under RCP8.5.

The five PISM model domains used in this study encompass the mountain glaciers in the 1) Santa, 2) Vilcanota, 3) Kaka and Boopi, 4) Copiapó and 5) Mendoza, Maipo, and Rapel hydrological catchments (Fig. 1). The glaciers in these hydrological catchments are particularly important for their role as meltwater sources for downstream populations (Masiokas et al., 2020; Vuille et al., 2008). The chosen domains cover three different climatological zones: domains 1, 2, and 3 are within the tropical Andes, with a diurnal temperature variation that outweighs the annual temperature variation. This leads to glaciers being sensitive to changes in precipitation that impact the presence and distribution of snowfall across the glacier surface (Hardy et al., 1998; Kaser, 1999). Domain 4 lies within the desert Andes, with high snowline altitudes. This arid climate has short snowfall events that cause glaciers to lose mass primarily through sublimation (Fyffe et al., 2021; Masiokas et al., 2016). Lastly, domain 5 comprises three adjacent mountain hydrological catchments within the wet Andes that are sensitive to temperature changes, due to receiving substantial snowfall during the winter months (Masiokas et al., 2016), while the presence of glacial lakes enhances mass loss through calving and proglacial lake-driven melting (Wilson et al., 2018).

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

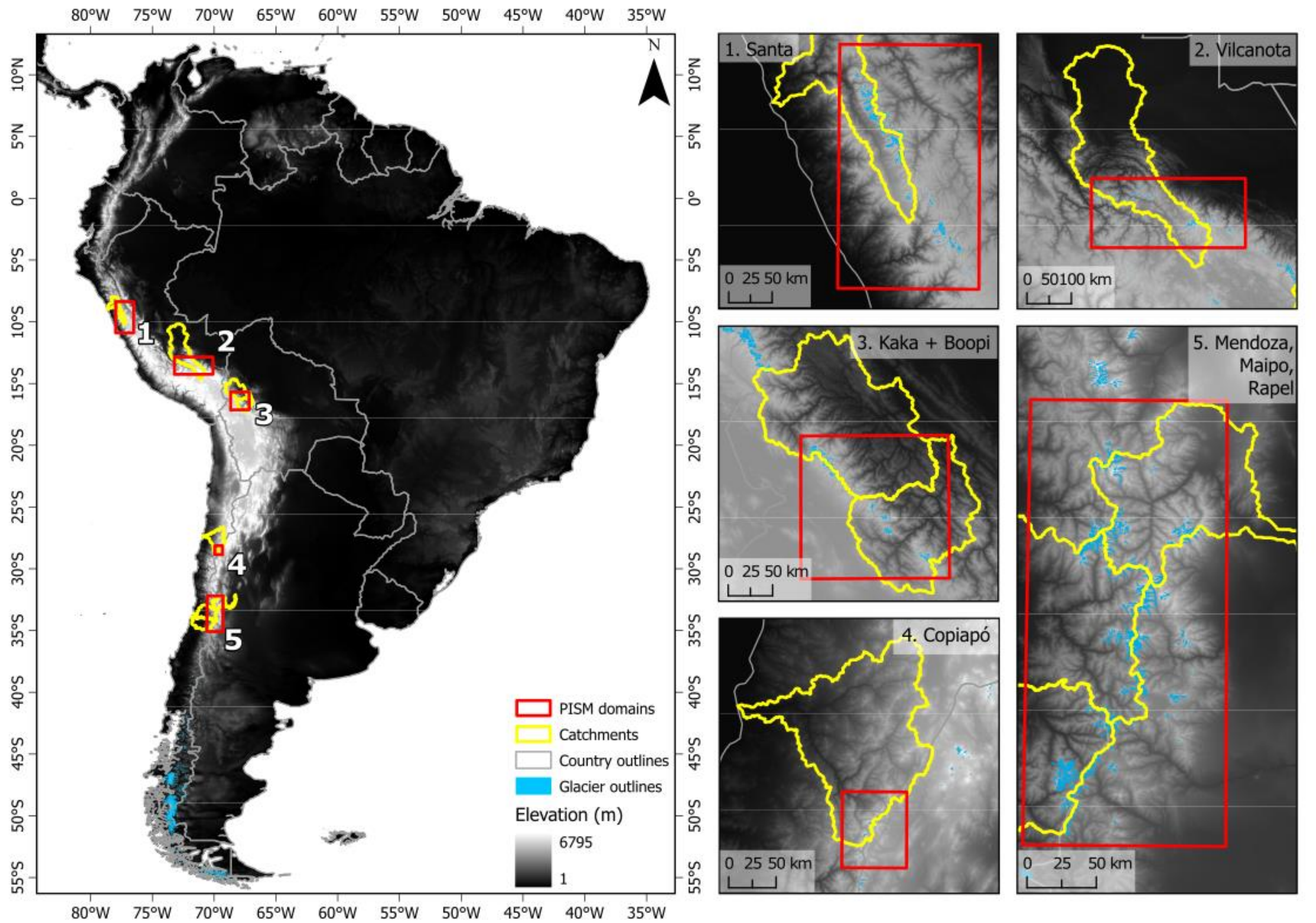

Figure 1: Chosen hydrological catchments and the five PISM domains across the South American Andean Mountains used in this sensitivity analysis. Red outlines show the model domains, focused on glacierized areas within each hydrological catchment. Hydrological catchment boundaries are from HydroSHEDS (Lehner et al., 2008).

The Andes have been the focus of numerous studies examining glacier extent changes in response to both centennial (e.g., Carrivick et al., 2024; Emmer et al., 2021) and decadal scales (e.g., Dussaillant et al., 2019; Taylor et al., 2022). Global-scale studies using simplified two-dimensional flowline models (e.g., OGGM; Maussion et al., 2019) have modelled individual Andean glaciers as part of broader global modelling frameworks, which apply uniform modelling frameworks across diverse climatic and topographic regimes. Although these global frameworks can assimilate regional climate data, they do not specifically optimise for Andean glacier dynamics and are unable to account for highly heterogenous climatic regimes such as those of Andean glaciers. However, regional-scale glacier modelling specific to the Andes remains limited. Most physically based modelling efforts have been concentrated on the Patagonian Icefields, a setting distinct from the rest of the Andes, while other studies are primarily focused on modelling from the Last Glacial Maximum to present (e.g., Cuzzone et al., 2024; Martin et al., 2022; Wolff et al., 2023; Yan et al., 2022). To date, only one study has focused in detail on modelling Andean Mountain glaciers outside Patagonia, assessing their response to climate extremes, however, this study is restricted to just two glaciers

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

(Richardson et al., 2024). Consequently, parameter choices and process understanding for physically based modelling of Andean glaciers remain poorly constrained.

3 Materials and methods

3.1 Parallel Ice Sheet Model

Here, we used the Parallel Ice Sheet Model (PISM v2.1) (Winkelmann et al., 2011) to conduct our numerical modelling. PISM is an open-source, three-dimensional, thermomechanically coupled, hybrid shallow ice, shallow shelf, approximation ice sheet numerical model. The parameter combinations of PISM can be calibrated to represent localised climate and glaciological conditions when sufficient observational constraints (e.g., mass balance data, surface velocity, past glacier extents) are known. Otherwise, default parameter values, which have primarily been tuned for the Greenland Ice Sheet, are set automatically if not specified. Key parameters we have chosen to change here are mentioned throughout the following sections and in Table 1.

Table 1: Chosen glaciological model parameters for sensitivity analysis within PISM. Letters on the leftmost edge of the table correspond to the component letter within PISM that the chosen parameters cover, which is also explained in the main text. All other parameters not mentioned within this table are left at their default values, which can be found in PISM's Configuration Parameters online manual (https://www.pism.io/docs/manual/parameters/index.html).

	Parameter	Default	Min	Max		Description
E	E_{SIA} / E_{SSA}	1	0.2	20	-	Enhancement factor for SIA and SSA: E_{SIA} and E_{SSA} controls how easily the ice deforms.
T	C	1	0.1	12	mm/a	Subglacial water decay rate: determines the amount of water discharge from a hypothetical layer of water beneath the glacier, conceptually this is presumed to be stored in sediment, but could also apply to subglacial cavities.
	W_{till}^{max}	2	0.1	10	m	Maximum subglacial water thickness: the amount of effective water thickness within the subglacial environment; all water above this is not retained.
	ϕ	30	5	45	º	Subglacial bed strength: a parameter in the Mohr-Coulomb criterion for yield stress, which is a shear strength parameter related to the geology of the bed.
S	q	0.25	0.05	0.95	-	Sliding exponent: controls the relationship between basal shear stress and sliding velocity within the Zoet and Iverson (2020) slip law.
	$U_{threshold}$	100	20	200	m/a	Velocity threshold: the velocity above which sliding occurs at the base of the ice.

3.1.1 Enhancement Factors (E Component)

We used PISM's hybrid shallow ice shallow shelf approximation (hybrid SIA+SSA). This is the combination of the shallow-ice (SIA; Hutter, 1983; Mangeney and Califano, 1998) and shallow-shelf approximations (SSA; Bueler and Brown, 2009; Weis et al., 1999), enabling PISM to represent both the vertical deformation and longitudinal stretching of the ice, along with basal sliding. This hybrid SIA+SSA has been applied in other valley-based glacial systems (Candaş et al., 2020; Golledge et al., 2012; Martin et al., 2022; Seguinot et al., 2018).

The stress balance, and the resulting rate of ice deformation ($\dot{\epsilon}$), is described by the Glen-Paterson-Budd-Lliboutry-Duval flow law (Lliboutry and Duval, 1985). This is the default enthalpy-based flow law within PISM, shown in Eq. 1,

$$\dot{\epsilon}_{ij} = EA(T,\omega)\tau^{n-1}\tau_{i,j}, \tag{1}$$

where E is the enhancement factor, A is the ice softness, T is the ice temperature, ω is the liquid water fraction, τ is the stress imposed on the ice, and n is the Glen's flow law exponent. E is implemented for both the SIA and SSA.

For the sensitivity tests, we changed the parameterisation of E for both the SIA and SSA. Many studies have varied E_{SIA} with values between 1 and 6 (Candaş et al., 2020; Ely et al., 2024; Johnson et al., 2023; Zinck and Grinsted, 2022), and E_{SSA} between 0 and 1.5 (Martin et al., 2022; Seguinot et al., 2018; Yan et al., 2023). We varied both E_{SIA} and E_{SSA} at the same time between 0.2 and 20 (see Table 1).

3.1.2 Subglacial properties (T Component)

In PISM, the subglacial hydrology and sliding scheme was originally developed for ice-sheet contexts and conceptualises the bed as a deformable layer, to represent subglacial 'till' or sediment, that can store water and influence basal resistance. The extent to which this subglacial sediment is under ice sheets is unknown, which is also the case for Andean glaciers, although thick layers of sediment are present in glacier forefields. However, the formulation for glacier sliding and hydrology does not require sediment to be present everywhere beneath the glacier. The effective pressure and sliding behaviour can equally represent hard-bedded conditions, where subglacial water storage may occur within bedrock cavities rather than within sediments. To note, while we use the term 'till' throughout this study for consistency with PISM terminology and previous studies, it should not be interpreted as implying continuous sediment cover beneath Andean glaciers.

The yield stress of the basal material (τ_c) in PISM is calculated using the Mohr-Coulomb criterion, which incorporates the till friction angle till friction angle (ϕ), a parameter influenced by the underlying bed geology (Albrecht et al., 2020; Cuffey and Paterson, 2010). This relationship is partly governed by PISM's subglacial hydrology model. The Mohr-Coulomb criterion used to compute yield stress is given in Eq. 2,

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

$$\tau_c = c_0 + (tan\phi)N_{till} \tag{2}$$

Where c_0 is the till cohesion that uses a default value of 0 (Schoof, 2006), and N_{till} is the effective pressure at the base of the ice within the till layer. For every domain we applied a spatially uniform ϕ. Previously used values of ϕ have generally been within ranges of values 5-45º, derived from lab-based experiments of different till types (Cuffey and Paterson, 2010; Koloski et al., 1989). The default value in PISM is 30°, while in the sensitivity tests, we varied ϕ between 5° and 45° (see Table 1).

Within Equation 2, N_{till} is determined in part by the hydrology beneath the ice. The hydrological model used here is a non-conserving model (Tulaczyk et al., 2000). This does not allow the conservation of any water above an assigned till water thickness (W_{till}^{max}). The thickness of the water layer stored within the till is determined by Eq. 3,

$$\frac{\partial W_{till}}{\partial t} = \frac{m}{\rho_w} - C \tag{3}$$

Where m is the basal melt rate, p_w is the density of fresh water (1000 kg m^3), and C is the till water decay rate that denotes how fast water is evacuated from the till water (Albrecht et al., 2020; Flowers, 2015). At all times within the model, $0 \leq W_{till} \leq W_{till}^{max}$ must be satisfied, with any water above W_{till}^{max} being removed.

C and W_{till}^{max} are tested in our sensitivity analysis through the T Component. The till water decay rate is varied between 0.1 and 12 mm/a, while the maximum till water thickness is varied between 0.1 and 10 m (see Table 1).

3.1.3 Basal sliding (S Component)

In PISM, basal sliding is represented by relating the basal shear stress (τ_b) to both the ice velocity (u) and effective pressure (N). A velocity threshold ($u_{threshold}$) marks when τ_b equals the yield stress (τ_c), and therefore when sliding occurs (Cuffey and Paterson, 2010). By default, within PISM we used the Zoet and Iverson (2020) slip law, which introduces a regularisation term that enables a smooth transition between the viscous-style Weertman sliding (Weertman, 1957), and the Coulomb-plastic behaviours (Aschwanden et al., 2013), without needing prior knowledge of bed type. The Zoet and Iverson (2020) slip law is expressed in PISM by Eq. 4,

$$\tau_b = -\tau_c \frac{u}{(|u|+u_{threshold})^q |u|^{1-q}}, \tag{4}$$

Zoet and Iverson (2020) in their equation parameterise $q = 1/m$ where $m = 5$, whereas PISM's default value of q is 0.25 (or where $m = 4$). While the Zoet and Iverson (2020) slip law is relatively new in PISM, being introduced in v2.0, few PISM

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

studies have utilised it. Those modelling efforts that have used the Zoet and Iverson (2020) slip law, (e.g., the Community Ice Sheet Model or CESM; Lipscomb et al., 2019), have varied it between narrow ranges. These have been at 0.2 (Khan et al., 2022; Moreno-Parada et al., 2023), 0.23 (Maier et al., 2022), or 0.33 (van den Akker et al., 2025; Hoffman et al., 2022; Joughin et al., 2024).

Within our sensitivity analysis, q and $u_{threshold}$, were tested through the S component. We varied q from 0.05 to 0.95 to maximise the coverage of potential parametrisations of q to the extremes. We also varied $u_{threshold}$, a parameter that has seen some variation in other modelling studies (Bevan et al., 2023; Martin et al., 2022; Seguinot et al., 2014, 2018). We varied the $u_{threshold}$ between 20 and 200 m/a (see Table 1).

3.1.4 Surface mass balance

We used PISM's default positive degree day (PDD) temperature-index scheme (Calov and Greve, 2005) to generate ice within the domains. This required monthly mean air temperature and yearly precipitation (see Sect. 3.3). Within the PDD scheme, there is stochastic 'white noise' to simulate additional undetermined daily variability, as well as a daily temperature standard deviation that is set by default at 5°C (Winkelmann et al., 2011). These can cause minor fluctuations in the climate, and thereby in the ice extent even under steady state conditions. We forced the model with a constant present-day climate (see Sect. 3.3), to allow glacial ice to reach steady state with its surrounding climate. Parameters that affect the PDD model component of PISM, such as degree day factors, were kept at their default values and not varied within this study due to these values being unknown and this study only being concerned with the internal ice model parameters.

3.2 Model setup and parameter sensitivity analysis

The five model domains simulated by PISM are shown in Fig. 1. Each domain had a 100 m horizontal grid resolution (dimensions in Table 2), with 50 vertical ice layers (quadratic spacing) and 10 bedrock layers. This resolution resolves the topography and flow characteristics while maintaining feasible wall-clock run times. All domains were initialised without prescribed ice thicknesses and run to steady state (~1,500 model years) under constant climate forcing (see Section 3.2).

Table 2: PISM study domains, detailed with their grid *x, y* sizes at 100 m resolution, and the domain area along with the RGIv7 ice area of each domain. The location of each domain, and the hydrological catchments they partially cover, are shown in Fig. 1.

	Domain	x	y	Area (km^2)	Ice Area (km^2)
1)	Santa, Peru	1600	2800	44,800	607
2)	Vilcanota, Peru	3400	1600	54,400	515
3)	Kaka and Boopi, Bolivia	1600	1600	25,600	240
4)	Copiapó, Chile	600	800	4,800	35

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

5) Mendoza, Maipo, and Rapel, Chile	1200	3600	43,200	1,303

Our sensitivity analysis focused on internal ice-flow parameters. These parameters define the physical properties and processes governing ice behaviour, such as the shallow ice, and shallow shelf approximation (SIA/SSA) flow enhancement factor, basal sliding, and subglacial mechanics. We targeted parameters that: (i) have shown substantial influence on glacier modelling in previous studies; (ii) are commonly tested in sensitivity analyses; and (iii) remain poorly constrained by observations or past modelling.

The analysis followed a two-stage approach (Fig. 2) to enable efficient identification of components that exert the greatest control over model outputs. This coarse screening (Stage 1) allowed subsequent parameter-specific tests (stage 2) to focus only on the most sensitive components governing ice flow. This aim of this is to reduce the dimensionality of the analysis and the computational cost of future ensemble experiments. This two-stage approach can be used by other sensitivity studies to facilitate more efficient sampling of key aspects of the model in question that causes the most effect on chosen outputs.

In stage 1 (135 model simulations: 27 per domain), we group individual parameters into components impacting three key ice-flow processes: enhancement factors (E), basal sliding (S), and subglacial properties (T). Parameter values spanned both commonly used and extended ranges to capture a broad spectrum of glacier responses. Each component was perturbed between its chosen minimum, maximum, and default values (Table 1), first individually (with all other components fixed at default values) and then simultaneously, to generate the ensemble design for each domain. Components that showed negligible influence on outputs were discarded from further analysis.

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

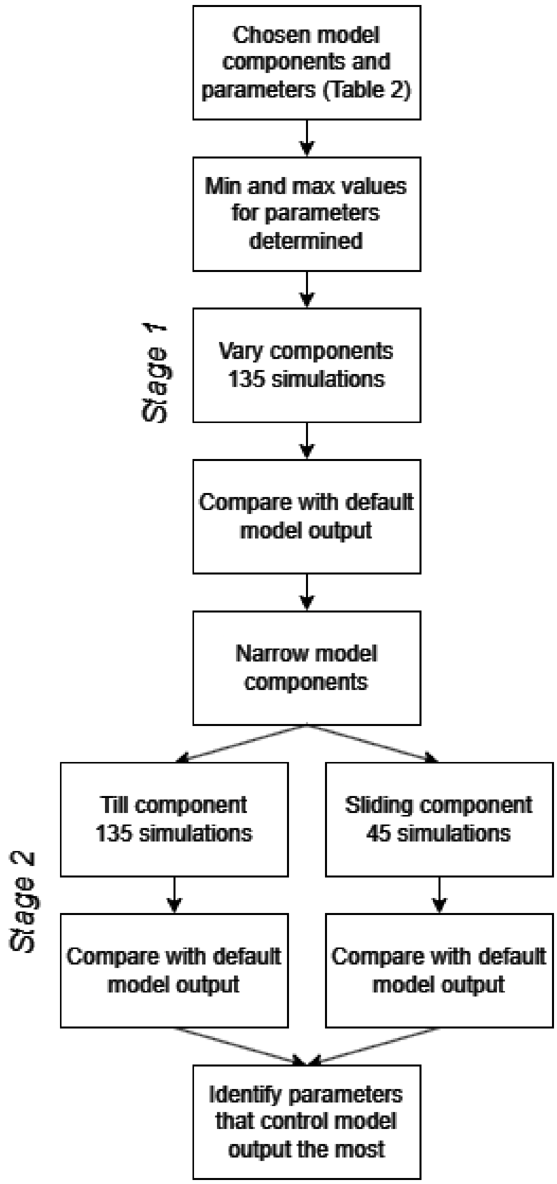

Figure 2: Flow diagram of sensitivity experiment design detailing the staged approach.

Stage 2 (180 model simulations: 36 per domain) comprised a detailed within-component analysis of only those components identified in Stage 1 as influential. Here, every individual parameter was perturbed one-at-time across their defined value ranges (min, max, default; Table 1), followed by simultaneous perturbation of all parameters within that component, rather than grouping them by component as in Stage 1. Parameter in each figure and table corresponds to a shortened name presented here; enhancement factor (E), till water decay rate (C), maximum till water thicknesses (Tm or W_{till}^{max}), till friction angle (Phi or ϕ), sliding exponent (q), velocity threshold (Uth or $U_{threshold}$).

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

Model outputs, of ice volume, ice thickness, and basal velocity, were compared against the baseline simulation using the default values for all parameters. To quantify influence, results were averaged over the domain and Pearson correlation coefficients were calculated between these and the parameter values, along with p-values to assess statistical significance of their effect. This approach provided both a ranking of parameter sensitivity and an assessment of the robustness of their effects.

3.3 Boundary conditions data

Topography is a key initial condition within PISM. We used the ALOS 30 m DEM (Tadono et al., 2014), due to its accuracy over complex mountainous terrain (Talchabhadel et al., 2021), resampled to 100 m using a bilinear interpolation. Basal topography was derived by subtracting present-day ice thicknesses of Millan et al. (2022) from the ALOS DEM. Ice thickness was not directly inputted to the model for the sensitivity experiments.

Geothermal heat flux is required to define and apply the temperature of the bed to the base of the ice. We used Davies (2013) which uses the relationship between basal heat flux to geology on a 2°×2° global grid. Due to the lack of regional specific geothermal heat flux estimates within our study areas and the coarse nature of the dataset, for each domain we assigned a single value based on the value from the grid cell containing the most glacial ice.

Climate input is required for the PISM PDD scheme. For our present-day climate, we used the WorldClim 2.1 data (Fick and Hijmans, 2017). WorldClim 2.1 is a gridded climate data for the years 1970-2000 collected from weather stations here we use the average air temperature (K) and average total annual precipitation (mm yr^{-1}), resampled from a grid resolution of ~900 m to 100 m bilinearly. Due to air temperatures from WorldClim being based on the 30 arc second SRTM DEM, it underestimates temperatures across mountain peaks. To remedy this, we applied a lapse-rate correction of 6.5°C/km based on elevation differences between the WorldClim SRTM and resampled ALOS DEMs. Erroneous adjustments due to DEM artefacts were removed and interpolated across linearly. Ultimately, we are not concerned about the size and shape of the glaciers produced. The role of the climate forcing is simply to produce some ice from which we can understand model sensitivity from.

4 Results and Discussion

Here, we outline results from the Stage 1 component sensitivity experiments for simulated volume change, then for the subsequent Stage 2 parameter sensitivity experiments, for all domains. Aggregated domain results are shown here, with individual model simulation outputs (area, volume, and percentage changes for each domain) available in the Supplementary Information (SI): component sensitivity (SI Tables 1–5), subglacial parameter sensitivity (SI Tables 6–10), and sliding parameter sensitivity (SI Tables 11–15). Final time-slice outputs of ice thickness and ice velocities, along with their differences

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

with the default model simulation for their respective regions, are shown in SI Figures 1-40. Key examples of these are shown throughout which are also shown in the SI for ease of comparison. As the ice area was largely unaffected by parameter changes, they are shown in the sensitivity bar graphs for transparency, but only volume outputs are discussed in any detail, though area is shown in some figures for comparison.

4.1 Stage 1 – Model component sensitivity analysis

Stage 1 is used to determine which model component influences the ice metrics the most, to guide the more detailed Stage 2 sensitivity analysis (Table 3; Fig. 3). We describe results for each component in turn here.

When varying E component parameters (E_{SIA} and E_{SSA}) were varied between their minimum and maximum values (Table 1) resulted in ice volume changes of +5.4% to -9.9% from their defaults across all domains. These changes are reflected primarily in ice thickness (Fig. 4), with maximum E values producing thinner ice (mean: -5.4%) and increased basal velocities (mean: +4.8%), though the Vilcanota (#2) domain showed a velocity decrease of -11.9%. Minimum E values led to thicker ice (mean: +3.2%) and reduced velocities (mean: -9.1%). Pearson correlations between E and ice volume were weak and statistically insignificant across all domains ($p > 0.53$; Table 4).

Table 3: Initial sensitivity analysis outputs detailing the default model simulation volume, and the maximum absolute percentage changes for volume for each domain across the ensemble when components were varied between their maximum and minimum values.

	Volume (km^3)			
Domain	**Default**	**Max**	**Min**	**Max abs change (%)**
Santa	10.1	35.2	8.8	247.2
Vilcanota	3.1	5.1	2.5	64.1
Kaka & Boopi	2.2	3.8	1.6	71.8
Copiapó	1.1	1.9	0.6	68.5
Mendoza, Maipo & Rapel	17.6	34.4	12.1	95.2

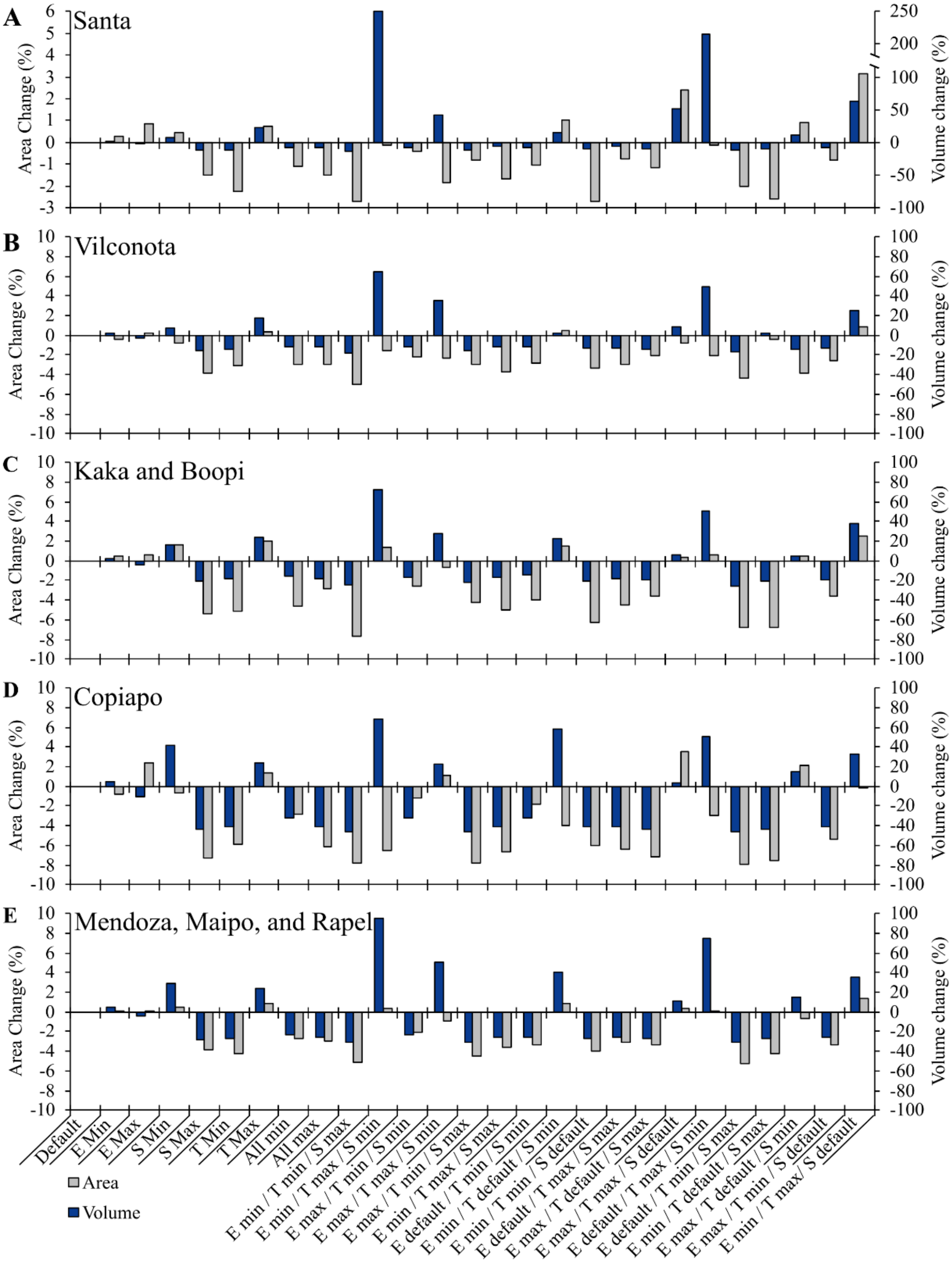

Figure 3: Initial sensitivity analysis detailing the area (grey) and volume (blue) absolute change percent due to changing all model component parameters together, for each of the five model domains. Blue and grey lines denote the default volume and area respectively for comparison. Component parameters are: E = enhancement factors, T = subglacial component, S = sliding component. See Fig. 1 for model domain locations. Note the break in y-axis for ice volume in A) detailing the significant increase in volume, above +200%.

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

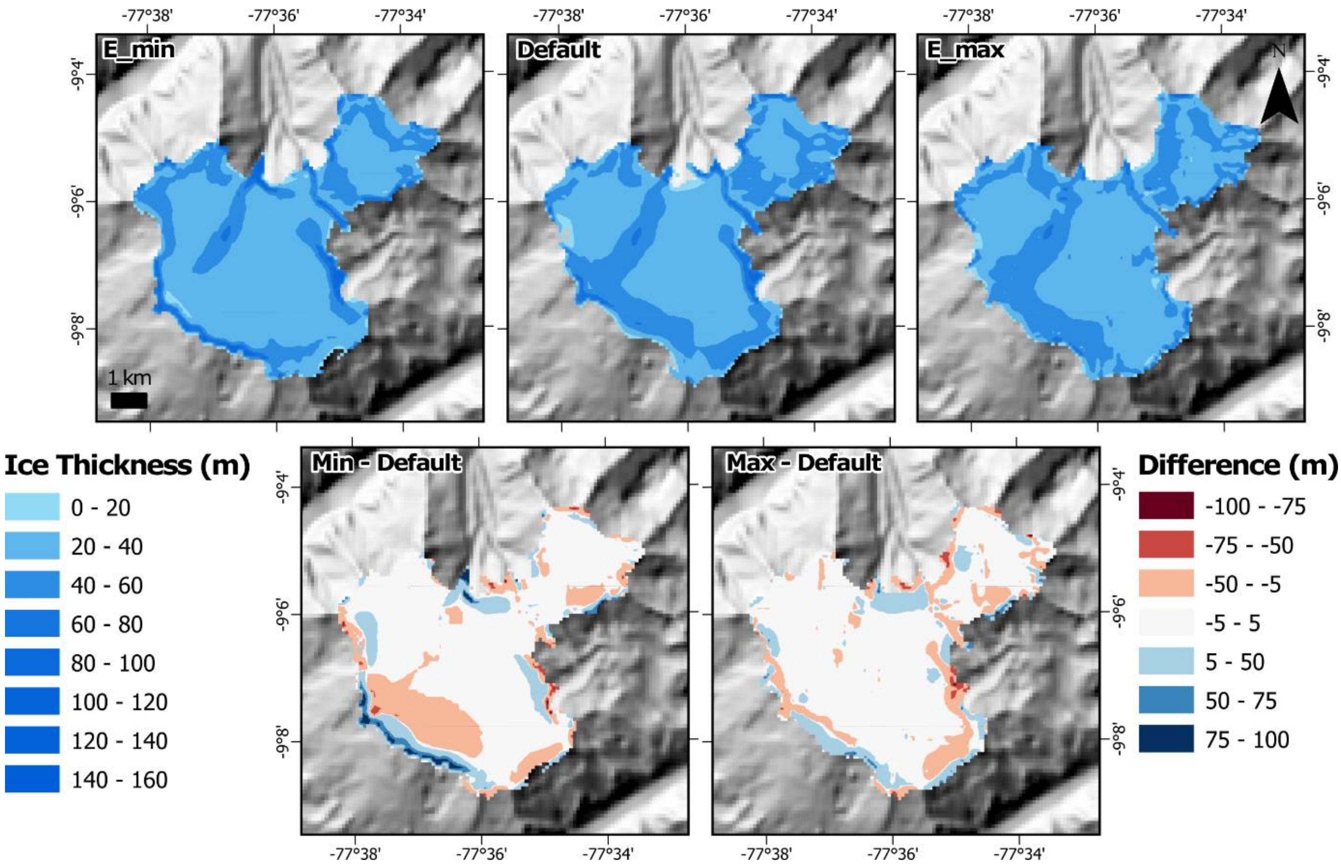

Figure 4: Example of the influence of the enhancement factors on simulated ice thickness in the Santa (#1) domain (Huascarán Ice Cap). Additional examples are provided in the Supplementary Information. Ice peripheral differences in ice thickness arise from internal variability in the PDD model, despite a temperature standard deviation of 5°C. Parameter values for 'max' and 'min' are listed in Table 1.

Similar results - i.e., non-significant variations in modelled outputs - were reported using PISM in other mountain glacier settings (Candaş et al., 2020; Martin et al., 2022) and for ice caps (Schmidt et al., 2020). More substantial effects from the enhancement factors that impact ice rheology, have been observed in models of ice sheets (e.g., Lowry et al., 2020; Phipps et al., 2021; Pittard et al., 2022). Given the minimal impact of enhancement factors in this study, they were excluded from the Stage 2 sensitivity analysis.

When the T component parameters (subglacial water decay rate, maximum subglacial water thickness and bed friction angle) were varied between their minimum and maximum values (Fig. 3; Table 1) resulted in volume changes of -40.5% to +23.6% from their defaults across all domains. Minimum T parameter values increased basal sliding velocities substantially: up to +213.4% in the Copiapó (#4) domain (SI Fig. 12), a mean of +62.4% across all domains, leading to a mean ice thickness reduction of -20.9%. In contrast, maximum T parameter values reduced mean basal velocities by -49.2%, resulting in a mean thickness increase of +22.5% (Fig. 5). The resultant difference in the ice velocities and ice thicknesses can be seen in the shift

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

of the ice divide, being primarily constrained to the glacier valley, to being more diffuse with minimal T component values, and being significant muted with maximum T component values.

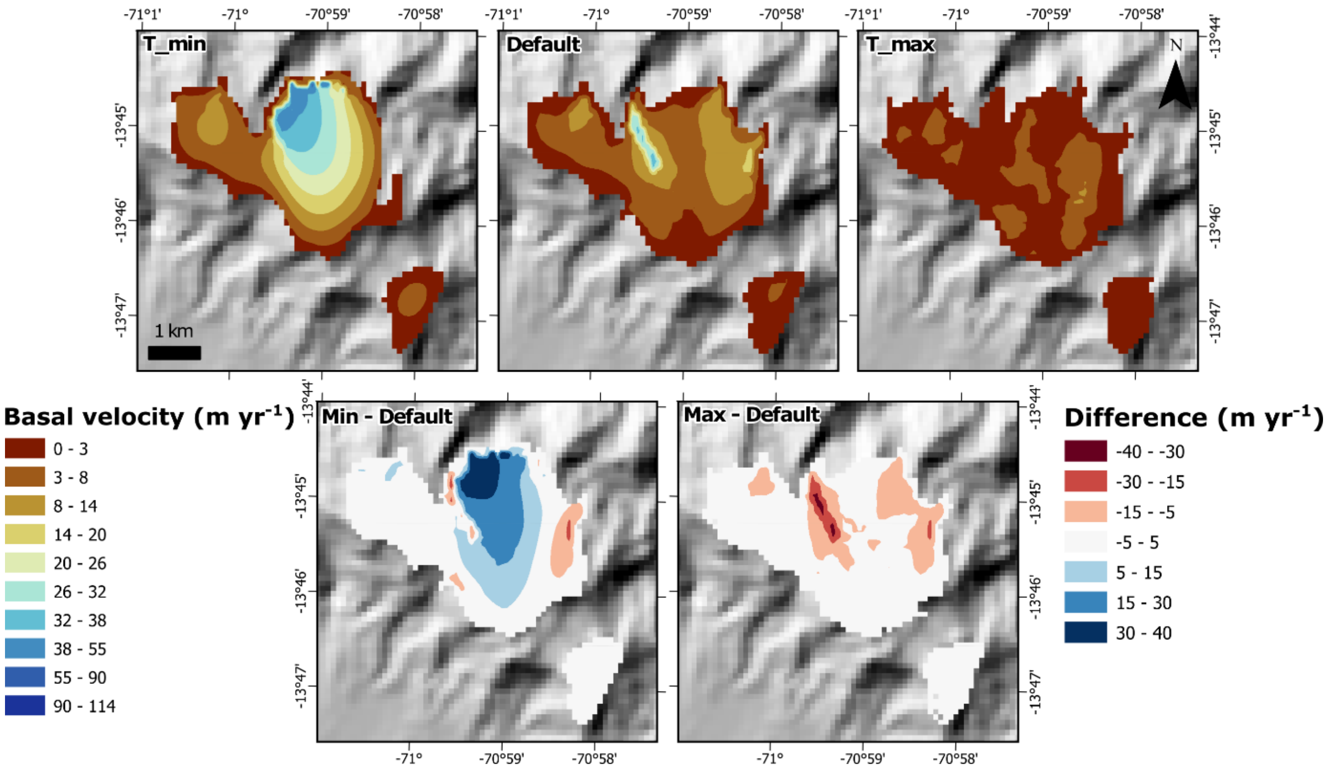

Figure 5: An example of the influence of the subglacial component chosen parameters on the output of ice basal velocity in Vilcanota (#2) domain (Quelccaya Ice Cap). Remaining examples are shown in the Supplementary Information. Increased values of the chosen parameters generate reduced basal ice velocities, while decreasing values increase them. This can also lead to changes in ice divides as seen in T_min, compared to T_max. Values that correspond to 'max' and 'min' parameter values are found in Table 1.

When the S component parameters (sliding exponent and velocity threshold) were varied between their minimum and maximum values (Table 1) resulted in ice volume changes of -43.2% to +41.2% (Fig. 3) from their defaults across all domains. Minimum S parameter values reduced basal velocities by a mean of -24.4% across all domains (-79.5% in the Copiapó domain), resulting in thicker ice (mean: +15.5%). Conversely, maximum values increased basal velocities by a mean of +47.7% (+235% in the Copiapó domain), leading to thinner ice with a mean of -17.3%. The larger percentage volume changes of the Copiapó domain reflect its low ice cover as small changes to the already small volume of ice (1.1 km^3) yields large relative differences.

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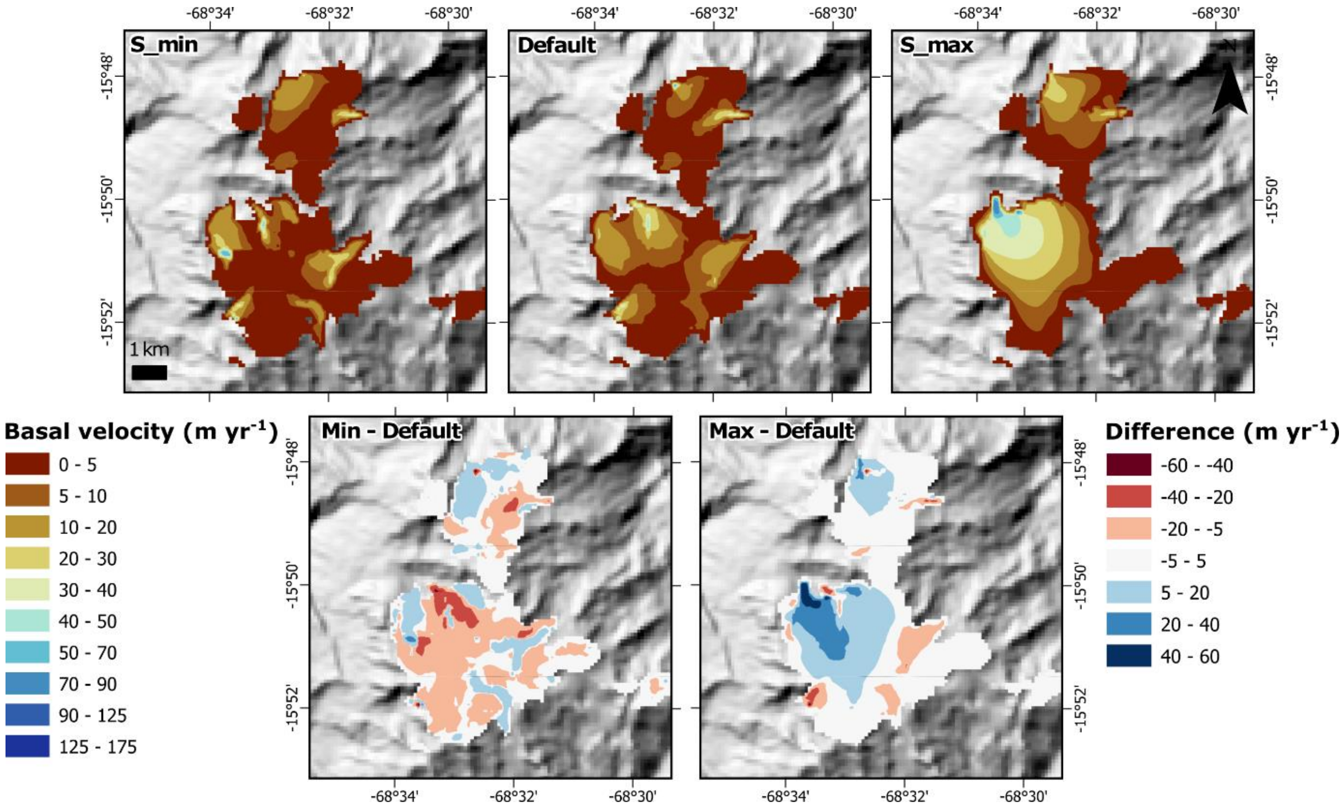

Figure 6: Example of the influence of sliding component parameters on basal ice velocity in the Kaka & Boopi (#3) domain (Ancohuma Ice Caps). Additional examples are provided in the Supplementary Information. Increased parameter values enhance basal velocities, while decreased values reduce them. Variations amplify or suppress sliding patterns already present in the default simulation. 'Max' and 'min' parameter values are listed in Table 1.

Collectively varying all parameters of the E, T, and S components between default, minimum, and maximum values (Table 1) produced a maximum mean ice volume increase of +109.3% across all five domains (Santa domain max: +247.2%), driven by the {E_min, T_max, S_min} combination (Fig. 3). The second highest mean increase of +89.3% (Santa domain max: +221.3%) resulted from {E_default, T_max, S_min}. Averaging across all combinations that include T_max or T_min produced mean ice volume changes of +33.6% and -22.6%, respectively, while those that include S_max or S_min produced changes of +38.6% and -23.2% respectively. Pearson correlation analysis (Table 4) confirms a strong and significant correlations ($p \leq 0.05$) for the T and S components and their effects on simulated ice volume in almost all domains.

Table 4: Pearson correlation statistics for all domains (n = 27 simulations per domain, 135 simulations overall) to understand the impact of model components on simulated ice volume. A value closer to zero (0) indicates a lower influence on the simulated volume output. A positive or negative number indicates that when the component value is varied it causes a gain or loss of simulated ice volume. These are then averaged, using their absolute values to show the overall influence across all domains. * = $p \leq 0.05$, ** = $p \leq 0.01$.

Domain	**E**	**T**	**S**
Pearson correlation	*Volume*	*Volume*	*Volume*

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

Santa	-0.16	0.47*	-0.39*
Vilcanota	-0.18	-0.36	0.51
Kaka & Boopi	-0.17	0.47*	-0.46*
Copiapó	-0.17	-0.46*	0.47*
Mendoza, Maipo & Rapel	-0.13	-0.49**	0.45*
Average	0.16	0.45	0.46

Given its limited influence on simulated ice volume, the enhancement factors (E) with E_{SIA} and E_{SSA} parameters, is excluded from the individual parameter sensitivity analysis of Stage 2. The subglacial (T) and sliding (S) components demonstrated significant impacts through both univariate and multivariate perturbations and were included in the Stage 2 sensitivity experiments (Sect. 4.2).

4.2 Stage 2 – Individual parameter sensitivity analysis

4.2.1 Subglacial model parameters (T Component)

The T component parameter tests investigated the subglacial water decay rate (C), the maximum thickness of subglacial water (W_{till}^{max}), and basal friction angle (ϕ). Summary statistics for the T component tests are presented in Table 5 and Fig. 7. Among all domains when the parameters were varied, the Copiapó domain, being the smallest, exhibited the largest change in simulated ice volume (-40.5%). The second largest change (+28.3%) occurred in the Mendoza, Maipo and Rapel domain, the largest and most ice-rich domain.

Table 5: Overall, subglacial sensitivity analysis outputs detailing the default model simulation volume, and the maximum absolute percentage changes for volume for each domain across all the model simulation when components were varied between their maximum and minimum values.

	Volume (km^3)			
Domain	**Default**	**Max**	**Min**	**Max abs change (%)**
Santa	10.1	12.5	8.95	23.6
Vilcanota	3.1	3.6	2.6	17.2
Kaka & Boopi	2.2	2.7	1.8	23.6
Copiapó	1.1	1.4	0.7	40.5
Mendoza, Maipo & Rapel	17.6	21.8	12.6	28.3

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Preprint. Discussion started: 22 January 2026

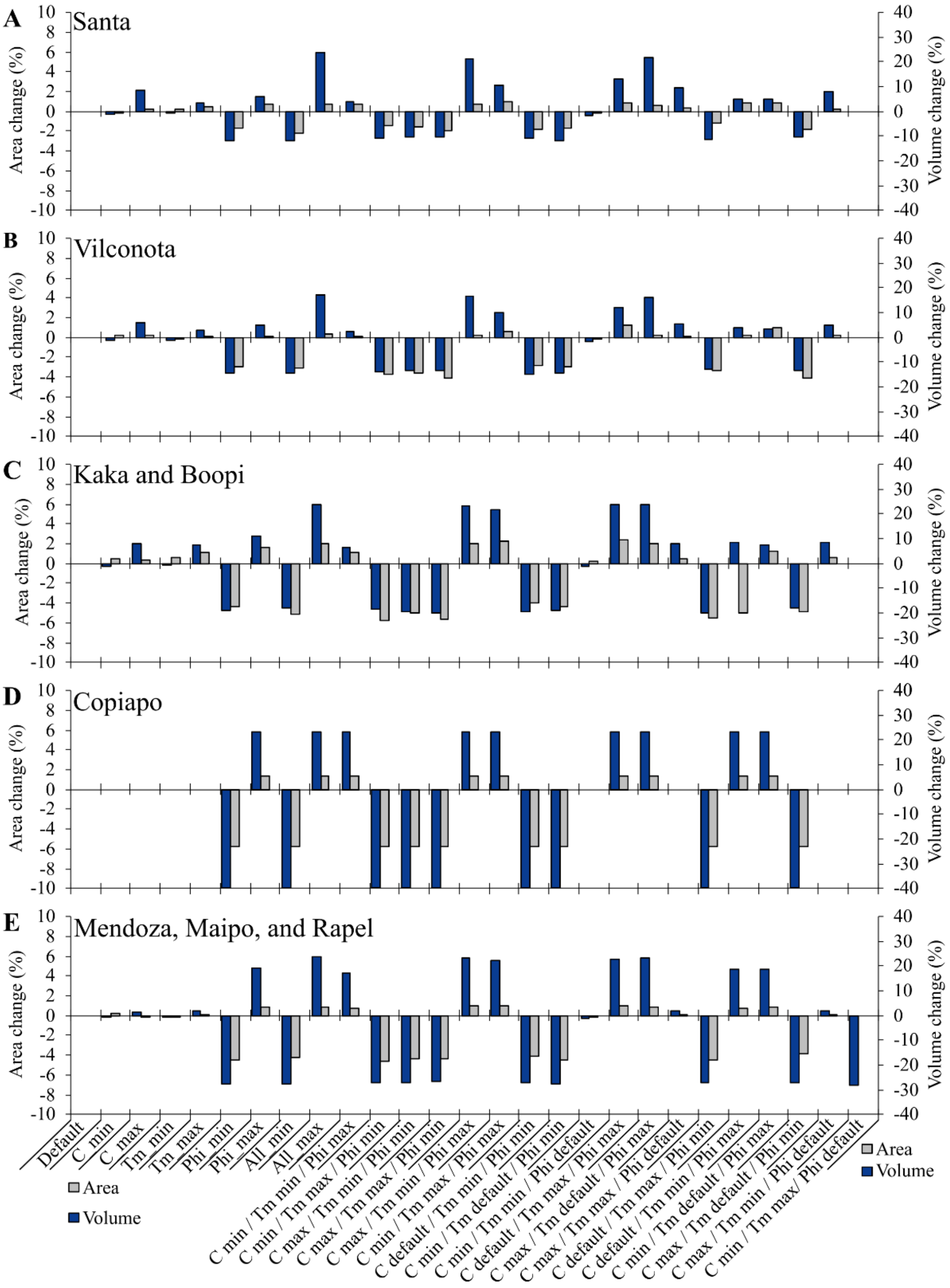
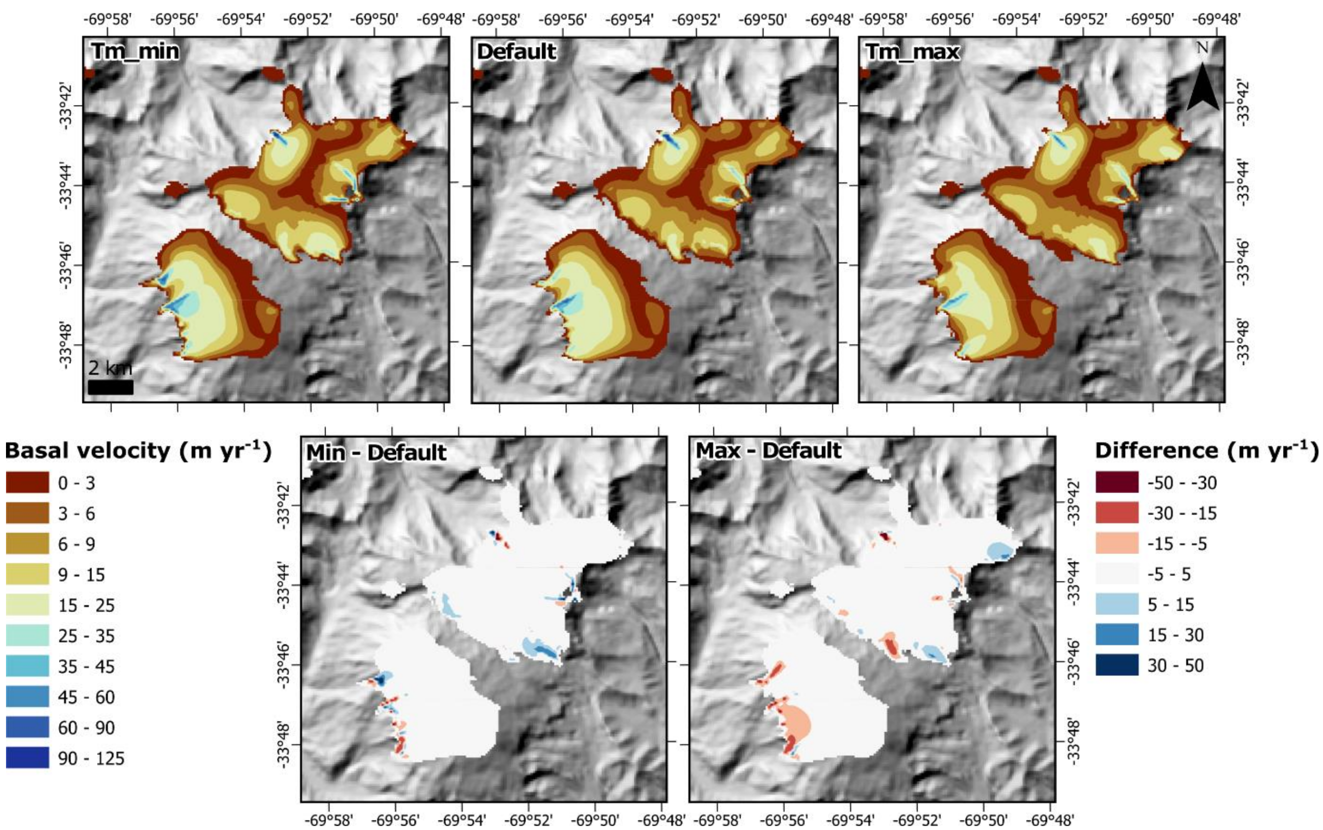


Figure 7: T sensitivity analysis detailing the area (grey) and volume (blue) absolute percentage changes due to changing the model component parameters all together, for each of the five model domains. Blue and grey lines denote the default volume and area respectively for comparison. Where there is no bar present for the component parameter, there was no change (0%). Subglacial parameters are, C = basal water decay rate, Tm = W_{till}^{max}, Phi = ϕ. See Fig. 1 for domain locations.

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

Varying the subglacial water decay rate (C) between its minimum and maximum values (Table 1) resulted in ice volume changes of -1.4% to +8.6% respectively across most domains. No change was observed in the Copiapó domain, likely due the small size of its glacial ice, or due to PISMs simplified hydrology model not able to affect the small glaciers due to the model resolution. Ice thickness and basal velocity changes across all domains were minor or negligible (e.g., no change in the Copiapó domain, Fig. SI 25). Minimum C values slightly reduced ice thicknesses (mean: -1.0%) and increased velocities (mean: +1.6%, -7.5% in the Vilcanota domain). Maximum C values increased thickness (mean: +5.1%) and decreased velocities (mean: -14.6%), reflecting the larger deviation of the maximum (12 mm/a) from the default (1 mm/a) relative to the minimum (0.1 mm/a).

When W_{till}^{max} was varied between its minimum and maximum values (Table 1), it resulted in ice volume changes of between -1.0% to +7.7% across all domains (Fig. 7). No changes were seen across the Copiapo domain. Minimum W_{till}^{max} saw minimal reductions in ice thickness (mean: -0.2%) and increases in velocity changes (mean: +3.3%), while maximum W_{till}^{max} provided slightly increased ice thickness (mean: +2.5%) and reduced ice velocity (-6.6%) across all domains (Fig. 8). A stronger reduction of -13.1% in ice velocity was identified in the Vilcanota domain with minimum W_{till}^{max} values, inferred to be related to the domain geometry or resolution effects within this region.



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Preprint. Discussion started: 22 January 2026

Figure 8: An example of the influence of the W_{till}^{max} (Tm in Fig. panels) parameter on the output of ice basal velocity in the Mendoza, Maipo, and Rapel (#5) domain (Volcán Marmolejo). Remaining examples are shown in the Supplementary Information. Increased values the Tm parameter generally sees no, or very little changes in basal ice velocities. Values that correspond to 'max' and 'min' parameter values are found in Table 1.

The parameters W_{till}^{max} and C had minimal, to no, impact on simulated ice outputs across all domains (Fig. 7). Similar minor effects of W_{till}^{max} over other valley glacier modelling efforts were reported by Candaş et al. (2020) and Žebre et al., (2021), although they saw greater sensitivity in their output than in our study due to W_{till}^{max} being varied in conjunction with the till effective fraction overburden (δ). No PISM-based studies to our knowledge have assessed sensitivity to C for valley glaciers. However, C has been shown to have an increased influence over ice sheets settings. Albrecht et al. (2020) details that increasing C from 1 to 10 mm yr^{-1} can cause PISM to simulate an additional 11 m sea level equivalent (SLE) of meltwater from the Antarctic Ice Sheet over multiple glacial cycle timescales. This increasing influence over ice sheets is likely due to the greater role of subglacial hydrology in driving glacial motion and ice streaming (Kazmierczak et al., 2022; Verjans and Robel, 2024). While subglacial hydrology does affect valley glaciers (Mair et al., 2002), they can effect glacier motion on diurnal time scales (Nienow et al., 2005) which would make modelling their interaction difficult.. Our results indicate limited impact from these specific parameters in PISM, that are likely due to either, an insufficient model resolution, the basal topography not being sufficient to majorly affect basal sliding, or that the PISM hydrology is too simplistic to accurately represent its effect over mountain glaciers. Neither parameter significantly affected valley glacier simulations in our PISM ensemble. These parameters can likely be excluded from future valley glacier sensitivity analyses.

When ϕ was varied between its minimum and maximum values (Table 1), simulated ice volumes were saw changes between –40.5% to +23.4% across the domains, respectively. Minimum values of ϕ led to substantial reductions in ice thickness (mean: -24.5%) due to increases in ice velocity (mean: +81.9%), while maximum ϕ values led to increases in ice thickness (mean: +19.3%) and reductions in ice velocities (mean: -23.3%) (Fig. 9). The most extreme differences were seen in the Copiapó domain, due to the region incurring the smallest glacier area, and any changes can lead to larger relative (%) changes.

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Preprint. Discussion started: 22 January 2026

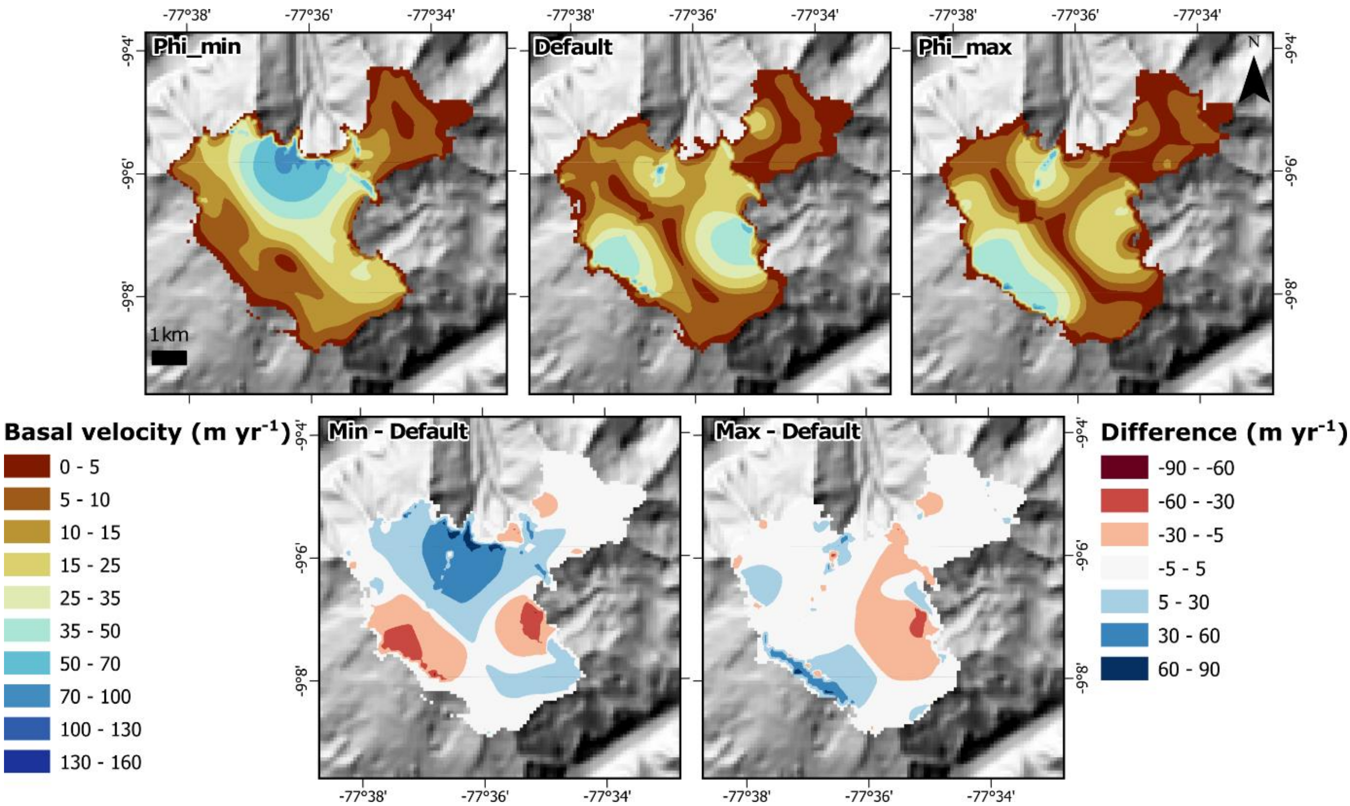

Figure 9: An example of the influence of the ϕ (Phi in Fig. panels) parameter on the output of ice basal velocity in the Santa (#1) domain (Huascaran Ice Cap). Remaining examples are shown in the Supplementary Information. Increased values of the ϕ parameter see a reduction in basal velocities, while the opposite is seen for decreased values. Values of 'max' and 'min' parameter values are in Table 1.

Among the T component parameters, ϕ accounted for the greatest variance in simulated ice volume (Table 7), with a consistent influence across all domains (Fig. 7). Due to ϕ representing how resistant the subglacial sediment is to shear deformation, lower values represent wet fine sandy sediments promoting more basal motion, while high values represent coarser dry gravels, or bedrock, reducing basal motion. This therefore led to decreased subglacial sliding, with higher values of ϕ leading to thicker ice (see *Phi_max* in Fig. 9), while lower values of ϕ increasing basal velocities leading to thinner ice (see *Phi_min* in Fig. 9). These influences over the ice basal velocities also yielded changes in the ice divides and flow regimes that can lead to subsequent changes in the ice thicknesses and ice velocity dynamics across the domain (see *Min – Default* in Fig 9). While ϕ has not been explicitly varied in previous valley glacier studies, to our knowledge, when modelling ice sheets ϕ is a key control on ice volume and subsequent ice dynamics (Albrecht et al., 2020; Koldtoft et al., 2021; Lowry et al., 2020). For example, lower ϕ values saw a reduction in modelled LGM volumes of the Antarctic Ice Sheet leading to accelerated retreat, whereas higher ϕ values tended to overestimate present-day ice sheet thicknesses (Albrecht et al., 2020; Lowry et al., 2020). Our findings highlight its importance in mountain glacier settings. Though a uniform ϕ was used here, it likely varies with

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

catchment-specific geology (Bareither et al., 2008; Clarke, 2018), suggesting future studies should tune ϕ regionally to improve accuracy in ice dynamics and volume simulations.

When all T component parameters were varied between their minimum, default, and maximum values, simulated ice volume differed by up to +40.5% relative to the default simulation s. Across all domains, ice volumes cluster into three distinct groups cantered on the minimum, default, and maximum ϕ values, most clearly seen in the Copiapó (#4) and the Mendoza, Maipo and Rapel (#5) domains (Fig. 7). While ϕ exerts dominant control over ice volumes, C and W_{till}^{max} cause only minor variations within these groups. The highest volumes occurred when ϕ and other subglacial parameters were set to their maximum values {All_max}. Pearson correlations (Table 6) confirm the strong overwhelming influence of ϕ on simulated ice outputs, with an average coefficient of 0.94 across all domains. Moreover, ϕ was the only subglacial parameter with a statistically significant effect ($p \leq 0.01$), underscoring its primary role in controlling model outputs in PISM.

Table 6: Pearson correlation statistics for all five model domains (n = 27 simulations per domain; 135 total) showing the influence of subglacial model parameters on simulated ice volume. Explanation of Pearson correlation values shown in Table 4. ** = p ≤ 0.01.

Domain	C	W_{till}^{max}	ϕ
Pearson correlation	*Volume*	*Volume*	*Volume*
Santa	0.36	0.11	0.88**
Vilcanota	0.26	0.12	0.93**
Kaka & Boopi	0.18	0.12	0.95**
Copiapó	0.00	0.00	1.00**
Mendoza, Maipo & Rapel	0.09	-0.04	0.96**
Average	0.18	0.08	0.94

Across both univariate and multivariate parameter tests, ϕ consistently exerted the strongest influence on model outputs among the subglacial parameters. This is due to its role in the Mohr–Coulomb criterion, which governs the pseudo-plastic sliding law and modulates basal resistance (Cuffey and Paterson, 2010). Higher ϕ values increase basal resistance, slowing ice flow and leading to thicker ice, thereby raising total ice volume while having limited effect on ice extent. This relationship is reinforced by the 'all max' scenario, which produced the thickest and highest volume ice across nearly all domains.

4.2.2 Sliding model parameters (S Component)

The S component tests focus on two parameters: the sliding exponent (q) and the velocity threshold ($U_{threshold}$). Summary statistics for these tests are presented in Table 7 and Fig. 10. The PISM domains of Copiapó and Mendoza, Maipo and Rapel, representing the smallest and largest glaciers respectively, display the most pronounced responses to parameter variation, with maximum ice volume changes of 44.1% and 30.0%, respectively.

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

Table 7: Sliding sensitivity analysis outputs detailing the default model simulation area and volume, and the maximum absolute percentage changes for ice volume for each domain across all the simulations when components were varied between their maximum and minimum values.

	Volume (km^3)			
Domain	**Default**	**Max**	**Min**	**Max abs change (%)**
Santa	10.1	11.0	9.0	11.4
Vilcanota	3.1	3.3	2.6	14.9
Kaka & Boopi	2.2	2.6	1.7	21.4
Copiapó	1.1	1.6	0.6	44.1
Mendoza, Maipo & Rapel	17.6	22.5	12.3	30.0

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Preprint. Discussion started: 22 January 2026

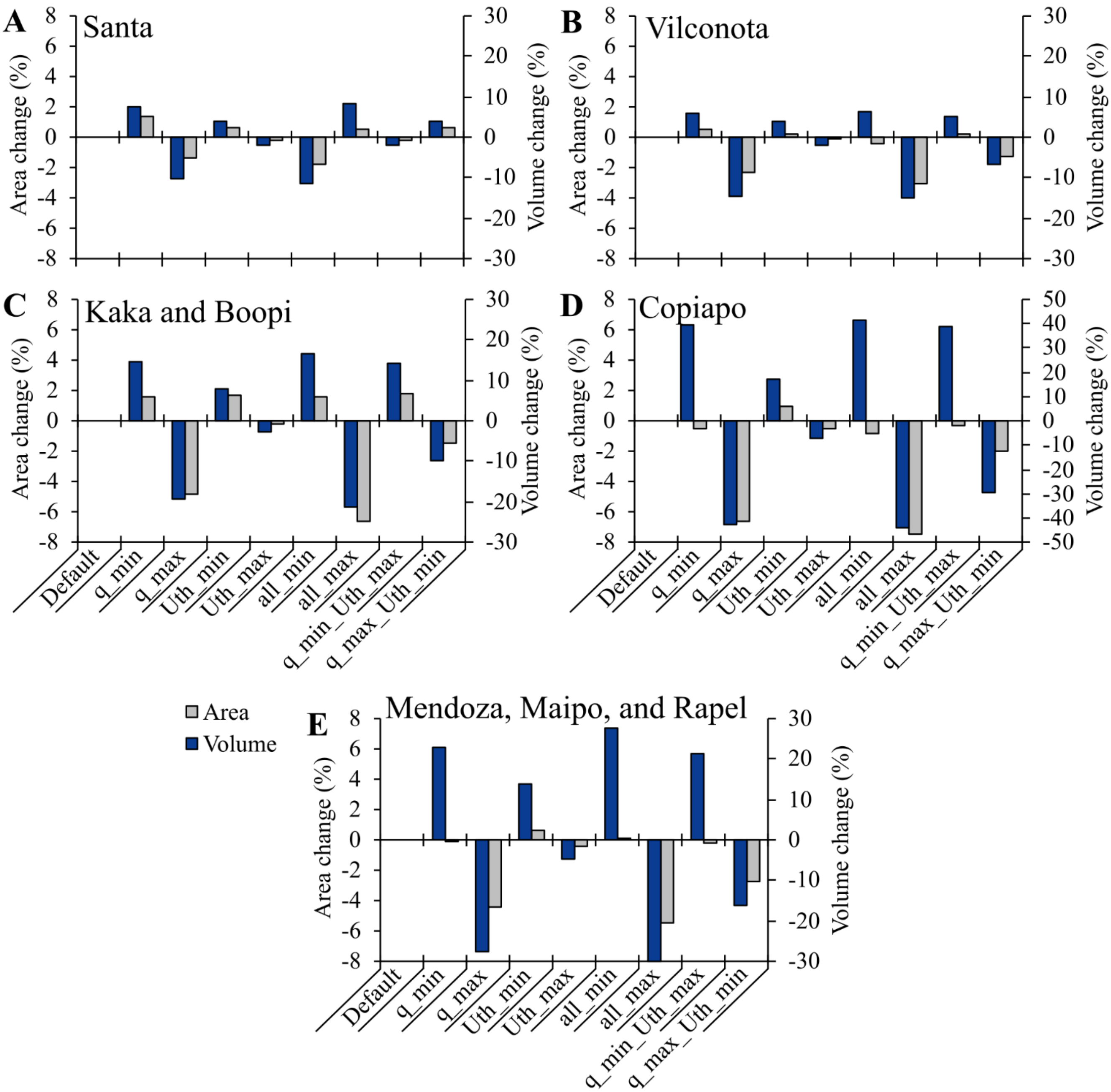

Figure 10: Sliding sensitivity analysis detailing the area (grey) and volume (blue) changes due to changing the model component parameters all together, for each of the five model domains. Blue and grey lines denote the default volume and area respectively for comparison. See Fig. 1 for domain locations. Note the change in y-axis in D), due to larger volume changes occurring in the Copiapo catchment, the catchment with the smallest ice area.

When $U_{threshold}$ was varied between its minimum and maximum values (Table 1) produced ice volume differences of +17.1% to -7.2% respectively, with an absolute average difference of 6.5%. Across all domains minimum $U_{threshold}$ saw increased ice

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

thicknesses (mean: +9.1%) and basal velocities (mean: -19.2%) (Fig. 11). Maximum $U_{threshold}$ saw reduced ice thicknesses (mean: -3.7%) along with increased basal ice velocities (mean: +7.8%).

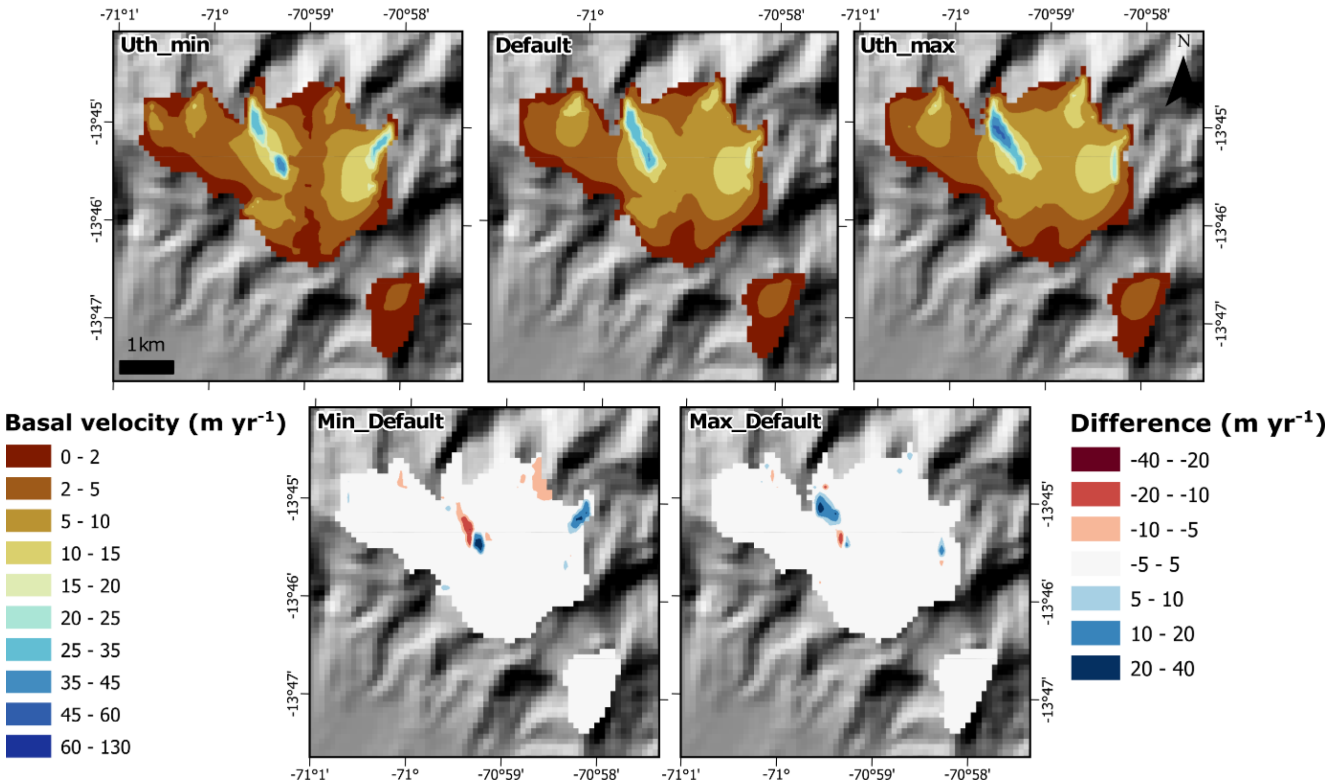

Figure 11: An example of the influence of the $U_{threshold}$ (Uth in Fig. panel) parameter on the output of ice basal velocity in the Vilcanota (#2) domain (Quelccaya Ice Cap). Remaining examples are shown in the Supplementary Information. An increase in the $U_{threshold}$ parameter sees increased basal velocities, while the opposite is seen when values are decreased. Values that correspond to 'max' and 'min' parameter values are found in Table 1.

Variations of the $U_{threshold}$, which controls the onset of basal sliding, leads to when the $U_{threshold}$ is set to lower values, ice flow velocities are decreased, increasing ice thickness and volume. However, while overall flow patterns remain very similar, their intensity shifts with varied $U_{threshold}$ values. As can be seen in Fig. 11, with decreased $U_{threshold}$ values overall mean velocities decreased, but small localised areas of increased velocities (~10 to 20 m yr^{-1}) are seen where in the default run saw lower velocities occurred. When the $U_{threshold}$ is increased, overall mean velocity increased, with areas of already faster flowing ice saw an increase in velocity (~20 m yr^{-1}), with locations of localised slower velocities remaining the same as those in the default. Despite this influence, $U_{threshold}$ is rarely tested in mountain glacier modelling, with most studies using a fixed 100 m yr^{-1} value (Martin et al., 2022; Seguinot et al., 2014, 2018). Our results, spanning 20 to 200 m yr^{-1}, show that $U_{threshold}$ meaningfully affects modelled dynamics and should be included in future sensitivity analyses.

When q was varied between its minimum and maximum values (Table 1), it produced a difference in the ice volume between +39.6% and -42.3%, with an absolute average difference of 20.4%. The two largest differences in ice volume detailed before were all seen in the smallest domain of Copiapó (-42.3%), the second highest difference is seen in Mendoza, Maipo, and Rapel domain (-27.7%), both when q is set to its maximum value. Across all domains when q was set to its minimum, there was an increase in ice thickness (mean: +18.9%) and a decrease in ice velocity (mean: -33.6%), when set to its maximum there was a decrease in ice thickness (mean: -21.7% and an increase in ice velocity (mean: +75.5%) (Fig. 12).

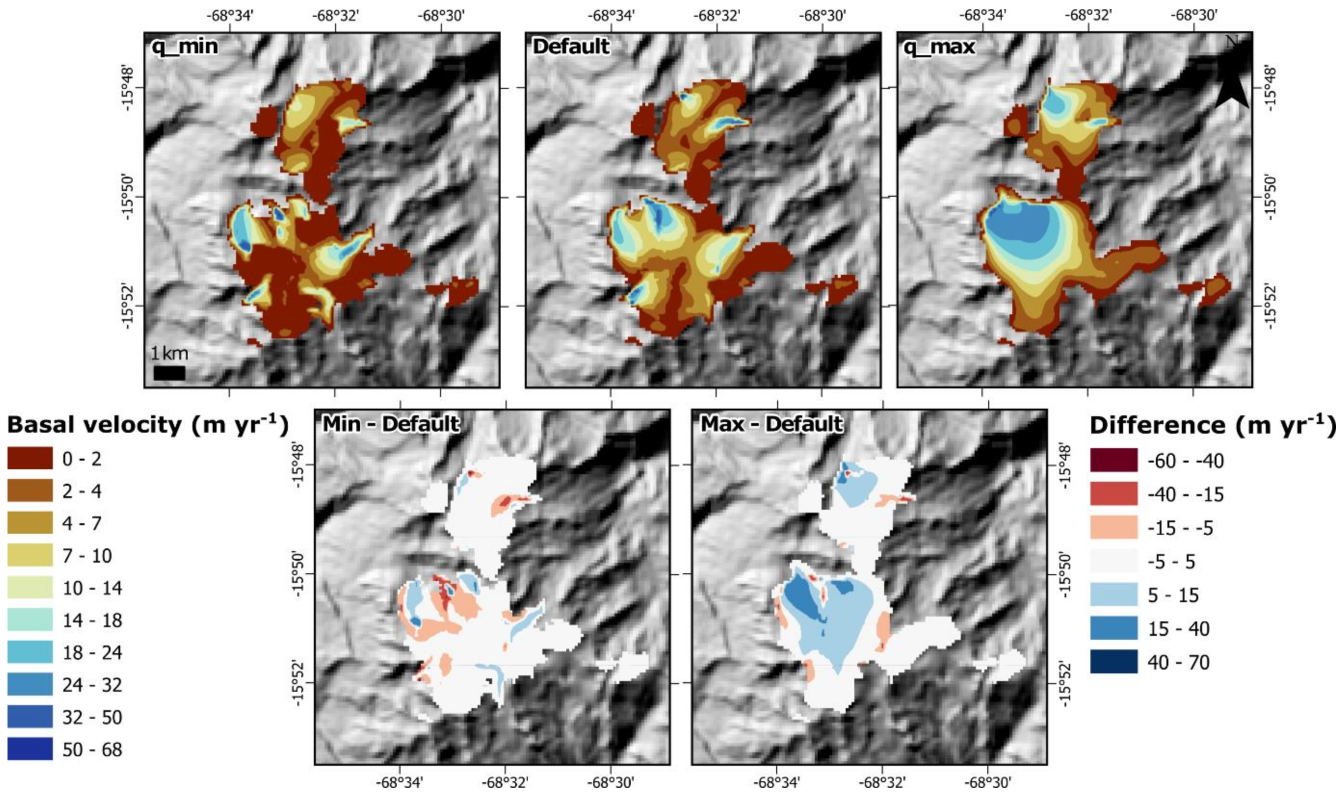

Figure 12: An example of the influence of the sliding exponent (q) parameter on the output of ice basal velocity in the Kaka & Boopi (#3) domain (Ancohuma ice caps). Remaining examples are shown in the Supplementary Information. An increase or decrease in values of the q parameter see almost no effect in basal velocities. Values that correspond to 'max' and 'min' parameter values are found in Table 1.

Variations of q within PISM exert a clear influence on simulated ice dynamics, due to its role in controlling the non-linearity of the basal sliding law (Zoet and Iverson, 2020). Higher q values suppress fast-flowing regions (e.g., >25 m yr^{-1}) but enhance sliding in slower-flowing regions, producing a more diffuse velocity field (see q_max in Fig. 12). In contrast, lower q values concentrate flow into narrow corridors, altering ice divides and increasing ice thickness in surrounding slower-flow regions by limiting basal sliding (see q_min in Fig. 12). Among PISM studies, q is the most frequently varied sliding parameter, however, this in within the context of using the default Coulomb sliding model. Using the Coulomb sliding model Candaş et

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

al. (2020) over valley glaciers found that varying q altered ice volume by +22.6% at q = 0 and -26.4% at q = 1. In ice sheet contexts, effects are mixed with Albrecht et al. (2020) reporting lower q reduced velocity and increased Antarctic volume at the LGM by up to ±3 m SLE. Over Greenland, Aschwanden et al. (2019) shows that the variance of q parameterization of 0.25 to 1.0 can lead to uncertainties on SLE contributions of 26-53% by 2100, 5-38% by 2200, and 2-33% by 2300. While the Zoet and Iverson (2020) slip law has been not used by other PISM modelling studies, no study to have used the slip law within ice sheet models (e.g., CISM; van den Akker et al., 2025) varied the parameterisation of the sliding exponent extensively. Our findings here support the previous conclusion that q significantly affects modelled ice volumes, particularly in regions dominated by valley-confined dynamic flow (see Section 4.2.2). The results, at least for q are the first to be presented using the Zoet and Iverson (2020) slip law. We therefore recommend that future valley glacier modelling studies, especially those focused on mass change, include q in their sensitivity analyses.

When q and $U_{threshold}$ are varied together between their default, minimum, and maximum values, the largest ice volume difference from the default simulation reaches -44.1%, observed in the Copiapo catchment (Fig. 10). Excluding this smallest domain, the maximum difference is -30.0% in the Mendoza, Maipo and R domain. While q alone exerts the strongest influence, combining both parameters amplifies their effects {All_max}. This is particularly evident when both are set to their minimum or maximum values, resulting in greater or lesser increases in ice volume than when varied individually.

The Pearson correlation analysis (Table 8) confirms q as the dominant control on sliding-related sensitivity, with strong correlations across nearly all domains except in the Santa catchment. Although the number of combined simulations is limited, $U_{threshold}$ still produces noticeable changes in simulated outputs (Fig. 11), but its influence remains secondary to q when both are varied simultaneously. This is likely because they both alter ice velocities, making it easier or more difficult for sliding to occur. This supports that these two parameters should continue to be investigated by future model efforts over mountain glaciers.

Table 8: Pearson correlation statistics for all five model domains (n = 9 simulations per domain; 45 total) showing the influence of sliding model parameters on simulated ice volume. Explanation of Pearson correlation values shown in Table 4. ** = p ≤ 0.01.

Domain	q	$U_{threshold}$
Pearson correlation	*Volume*	*Volume*
Santa	0.13	0.16
Vilcanota	-0.90**	-0.25
Kaka & Boopi	-0.94**	-0.24
Copiapó	-0.94**	-0.17
Mendoza, Maipo & Rapel	-0.93**	-0.24
Average	-0.72	-0.15

4.3 Implications and recommendations for future work

https://doi.org/10.5194/egusphere-2025-6169
Preprint. Discussion started: 22 January 2026

The findings here using PISM suggest the less influential parameters mention previously can be excluded from future sensitivity ensembles or parameter optimisation simulations, at least for Andean Mountain glaciers under climates close to present day. This aligns with findings from other PISM-based studies in other contexts (e.g., Albrecht et al., 2020; Candaş et al., 2020; Žebre et al., 2021), which similarly report minimal differences in modelled outputs when E_{SIA}, E_{SSA}, q, and C are varied within reasonable bounds. Their exclusion offers the potential to streamline future modelling efforts on their parameter perturbation selection, reducing computational demands and enabling more efficient ensemble designs. This enables researchers to allocate computational resources toward exploring more influential parameters in greater depth or across broader ranges. Further, some parameters in PISM have historically been left as 'model defaults' and unchanged, based on physical assumptions or field data derived from non-valley glacier environments (or continental scale ice studies), limiting their applicability. Additionally, many parameters have not been explored in-detail within PISM for valley glaciers which, with the reduction in potential parameters to be perturbed, can now be focused on. For example, future work could examine the impact of subglacial hydrology model choices, such as the difference between mass-conserving routing models and the non-conserving null model used here on valley glacier dynamics.

Results from this study demonstrate that ice flow parameters influence simulated ice volume, while for ice area it is mainly unaffected. For applications related to water resources, such as runoff or meltwater estimates, understanding the internal ice physics and associated parameter sensitivities on ice volume is essential to understand how much ice (or water) remains in the future. However, studies that focus on glacier area, or are lacking robust ice volume constraints, should prioritise sensitivity analysis for climatic parameters: in particular, those using PDD models for transient simulations will likely find that climatic parameters exert the strongest control over both ice area and volume.

5 Conclusion

This study investigated the influence of internal ice flow parameters within PISM over valley glaciers across our five Andean domains (8 hydrological catchments) in South America. We examined parameters previously tested in smaller-scale studies, and others identified as influential in different glacial environments. By applying these tests across multiple domains of varying sizes, we evaluated whether sensitivity differed with glacier scale. While the smallest (Copiapó) and largest (Mendoza, Maipo and Rapel) model domains, with the least and most ice respectively, exhibited the most pronounced volume differences, the overall response to parameter perturbations was relatively consistent across all domains.

Of the components assessed, the enhancement factors showed the least sensitivity, producing the least difference in ice volume. Within the subglacial component, the parameters C and W_{till}^{max} saw negligible impact on modelled ice outputs. We therefore

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Preprint. Discussion started: 22 January 2026

suggest that further testing of these parameters is unnecessary for similar valley glacier modelling applications in PISM, especially under climate and glacier conditions close to present day.

The sliding component parameters of the velocity threshold ($U_{threshold}$) and sliding exponent (q), exhibited moderate influence over ice volume. While both impacted ice thickness and velocity, q had the dominant influence when the sliding component parameters were perturbed together. Within the till component, the greatest overall control on simulated ice volume came from the till friction angle (ϕ). This saw the largest differences produced in ice thickness and basal velocities. This underscores the dominant role of basal conditions in valley glacier dynamics within PISM and a parameter that should see further investigation within modelling studies.

Unlike most previous PISM sensitivity studies, which have focused on ice sheets or limited mountain glacier domains, this study systematically examined the influence of internal ice dynamics on valley glaciers in the Andes. Our findings reinforce the need for detailed investigation of subglacial-related parameters, especially basal resistance (ϕ). We also detail continued support for the investigation of the sliding exponent (q) within the Zoet and Iverson (2020) slip law, which was recently implemented into PISM and has not been varied before this study. We also recommend that future studies explore the role of subglacial hydrology models, such as the choice between mass-conserving and non-conserving schemes, and their potential influence on modelled glacier behaviour, and just how this influence may be affected by model resolution.

This work represents the first stage in the glacier modelling workflow of the *Deplete and Retreat* project. The insights gained here will directly inform the design of a Latin Hypercube ensemble by eliminating parameters with negligible impact, thereby refining the efficiency and robustness of subsequent simulations. Our results can inform future sensitivity analyses and optimisation studies for glacier and ice sheet models, enabling researchers to prioritise parameters with substantial impacts on model outputs and avoid testing those with minimal influence. This efficiency can help conserve computational resources while guiding more targeted investigations into parameter effects on modelled ice outputs.

Supplementary Information. Extra information on ice metrics can be found within the Supplementary Information, along with extra figures that detail ice outputs from each domain. An example of the scripts used to conduct the modelling are available at the DOI: 10.5281/zenodo.17878114.

Competing Interests. The authors declare that they have no conflict of interest.

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*Author Contributions***.** JE and EL conceptualised the study. EL collated the model input data and conducted the numerical modelling for the study. EL and JE analysed the model output. EL wrote the first draft. Manuscript comments and edits were provided by all authors.

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